4-C/4-D at Teal South

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In late 1996, Texaco and Input/Output embarked on a novel experiment to test a low-cost 4-C/4-D permanent reservoir monitoring system (PRMS). Western Geophysical and Digicourse were brought into the project to provide data acquisition and positioning services. In July and August 1997, four-component (4-C) data acquisition was performed over 9 km^2 in Eugene Island Block 354 (Teal South), using a dense shot grid (25×25 m). In late 1997, Texaco turned control of the project over to the Energy Research Clearing House and invited industry participation. The consortium remains open to new members.

This article represents a snapshot of the first phase of the project. Acquisition for Phase 2 is planned at about the date of publication.

Background. The 4-D "signal" or seismic contrast in a producing reservoir over time is a function of acoustic impedance changes that result from hydrocarbon production. These changes can be very small and, consequently, the repeatability requirements for 4-D can be very high. Although many projects have succeeded with repeated marine streamer or OBC surveys, the repeatability problems associated with positioning, geometry, and receiver coupling can represent significant barriers to 4-D success in many areas (Figure 1).

The conventional wisdom is that PRMS is expensive; but it should be noted that the incremental cost of future data acquisitions using PRMS might be lower. The cost crossover may occur within 2-3 acquisitions for some surveys; however, in others, the crossover may take 10-20 acquisitions (Figure 2).

The few pioneering PRMS projects of the last few years have had varying success. The main problem has been that the technology has involved modifications of traditional 3-D systems. However, with a traditional 3-D system, one or two channel failures per day may be acceptable. PRMS requires a failure rate at least 100 times better. This would seem a daunting engineering challenge, but several factors make it easier than it appears.

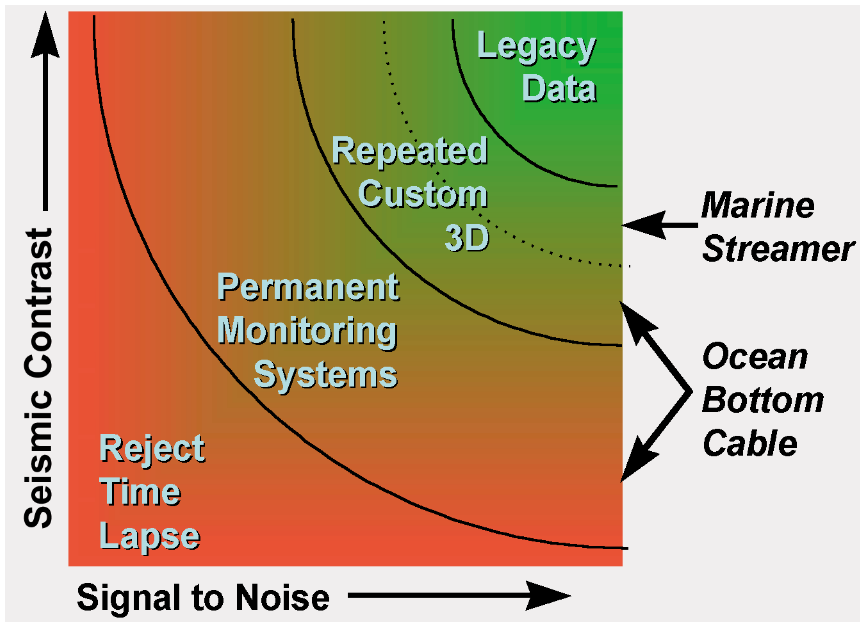

Figure 1. The easiest 4-D problems can be successfully resolved using mismatched legacy data. As the problems get more severe, custom-designed matched surveys become a requirement and OBC becomes increasingly attractive (because it eliminates the nonrepeatability of streamer "feathering"). For the most difficult problems, only PRMS systems can achieve the desired repeatability. (Figure courtesy of Dave Johnston.)

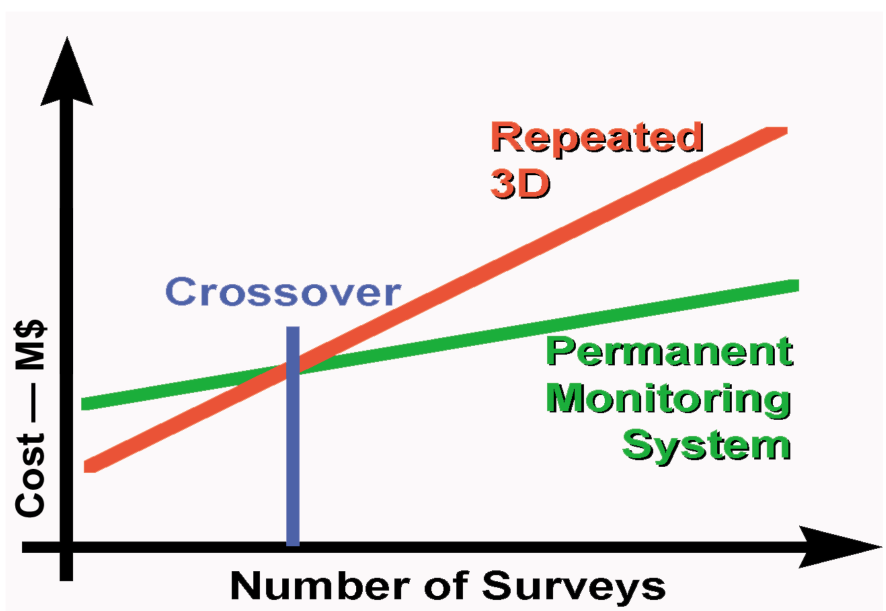

Figure 2. Simplified 4-D cost model.

A 3-D system is designed to be flexible enough to operate in different terrain (Alaska in the winter, Louisiana in the summer) and to be reconfigured to image many different targets. Since a PRMS is designed for a single (usually very stable) environment and will image a small number of known targets, it doesn't require the flexibility built into traditional 3-D systems. Removing connectors and other electromechanical parts from the system massively improves reliability. Furthermore, many traditional 3-D projects are overshot because of the equipment available. If 32-m groups are necessary but only 25- or 50-m systems are available, the operator must accept reduced data quality or overshoot. A PRMS can be designed precisely to a specific purpose, usually resulting in cost savings.

Over the last few years, acquisition equipment manufacturers have significantly reduced 3-D costs by distributing the recording electronics from a central location to the ground equipment. However, for a PRMS, this architecture must be reevaluated. For a PRMS, ground equipment is left in place over each reservoir, whereas the central electronics travel from project to project, allowing cost to be shared among many operators. Consequently, the ideal PRMS might look more like an "old-fashioned" 3-D system than a modern one.

Texaco's Teal South Field is in shallow water (85 m). Its multiple reservoirs (unconsolidated Tertiary sands) produce both oil and gas from depths of 4000 to 8000 ft. This field was chosen as a time-lapse test site because high flow rates and small volumes shorten the production life of its reservoirs to a couple of years. Hence, unlike large low-permeability reservoirs where production can exceed a century, Teal South is a sort of time machine where we can observe reservoir depletion in tens of months. The 4500-ft sand was one of several targets in the time-lapse survey. At the time of the OBC survey (23 July-1 August 1997), the 4500-ft sand had been in production for over eight months and had one of the larger time-lapse changes in the survey area.

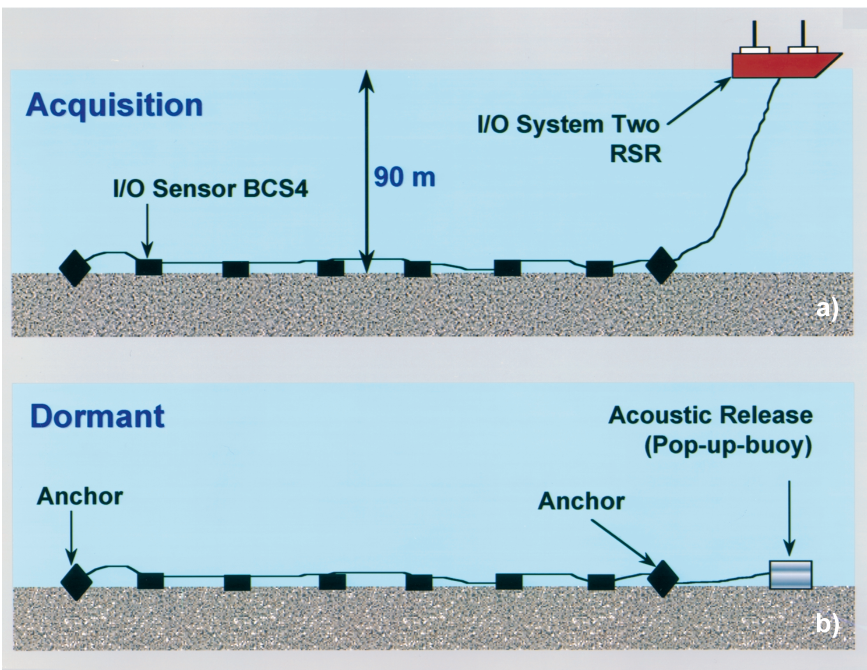

Figure 3. Teal South sensor equipment. (a) During data acquisition, the analog riser cable carries the signals to the surface where the data are recorded in a buoy. (b) In the dormant stage between acquisitions, cables and sensors remain on the ocean bottom. Recording equipment is available for other projects. An acoustic release is attached to the riser cable so that it can be returned to the surface.

Table 1. A comparison of the requirements for a 3-D system and permanent reservoir monitoring system.

	3-D system	Permanent reservoir monitoring systems
Mean time between failures (per channel)	5-10 years	200-1000 years
Number of operating environments	Many (unknown)	1 (known)
Number of geophysical objectives	Many (unknown)	Few (known)
Typical ground equipment (channels) per central electronics	1000-4000	20 000-200 000

Acquisition. In order to minimize the cost of the permanent system, a sparse receiver grid (four lines of six 4-C receiver stations) was deployed. The line interval was 400 m, and the station interval was 200 m. In order to achieve adequate fold, a dense (25 × 25 m) grid of shots was acquired over an area extending 1000 m in all directions around the receiver grid. This produced a full-fold, fully migrated P-wave image of the 4500-ft sand. This geometry also gives a unique receiver gather containing all offsets and all azimuths, allowing extensive examination of source, receiver, and earth anisotropy effects.

The dense shot grid also allowed accurate determination of receiver location and orientation.

Several features were built into the system to minimize costs and to meet the requirements defined in Table 1.

- Dual axis gimbaled sensors allowed inexpensive deployment of the cable by a vessel (without ROVs or divers) while ensuring correct receiver orientation on the ocean bottom.
- Sandbags (under license from ARCO) were used to match sensor acoustic impedance to water bottom acoustic impedance; this improved coupling and reduced noise from turbulent flow over the sensors.
- Orientation determination was made from analysis of first breaks, removing the need for expensive orientation sensors in the 4-C units.
- Lightweight, low-cost cables minimized manufacturing cost, and one-time deployment cost (conventional OBC cables can be very heavy to withstand daily recovery and deployment).
- An analog "riser" cable connected the ocean bottom sensors to a temporary recording system (Figure 3). In a "sealed" system of this type, the transmission line losses in the cables are considered repeatable, and thus negligible in the 4-D context.

The recording equipment was a standard I/O System Two RSR, in which four six-channel recording units were housed in a buoy at the end of each cable. This system stores data in internal memory in the recording buoy, thus removing any requirement for each cable to be hooked up to a recording boat. A conventional radio telemetry system could have been used, but that would pose problems for future commercial scale operations with very high channel counts (due to the requirement for rapid air-gun cycle times with the dense shot grid).

It was decided to use a source with a highly repeatable, high-frequency signature, with minimal directionality. The choice was Seascan's 1120-in^3 Tricluster array of I/O sleeve guns, which was used at a depth of 3 m. This array's sprung rigid frame maintains its geometry at different towing speeds, and is symmetrical in both the in-line and cross line directions.

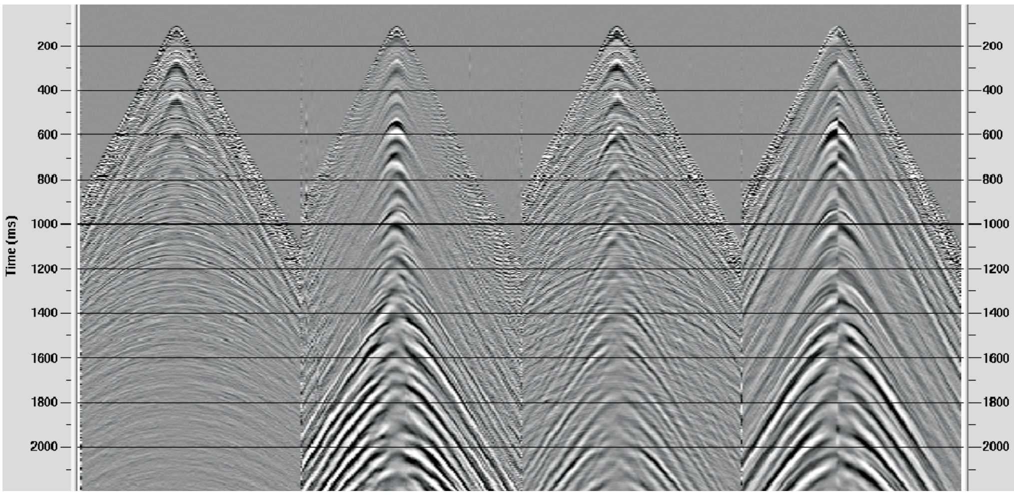

Figure 4. Common receiver gather: (a) hydrophone, (b) cross-line geophone, (c) vertical geophone, and (d) in-line geophone.

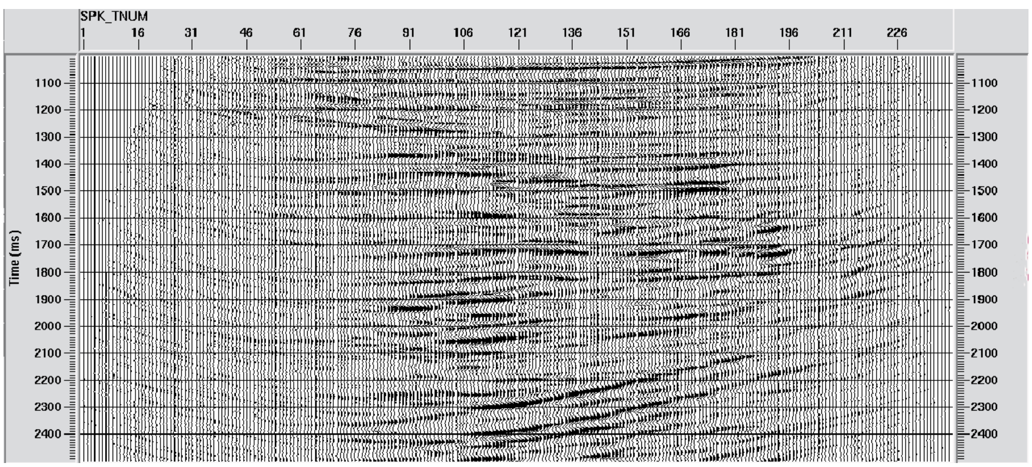

Figure 5. *P*-wave section.

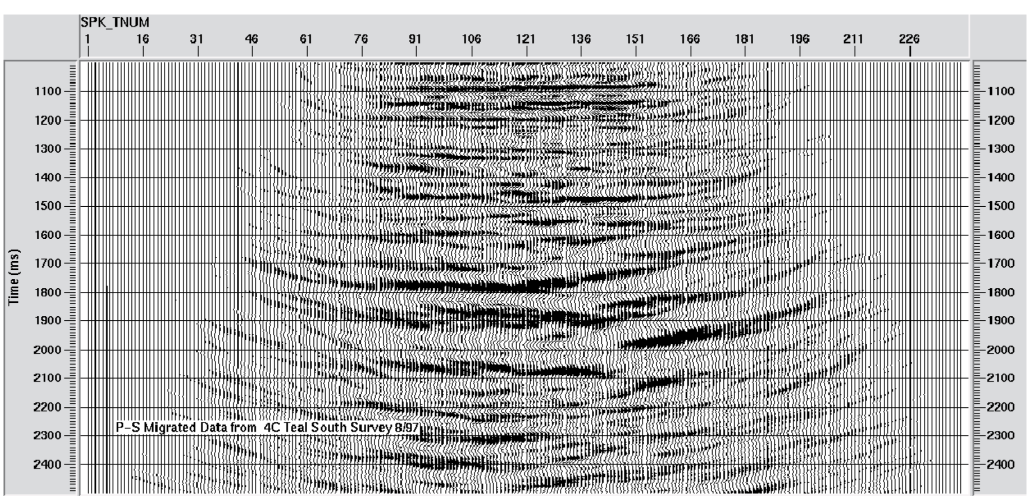

Figure 6. *C*-wave section.

Data acquisition, carried out in calm summer conditions, was relatively rapid and low cost. Cables were deployed by hand from the *Dino Chouest* over 12 hours. Although deployment was quite straightforward, a dynamic positioning system was instrumental in the speed and ease of deployment.

The memory in the prototype recording buoys was sufficient for about 3000 shots, so data had to be collected from the recording buoys at least once each day.

The 25×25 m shot grid meant great care had to be taken to avoid the recording buoys. This created a number of small irregularities in coverage. The 3-D data were successfully acquired without incident. Sadly, recording of a 2-D line (wisely acquired at the end of the survey, but unwisely at night) resulted in an entanglement between a recording buoy and cables with the source array. Surprisingly, the cable proved to be reparable and will be redeployed during Phase 2 acquisition.

Processing and interpretation. Data quality observed in the field was excellent (Figure 4). Initial data processing was a brute prestack depth migration of the 3-D common receiver gathers. The initial results (Figures 5 and 6) are encouraging for both the *P*-wave and *C*-wave (converted wave) sections, but much work remains to be done, particularly with the shear-wave volumes. Although the surveyed area is adequate to image the 4500-ft sand on the *P*-wave section, significant migration artifacts are visible on the *C*-wave section, due to the reduced common conversion point coverage. This coverage will be extended in Phase 2.

At the time of writing, only one OBC data acquisition using the PRMS has taken place. Figure 7 (the difference cube, after subtracting the migrated hydrophone data of the OBC survey from a preproduction streamer survey) shows amplitude changes inferred as production-related in the 4500-ft reservoir. Some noise can also be seen. This can largely be attributed to differences in the acquisition geometries, and the data processing sequence used, notably the velocity analysis. It is hoped that the images will be even clearer when the Phases 3 and 4 data sets are compared in the future.

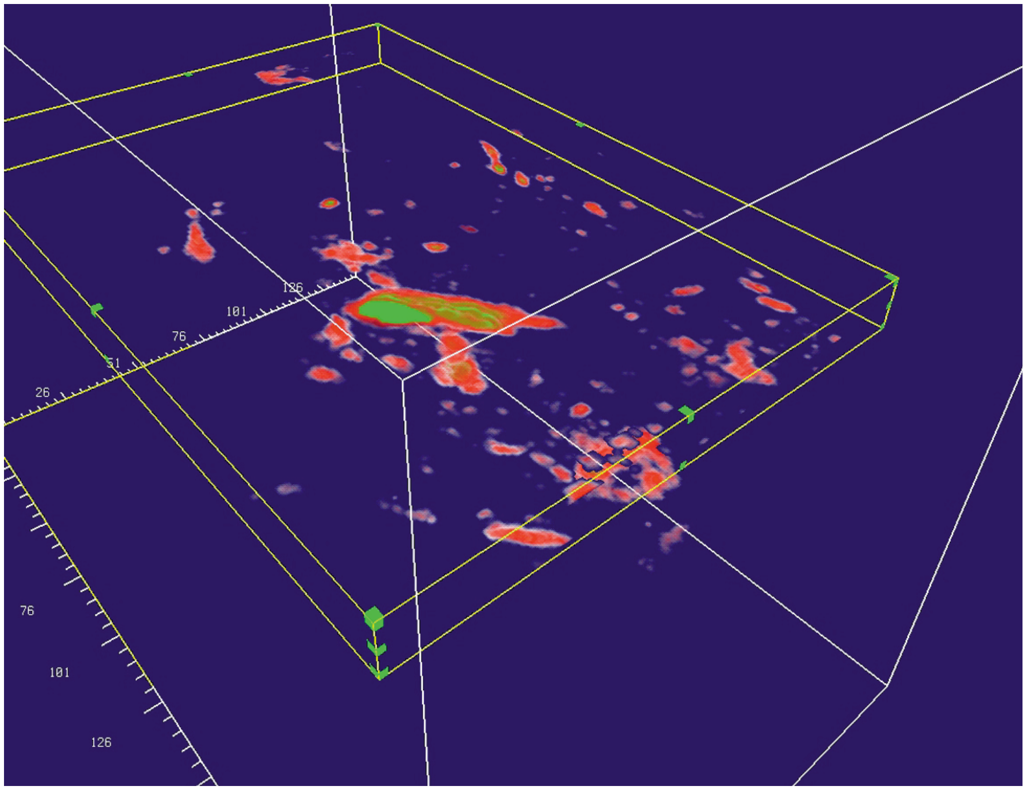

Figure 7. Difference volume. (transparent = little change, opaque red = some change, opaque green = most change).

Conclusions. The Teal South data sets will "benchmark" new reservoir monitoring techniques and instrumentation for many years. The methods used in this research are a first step toward low-cost, high-quality 4-C, 4-D. Although conventional equipment was adapted for test, further improvements in efficiency are likely when custom-designed 4-D systems emerge.

After the initial data acquisition, two of the four cables were lost, presumably to fishing activity. Thus, it is probable that PRMS will require cable burial for long lifetimes, although cable burial does not appear to be required from a data quality viewpoint. Some cables will be buried during the next two phases of the project.

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