Cold Lake 3-D seismic data analysis

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ABSTRACT

Two 3-D seismic surveys have been acquired by Imperial Oil Ltd. across part of a heavy oil field at Cold Lake, Alberta. The field is under production by means of cyclic steam stimulation of the reservoir. The surveys were acquired in 1990 and 1992 and it is hoped that the temporal change in reservoir conditions may be inferred from the seismic character and attribute differences between them. It is also anticipated that the tight steaks that act as permeability barriers may be detected on the seismic data.

The two surveys were reprocessed in order to keep the differences between them above the reservoir zone to a minimum and were also processed to retain true amplitude information for amplitude-versus-offset analysis. The processing procedure is discussed in this paper. The final, migrated 3-D data will be analysed on a workstation.

INTRODUCTION

The Cold Lake oil sands occur in east central Alberta and are part of the Lower Cretaceous heavy oil deposits that occur in a discontinuous trend in the eastern part of the Western Canada Sedimentary Basin. They cover an area of about 6500 km^2, from Twp. 52, Rge. 4, W4M to Twp. 67, Rge. 10, W4M and are the second largest oil sands deposit in Canada. Figure 1 shows the location of the Cold Lake oil sands and Imperial Oil's D3 pad.

The oil sands are contained within the Mannville Group, in which the primary reservoir is the Clearwater Formation (Figure 2). This formation is a transgressive wedge and the sands are predominantly deltaic and foreshore/shoreface facies. The sands are highly saturated with bitumen, which is of low specific gravity (1000 kg/m^3 or 10° API), high viscosity and free of underlying water. In order to produce the bitumen, the reservoir must be stimulated by an in-situ thermal recovery process.

At the D3 pad at Cold Lake (Figure 1), Imperial Oil is producing the bitumen by cyclic steam stimulation (CSS). The cycle involves a 30-50 day steam injection period followed by a production period of about a year, the same wells being used for both injection and production. It was expected that ten CSS cycles over ten years would be needed to recover 20% of the bitumen in place. At the D3 pad, the Clearwater sands have a gross thickness of 55 m and are at depths of 420-475 m. They have an average porosity of 32%, permeability of 1 D and average net pay of 15 m.

In order to produce the reservoir efficiently, it is necessary to maximise the volume of sand swept by the steam. This entails knowing the distribution of the steam and which parts of the reservoir have been produced. The steam does not penetrate the reservoir uniformly but flows preferentially through channels which have developed during CSS. Also, displacement efficiency is impaired because of the resaturation during production of zones swept of bitumen during the injection cycle (Boone, Gallant and Kry, 1993).

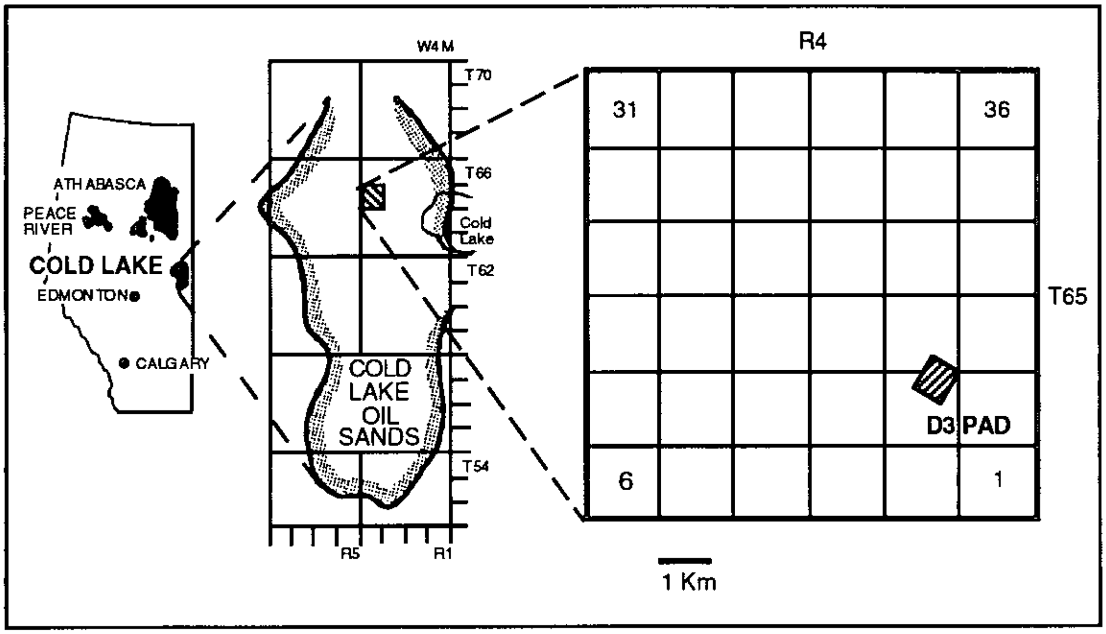

FIG. 1. Location of the D3 pad at Cold Lake (after Harrison et al., 1979).

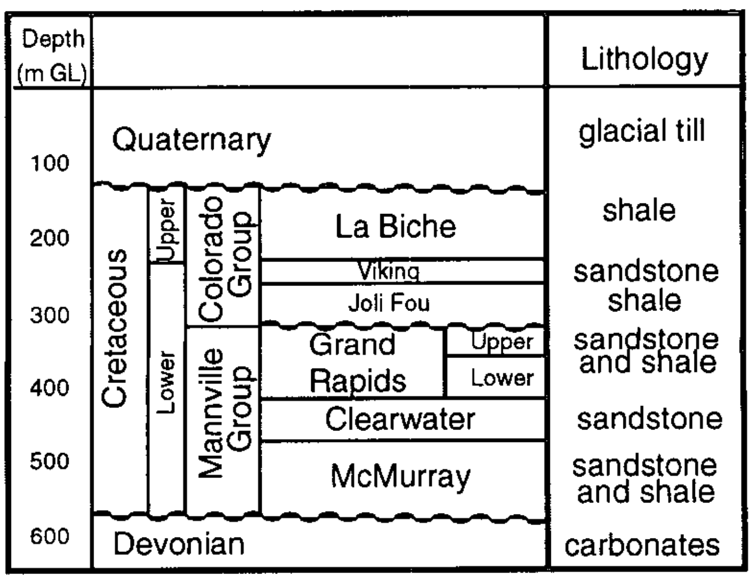

FIG. 2. Generalised stratigraphic chart of the Cold Lake area (after E.R.C.B.).

One method of investigating the distribution of steam in the reservoir is from the interpretation of seismic data. Laboratory measurements have shown that the raised reservoir temperatures associated with certain enhanced oil recovery (EOR) processes can cause a significant reduction in the compressional wave velocity of the reservoir (Nur et al., 1984; Nur, 1987). The application of seismic methods in EOR projects has been discussed by several authors (e.g., Macrides and Kanasewich, 1987; Laine, 1987; Paulsson et al., 1992). It is hoped that by conducting two seismic surveys at different times, the change in the distribution of the steam in the reservoir may be observed. Differences in seismic attributes between the two surveys in the reservoir zone may be attributed to differences in reservoir conditions at the times of acquisition.

3-D SEISMIC DATA

CREWES has access to two high-resolution 3-D seismic surveys acquired over the D3 pad at Cold Lake. The first survey was acquired in April, 1990, during the sixth production cycle and the second in January, 1992, during the eighth injection cycle.

The two surveys each cover the same area of the pad. This area, 576 m x 672 m, encompasses fifteen directional injection/production wells and six vertical observation wells. The survey layout was designed to give full-fold coverage over an area of 200 m x 300 m, centred on the D3-8 well's bottom hole location. The five NE-SW source lines were laid out 128 m apart and the eight NW-SE receiver lines 96 m apart. On each source line, shots were fired at 43 stations, 16 m apart, for a total of 215 shots. The data were recorded by eight lines of 37 geophones stationed 16 m apart (a total of 296 receivers). The geophones were buried 10 m deep in order to be below the water table and the unconsolidated surface till. The survey layout is shown in Figure 3. Some of the shot and receiver locations had to be skidded because of surface facilities.

It is hoped that examination of the two seismic data sets will reveal differences between them that can be attributed to the change in reservoir conditions. It was observed on the original processing that there are seismic character differences between the two data sets above the zone of interest, where the geological conditions can be expected to be identical. If differences observed within the reservoir zone are to attributed solely to changes in reservoir conditions, then we must be confident that the two data sets are alike in all other areas. It is acknowledged that obtaining a perfect match will be impossible but the parameters used during the processing stream were chosen to keep the differences between the data sets to a minimum. In order to observe these differences, a computer programme, "Matchseis", was developed, which allows the user to select any corresponding part of two data sets and subtract the two for the purposes of comparison. The difference may then be viewed interactively and plotted. The user may also apply a calculated or selected static shift before the data subtraction. Differences in trace amplitude magnitudes between the two data sets are compensated for prior to subtraction by calculating the ratio of the sum of the absolute trace amplitudes for each corresponding pair of traces and multiplying the values of trace 2 by this ratio.

It was found that, in the original data, there is a static shift of 2 - 4 ms between the two data sets which varies across the survey. It has been suggested that this varying static shift is not important if isochrons are mapped rather than single events. However, examination of two events away from the steamed zone showed variations in the isochron values at corresponding locations on the two surveys. The reprocessing was intended to eliminate this variable static shift as well as to minimise the seismic character differences between the two surveys away from the reservoir zone.

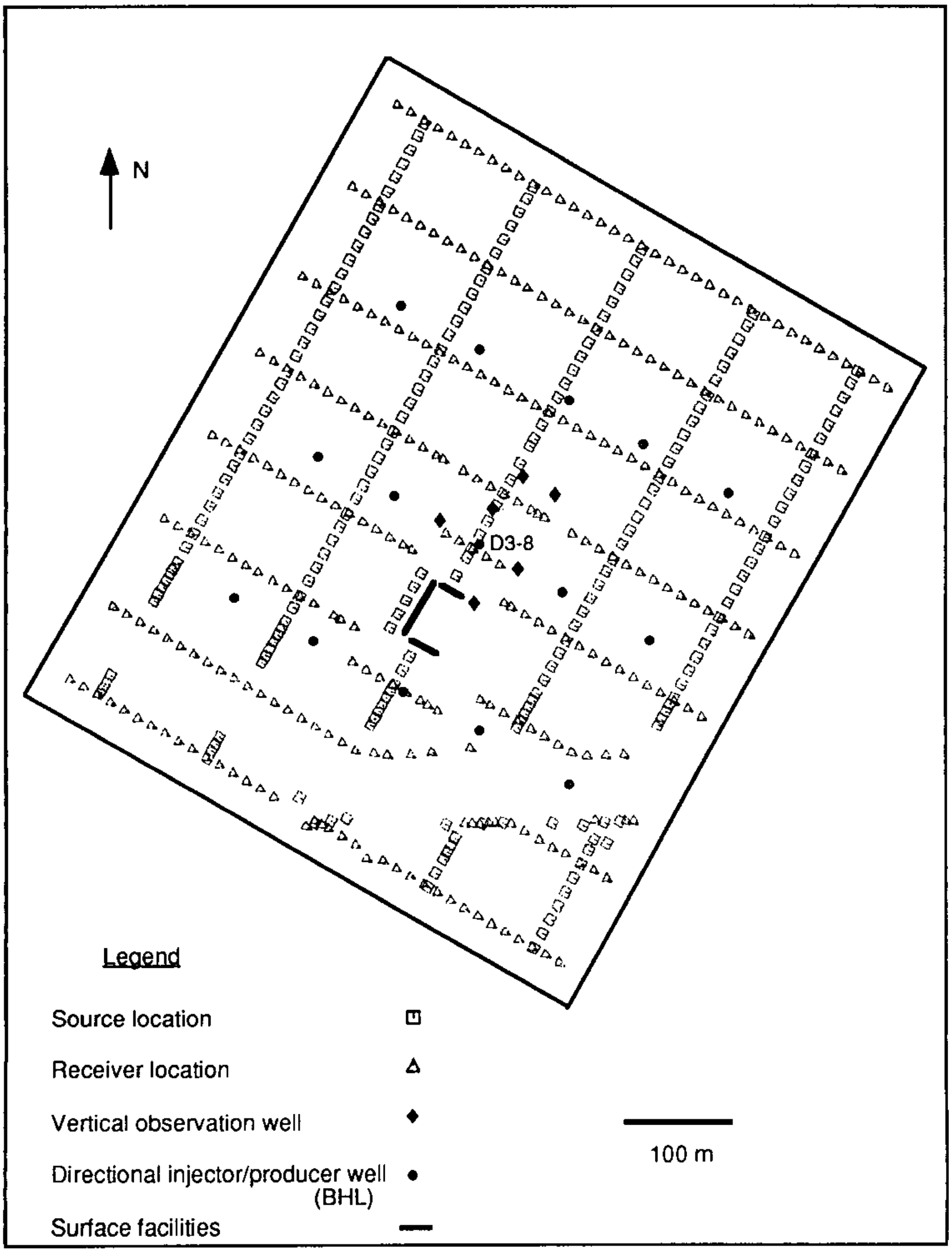

FIG. 3. Layout of seismic grid at the D3 pad.

3-D Seismic Data Processing

The basic processing flow is shown in Table 1. The data were also processed to retain true amplitude information as it is wished to study AVO effects and the data have not previously been processed for true amplitudes.

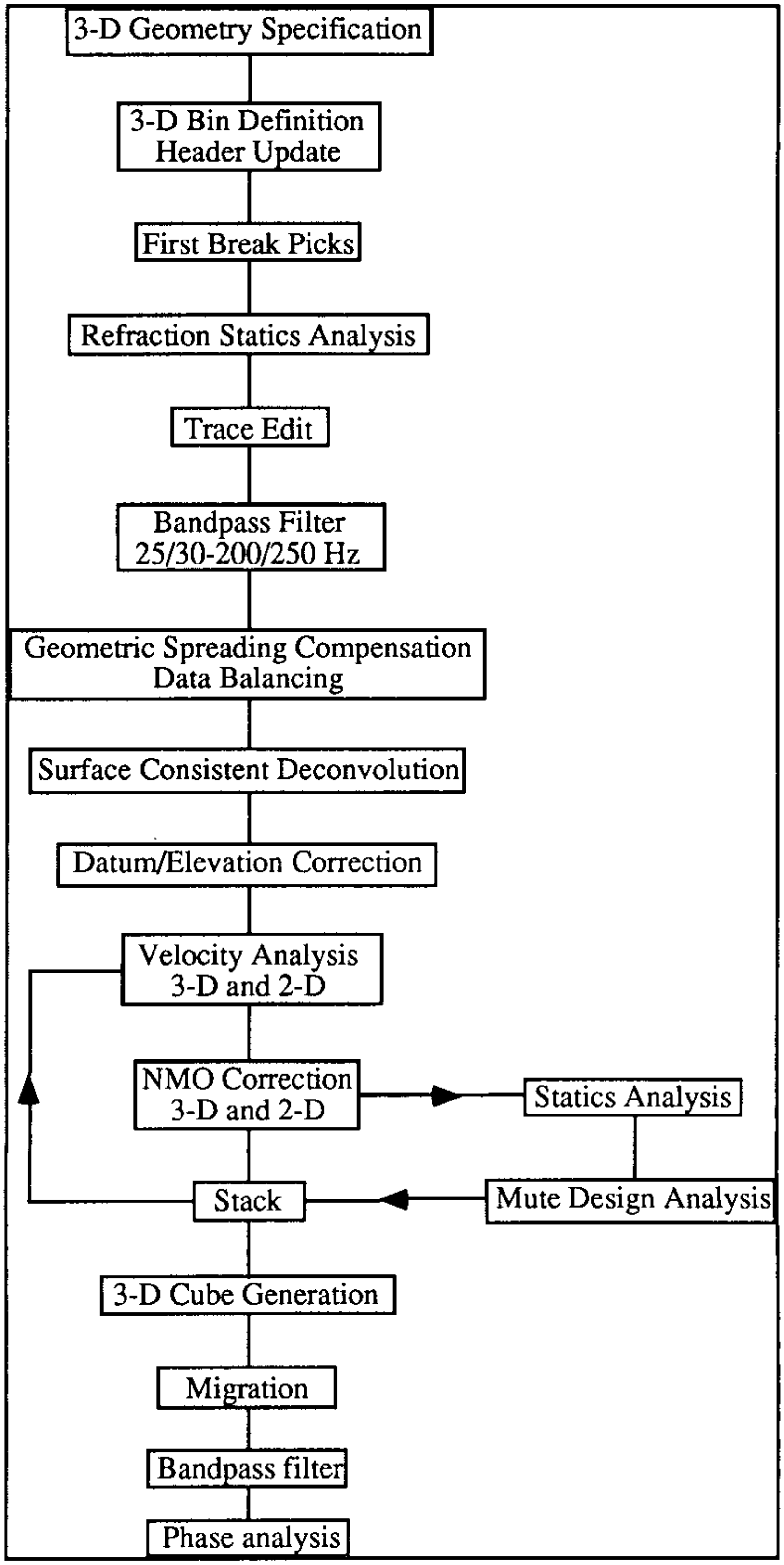

Table 1. Processing Flow.

Although the field layout was identical for each survey, some of the acquisition details were not. These differences are summarised in Table 2.

	1990	1992
Contractor	Western Geophysical	GECO
Recording instruments	Sercel 386	I/O System One
Source	.1 kg dynamite	.125 kg dynamite
Field filter	out/355.6 Hz	3/12 - 360/375 Hz
Pre-amp gain	27/42 dB	36 dB

Table 2. Summary of acquisition differences between the two surveys.

The data were recorded to 3 s at a sample rate of 1 ms but only the first 1 s of data are processed because the zone of interest is above 0.5 s and because of computer disk space limitations.

As can be seen in Figure 4, the field records show differences between the two data sets. This figure shows one receiver line of data from a corresponding shot from each survey. The 1992 data are higher amplitude and appear to be lower frequency than the 1990 data. The strong event observed at around 0.6 s is the Devonian reflector and the zone of interest, the Clearwater Formation, is 50-100 ms above the Devonian event. On some receiver lines the data are contaminated with shot-generated low-frequency, high-amplitude noise. This noise was removed quite well by filtering.

Survey information was input from the survey tapes and observer's notes, with skidded locations corrected by hand. The common depth point (CDP) binning grid coordinates were based on those used by Western Geophysical in the original processing of the 1990 data. The CDP bin spacing is 8 m, half of the shot and receiver spacing. Plots of the CDP coverage were generated for quality control.

First breaks were picked on the 1990 data and copied to the 1992 data. Both data sets were then observed at the same time, in shot sequential order. It was seen that the first break picks from the 1990 survey fitted very well the 1992 data and little editting was needed. Bad and reverse traces were editted and out of order shots corrected. Refraction statics analysis was undertaken using Hampson and Russell's "GLI3D" programme. The first breaks were found to lie on a straight line with no break in slope and a sub-weathering velocity of 1750 - 1800 m/s was indicated. It is surmised that the burial of the geophones at a depth of 10 m has put them below the weathering layer everywhere throughout the survey and thus refraction statics are not applicable.

A bandpass filter of 25/30 - 200/250 Hz was applied to remove low frequencies from the data. On some of the records, this low frequency noise is dominant. High bandwidth is much more important because data with high lateral and vertical resolution are desired.

Geometric spreading compensation was applied using a velocity function derived from sonic log velocities. The data were also balanced on a record basis by scaling to a defined energy level so that the very high amplitude early arrivals did not dominate the data.

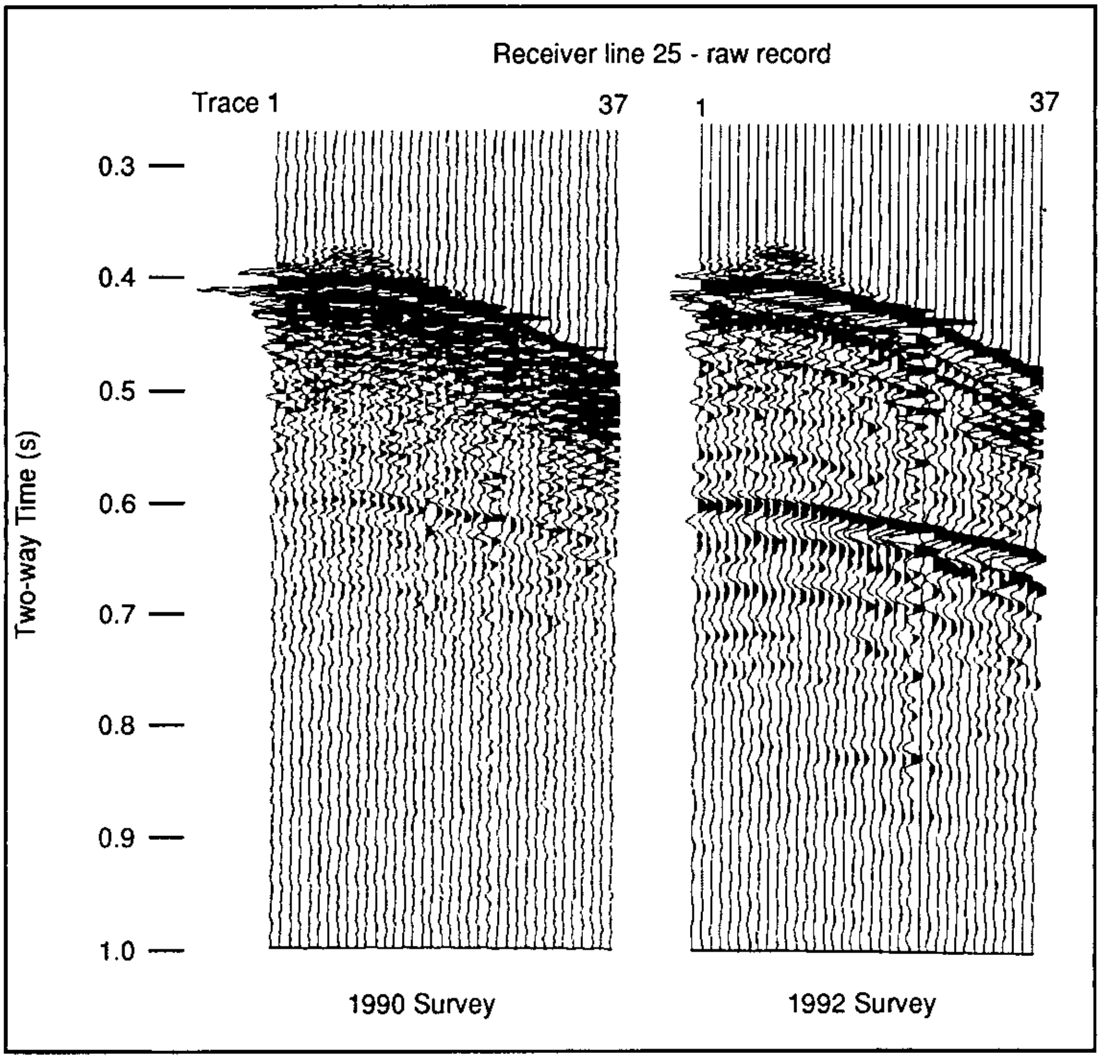

FIG. 4. Corresponding receiver line of raw data from a corresponding shot from each survey.

Surface-consistent deconvolution was chosen to preserve relative trace amplitudes. Deconvolution was performed on source gathers followed by deconvolution on receiver gathers, with the same parameters. An offset-dependent front-end mute was designed to eliminate noise prior to the first arrivals and was applied before and after deconvolution. The method of deconvolution applied was that of prediction error filtering, which assumes the reflectivity series to be random and white and the source wavelet to be minimum phase. Jurkevics and Wiggins (1984) showed this method of predictive deconvolution to be robust under a wide variety of input conditions. After a few tests with different lengths of operator, the operator length was chosen to be 150 ms.

Figure 5 shows the same records as in Figure 4 after surface-consistent deconvolution. Events in the zone of interest have been enhanced and the two data sets look much more alike in terms of frequency content and character. It can be seen that there is a small static shift between corresponding events in the two surveys.

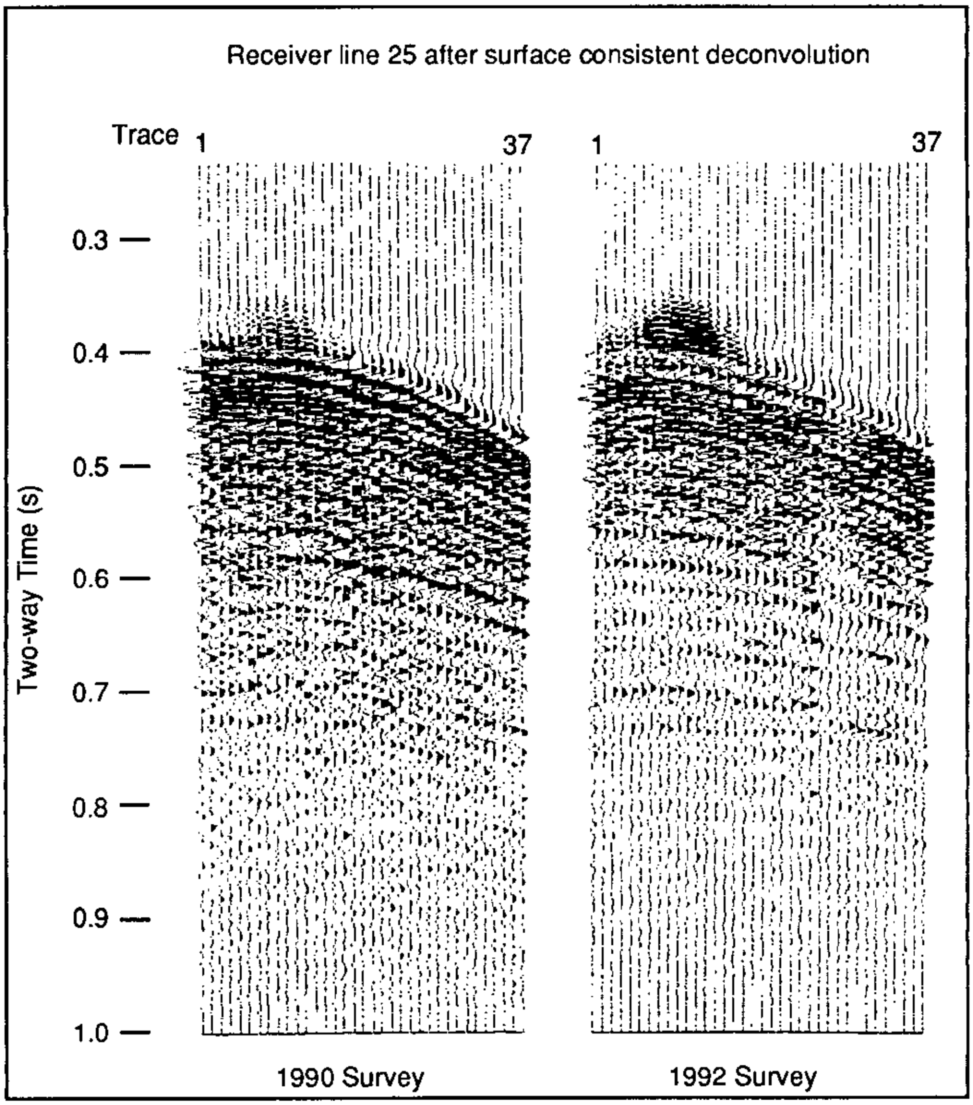

FIG. 5. The same receiver line as in Figure 4, after bandpass filtering, geometric spreading compensation and surface consistent deconvolution.

The data were corrected to a floating datum for each CDP gather with a replacement velocity of 1800 m/s. After the CDP gathers had been stacked, a datum of 600m was applied, using the same replacement velocity.

Stacking velocities were analysed using both 3-D and 2-D velocity semblance plots. The 3-D semblance analysis algorithm sorted the data into four sectors by the azimuth of the shot - receiver direction so that velocities could be selected according to azimuth. It was observed on these semblance plots that the velocities are not azimuthally dependent.

In areas of dip, the apparent velocity will differ from the true velocity according to the angle between the true dip direction and the source/receiver azimuth. Levin (1974) showed that the ratio of apparent NMO velocity to true velocity is related by

$$\frac{V_{app}}{V} = (1 - \sin^2\phi.\cos^2\theta)^{-1/2}$$

where V_{app} = apparent NMO velocity

V = true velocity

ϕ = dip angle

θ = angle between profile line and dip line

It is seen that for small dip angles the apparent velocity will be very close to the true velocity so azimuthal effects will be negligible. From wireline logs run in the observation and production wells at the D3 pad, geological dip across the pad appears to be very small (< 2.5°). For a dip angle of 3° the difference between the true velocity and the apparent velocity is less than .1% so the observed independence here of velocity and azimuth is reasonable. Stacking velocities were subsequently selected on the basis of the 3-D semblance plots and 2-D constant velocity stacks. The velocities picked from the 1992 data were seen to apply equally well to the 1990 data for all times.

Both 3-D and 2-D normal moveout (NMO) corrections were applied independently to compare the results, the same velocities being used in each case. The 3-D NMO correction routine did not work as well as the 2-D NMO algorithm and the stack quality was superior for the 2-D case.

Residual statics could not be applied because the processing routine was not properly set up for 3-D data. Tests were undertaken using data correlation routines for each data set independently and trim statics were selected on the basis that the differences between the data sets on a selected test line using "Matchseis" were minimised. Trim statics were applied to NMO-corrected CDP gathers.

An attempt was made to design an offset-dependent mute function that would eliminate the noisy first arrivals observed on some traces but keep the good data observed on others. Application of such a mute impaired the quality of the stack at around .3 s so only the front-end mute applied in the deconvolution process and the mute applied to eliminate high NMO stretch were applied.

The data were 3-D migrated by two passes of 2-D *f-k* migration. *F-k* migration was selected because it retained the seismic character observed on the stacked sections (as 3-D phase-shift migration did not). Extensive tests were done to determine the best migration velocities, concentrating on the zone of interest between .3 s and .6 s.

Figures 6 and 7 show examples of a corresponding crossline of data from the original processing and the reprocessed data, respectively, selected from the middle of the 1990 survey. Figures 8 and 9 show the same line from the 1992 survey. The end portions of the lines, where data quality is poor and fold is low, are not displayed. The data have been bandpass filtered between frequencies of 25/30-100/120 Hz for these displays. The reprocessed data lack the continuity of the original processing in the section above about .3 s but the reprocessing had not been directed to focus on that zone. A high amplitude event can be observed within the Clearwater Formation on the 1992 survey.

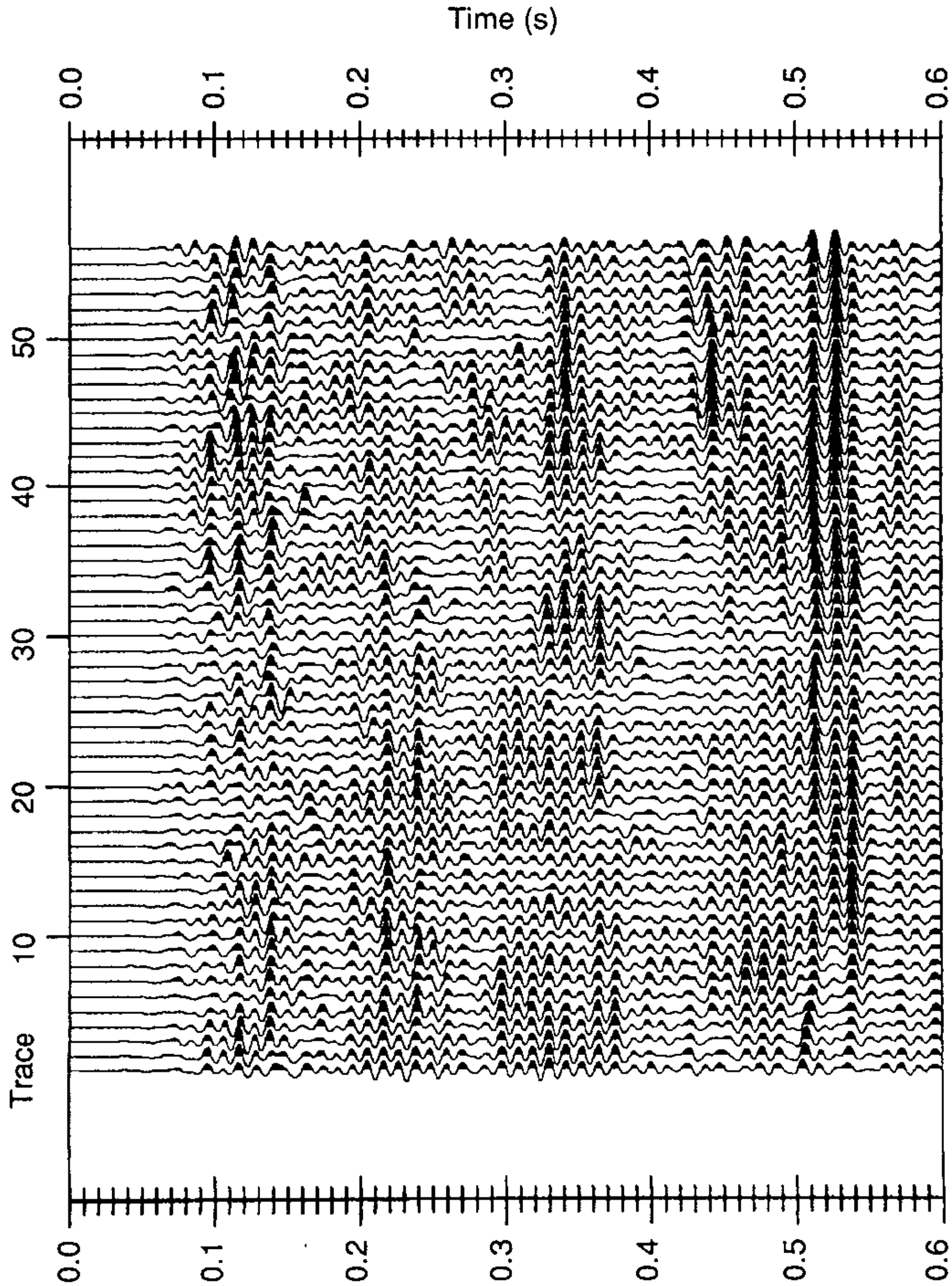

FIG. 6. A crossline of migrated data from the original processing of the 1990 data. The zone of interest is between 0.41 and 0.46 s.

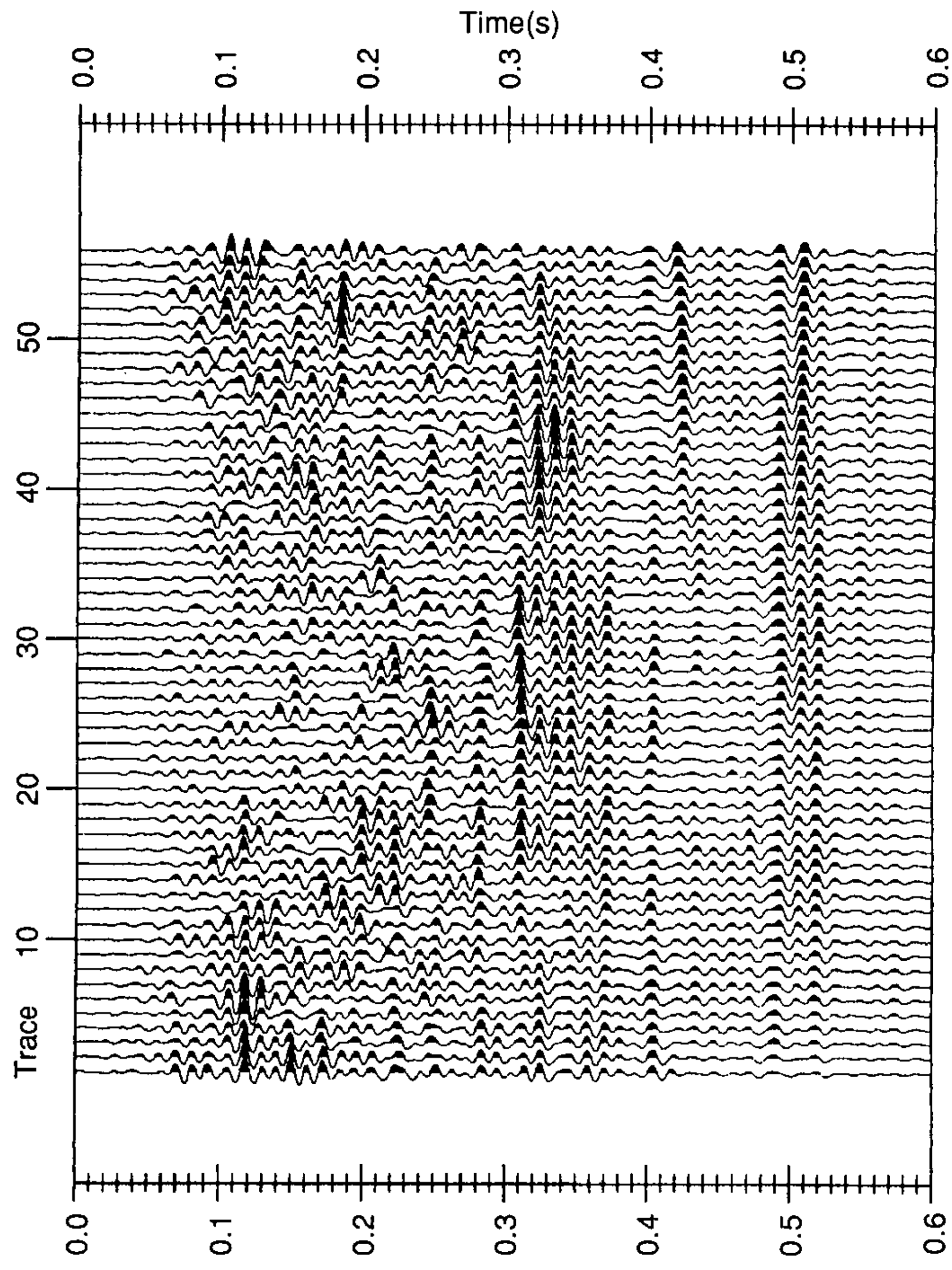

FIG. 7. Same line as in Figure 6 but from the reprocessed 1990 data set. The Devonian reflector is at about 0.5 s. There is a time shift between the original and the reprocessed data even though they are supposed to have the same datum of 600m. The event at 0.31 s, just above the Grand Rapids Formation, is stronger and more continuous than in Figure 6.

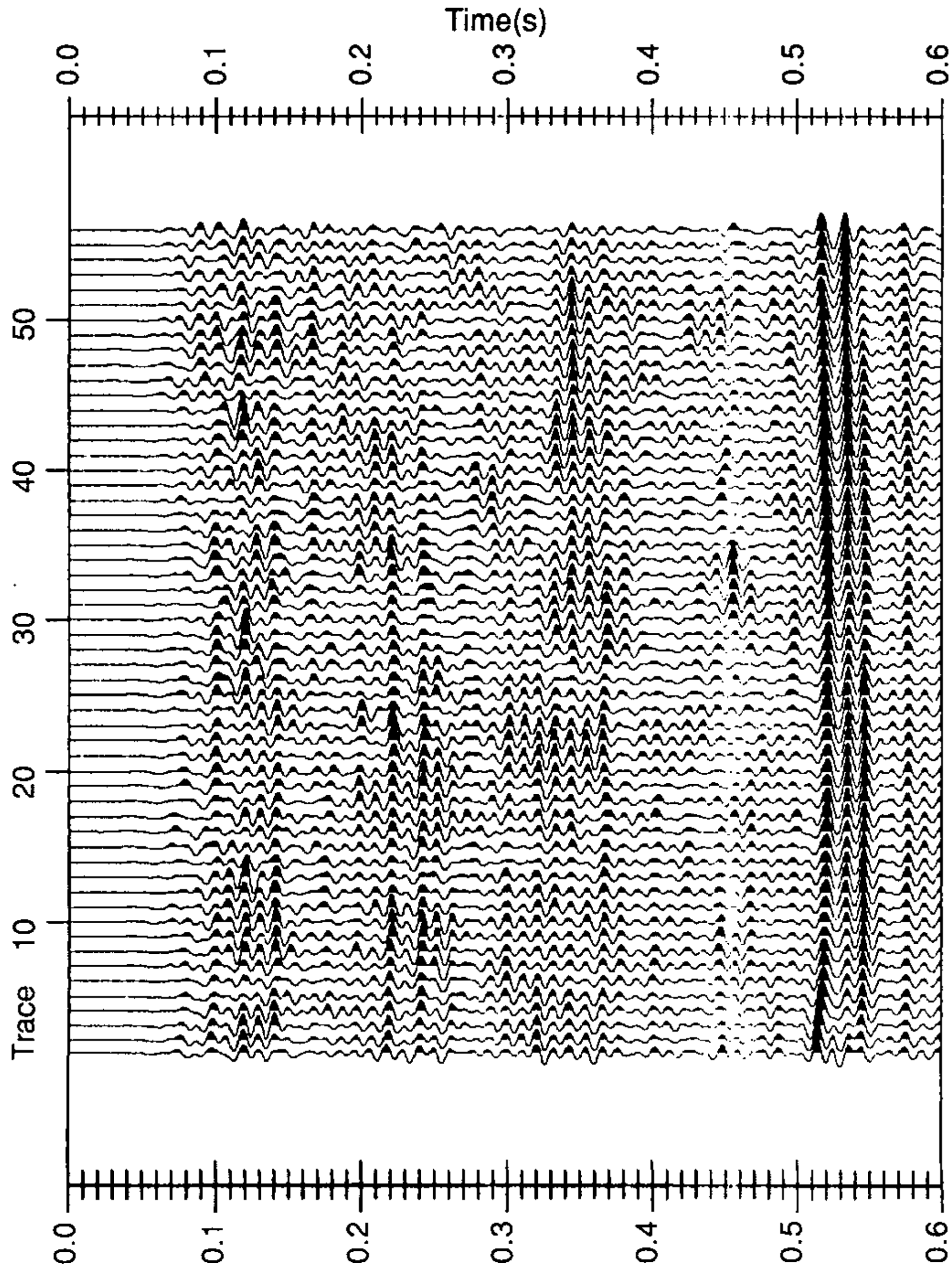

FIG. 8. The corresponding line to that in Figure 6 from the original processing of the 1992 data. Note the static shift between this line and that of Figure 6. The same gain scalar has been used for the display.

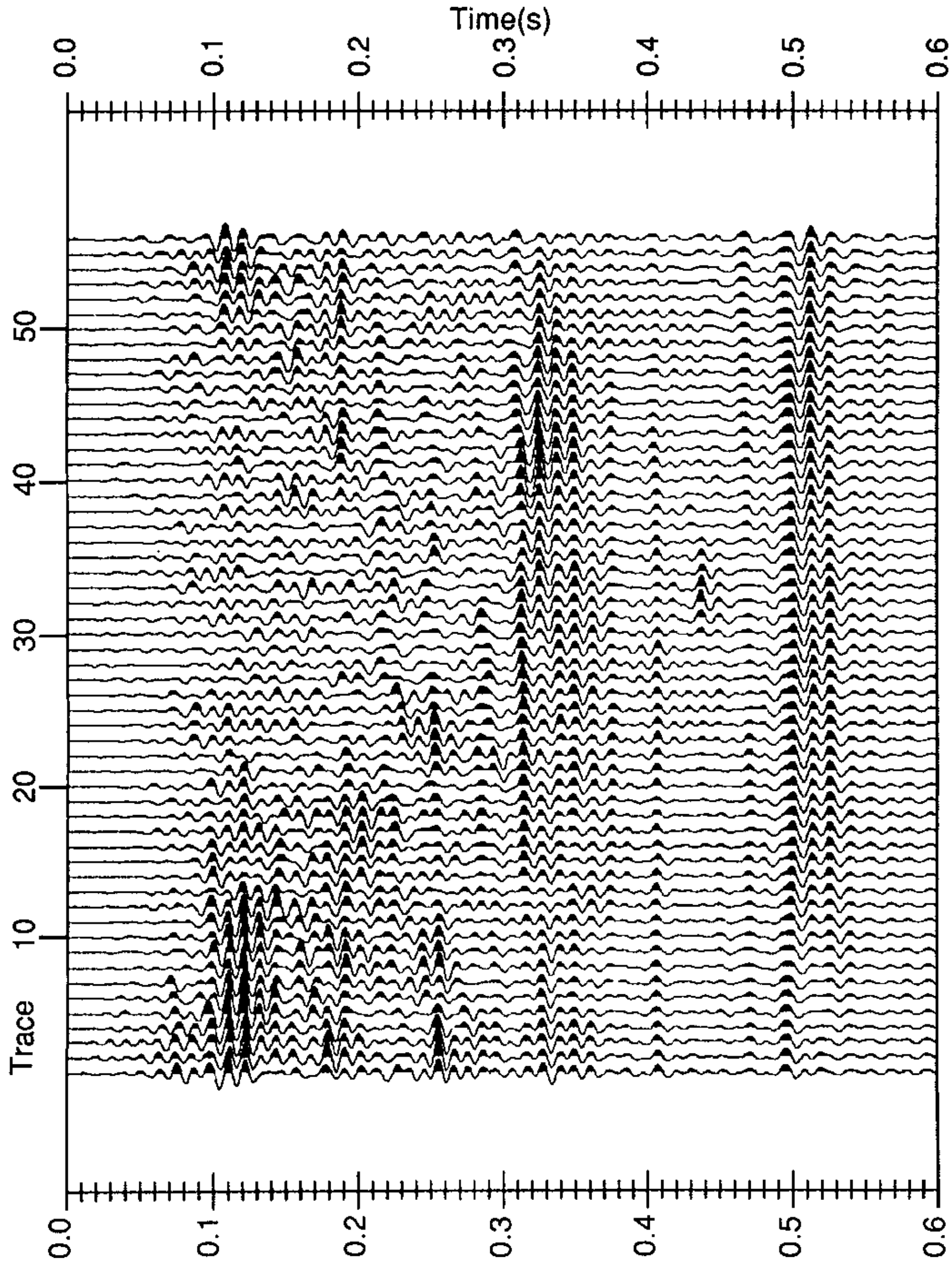

FIG. 9. The corresponding line from the reprocessed 1992 data set. Note the high amplitude event at about 0.44 s on a few traces, which can be seen also in Figure 8, at about 0.46 s. Note also the corresponding decrease in amplitude of the event beneath it at 0.47 s. The Devonian reflector appears to sag compared to that on the 1990 survey (Figure 7). This push-down in time is caused by the lower velocities in the reservoir zone. The reprocessed data appear to be the reverse polarity of the original processing.

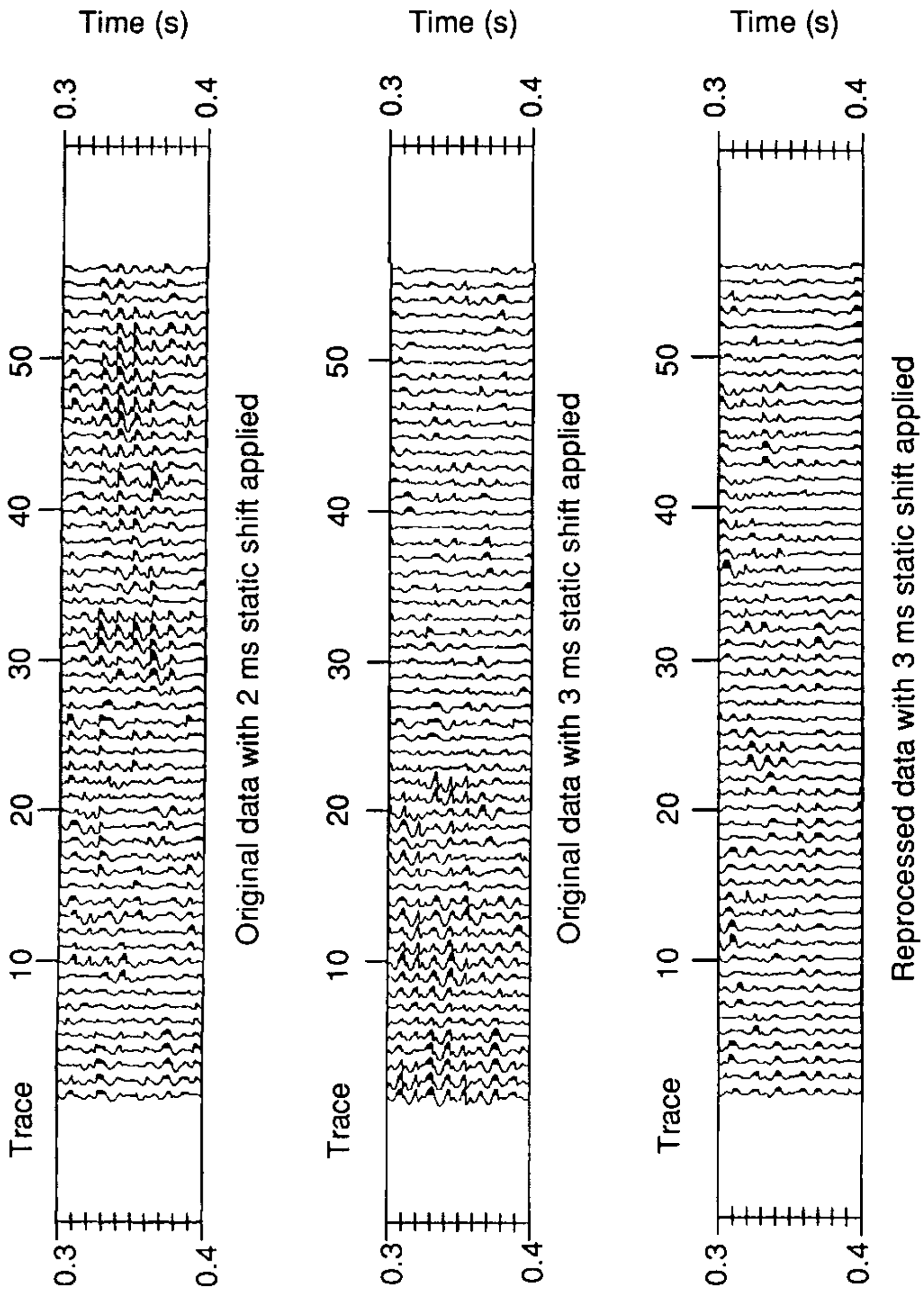

FIG. 10. Three panels of data showing the differences between the 1990 and 1992 data sets. The panels are selected from a zone of good data above the reservoir zone. 10a is from the original data with a 2 ms static shift applied; 10b is the same but with a 3 ms static shift applied; 10c is from the reprocessed data with a static shift of 3 ms.

Some results of "differencing" using "Matchseis" are shown on Figure 10. Each panel shows the difference between the 1990 and 1992 data sets for the same crossline as in Figures 6 to 9. Amplitude compensations and static shifts were applied prior to subtraction. The data panel is selected from a zone of good data above the reservoir zone in order to see if the differences there are minimal. If they are, then the differences observed in the reservoir zone may be attributed to changes in reservoir conditions and not processing artifacts.

The data used to produce the differences seen in Figure 10 were bandpass filtered between frequencies of 25/30 to 100/120 Hz. The traces are plotted with the same gain scalar as used for Figures 6 to 9. Figures10a and 10b show the effect of the varying static shift observed on the old data. They show that a static shift of 2 ms is best for traces 1 to 22 and a shift of 3 ms best for traces 23 to 56. Figure 10c is the difference obtained from the reprocessed data with a static shift of 3 ms applied. This static shift is found to be very consistent throughout the entire reprocessed, migrated 3-D data set.

FUTURE WORK

These "differencing" results and the good quality of the reprocessed data are encouraging. The data will be correlated to sonic logs run in the observation wells and synthetic seismograms to ensure that the data are zero phase and of normal polarity. Finally the data will be bandpass filtered.

The data will be transferred to a workstation, interpreted and analysed. A velocity model based on sonic log data is available to us and will be integrated into the seismic data analysis. Attributes such as reflection time isochron, relative amplitude, dip and azimuth and complex trace attributes such as instantaneous phase and frequency will be analysed. In general, reflection amplitude, interval transit times and frequency and phase variations may all be correlatable with reservoir parameters such as porosity, fluid type, lithology and net pay. The reduction in *P*-wave velocity in the steamed zone will cause an increase in interval transit time between reflectors straddling the reservoir zone. Mapping of such transit times from both 3-D surveys should indicate zones of reduced velocity, and therefore increased temperature due to steam injection, in the reservoir. Seismic reflection strength is related to porosity and temperature, so the steamed zone, if thick enough, should be indicated by changes in amplitude.

It is intended to include statistical methods such as co-kriging in the integration of the observed changes in seismic attributes with petrophysical parameters.

We also intend to evaluate the 3-D data for azimuthally-dependent AVO effects and to develop a way of presenting the results.

3-C seismic data analysis provides another method for interpreting petrophysical properties and is a major component of research in the CREWES Project. Analysis of *P*-wave and *S*-wave data can be applied to the estimation of rock properties (Domenico, 1984; Winterstein, 1986). Preferred permeability directions may have a significant impact on steam distribution in the reservoir and subsequent production. *S*-wave splitting can be used to determine fracture orientation and lateral changes in permeability (Crampin, 1985; Martin and Davis, 1987). Imperial Oil is intending to acquire a 3-C seismic line over a producing pad similar to D3 in November, 1993. We will process and analyse the data.

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