SHEAR-WAVE TOMOGRAPHIC IMAGES OF AN OIL RESERVOIR AT M.I.T.'s MICHIGAN TEST SITE

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ABSTRACT

We conducted a P- and S-wave crosswell survey with Conoco's orbital vibrator source and three-component receivers at M.I.T.'s Michigan Test Site. The receiver and source wells bracket a known oil reservoir. Applying a nonlinear crosswell traveltime tomography method, we reconstruct the velocity structures in the oil reservoir using P- and S-wave data separately. The P-wave tomogram shows a similar image to the one by Matarese (1993), and it does not present much velocity variations in the oil producing zone. However, the S-wave tomogram clearly shows the image of the reservoir zone, which is characterized with low velocities in a pinnacle reef. The S-wave velocities in the reservoir are about 20% lower than those of the surrounding carbonates.

INTRODUCTION

The Earth Resources Laboratory (ERL) at M.I.T. operates two research wells in the Michigan basin, near Traverse City. The two wells—Burch and Stech—bracket a pinnacle reef, a known oil reservoir, producing through a well owned by Shell Petroleum (see Figure 1). For the past 19 years, Shell Petroleum has obtained nearly 1 million bbls of oil from the reservoir. Over the years, ERL/MIT has acquired a variety of seismic data sets over the pinnacle reef, including a 3-D reflection survey, VSP and crosswell experiments. In 1990 and 1991, BP America Inc. acquired crosswell P-wave data using a piezoelectric source and hydrophone at M.I.T.'s Michigan test site (Lee *et al.*, 1992). Applying a nonlinear traveltime tomography method, Matarese (1993) inverted BP's crosswell data to reconstruct a tomographic image of the reef. All of these previous results, within their limits of resolution, provide us with knowledge of the reef. However, most of them present a view of the carbonate layers (A1 Carbonate, A1 Evaporite, A2 Carbonate, A2 Evaporite) that overlay the reef, but with little or no knowledge of the reef material itself. While this is sufficient for the exploration phase (i.e., finding the reef), it does not help in reserves estimation or reservoir development.

In 1995, we conducted the second crosswell experiment at the test site with Conoco's orbital vibrator source and three-component receivers. The source is sufficiently powerful for a recording range up to 4,000 ft. Its frequency range is between 70 and 380 Hz. This source can be decomposed into one that is "inline," i.e., in the plane containing the two boreholes, and another one that is "crossline," i.e., perpendicular to that plane. Therefore, the source can generate both P- and S-wave energy. Figure 2 shows the H-1 component recording from an inline source in which P waves dominate, and the H-2 component recording from a crossline source which shows SH waves. The receiver is at a depth of 4,936 ft.

The design of the optimal acquisition parameters became an important issue prior to the crosswell experiment in 1995. The goal of the survey was to image the oil producing zone beneath the A1 Carbonate. Therefore, we had to generate steep ray paths such that energy actually penetrates the producing zone instead of propagating across the region as head waves in the A1 and A2 carbonates. Using the P-wave velocity model from Matarese (1993), we applied a raytracing method to design optimal source and receiver geometries for a better ray coverage in the target zone (Chauvelier *et al.*, 1996). This led to a decision that applies smaller source and receiver spacings near the top and bottom of the survey zone.

In this paper, we present a new crosswell tomography method and its application to the crosswell data acquired in the 1995 experiment. Both P- and S-wave tomograms are reconstructed, and the results clearly show the image of the oil reservoir, which is characterized with low velocities. The S-wave image of the reservoir seems better resolved, because of larger traveltime delays through the reef.

NONLINEAR TRAVELTIME TOMOGRAPHY METHOD

We apply a rapid structure-driven wavefront method (Zhang and Toksöz, 1996) to calculate P- or S-wave traveltimes for a given velocity structure. The approach applies graph theory to expand a wavefront from the source and calculates traveltimes through the entire model. It accounts for many wave effects such as diffraction and head waves. Prior to raytracing, we calculate the spatial derivatives of the model and generate sparse traveltime nodes in the model grid by eliminating the nodes where the derivatives are too small. This procedure helps reduce computational efforts and increases calculation accuracy.

We solve a regularized nonlinear inverse problem. In particular, we invert traveltime curves by fitting both traveltimes and their derivatives. Specifically, we minimize the following objective function,

$$\Phi(m) = (1-\omega)\|d - G(m)\|^2 + \omega\|D_x(d - G(m))\|^2 + \tau\|R(m_0 - m)\|^2 \qquad (1)$$

where d is traveltime data; m is the model parameter, $G(m)$ is the calculated data; D_x is a derivative operator; $D_x(d)$ gives traveltime derivatives with respect to distance; R is a regularization operator (we chose it to be a Laplacian operator); m_0 is an *a priori* model where we put sonic log constraints; ω is a data weighting parameter; and τ is a trade-off parameter for regularization. To minimize the above objective function, we apply a nonlinear Conjugate Gradient Method.

Numerical experiments show that inverting traveltime curves rather than traveltimes gives a more meaningful data fit and maintains a wave resolution as it is implied in the data (Zhang and Toksöz, 1996).

IMAGING THE OIL RESERVOIR

To image the oil reservoir using P- and S-wave data collected from M.I.T.'s research wells, we apply the nonlinear traveltime tomography method to invert P- and S-wave velocities separately. The purpose of separate inversions is to understand the independent information of reservoir structure in each type of data. In this study, we used 12,400 P- and S-wave first arrival traveltime picks out of a possible 62,000 for the array of 200 sources by 155 receivers. Therefore, the current results are preliminary.

With a grid spacing of 15 ft, we grid the image area (2,100 ft × 3,015 ft) with 141×201 cells. In addition to the traveltime data, full waveform sonic logs from receiver and source wells provided slowness information along the borehole trajectories. We construct an *a priori* model m_0 with this additional information included, and apply it to the inversion as described in equation (1). Matarese (1993) inverted P-wave traveltime data that were acquired during a crosswell experiment in 1993 at the same site and constructed an image from depth 3,500 ft to 5,500 ft. To make a starting model for P-wave traveltime inversion, we extend his image on the basis of well logs to a range of depths from 3,285 ft to 6,300 ft, and replace the image at depths from 4,500 ft to 5,500 ft with a constant velocity. The starting model for S-wave inversion is created by scaling the initial model for P-wave inversion with a factor of 1/1.73.

Figure 3 shows the inversion results. Both P- and S-wave tomograms clearly show a low-velocity zone in the reef. This low-velocity image did not appear in the previous tomogram constructed by Matarese (1993). In particular, the S-wave velocities in the zone are about 20% lower than those of the surrounding carbonates. We found this low-velocity image area well corresponds to a porous and permeable reservoir that was inferred from Shell's log data. The porosity in the reservoir is about 10%. Currently this reservoir zone is mostly saturated with water, and oil production is in the late stage.

CONCLUSIONS

The crosswell experiment in 1995 at M.I.T.'s Michigan test site successfully provided P- and S-wave data for high-resolution tomographic imaging. We owe this success to Conoco's orbital vibrator source and three-component receivers, and also to the optimal survey design and new tomography approach. The tomographic images gave us a new look and new understanding in the reservoir.

ACKNOWLEDGMENTS

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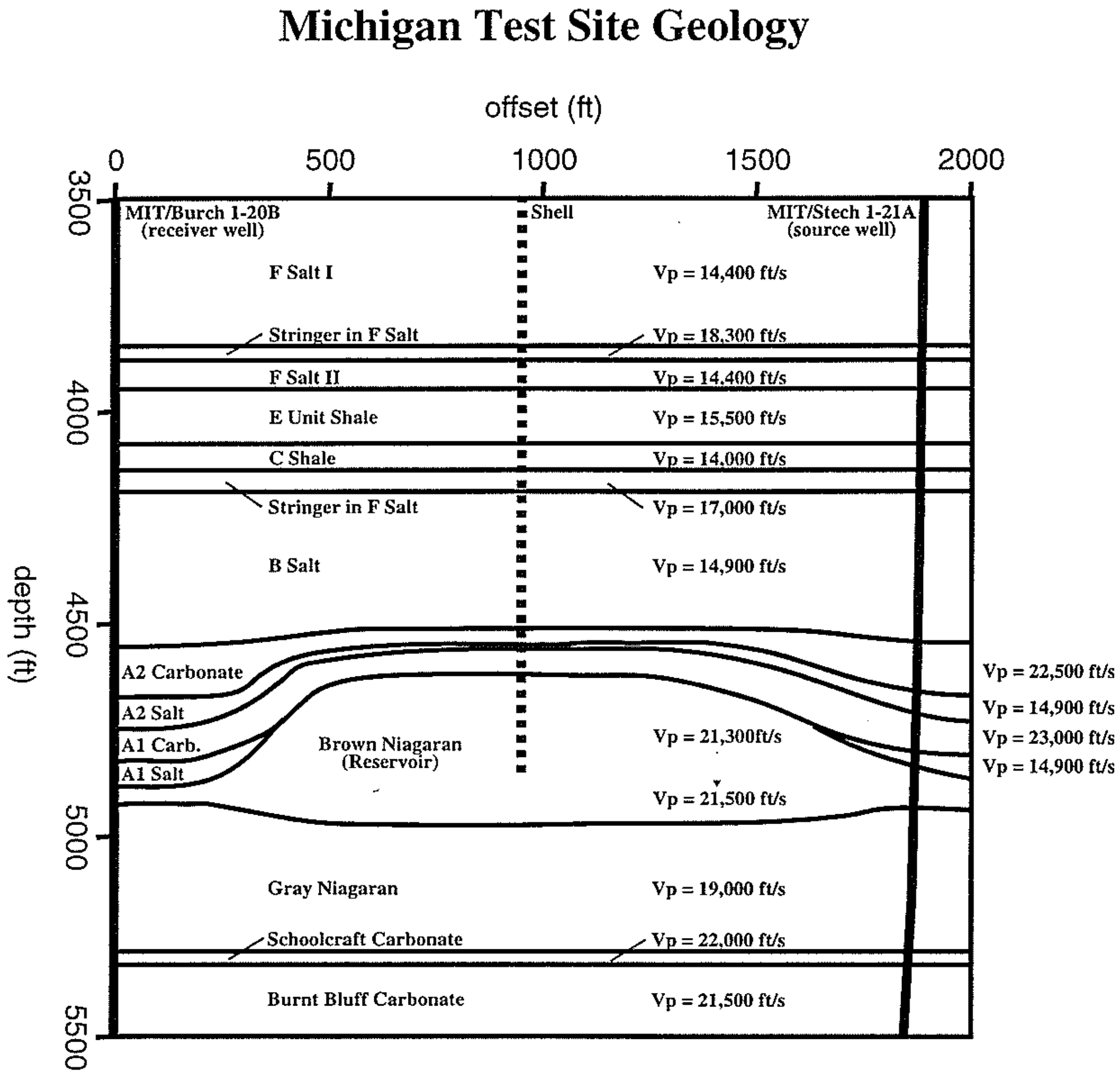


Figure 1: Geology of the ERL/MIT Michigan test site for the 3500–5500 ft depth interval.

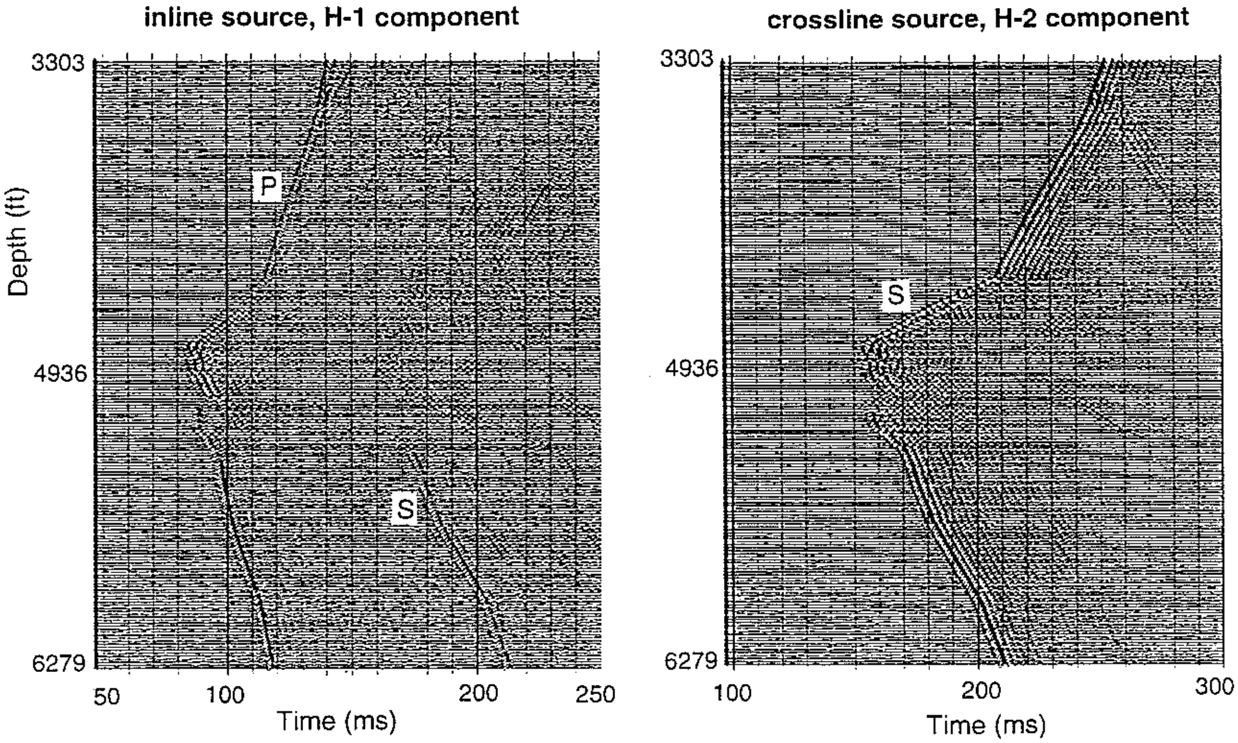
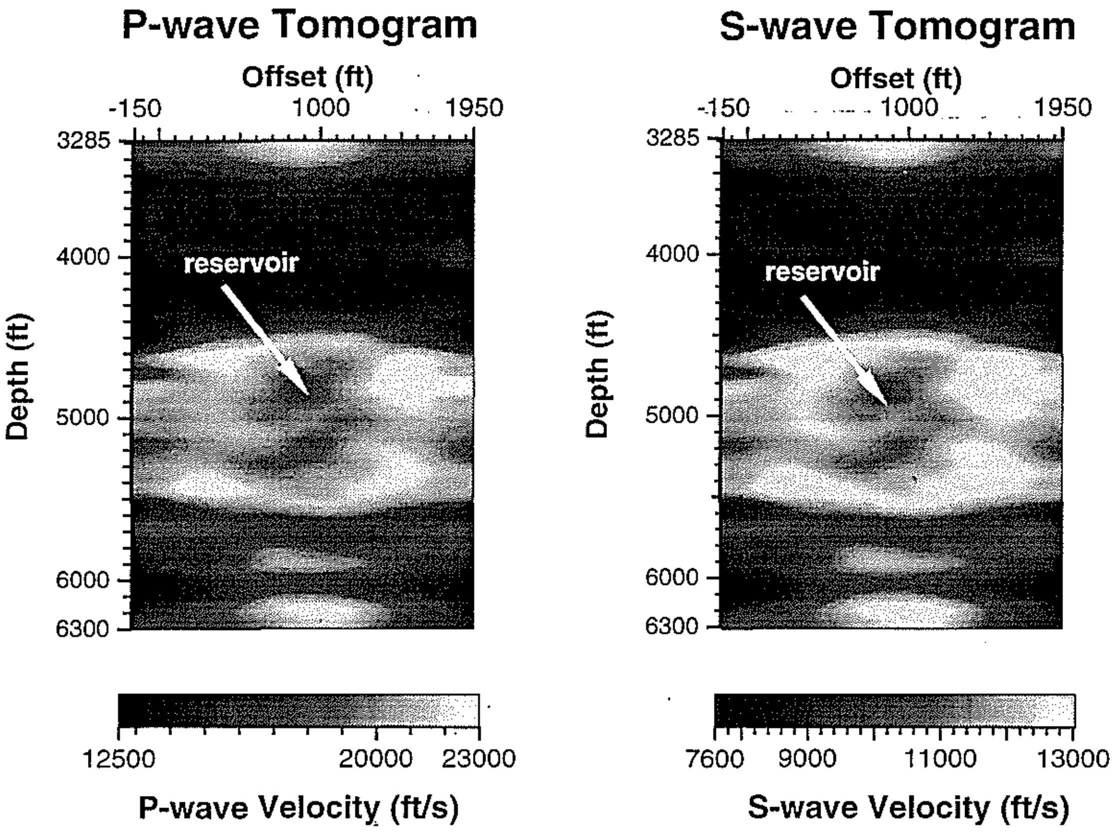


Figure 2: Crosswell data recorded at a receiver at a depth of 4936 ft. The H-1 component from the inline source mainly shows P waves, and the H-2 component from the crossline source shows SH waves.


P-wave Tomogram

S-wave Tomogram

Figure 3: P- and S-wave velocity reconstruction using traveltime data and slowness logs.