The Marlim Field: Incorporating 4D Seismic in Reservoir-Management Decisions

Rildo M. Oliveira, Petrobras

Abstract

Many brownfields have had 4D-seismic technology applied successfully to optimize reservoir production and recovery. This paper describes how 4D-seismic results were incorporated into the geological model and illustrates applications in reservoir-management decisions, thereby mitigating drilling risks in Marlim deepwater turbidite heavy-oil field. It highlights the repositioning of many planned wells and the improvement in the history match by use of the updated geological model.

The Marlim field is off the eastern Brazilian coast in water depths varying from 2,000 to 3,600 ft **(Fig. 1).** The field is the largest producing oil field in Brazil. Three seismic surveys cover the Marlim field. The first was acquired in 1986 and the others in 1997 and 2005. The most recent survey was acquired specifically for reservoir-characterization and -monitoring purposes.

Introduction

The Marlim field was discovered in 1985. The reservoir is an Oligocene/Miocene turbidite with excellent rock characteristics. Relative permeabilities are favorable to water injection, and well productivities are very high (Pinto et al. 2001). The field area is 56 sq miles. The oil gravity ranges from 18 to 24°API, the reservoir-oil viscosity is between 4 and 8 cp, the original pressure was 4,082 psi, and the saturation pressure was 3,769 psi.

Initial oil production from the Marlim field was in March 1991. Water injection started in 1994. Currently, oil production is approximately 390,000 B/D, water injection is 705,000 B/D, and the actual recovery factor is 25%. The water production is 252,000 B/D (bottom sludge and water=39%). A total of 205 wells were drilled in the Marlim field, of which 125 wells are operating—81 producers and 44 injectors. The production peak (615,000 B/D) in Marlim field was achieved in early 2002.

Three seismic surveys cover the field. The appraisal survey was acquired in 1986. A reservoir-characterization survey was acquired in 1997. The most recent survey, in 2005, was acquired specifically for reservoir-monitoring and -characterization purposes (Johann et al. 2006).

__Rildo Oliveira__ is a technical consultant–senior geologist with Petrobras. He has 18 years' experience as a reservoir geologist in Petrobras, and he has worked on many projects involving reservoir characterization and reservoir management in carbonate and sandstone reservoirs. Oliveira earned an MS degree in petroleum geology at the University of Ouro Preto, Brazil.

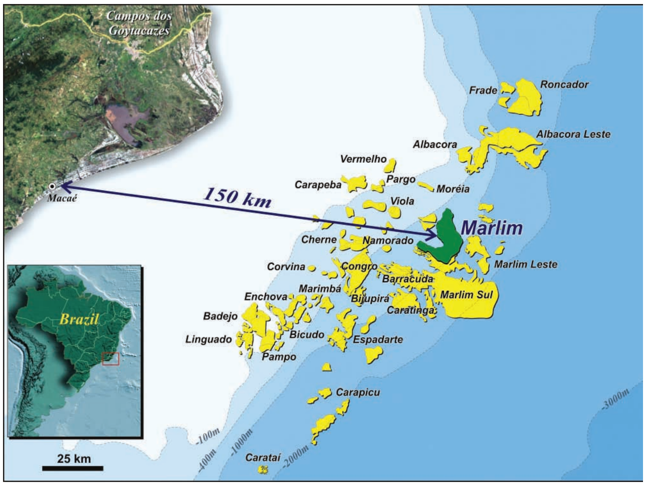

Fig. 1—Marlim field in Campos basin offshore Brazil.

The initial development phase ended in 2002, and a new phase of complementary development is under way. This new phase is characterized by projects of border wells and infill-drilling wells. The 4D seismic was identified as the best technology to minimize risk and optimize the new projects, mainly the infill-drilling projects. A new seismic acquisition, for monitoring purposes, is planned for 2009.

Geology

The Marlim reservoir is part of the lowstand systems tract of a third-order stratigraphic sequence, which is associated with an important eustatic, sea-level fall of approximately 25 million years. The turbidite lobes fill an intraslope, wide depression developed by downslope gliding of underlying Aptian evaporites.

Reservoir facies comprise amalgamated graded beds of poorly consolidated, unstratified, medium- to fine-grained sandstones. Porosities and permeabilities are excellent. All of the sandstone facies are poorly consolidated, poorly sorted, and have average low silt (<10%) and clay (<2%) contents. These sand-rich facies are interbedded with bioturbated mudstones and marls (Bruhn et al. 2003).

This is paper SPE 109336. **Distinguished Author Series** articles are general, descriptive representations that summarize the state of the art in an area of technology by describing recent developments for readers who are not specialists in the topics discussed. Written by individuals recognized as experts in the area, these articles provide key references to more definitive work and present specific details only to illustrate the technology. **Purpose:** to inform the general readership of recent advances in various areas of petroleum engineering.

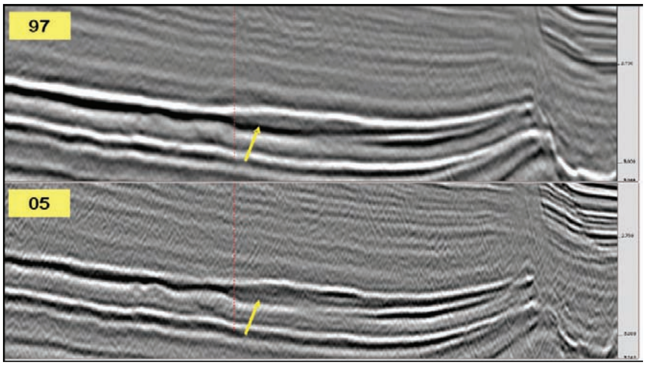

Fig. 2—Seismic section (1997 and 2005) showing the 4D effect at the reservoir base (arrow).

In the Marlim field, at least two active feeding systems resulted in two turbidite systems. The Marlim reservoir was subdivided into nine production zones, mostly on the basis of stratigraphic discontinuities recognized from well logs and cores. The eastern margin of the field is fault-bounded, with the limits of the rest of the field defined by sand pinchout that determines the "zero line" of the reservoir (Oliveira et al. 2005). The reservoirs in this field are partially eroded by a single, 0.5- to 2.5-mile wide, up to 230-ft-deep, northwest/southeast channel.

The majority of the sand-rich reservoirs from the Marlim complex are part of 15- to 200-ft-thick, 1- to 5-mile-wide, and 3- to 7.5-mile-long turbidite lobes. The amalgamation of several lobes can comprise up to 400-ft-thick successions, with a net-/gross-pay-thickness ratio typically ranging from 80 to 100%.

Geological Model for Flow Simulation

The geological model was built by use of the same grid as the simulation model. Cell size was 328×328 ft, with 14 layers. 3D-seismic interpretation characterized the external geometry, separation of the two turbidite systems, and internal faults in the field. Very good well control exists in the Marlim field (205 well controls to estimate the reservoir top).

The porosity, gross pay, and net-/gross-pay-thickness ratio were mapped for each layer from the well-log data. Permeability was mapped with data obtained from the drill-stem test (DST). The initial water-saturation values were taken from well logs over each stratigraphic zone. Shales and marls were mapped deterministically and were introduced in the simulation model as a transmissibility matrix. The main uncertainties in the geological model that have a strong effect on history matching are permeability distribution and the occurrence of deterministic shales.

Incorporating 4D Seismic Into the Geological Model

The new seismic survey was aimed at better reservoir characterization and monitoring. In terms of reservoir characterization, benefits were gained mainly in the south area of the field, with improved separation of the two turbidite systems (vertical-resolution improvement). In general, the new seismic interpretation did not improve interpretation of the reservoir's internal geometry. However, in terms of monitoring, several benefits were achieved, which are outlined below. Even before the 4D processing, a 4D effect was observed in comparing the seismic data of 1997 and 2005, as illustrated in **Fig. 2.**

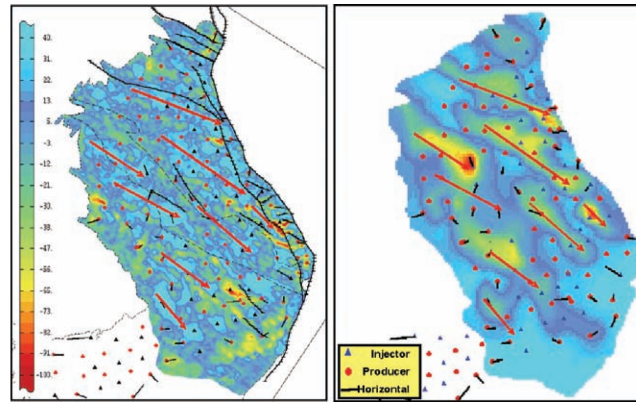

Fig. 3—Left: amplitude-difference map of the reservoir base between 2005 (monitor) and 1997 (base). Light blue=high oil replacement by water. Right: an absolute-horizontal-permeability map derived from 4D imaging and permeability from the DST.

Although the 2005 seismic data have higher frequencies, at a 20-dB signal/noise ratio, the usable frequency was 20 Hz for 1997 and 2005 seismic data. One of the most important contributions of the 4D-seismic interpretation for the geological modeling was to characterize absolute-horizontal-permeability trends for Turbidite System 1. Analyzing the 4D amplitude-difference [1997 (base) –2005 (monitor)] map at the reservoir base, an important anisotropy was observed in water displacement around the reservoir base **(Fig. 3).** This anisotropy was introduced into the absolute-horizontal-permeability maps of the lower zones in Turbidite System 1, and the history match of the field was improved by use of the more-realistic geological permeability maps.

Before updating the geological model by use of the 4D results, good history match existed, but to get it, the engineer spent more than 1 year fitting the data and had to introduce major changes in the original absolute-horizontal-permeability distribution, resulting in a true "geological monster" after the fitting **(Fig. 4).** This stratagem introduced into the model made it unreliable and increased management-decision risks.

By use of the absolute-horizontal-permeability distribution derived from the 4D-seismic data, as shown in **Fig. 5,** history matching improved without many changes in the original permeability map, yielding a more reliable model. Also, the time spent in history matching was reduced to 3 months (note that advantage was taken of the work in the previous model).

Detailed mapping of the faults and lineament was incorporated into the geological model. 4D-seismic amplitude-difference maps also revealed the existence of some sealing or partially sealing faults **(Fig. 6).** Before 4D-seismic interpretation, only 14 internal faults had been mapped. Now, 33 such faults have been mapped in the Marlim field. The faults have insignificant throws and were mapped with the 1997 and 2005 seismic data.

To illustrate the importance of sealing or partially sealing faults in the history matching of the Marlim field, a case showing the fitting of Wells P1 and PH1 is presented. These wells are inside the erosive channel close to two faults. A

(cont'd. on page 107)

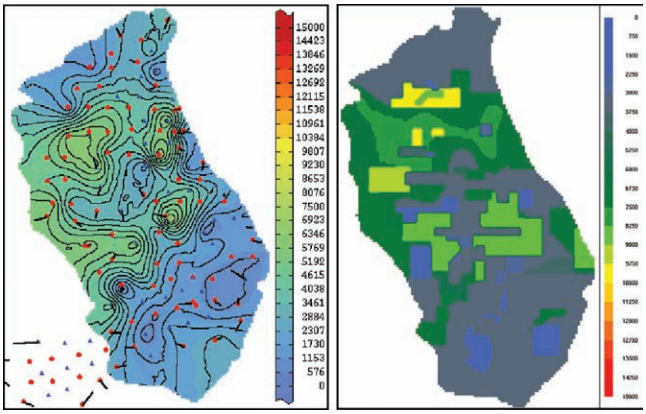

Fig. 4—Left: original absolute-horizontal-permeability map from permeability data from the DST. Right: the same map changed after the history matching but before 4D-seismic interpretation.

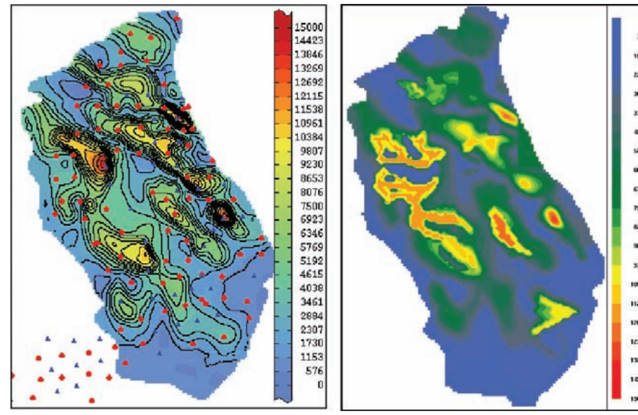

Fig. 5—Left: an absolute-horizontal-permeability map from the 4D-seismic anomalies. Right: the same map after 4D-seismic results were integrated and after history matching.

good history match was never achieved for these wells. However, looking at the importance of some sealing or partially sealing faults, an attempt was made to decrease the transmissibility of the faults near these wells with very good results, as illustrated in **Fig. 7.**

Application in Reservoir-Management Decisions

In the current phase of the field, approval has been received to implement six new well-drilling projects. These projects were defined before the 4D-seismic interpretation, but four of these projects could benefit from that interpretation. Another well was drilled recently, with five wells now drilled after 4D-seismic interpretation.

Two wells were drilled near the borders, in thickness of approximately 66 ft, and showed the presence of only oil, as indicated by 4D-seismic image. In addition, two infill wells were drilled, and the 4D-seismic interpretation indicated the existence of water at the reservoir base and oil at the top. Both wells were drilled in a region of 295-ft thickness, and there was an oil/water contact indicating a water zone at reservoir bottom. **Fig. 8** shows one of these wells.

The 4D-seismic interpretation also led to a change in position of one injector well because of the presence of a sealing or partially sealing fault. Only after starting injection in this well can the transmissibility of this fault be evaluated, but the well confirmed the 4D data that indicated the presence of only oil at this location, drilled in a region of approximately 197-ft thickness.

The main application expected in the near future for 4D-seismic interpretation is to reduce the risk of 13 locations in a new project of the complementary development phase of Marlim field (Phase 3). The new geologic model, incorporating the 4D-seismic data and the new simulation model (with an improved history match), resulted in two wells being canceled. Also, many of these locations were repositioned slightly—nine locations were optimized, and one location had a major repositioning in view of water indications shown in 4D-seismic interpretation. **Fig. 9** illustrates a 4D-seismic-interpretation-oriented repositioning of one location because of indications of high water saturation (light blue) in the well's previous position.

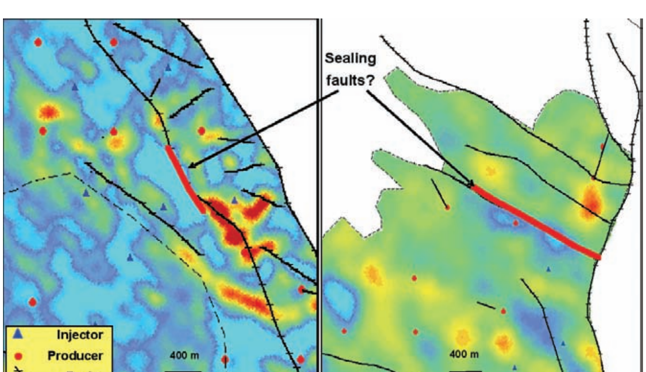

Fig. 6—Amplitude-difference map of reservoir base (left) and top (right), showing sealing or partially sealing faults. Dominant swept areas are shown in blue.

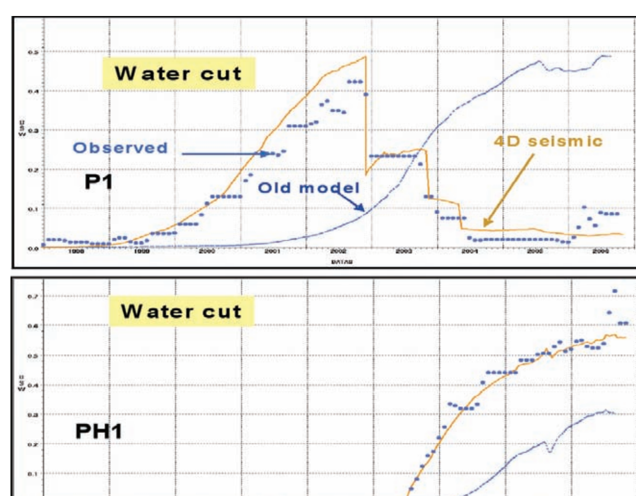

Fig. 7—Water-cut history matching of Wells P1 and PH1. The curve in blue is the fitting before 4D seismic, and the curve in orange is the fitting with the new horizontal-permeability map and the partially sealing faults derived from 4D-seismic interpretation.

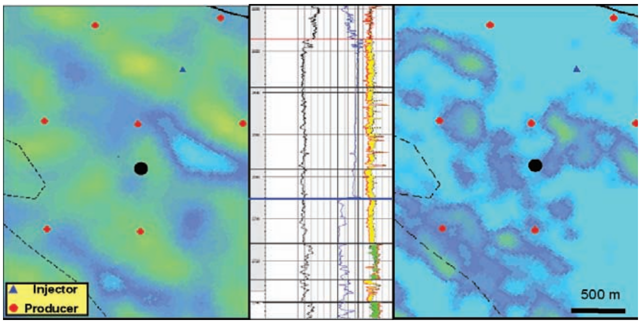

Fig. 8—4D-seismic amplitude-difference maps from top (left) and base (right). At the location (black point), the 4D-seismic-interpretation maps indicate water saturation at reservoir base and oil at top (light blue=high water saturation). The drilled well confirmed this, and the oil/water contact is drawn as a blue line on the log.

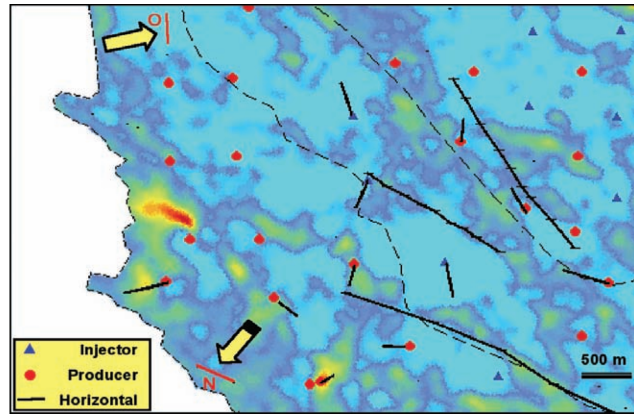

Fig. 9—4D-seismic amplitude-difference map for reservoir base showing the repositioning of one location from the Position O to Position N because of the high water saturation at O (light blue).

Comparing the simulation results of Phase 3, before vs. after 4D-seismic interpretation, it was observed that the net present value of the project doubled, the total oil production increased 4.76% (the number of wells to be drilled decreased from 13 to 10), and the production per well increased 24%. Most of this improvement can be attributed to the 4D-seismic-interpretation results that canceled two wells and caused the repositioning of many others.

Another application of the 4D-seismic interpretation was identification of a confined overpressured region, probably because of subseismic faults **(Fig. 10).** The confined region was confirmed by a recently drilled well that indicated an overpressure of approximately 427 psi above original pressure.

In areas with many producer and injector wells, the history matching could be improved by use of 4D-seismic data because these data indicate the source of water that reaches the producer. **Fig. 11** illustrates such a case. Before use of 4D-seismic interpretation in the simulation model, the water in producing Well P3 was shown as coming from Injector I1 (Fig. 11). However, the 4D-seismic interpretation showed that the water comes from Injector I3.

Another interesting observation in Fig. 11 is the high water saturation close to Injector I4 in the simulation model. This high water saturation is absent in 4D-seismic imaging and was not understood. Recently, it was observed that because of operational problems, Injector I4 did not inject the amount of water reported in the data base and used for simulation. This well and others inject through a manifold, and Injector I4 was not injecting.

With the 4D-seismic imaging, it was possible to recognize a secondary gas cap like the one presented in **Fig. 12** and confirmed by a previously drilled producer, Well P4, and by the production of a horizontal well, Well PH3, for which production was limited by a high gas/oil ratio. A new horizontal injector well in this area near the border allowed Well PH3 to produce without a rate limitation, thus increasing this well's production by approximately 15,000 B/D.

The amplitude-difference map for the reservoir top and base show the presence of water in the region of Injector I6 and Producer P6 **(Fig. 13).** These wells are in a region with thickness greater than 213 ft. Changing the perforated interval in the injector well, along with the presence of continu-

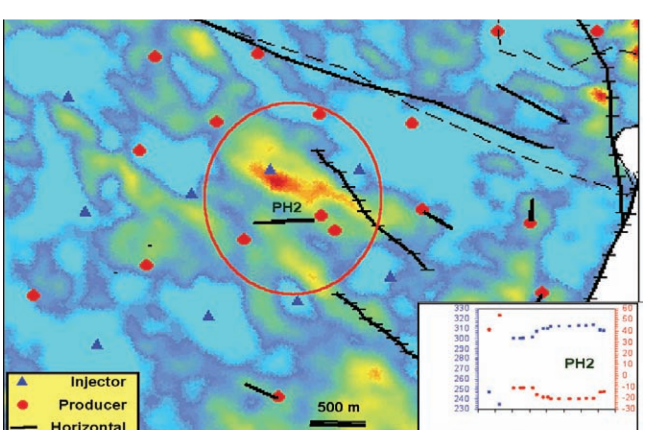

Fig. 10—4D-seismic amplitude-difference map for reservoir base showing a probable confined region. Well PH2 indicated an overpressure of 427 psi in the repeat formation test performed in the pilot well.

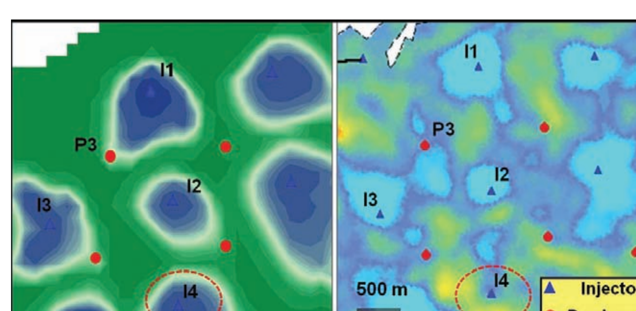

Fig. 11—Water-saturation map of simulation before 4D (left side) shows the water in Producer P3 coming from Injector I1. The amplitude-difference map for reservoir base (right) shows the water in Producer P3 coming from Injector I3, instead.

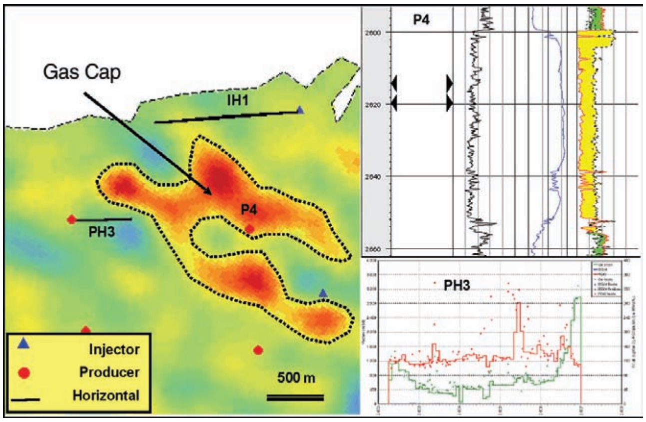

Fig. 12—Secondary gas cap identified in the 4D-seismic amplitude-difference map of the reservoir top. The log of Well P4 at the top shows the gas cap when the well was drilled. The production history of the horizontal well, Well PH3, is shown at the bottom. The increased oil production in Well PH3 (green curve) is seen after drilling Injector IH1.

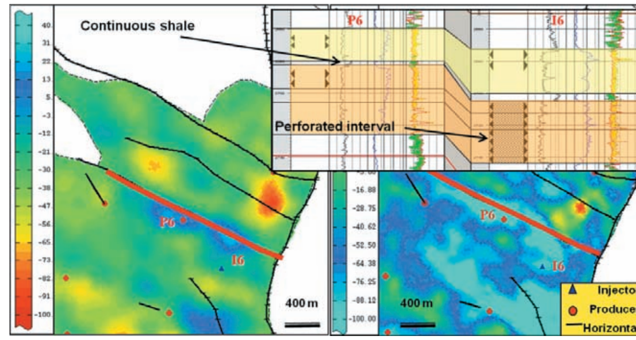

Fig. 13—Amplitude-difference map for reservoir top (left) and base (right) indicating water between Producer P6 and Injector I6. The presence of water at reservoir top results from the presence of a continuous shale and the positioning of the perforated intervals.

ous shale between the injector and the producer, explains the presence of water at reservoir top. Initially, water was injected below the shale and then, above the shale. The producer well is perforated above and below the shale. If the shale was not continuous between the wells, the water injected above the shale would migrate down by gravity, and there would not be an anomaly in the 4D-seismic data indicating water at the reservoir top. Then, the 4D-seismic indication of water at reservoir top and base confirmed the presence of heterogeneity between the wells and channeling of water above the shale.

One of the best applications of 4D-seismic data was the possibility to obtain a more reliable model that decreased the risk of the existing and new projects. The model resulting from introducing 4D-seismic interpretation into the simulation is more realistic, and the geologic maps were not changed extensively after history matching. Therefore, the forecasted production curves are trusted more.

The main difficulties in interpreting 4D-seismic data were choosing the correct color palette to reproduce the seismic anomalies and selecting the areas in which the 4D-seismic data can be used. Therefore, it is important to combine the 4D-seismic data with information such as saturation logs, tracers, and good reservoir data including measurements of oil, gas, water, and pressure.

Conclusions

The use of 4D-seismic imaging in the Marlim field enabled detecting the movement of oil, gas, and water through a reservoir. It allowed improved static and dynamic modeling and provided more confidence to predict future reservoir behavior, thus reducing risk in the existing projects. It also helped to locate bypassed reserves and optimize placement of infill-drilling wells.

After 4D-seismic interpretation, five wells were drilled confirming the 4D-seismic indications. Also, a secondary gas cap, a confined region with overpressure, and heterogeneities were identified by 4D data and confirmed by production and well data. Many well locations were repositioned because of water indication and the presence of sealing faults. In addition, permeability maps were improved because of the pattern of water displacement shown by 4D-seismic imaging.

In other words, the 4D seismic was a valuable tool in reservoir management, requiring a multidisciplinary integration (geophysics, geology, and engineering) to ensure the full use and success of this technique. However, the information provided by 4D seismic must be coupled with additional information such as saturation logs, tracers, formation testes, and pressure. Particularly, additional work is needed in recognizing 4D-seismic signatures for tuning particular areas.

These studies were based on 4D-difference maps between the 1997 and 2005 acquisitions. Preliminary analyses of 4D acoustic inversion show similar results. The 4D elastic inversion is ongoing, and it can provide a better understanding of pressure and saturation effects. In addition, a synthetic-seismic model is being generated from simulator output to confirm the improvements obtained by incorporating 4D-seismic interpretation in the history-matching process.

Acknowledgments

Collaborators on this paper were Dirceu Bampi, Rui C. Sansonowski, Nier M.S. Ribeiro Júnior, Paulo R. Schroeder Johann, Marcos S. dos Santos, and Deise M. Ferreira. The author would like to thank Petrobras for granting permission to publish this paper and PRAVAP 19 for its support to the reservoir-oriented applied-seismic reservoir-research projects in the Marlim field.

References

Bruhn, C.H.L., Del Luchesse, C., Gomes, J.A.T., and Johann, P.R.S. 2003. Campos Basin: Reservoir Characterization and Management—Historical Overview and Future Challenges. Paper OTC 15220 presented at the Offshore Technology Conference, Houston, 5–8 May.

Johann, P.R.S., Thedy, E.A., Gomes, F.G., and Schinelli, M. 2006. 4D Seismic in Brazil: Experiences in Reservoir Monitoring. Paper OTC 18400 presented at the Offshore Technology Conference, Houston, 1–4 May.

Oliveira, R.M., Ribeiro, N.M. da S. Jr., Johann, P.R.S., Júnior, L.F.C., Steagall, D.E., Kerber, P.A., and Carvalho, M.R.J. 2005. Using Seismic Attributes To Estimate Net Thickness in Pinch-Out Areas: Marlim Deepwater Turbidite Field, Campos Basin. Paper SPE 94913 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, 20–23 June. DOI: 10.2118/94913-MS.

Pinto, A.C.C, Guedes, S.S, Bruhn, C.H.L., Gomes, J.A.T., de Sá, A.N., and Netto, J.R.F. 2001. Marlim Complex Development: A Reservoir Engineering Overview. Paper SPE 69438 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Buenos Aires, 25–28 APRIL. DOI: 10.2118/69438-MS. **JPT**