McKittrick Cross-Well Seismology Project: Part I. Data Acquisition and Tomographic Imaging

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Summary

A cross-well seismic tomography survey was conducted jointly between Chevron and Texaco in the Texaco portion of the McKittrick oilfield. The McKittrick oil field is shallow, less than 1300 feet, and contains low gravity oil which is perched above the water table. The formation consists of unconsolidated sands, conglomerates and diatomite. The P- and S-wave velocities are slow, sometimes very slow, and the sediments are highly attenuating. A downhole hydraulic vibrator developed at Chevron was used as the seismic source.

The primary objective of the survey was to map a sealing fault that separates saturated from unsaturated parts of a thick oilsand. A second objective was to evaluate the performance of the downhole vibrator.

The source depths ranged from 200 to 920 feet with mostly a 20 feet vertical spacing. There were four receiver wells, two within 100 feet of the source well, one 315 feet from the source well, and the fourth 467 feet from the source well. The vertical spacing between each receiver was 20 feet in the far wells and 10 feet in the near wells.

The cross-well data are of generally good quality, and the vibrator operated without problems for over 3000 sweeps. Both P and Shear wave direct arrivals are clearly seen as well as a number of reflections. The latter can be used to map bed boundaries and apply constraints to the tomogram inversion. The tomogram presented in this paper was computed using an ART algorithm. The sealing fault and saturated zone can be identified by a sharp P-wave velocity contrast, and the velocity distribution provides a detailed picture of the geologic structure between the wells.

Introduction

The McKittrick experiment was initiated through the DOE sponsored Oil Recovery Technology Partnership organized by Los Alamos and Sandia National Laboratories. The Oil Recovery Partnership was organized as a forum for cooperative work between the oil industry and DOE. The purpose of the cooperative work is to stimulate the development of better technology for reservoir characterization via cost share arrangements. The background to this effort is a realization that the main U.S. domestic oil resource can now be found in already located oil reservoirs. It is estimated that 60 to 70 percent of the mobile oil is left in the ground when an oil reservoir is considered economically depleted (DOE 1986). The large percentage of mobile oil left in the ground is due in part to macroscopic inhomogeneities in the oil reservoirs. An oil well typically only taps a small fraction of the reservoir due to impermeable layers, which effectively transform a large oil pool into a number of isolated pockets of oil. Cross-well seismology has been identified by DOE, and increasingly by the oil industry, as a critical technology to map the inhomogeneities in the reservoirs.

The basic concept of the experiment in the McKittrick field was to demonstrate that cross-well seismology could be used to map zones of by-passed oil in mature reservoirs. Texaco recommended the McKittrick site to the Oil Recovery Partnership since it was known from well logs that a zone of bypassed oil existed in the hanging wall of a sealing fault. As an additional objective, Chevron was invited to participate in the field trial in order to test their borehole vibrator.

Several advantages are realized when downhole seismic sources and multilevel receiver strings are used for reservoir characterization. For example, the attenuating weathered layer is avoided. It has been shown by Paulsson (1988), as well as Harris (1988), that when source and receivers are below the weathered layer, frequencies up to 1000 Hz can be recorded, which is more than one order of magnitude greater than what can be recorded on the surface. This results in a corresponding improvement in the resolving power of well-to-well data.

Experimental setup, data acquisition and data

The relative placement of the source and receiver wells is shown in Figure 1. Well 806 was selected as the source well because it penetrates the oil saturated zone and was thought to have the best cement bond and casing conditions, two important considerations when using borehole sources. Four receiver wells were chosen near the source well in such a way that we had two cross sections, each with two co-linear receiver wells.

The downhole vibrator is described by Paulsson (1988). The vibrator is rigidly clamped against the borehole wall, and energy is transmitted to the formation by the clamp acting against an axially vibrating reaction mass. The downhole receivers are described by Wuenchel (1976). They are short, 30 inches (0.76 m), have a high clamp/force ratio, and are equipped with three Sensor 10 Hz geophones. High quality receivers are essential for recording the broadband data generated by the downhole vibrator. The vibrator is capable of generating essentially a flat force output spectrum from 10 Hz to 670 Hz.

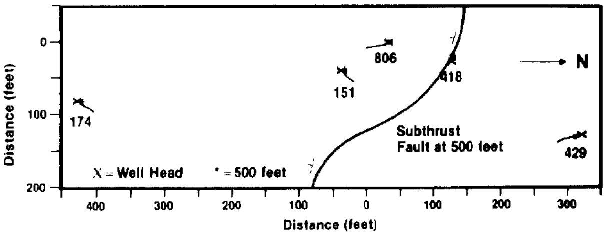

Fig. 1. Map of well locations for the McKittrick Cross-well experiment. Well 806 used as source well and wells 174, 151, 418, and 429 used as receiver wells. Well courses were obtained from gyro logs.

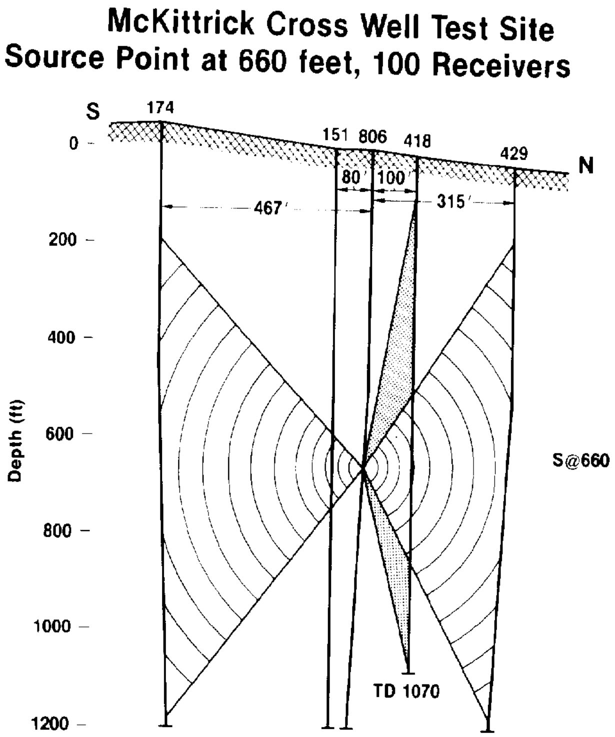

Fig. 2. Cross section through the experimental site. Data aperture for Figures 3, 4, and 5, are indicated from source clamped at 660 feet.

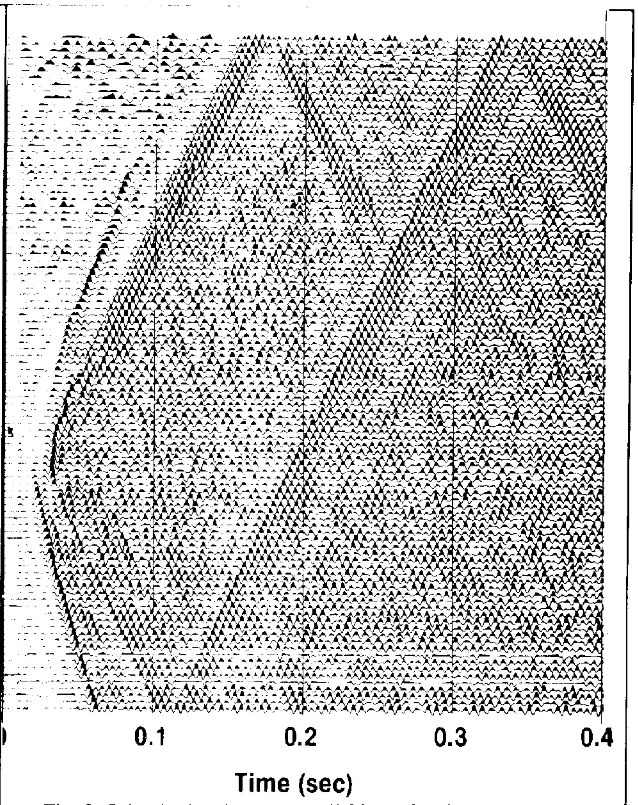

Fig. 3. Seismic data between well 806 and 418. Vertical component shown with AEC of 25 msec. The data are eight stacked 14 second sweeps from 10 to 360 Hz.

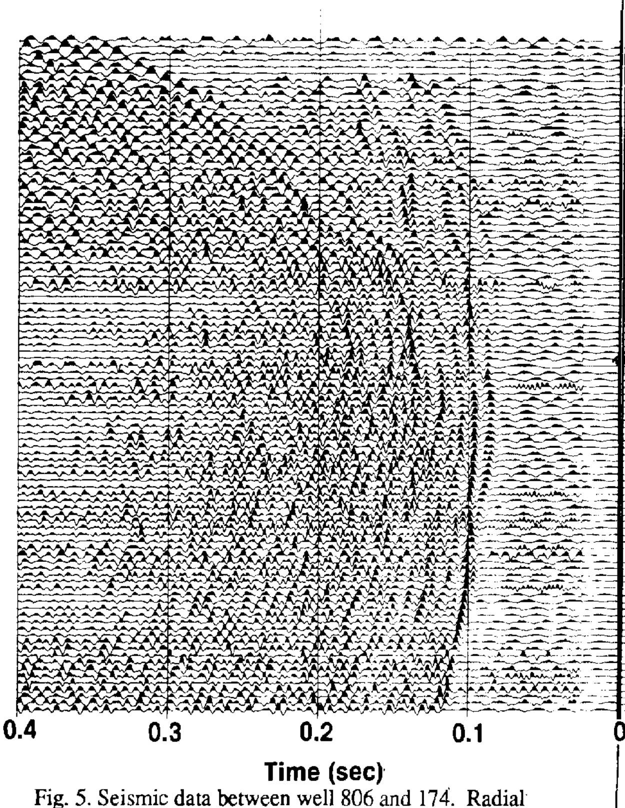

Fig. 5. Seismic data between well 806 and 174. Radial component shown with AEC of 25 msec. The data are eight stacked 14 second sweeps from 10 to 360 Hz.

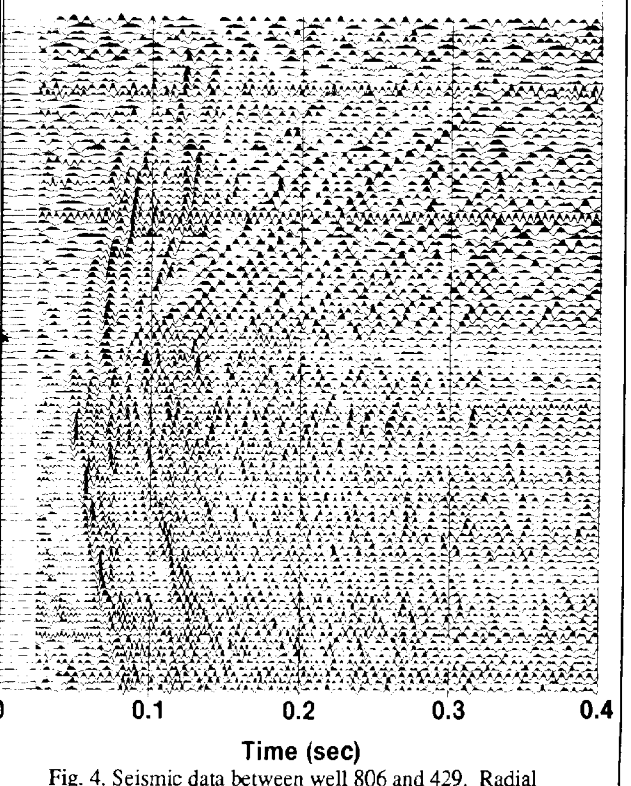

Fig. 4. Seismic data between well 806 and 429. Radial component shown with AEC of 25 msec. The data are eight stacked 14 second sweeps from 10 to 360 Hz.

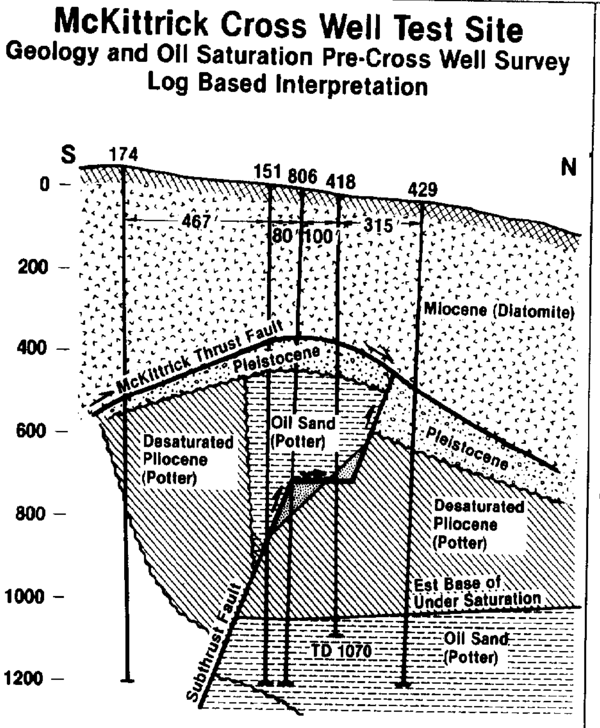

Fig. 6. Geology and oil saturation image generated before the cross-well experiment. The image is derived from well logs only.

For quality control all data were stacked, correlated and processed in the field using a real time stacker-correlator and an in-field processing system. In the initial phase of the experiment the spectrum of the recorded data were analyzed, and it was found that no energy above 350 Hz could be recorded, even in the near receiver wells 100 feet from the source. The sweep was subsequently set to a linear sweep from 10 Hz to 360 Hz. The sweep length was 14 seconds with a listen time of 2 seconds. Four sweeps per V.P. were found to be a good compromise between the requirements of a good signal-to-noise ratio and efficient field operations.

For most source stations 33 receiver positions were recorded. The vertical spacing between each receiver in the two near wells, 418 and 151, was 10 feet, and the vertical receiver spacing in the two far wells was 20 feet. The number of receiver points and the vertical spacing was chosen to give a data aperture of ± 45° between the source well and receiver well 429. The aperture in the two near wells was approximately ±60°, and in the far well, 174, the aperture was only ±34°.

A special data set was collected at the source depth of 660 feet. For this source point 100 receiver stations were recorded with a vertical spacing of 10 feet in all the wells. The apertures for the source and receiver wells are shown in Figure 2. The vertical component recorded in well 418 and the radial components recorded in wells 429 and 174 are shown in Figures 3, 4, and 5.

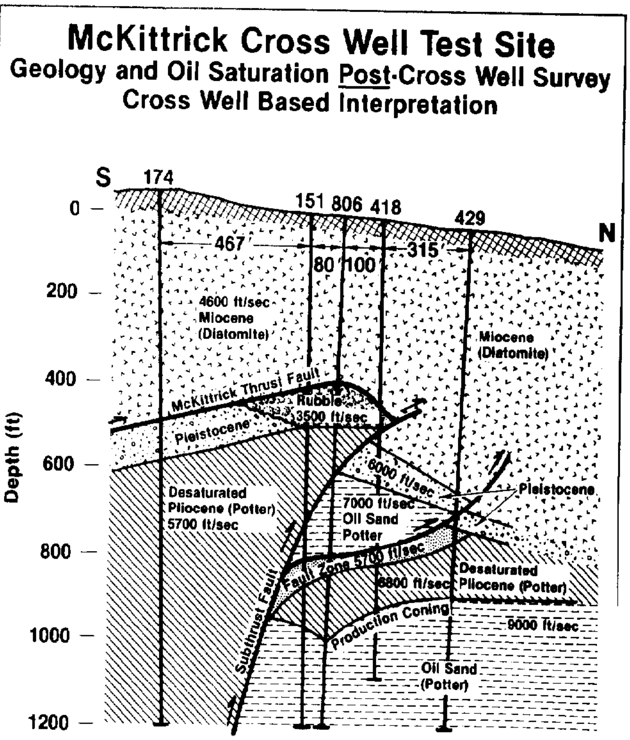

Fig. 7. Geology and oil saturation image generated after the cross-well experiment. The image is derived from cross-well seismic data and well logs.

As seen from the figures, the data from the downhole vibrator are good. This was especially gratifying since the sediments here are known to be highly attenuating, and the cement bond logs show little or no bonding between the casing and cement. The strong linear events seen on well 418 (Figure 3) are tube waves generated by the shear wave impinging on the borehole. Wells 429 and 417 were dry so tube waves were not generated. The decrease in P-wave amplitude near the shot depth in well 418 is due to the fact that most of the P-wave energy is polarized in the horizontal plane. It is interesting to note the existence of strong P-waves when the source and receivers are near the same depth (Figures 4 and 5) even though there is a null in the theoretical radiation pattern for this type of source.

Note the complexity of events, particularly from wells 429 and 174. Many of them are reflections (and converted reflections) from dipping interfaces which interfere with the direct arrival and peel off with unpredictable moveout. The strong low velocity events that begin at a depth of about 400 feet in well 174 and 600 feet in well 429 are shear waves propagating in the low velocity diatomite above the McKittrick Thrust.

Tomographic Processing and Results

Chevron and Texaco processed and interpreted these data separately, and what follows are Chevron's preliminary results. Texaco's results are discussed in the accompanying paper. Work continues within both companies to determine shear wave velocities, incorporate reflections in the tomogram, and invert the tomograms from all four wells simultaneously.

A ray tracing algorithm described by Cerveny (1985) was used to compute the geometric raypaths and total traveltimes. The velocity section was reconstructed using Algebraic Reconstruction Tomography (ART) as described by Lytle and Dines (1980) and Peterson, et al. (1985). The velocity imaging process is iterative with two loops: the inner one is the ART; and the outer is the ray tracing loop. The ART algorithm minimizes the difference between the observed travel times and the travel times computed for the current model by ray tracing. The starting model has constant velocity and is obtained by simple back projection. After each ART minimization, new raypaths and travel times are computed. The process is repeated until a convergence criteria is reached, which in this case is no further reduction in residual travel times.

The velocity model obtained from tomography, along with Chevron's interpretation of it, are shown in Figure 7. This is to be compared to Figure 6, which was Texaco's geologic model before the survey. The zone of bypassed oil within the Potter sand is seen as a wedge with a velocity of 7000 feet per second. This is underlain by a layer of low velocity material which we associate with the fault zone. The abrupt change in velocity and structural style to the left of well 806 leads us to suggest that the subthrust fault is splaying out. The very low velocity zone at the top of the McKittrick Thrust is anomalous but is supported by the travel time data in wells 418 and 151. We interpret it as a rubblized zone along the fault boundary. Although these interpretations are preliminary, and there is considerably more information in the tomograms that will refine and improve them, it is quite clear that the geology is more complicated than originally thought.

Conclusions

Chevron's borehole vibrator was successful in recording P and Shear waves in the structurally complex , highly attenuating sediments of the McKittrick Oilfield. The resulting velocities, computed using an ART algorithm, outlined the zone of bypassed oil and refined the existing structural picture.

Acknowledgement

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