# What is 4-D and how does it improve recovery efficiency

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This first part of a six-part series explains how 4-D was developed, and how any company can take advantage of this new technology. Actual seismic response at various times in the life of a producing field are used to illustrate how 4-D technology is applied. Bypassed production is identified, and improved reservoir management is the end result.

**WHAT IS 4-D?**

3-D seismic surveys became an effective delineator of oil and gas deposits because the full length, width and depth of a subsurface volume was acoustically imaged for the first time. With 2-D seismic profiles, which measured length and depth only, dangers and unpleasant surprises were always lurking between the seismic coverage. The value of 3-D seismic surveys has now been well documented to increase not only the success rates of exploratory drilling, but also recovery efficiencies in old producing properties, e.g., see the *3-D Seismic Atlas* published in 1996 by AAPG and SEG.

## About the series

This series, by the Lamont 4-D Technologies Group, will be about the coming revolution in production management: 4-D Reservoir Monitoring. Articles will appear in *World Oil* throughout 1997, and form the core of a new *World Oil* publication: *The handbook of 4-D reservoir monitoring.*

Tentative topics for future articles in the series are:

- Why use 4-D now?
- Business overview of 4-D
- Benefits of 4-D to oil producers
- Benefits of 4-D to service companies, and
- Remaining technical hurdles to acceptance of 4-D technology.

The handbook will contain an accompanying CD-ROM with color digital images, a Lamont 4-D Software demonstration, and animations of drainage effects on seismic and other reservoir observations over time.

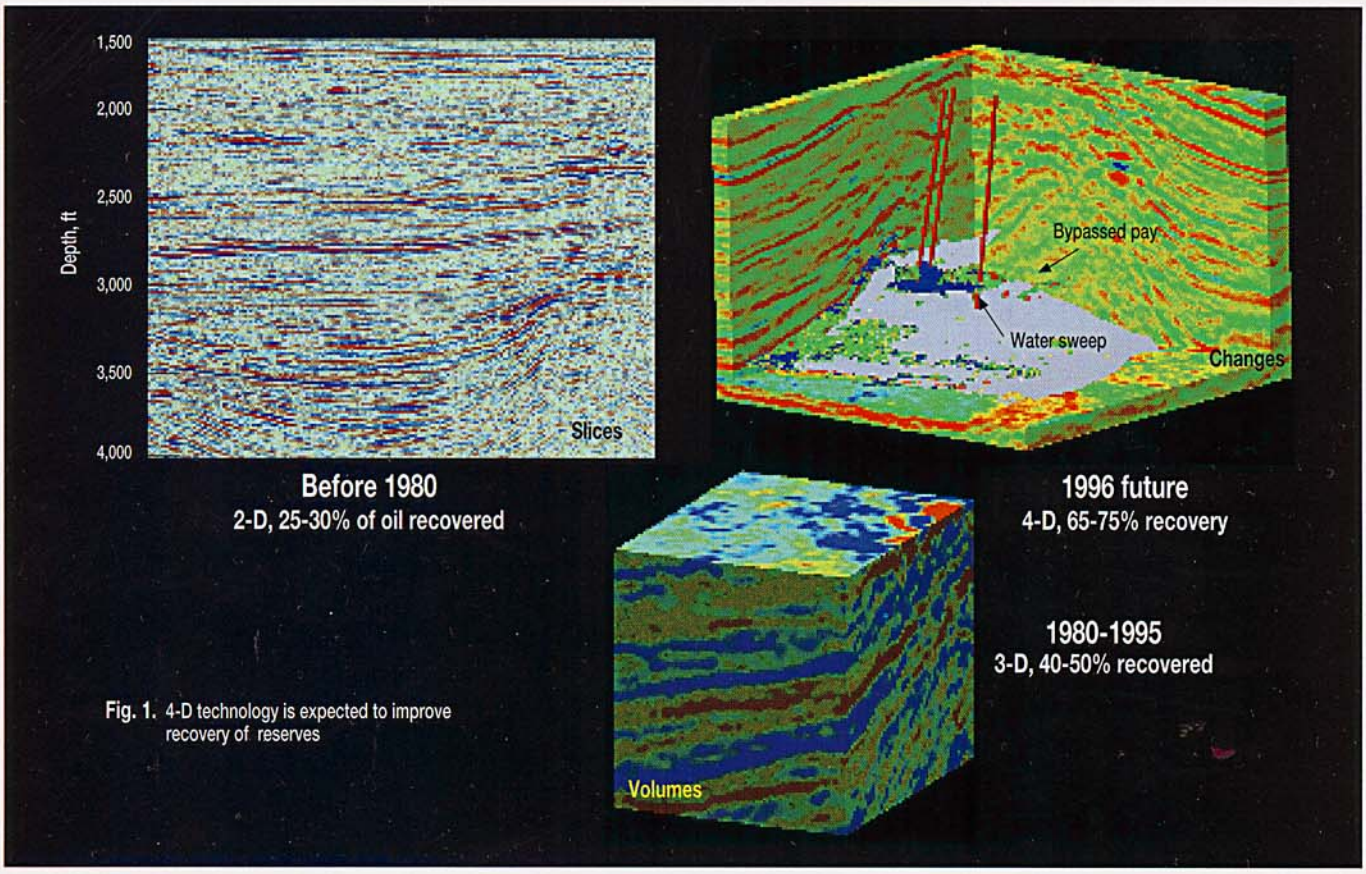


Fig. 1. 4-D technology is expected to improve recovery of reserves

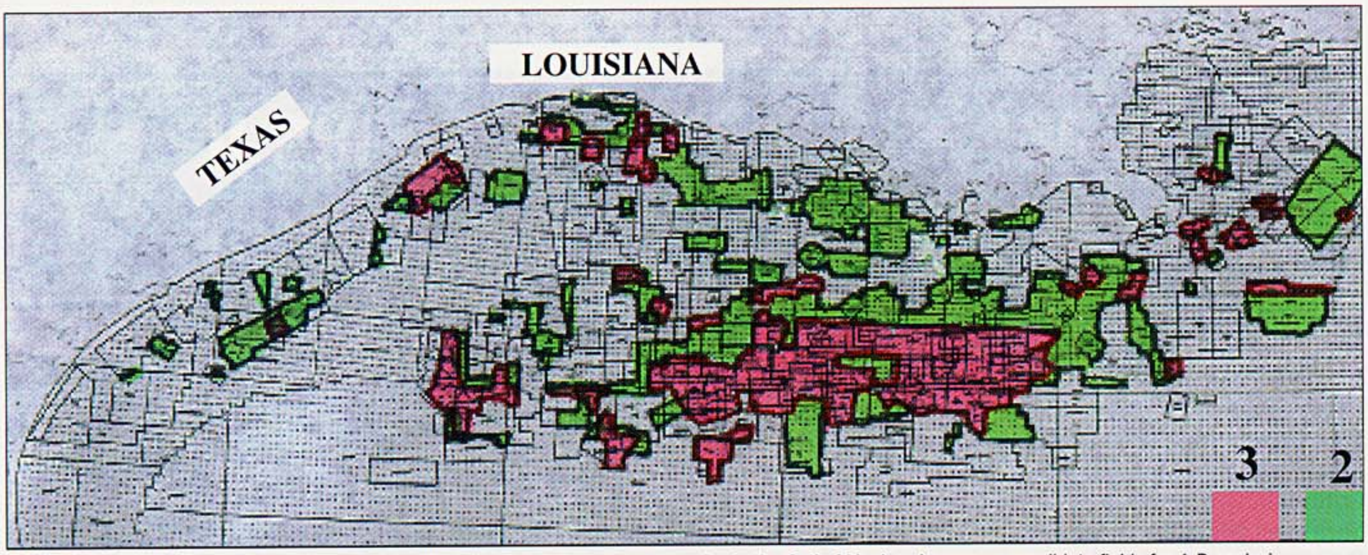


**Fig. 2.** Legacy 3-D seismic surveys recorded by oil companies and service companies in the Gulf of Mexico show many candidate fields for 4-D analysis.

This was a surprising, added bonus to the new 3-D seismic technologies, because the technology was originally conceived only as an exploration tool. What actually happened was, first applications of new 3-D seismic technologies were recorded over "known" oil fields. This enabled oil companies to calibrate the results, and lo-and-behold, seismic evidence of extensive bypassed pay appeared almost immediately.

These first 3-D seismic surveys were, therefore, the first 4-D, or time-lapse, seismic monitoring projects. As often as not, they were also over steam floods where subsurface response could be directly linked to fluid fluxes entering and exiting a field over time. Cased-hole logs have always been 4-D tools used to search for bypassed pay. Cross-hole tomography and well-to-well acoustic imaging were also early 4-D tools because they too were first "calibrated" in producing fields.

Put in a nut-shell, 4-D seismic monitoring is the processing of multiple 3-D seismic surveys acquired repeatedly in the same oil or gas field to observe seismic differences caused by the movement of oil, gas and water in reservoirs over time. The sole missions of 4-D reservoir monitoring are: 1) to identify successful drainage, and 2) to target bypassed oil and gas within reservoirs, with the explicit intent of, 3) drilling new wells to produce new oil from old fields.

The transition from a 2-D to a 3-D "mindset" in the industry has resulted in improved recovery efficiencies, up from the traditional 25–30% of oil-in-place with 2-D control to 40–50% with 3-D coverage (Aylor, Offshore Technology Conference, 1996). BP expects the industry's most ambitious 4-D project in Foinaven, West of Shetlands, to improve those statistics to 65–75% recovery (*Petroleum Engineer International,* February, 1996), Fig. 1.

**What does it take to get into the 4-D game?** From a manager's perspective, 4-D adds: 1) verification of past drainage, and 2) prediction of locations of bypassed pay to be drained in the future, so that 3) revenues can be maximized, and 4) risk minimized over the entire life of a field. A further benefit is accrued through ground-truthing of a field's reservoir simulation so that future production can be better planned.

An obvious requirement for getting into the 4-D game is that multiple 3-D seismic surveys must have already been acquired over the field. Luckily, as the 3-D seismic industry has improved the technology of 3-D acquisition in the last ten years or so, many overlap areas now exist among different vintages of 3-D seismic surveys acquired in the past. We call these "legacy" 3-D seismic surveys.

Offshore U.S., in the Gulf of Mexico (GOM), several thousand blocks have two, and often more, 3-D surveys in various oil and service company databanks of proprietary and speculative seismic data. In active exploration provinces, such as the deepwater and sub-salt plays, it is not unusual to find three or more 3-D surveys ready for 4-D interpretation, Fig. 2.

4-D reservoir monitoring is in the

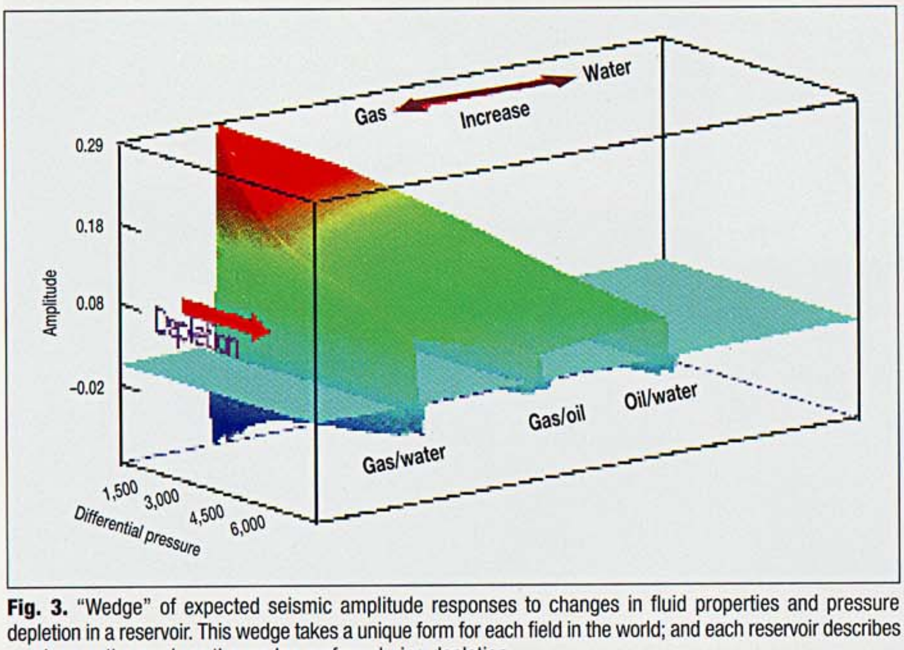


**Fig. 3.** "Wedge" of expected seismic amplitude responses to changes in fluid properties and pressure depletion in a reservoir. This wedge takes a unique form for each field in the world; and each reservoir describes a unique pathway along the wedge surface during depletion.

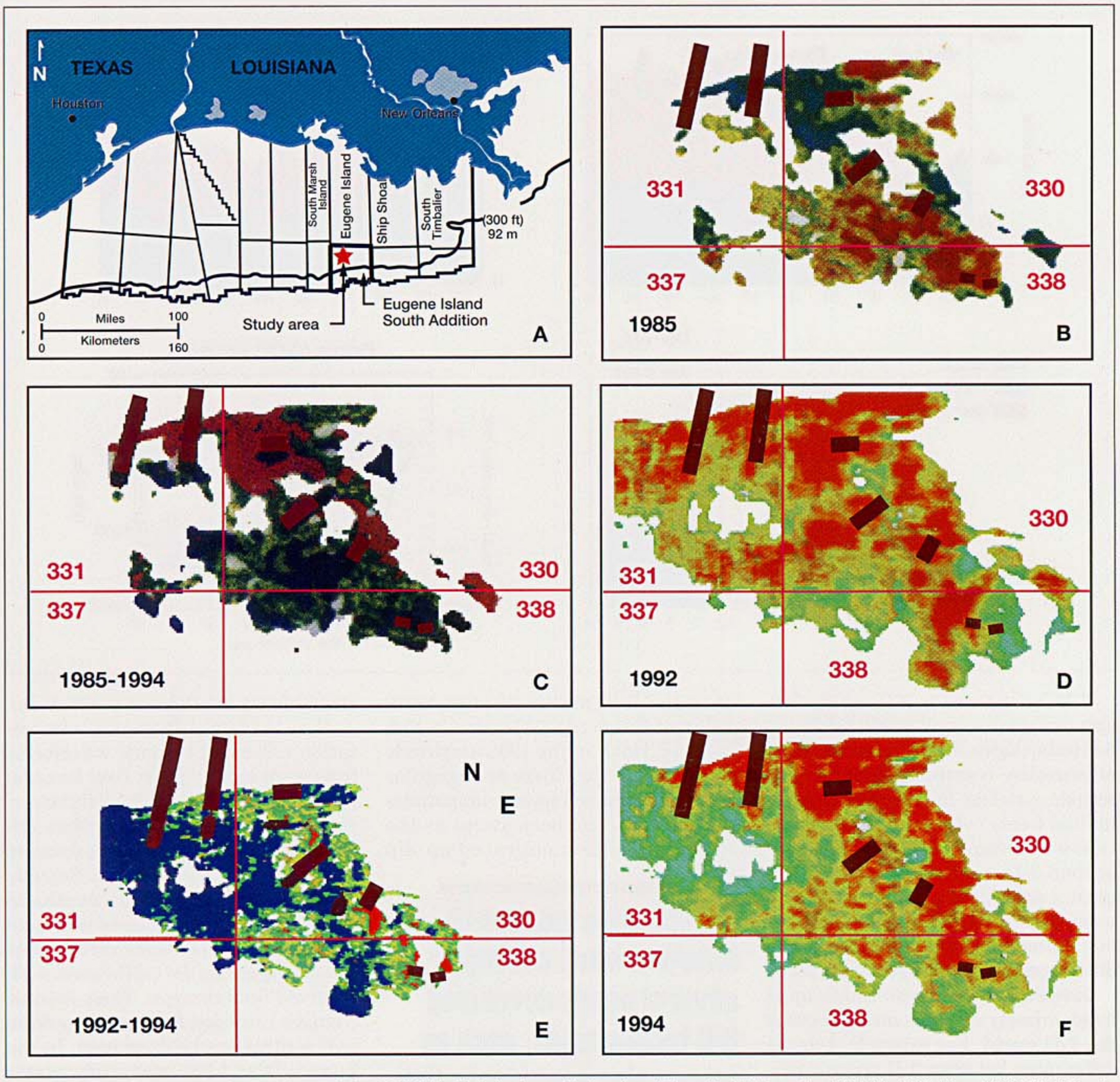


**Fig. 4.** Location of the case study area, Eugene Island 330 field (A). Seismic amplitudes along LF sand in FBA from the 1985 (B), 1992 (D) and 1994 (F) 3-D seismic surveys. Seismic changes in LF sand from 1985 to 1994 (C), and from 1992 to 1994 (E). Red shows increased amplitude, blue is dimmed amplitudes over time, and green indicates sustained, high amplitudes, possibly indicative of bypassed pay.

early stages of market acceptance, and as with most new technologies in the E&P business, integrated major oil companies are now planning and executing most of the 4-D studies ongoing around the world. There are presently about 40 field studies in various stages of development—from nearly finished, to ongoing, to the repeated-acquisition phase, to initial planning for the first 4-D survey. Good summaries of the present state of 4-D exist on our World Wide Web homepage at http://www.ldeo.columbia.edu/4d4, and at the Energy Research Clearing House homepage at http://www.erch.org.

**Geophysics and engineering of 4-D.** First-and-foremost, 4-D seismic monitoring is a fluid-flow problem. The interactions between rock and pore fluids during drainage produces engineering changes in production mixes and pressures that must be rationalized with acoustic changes produced by the same fluid-flow drainage process. This response varies from field to field, and often from reservoir to reservoir—such as between water-drive and depletion-drive reservoirs.

4-D reservoir monitoring technologies actually grew from the monitoring of steam floods and gas injection projects initiated more than 20 years ago. There, the flux of fluids into, as well as out of, the reservoir were known. Where fluids went to and came from were the unknowns.

A 4-D project begins with modeling of expected seismic changes from depletion of pressures, and changes in the oil, gas and water mix, Fig. 3. In some reservoirs, oil drainage produces dimming of seismic amplitudes, as in Fig. 3, a Pleistocene sand reservoir in the GOM. In other fields, oil drainage produces brightening at the oil/water contact, as in the North Sea, and opposite to that shown in Fig. 3.

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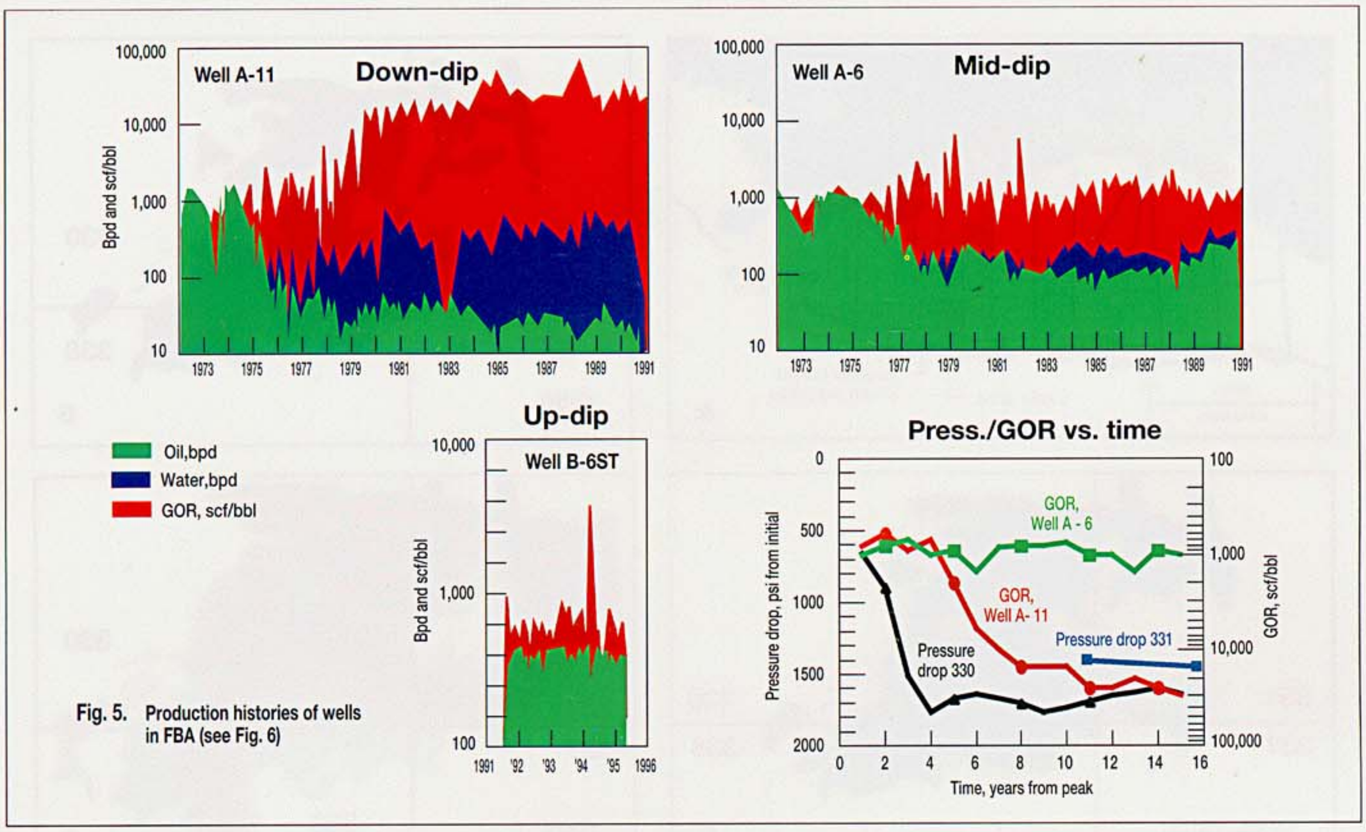


Fig. 5. Production histories of wells in FBA (see Fig. 6)

4-D (as opposed to 3-D) interpretation combines several newly developed 3-D technologies, such as reservoir characterization, reservoir simulation and seismic modeling, to determine changes in fluid fronts over time. 4-D interpretation also requires additional tools beyond 3-D, such as amplitude, frequency and phase normalization software, to better equalize legacy 3-D seismic datasets before similarities and differences can be confidently examined.

However, 4-D interpretation must be seamlessly movable into and out of the 3-D world. For example, seismic differences between 3-D seismic surveys acquired at Time 1 vs. those at Time 2 must be compared to horizon and fault interpretations, and coherency/attribute variations seen within each 3-D survey.

**4-D images drainage patterns.** Consider as a case study, Eugene Island 330 field, offshore GOM, Fig.4. Three different 3-D surveys were acquired over the LF sand in Fault Block A (FBA) in 1985, 1992 and 1994. FBA is a Pleistocene sand about 120-ft thick that dips gently to the West away from a rollover anticline which abuts a classic, Gulf Coast growth fault.

Drainage began in 1972, and by the time of the first 3-D survey, about half of the fault block had already been drained. Remaining oil and gas shows up in the 1985 survey as prominent, coherent "bright spots," shown in red, in Fig. 4. Holes in the 1985 amplitude map indicate that there are irregular areas with dimmed seismic amplitudes that already had been swept as the oil/water contact migrated up-dip

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somewhat irregularly, Fig.4. FBA was re-surveyed in 1992, and again in 1994. The reservoirs have shrunk in volume between those time intervals, as can be seen from Fig. 4; but again, the oil/water contact did not move smoothly up-dip following structure.

Here is where 4-D seismic interpretation comes in. Seismic waveforms from each survey must first be carefully normalized to match all three surveys as closely as possible before differencing can be applied to the datasets to identify areas of change. Seismic changes near perforation depths in wells can then be compared with production histories to make certain that the changes can be calibrated with observed fluid changes. Then, seismic changes recorded farther away from well control can be examined. In the Eugene Island 330 case study: water encroachment is mapped from seismic dim-out (blue); formation of a gas phase causes brightening (red) with time; and, most important, unswept and bypassed oil maintains its high amplitudes over time (green), Fig. 4.

### COMPARISON WITH PRODUCTION.

In Fig. 4, the 1992 survey shows considerable change in seismic amplitudes since 1985. Amplitude increases are mapped along the northern fault boundary far down-dip, and dimming is mapped near the southern property boundary. Production from 1985 to 1992 was from Wells A-11 and A-6 in Block 331, Well B-7 in Block 330 and Wells A-12, A-13 and A-15 in Block 338. About 1.6 MMbbl were produced from these

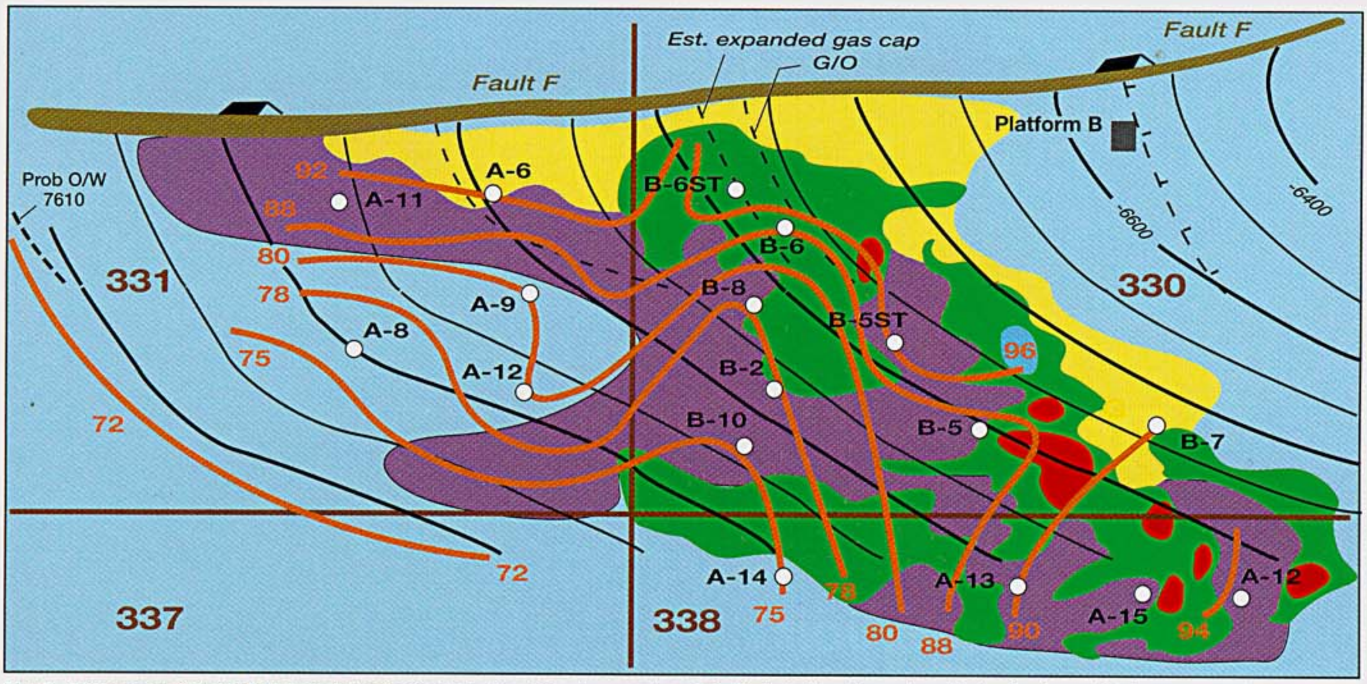


**Fig. 6.** Drainage predicted in FBA from 4-D seismic study. Remaining bypassed pay is indicated at locations where high seismic amplitudes were sustained throughout the 1985–1994 study interval, shown in green. Purple indicates areas that dimmed (drained) between 1985 and 1994, yellow is shown in areas that first brightened, then dimmed between intervals 1985–1992 vs. 1992–1995. Red indicates areas that brightened from 1985 to 1992 to 1994, indicative of secondary gas cap formation.

wells between 1985 and 1994.

Addition of a second time-lapse seismic image of the change from 1992 to 1994 adds considerable understanding to what is happening in terms of acoustic change during drainage of the LF sand in FBA. By 1994, the area down-dip that had brightened between 1985 and 1992, had dimmed. An examination of production histories of the down-dip wells shows that during this interval, the farthest down-dip well, A-11, was producing an order-of-magnitude more gas than mid-dip Well A-6, Fig. 5. Direction of production changes, moving from down-dip to up-dip—decreased gas production and increased oil production—opposite to that expected from completely gravitationally controlled drainage.

Possibly, the area around Well A-11 became brighter between 1985 and 1992 because of the drop in pressure down-dip, which obviously produced more gas coming out of solution in the reservoir at this location. Both wells were being pulled very hard and the downdip gas was produced, rather than being able to migrate updip to form a secondary gas cap. By the time of the 1992 survey, both wells were depleted and shut-in. In 1992, amplitudes in the area of these wells were indeed dimmed.

Between the 3-D seismic surveys of 1992 and 1994, there were only three wells active in FBA, i.e., two new wells drilled in 1992, B-5ST and B-6ST in Block 330 and Well A-12 in Block 338. About 1 MMbbl were produced from these wells during this time interval. By 1992, another bright interval had grown downdip; this time toward the southern block boundary to the southwest, where no wells were producing. This brightness also disappeared by the time of the 1994 survey. It could have already been drained, but further-lowered pressures caused gas to come out of solution down-dip, which by 1994 was gone again from these locations.

The overall drainage pattern in FBA, after reconciling seismic and production changes from 1985 to 1994, is shown in Fig. 6. Considerable high seismic amplitude acreage remains along the up-dip oil rim in 1994, suggesting that bypassed pay remains along the Block 330/338 property line.

Recovery of this bypassed oil will require placement of another well into the fault block; and therein lies the power of 4-D reservoir monitoring. Each new well recovers an additional percentage of the oil-in-place, increasing the field's ultimate recovery efficiency. Through such iterative interpretations, 4-D reservoir monitoring offers the hope of controlling and optimizing oil drainage in real-time, and thus recovering more oil from old fields at a time when the world surely needs these added supplies. **wo**

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