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3D SEISMIC — A COST-EFFECTIVE APPROACH

F.M. PETERSON[1] AND W.C. REYNISH[2]

ABSTRACT

Three-dimensional seismic is generally perceived as a very expensive tool that is not suitable for use by other than major oil companies, or for the solution of conventional exploration geophysics problems. This paper will illustrate how 3D techniques were utilized to provide a very cost-effective solution to a specific exploration project. A basic geological and historical seismic outline will establish the economic and environmental framework for the survey. Discussion of the acquisition method and processing approach will demonstrate how it was accomplished. Drilling results and comparisons with conventional data will be given to illustrate the effectiveness of the 3D approach.

This survey was carried out during February of 1982 in the Black Creek basin of northwestern Alberta. Prolific and abundant Devonian Keg River pinnacle reefs with reserves in the 0.2 to 100 million barrel recoverable categories provide the exploration target. A prospective area of approximately six square miles was covered with a 165-ft subsurface grid of 1200% CDP data. Field data were acquired with a conventional 96-trace dynamite crew utilizing a rolling, crossed-array technique. Data processing was carried out with a flexible, conventional seismic processing package. The results of wavelet deconvolution, surface-consistent static solution, 3D migration and geologic slice displays will be demonstrated. Total cost of the survey was $50,000.00 Canadian per sq mi.

An objective of this paper will be to demonstrate the interpretive power of 3D surveys.

INTRODUCTION

The advantages of 3D acquisition and processing techniques have long been recognized. By providing a finer sampling of the subsurface and using 3D migration techniques, anomalies can be better defined. The techniques have been used for a number of years in complex marine and land environments. Because of the cost of the present acquisition and processing methods, they have had limited use for small plays and anomalies.

The purpose of this paper is to describe a 3D seismic survey conducted in the Black Creek Basin of northwestern Alberta in February of 1982, and to demonstrate that 3D techniques can be a very cost-effective tool.

The first section of the paper briefly reviews the geology of the area and the nature of the exploration targets, borrowing heavily from AAPG papers by Barss, Copland and Ritchie (1970) and McCamis and Griffith (1975). The second section describes the field acquisition technique, processing approach, display and interpretation results, and cost effectiveness. In the third section of the paper, an example of a 3D survey over a Leduc Reef Trend further illustrates the resolving ability of the technique.

GEOLOGY

The Black Creek basin is located in extreme northwestern Alberta. It was the site of prolific reef growth during the middle Devonian period. Pinnacle and atoll reef forms grew to a vertical height of up to 820 ft and varied in area from a few acres to approximately 6 sq mi. The regional relationship between this area of reef growth and the larger Elk Point Basin is depicted in Figure 1. A barrier-reef complex separated the open-marine deposition to the northwest from evaporite deposition in the southeast. It was in the vicinity of this subsiding barrier complex that Keg River reef organisms found conditions favourable for growth.

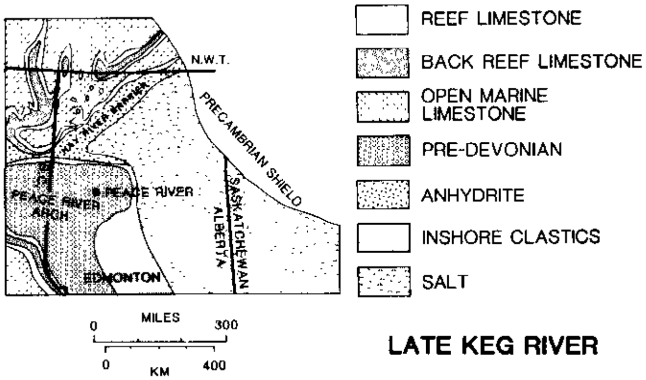

Fig. 1. The location of the 3D survey. A barrier-reef complex separates open-marine deposition to the northwest from evaporite deposition of the southeast.

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[1] Prime Energy Ltd., 820, 602 - 12th Ave. S.W., Calgary, Alberta
[2] Veritas Seismic Ltd., 615 - 3rd Ave. S.W., Calgary, Alberta T2P 0G6

Figure 2 illustrates some of the details of basin reef development. Initial sedimentation consisted of Lower Elk point evaporites and redbeds sitting directly on the Precambrian. At the beginning of Keg River time these evaporitic conditions were succeeded by a rapid transgression during which bituminous open-marine limestones and dolomites of the lower Keg River were deposited over much of northwestern Alberta. With a slowing in the rate of subsidence, reef growth was initiated in favourable areas and continued in bank, pinnacle and atoll forms. A pinnacle is illustrated in Figure 2. A broad regional uplift resulted in a hypersaline restricted area between the Hay River barrier and Shekilie barrier, filling the Black Creek basin with halite. Up to 270 ft of the Black Creek salt member is present in parts of the basin today. Subsequently, renewed subsidence of the Elk Point basin produced the Musket anhydrites and dolomites, followed by a period dominated by the marine carbonates of the Sulphur Point and Slave Point. Subsequent to this era, major solution of the Black Creek salt occurred contemporaneously with deposition of 2000 ft of Devonian shale, then 750 ft of Devonian Wabamun carbonates and, finally, another clastic phase.

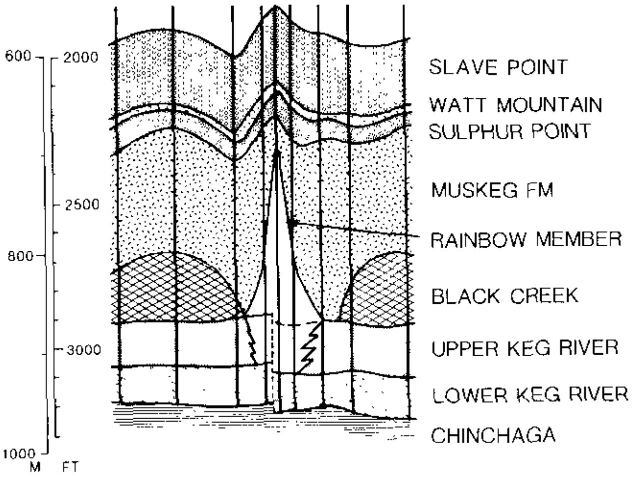


Fig. 2. Pinnacle reef development.

The synthetic seismogram in Figure 3 illustrates the seismic response expected in this area. The two transitions from clastics to carbonate (intervals A to B and C to D), along with the basement complex (not shown), provide three mappable events. Dissolution of the salt from around the reefs creates relief on the overlying Slave Point event. Mapping isochron changes between the three major events has allowed quite accurate mapping of the underlying reefs, so that during a four-year period after the initial discovery in March 1965, seismic techniques were used in the discovery of over 1.5 billion barrels of oil and 1 TCF of gas in place.

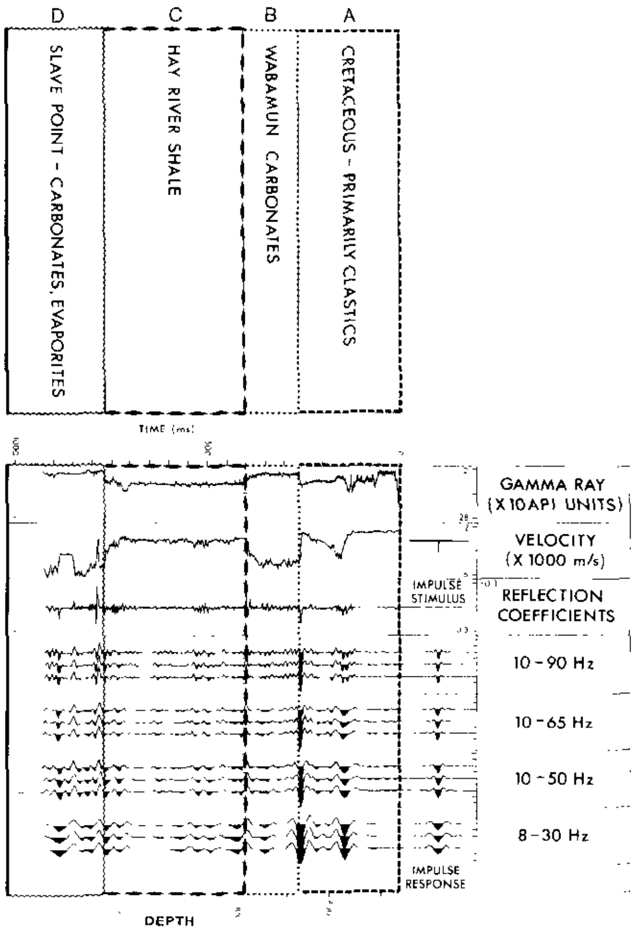


Fig. 3. Synthetic seismogram illustrating the seismic response expected in the area.

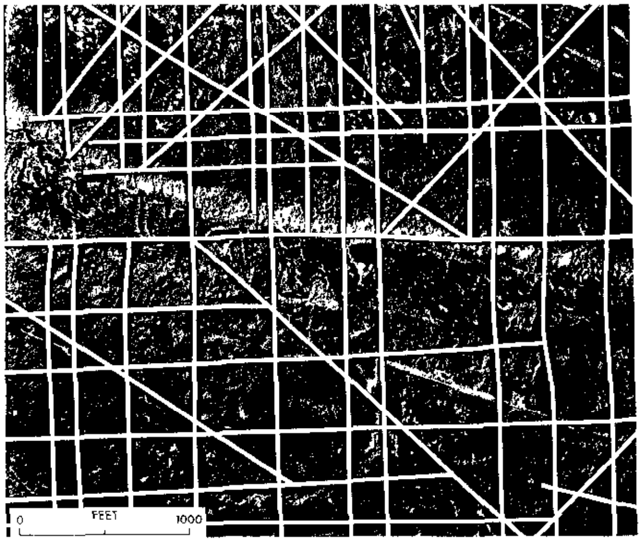


Fig. 4. Topographical map outlining the density of the conventional seismic lines, in white, for a typical part of the basin.

Figure 4 shows the density of conventional seismic coverage in a typical part of the basin. Clearly, with such dense seismic control, most reefs should already have been found. However, as a result of geological complexity, small areal size, poor data quality and changing economics, new reefs continue to be found in several parts of the basin. The area is today one of the more active exploration regions of Alberta. Discoveries are generally in the million-barrel recoverable range, with a completed well costing about one million dollars Canadian. The problem of correctly identifying reefs and properly locating wells is best handled by 3D seismic techniques.

ACQUISITION

A 96-trace DFS V dynamite crew from Quest Exploration was used to acquire 1200% data on a 165-ft subsurface grid using a rolling crossed-array mode.

A six-square-mile area was surveyed consisting of six 3-½-mi source lines and 23 orthogonal 2-mi receiver lines. Two typical geophone spreads are illustrated in Figures 5 and 6. Each shot location was recorded on six one-mile-long geophone lines with 16 geophone groups per line. The geophone lines were separated by a nominal 660 ft but several existing lines were utilized, so that actual spacing ranged from 440 ft to 880 ft. Since there is a strong multiple near the objective zone, a uniform distribution of offsets up to 5000 ft is desirable. For this reason, all shots were fired from the ends of the six live geophone lines. In order to provide sufficient stack multiplicity, shots were fired from both ends of each six-line geophone spread. The geophone spread was then rolled one geophone line along the source-line direction and another set of shots fired. Two one-mile-wide swaths of 3D coverage were thereby obtained, with coupling between the two sets provided by an overlapping band of common depth points.

Environmental impact is a consideration in any seismic data acquisition and, in this case, was minimized by using 50 mi of existing cut line, 16 mi of new hand-cut receiver line and only 2 mi of bulldozed new cut. The CDP binning technique used during processing solved any problems caused by the lines not lying on a regular grid. The acquisition took 7 days, during which approximately 600 96-trace shots were recorded for a total cost of $250,000.

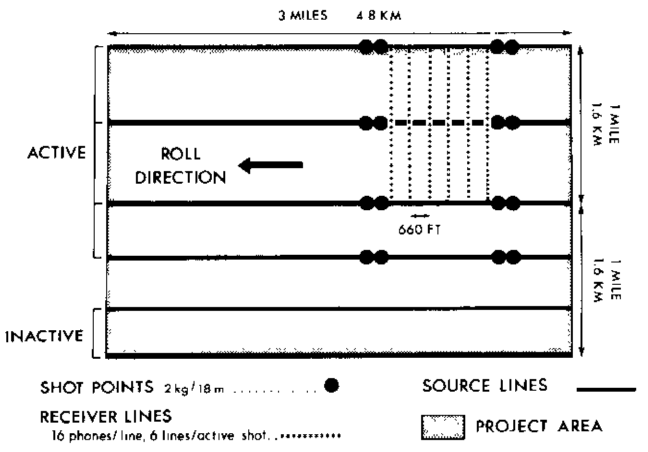


Fig. 5. The data set was acquired in two one-mile-wide swaths. The source and receiver layout used is shown. The upper mile is active in this figure.

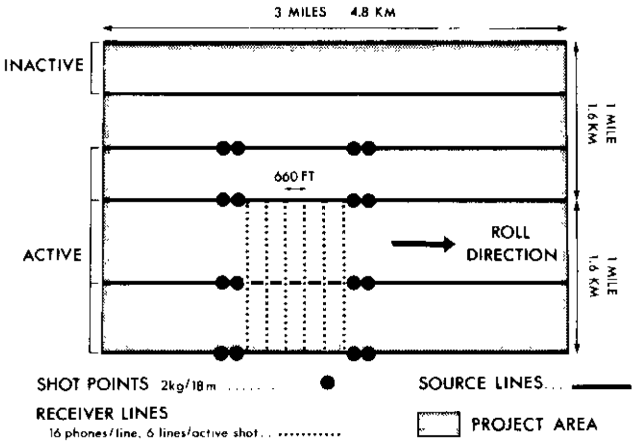


Fig. 6. The data set was acquired in two one-mile-wide swaths. The source and receiver layout used is shown. The lower mile is active in this figure.

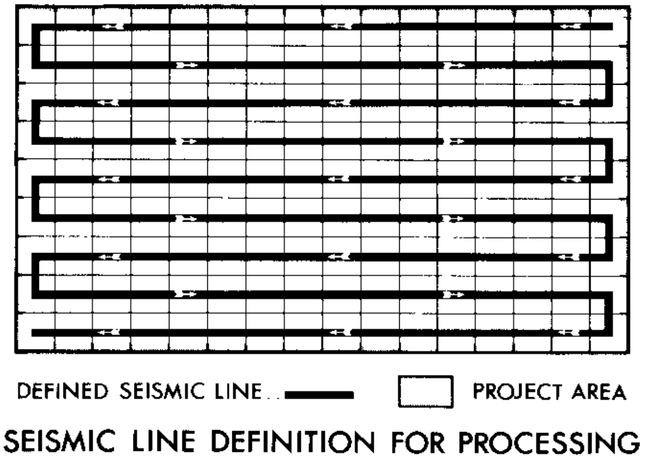


Fig. 7. Schematic drawing of the subsurface showing the grid of coverage and the 2D crooked-line method of geometry input.

PROCESSING

Because the shooting geometry could be satisfactorily described in terms of a crooked 2D line, the data set was processed through a conventional 2D system with minor modifications. As shown schematically in Figure 7, the data set was treated as a long, crooked line, accordion-folded with 65 parallel segments 3 mi long. The CDP bin size was defined as a 50-m square, resulting in a grid of 123 by 65 bins. The CDP coverage obtained over part of the survey is indicated in Figure 8.

Figures 9 and 10 illustrate the general data quality. The primary zone of interest is outlined in black, with the Slave Point at approximately 1.0 s and the basement complex at 1.3 s. It can be seen that the Wabamun top at 0.6 s is in fact present on only about half the offsets, a factor that must be considered when designing the acquisition parameters.

Generally, this region is characterized by severe static and multiple problems, but little horizontal velocity variation. Ideally, a refraction analysis should be performed to determine the long-wavelength statics solution, but this option was not available. Consequently, the conventional 2D residual statics program left a long wave static component which manifested itself as a line-to-line jitter in the stacked data after re-sorting in the orthogonal direction. This problem was resolved by doing a two-dimensional smoothing of the calculated statics before applying them to the data.

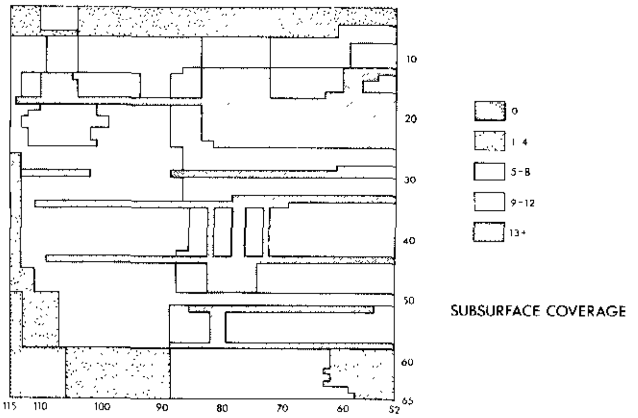


Fig. 8. Subsurface coverage map over a portion of the 3D data volume.

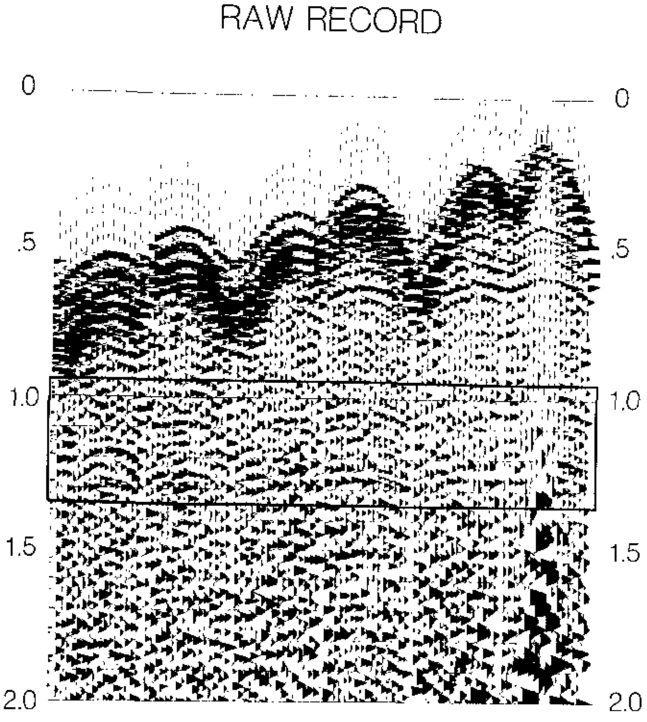


Fig. 9. A shot from the 3D data set with field recorded gain and exponential scaling applied.

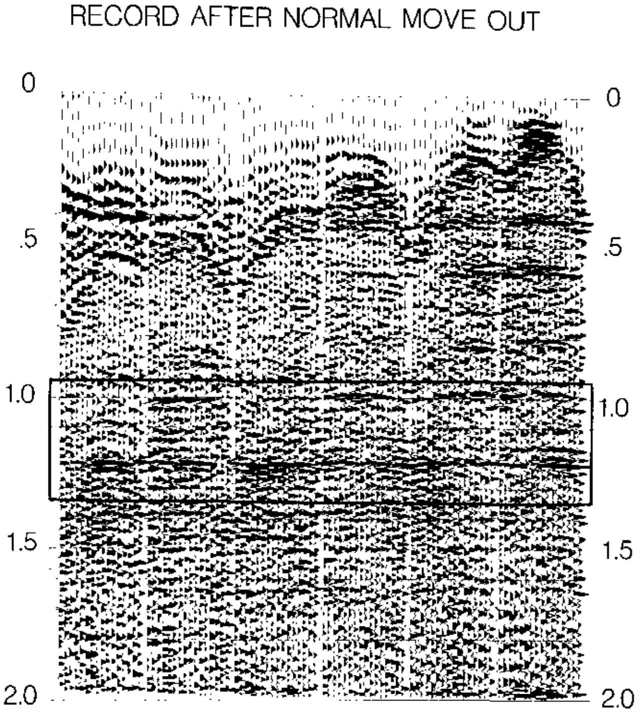


Fig. 10. The same shot as Figure 9 with scaling, instrument dephasing, deconvolution, normal moveout, filter and low-velocity-layer corrections applied.

The final processing step is 3D migration of the data. Before migration, any residual long-wavelength static problems were eliminated by flattening the data on the shallow carbonate marker. This is a reasonable approximation to the true structure, and was selected as being less damaging to the migration than unresolved long-wavelength statics. Figures 11 and 12 show one line from the final stacked set before and after the flattening procedure. The 3D migration was accomplished by performing two 2D migrations in orthogonal directions (Gibson *et al.*, 1983). The data set was migrated in one direction, re-sorted to the orthogonal direction and migrated again.

To minimize the paper volume, a compact display technique was used. Figures 13 to 17 illustrate "zone of interest" or data-slice displays. A region of data around the zone of interest is selected from each line and displayed *en echelon*. In this case, the zone selected was from just above the Slave Point to just below the basement.

The data slices in Figure 13 are the input to the migration. Three adjacent east-west lines are shown in the diagram. Figure 14 shows the results of the first 2D migration pass which, in this case, was orthogonal to the line direction displayed. It is particularly interesting to note the middle section of Figure 14 just below 1.1 s. Several events are not present on the corresponding unmigrated section in Figure 13 and have essentially been migrated into the plane of this section from adjacent sections. Also noteworthy is the improved general continuity of the Slave Point.

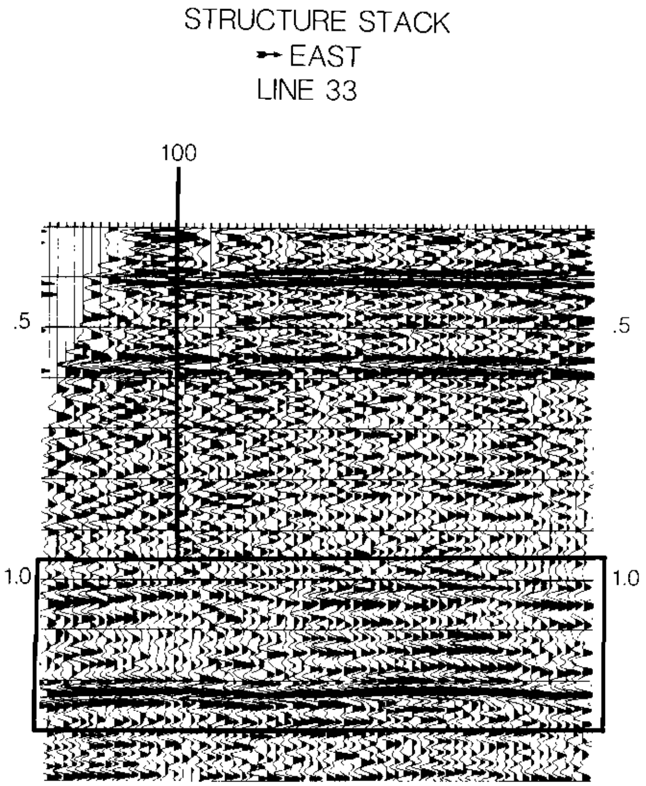


Fig. 11. A single east-west line from the fully processed data set.

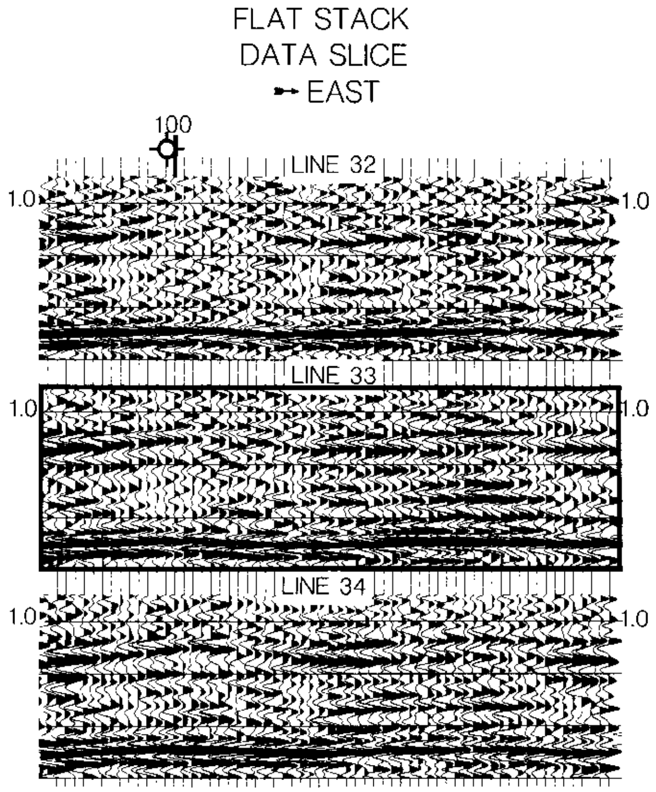


Fig. 13. East to west orientation "Zone of Interest" or Data Slice Displays of the unmigrated stack. A region of data from above the Slave Point to below the basement is selected from 3 lines and displayed *en echelon.*

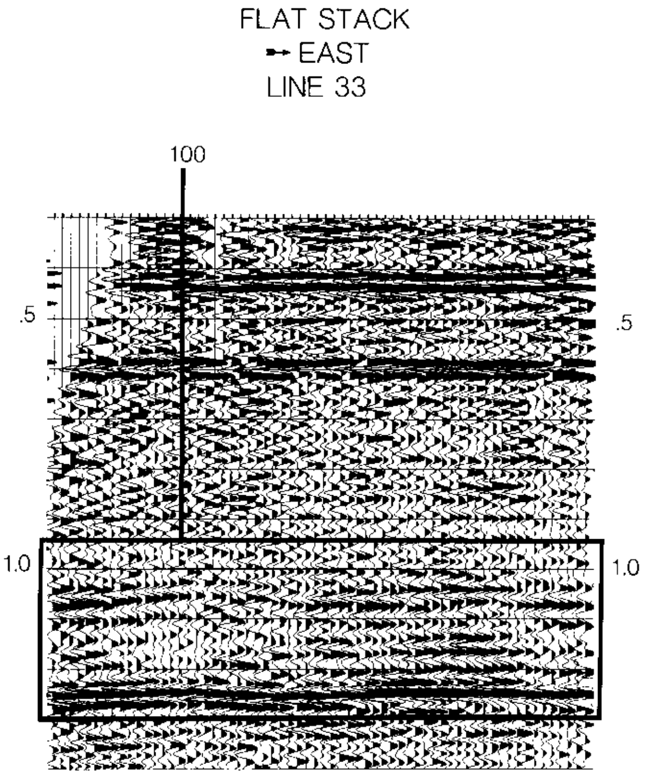


Fig. 12. The same line as Figure 11, with the shallow carbonate marker moved to a constant time of 0.6 s.

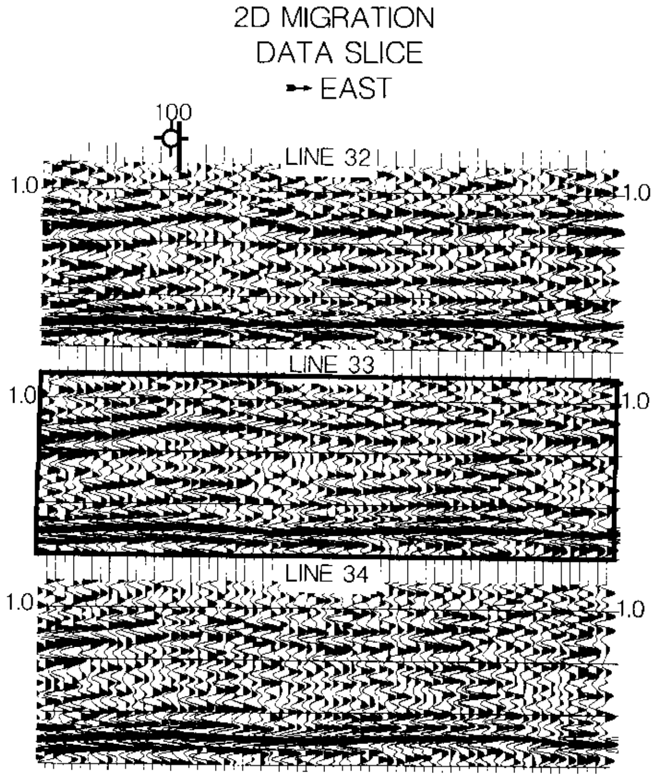


Fig. 14. The same sequence of data slices as Figure 13, with the first migration pass applied (in this case, the migration was orthogonal to the line display orientation).

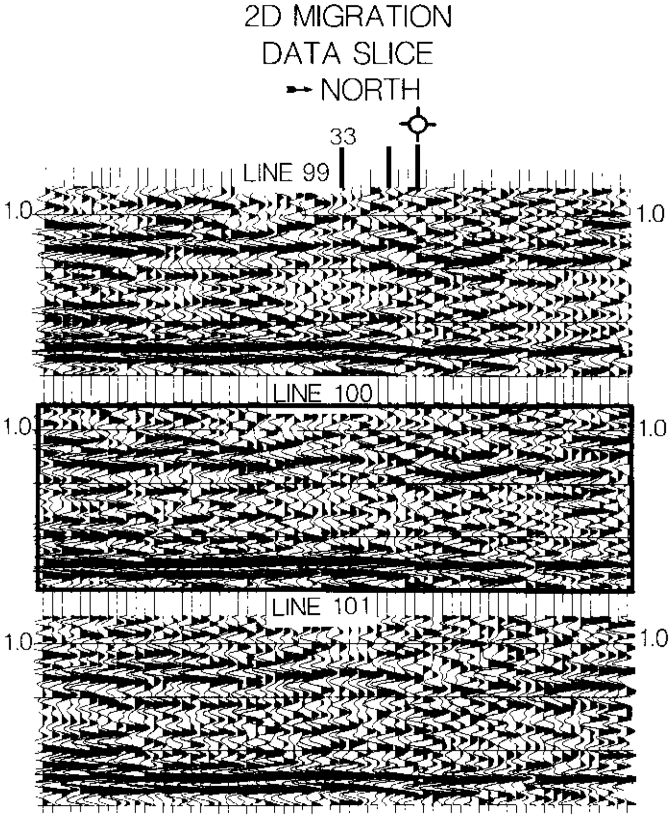


Fig. 15. North-south orientation data-slice displays of the first migration pass.

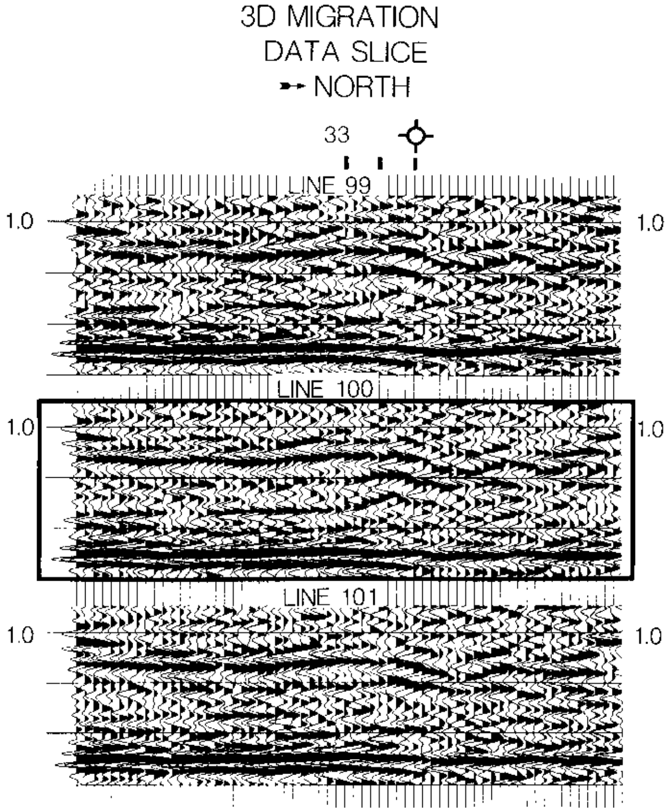


Fig. 16. The same sequence of data slices as in Figure 15, with the two 2D migrations in orthogonal directions applied.

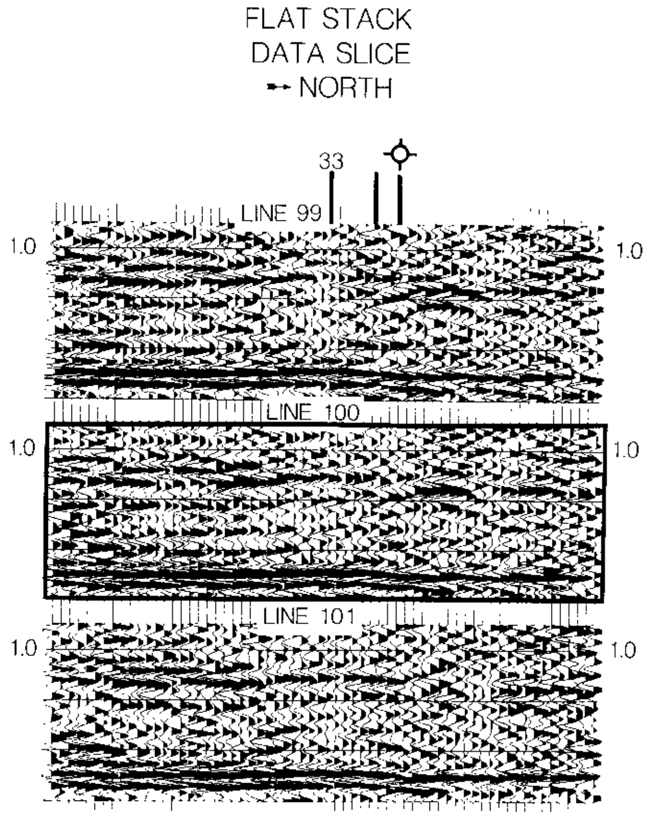


Fig. 17. The same sequence of data slices as Figures 15 and 16 before any migration.

Figures 15 and 16 show the effect, in the north-south direction, of the two migration passes, first after a single pass in one direction and then after two orthogonal migrations. The most significant difference is at the Slave Point reflector between 1.0 and 1.1 s, where the migration has apparently made sense of the previous confusion. Figure 17 shows the same sequence of data slices before any migration, and the difference is remarkable.

DISPLAY AND INTERPRETATION

The map in Figure 18 indicates the location of the migrated data slices and the dry-hole location. Also indicated is the location of a conventional line to be examined later.

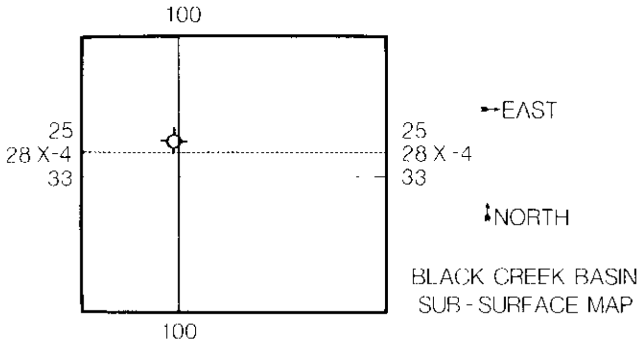
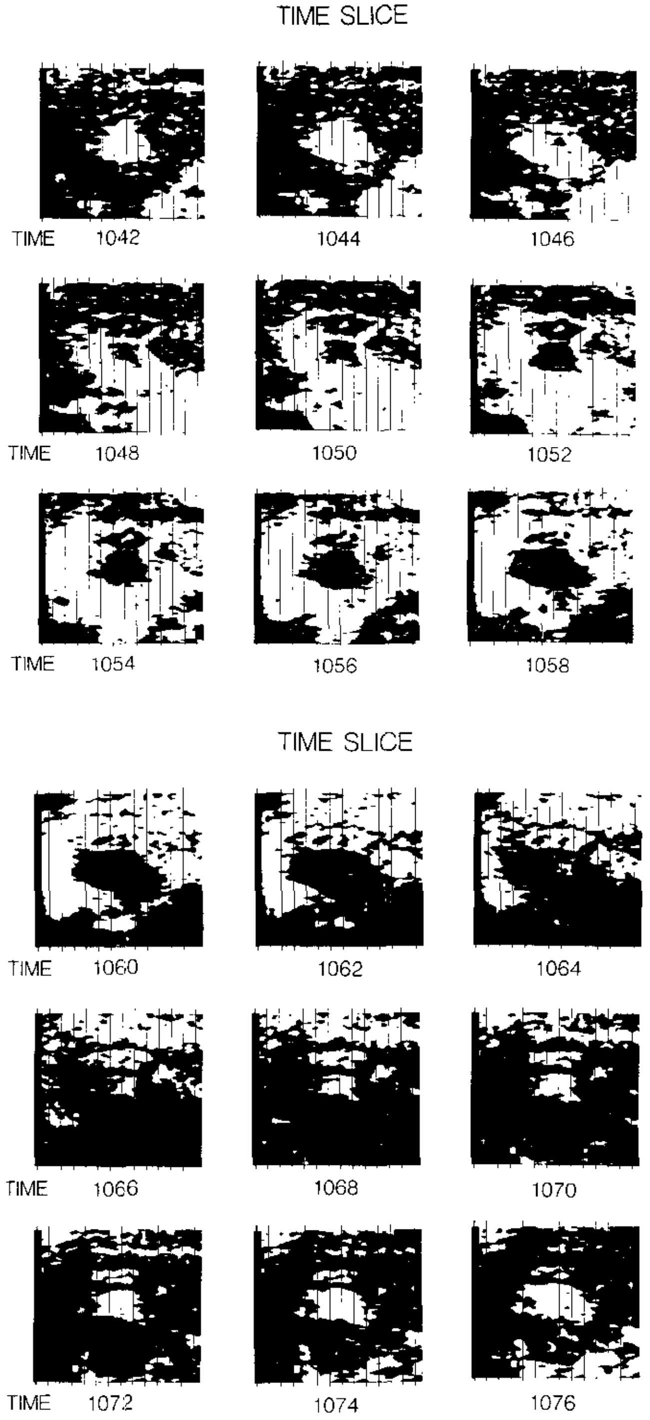


Fig. 18. Map of the 3D data volume indicating location of the lines examined and the location of a dry hole.

A useful presentation of the data set can be obtained by displaying the data at a constant time (Bone *et al.*, 1983). Whereas conventional 2D displays represent vertical cross sections through the earth, the "time slice" display can be thought of as a horizontal cross section. Figures 19 and 20 illustrate 18 consecutive constant time slices, each 2 ms deeper than the last, that clearly indicate and neatly map an anomaly. Note the small black area in the middle of time slice 1046, which grows as the slices step deeper in time. Each successive time slice defines the reef 2 ms deeper in time, or approximately 15 ft. This anomaly has since been drilled and confirmed as a reef buildup with commercial hydrocarbons.



Figs. 19, 20. Eighteen "time slices" or horizontal cross sections of the data set, each covering the same area as the map in Figure 18, displayed at 2-ms intervals.

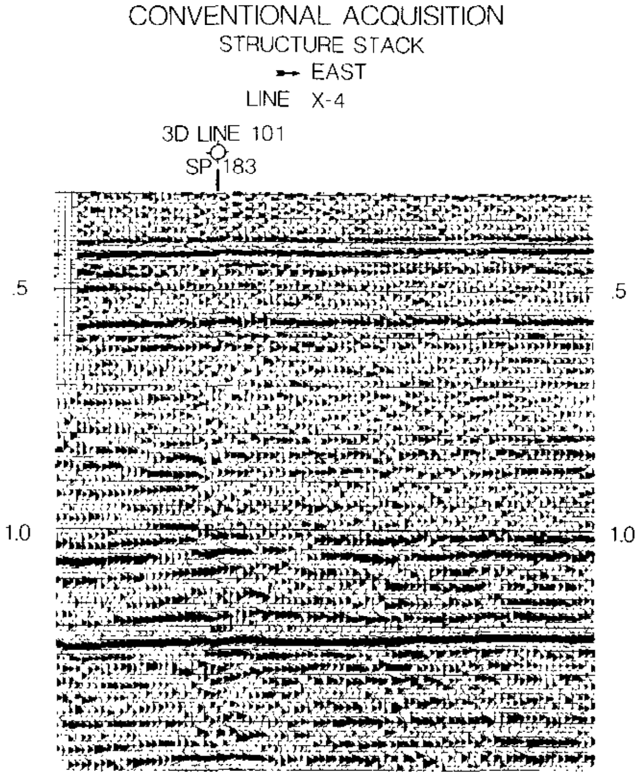


Fig. 21. A conventional 2D line from the area. See map in Figure 18 for its location.

By way of comparison , the best conventional modern 12-fold data available are illustrated in Figure 21. Some of the problems in understanding the geology are illustrated in this figure. The Slave Point possibly crosses two reefs but seems disturbed, and the interpretation is unclear. The dry-hole location and the position of this line with respect to the 3D data volume are shown on the map in Figure 18. The reef was crossed by a number of conventional lines but was never properly tested.

In addition to this reef, at least two other potential locations have been identified on this data set. A well in this area costs $1,000,000. A 3D data volume, acquired and processed, costs $50,000 or less per square mile. Stated in ratios, 20 one-mile-square 3-D surveys equal the cost of one well. Some areas of the basin have several pinnacles in a single square mile. Whipstocking a well because the reef crest was missed can also cost the equivalent of 10 to 20, 3D surveys. The environmental compatibility of the technique also offers some major benefits. Only 2 mi of bulldozed new cut were required for this program, while the subsurface was sampled at a 50-m interval in both X and Y directions.

FURTHER EXAMPLE

A second example of the resolving power of 3D surveys is shown in Figures 22 to 27, this one a Devonian Leduc reef from central Alberta. Again, we are looking for a few million barrels recoverable from a few tens of acres.

Figure 22 illustrates a good conventional line which crosses two proved pinnacles at the indicated locations. A shale event overlying the reefs, black on this display, is indicated. Mapping the compaction draping of this event enabled explorers to find some of these reefs. The reef farthest left on this section is readily evident, while the smaller anomaly to the right lacks clear definition. Drape on the event above the shale was probably the basis for the well. It was also the basis for many dry holes, as this interval is plagued with salt and salt-solution effects. Figure 23 is extracted from a 3D data set encompassing these reefs. It is roughly coincident with the line in Figure 22. The overlying shale marker is again indicated and the small pinnacle is still difficult to detect.

Figure 24 is the same 3D line after 3D migration. Observe the clearly evident shale draping over the small reef and also the focusing of the events below the shale. In addition to these diagnostic indicators, the reef formation itself is now clearly visible.

Figures 25 and 26 are data-slice displays showing the reef interval from three adjacent lines, before migration

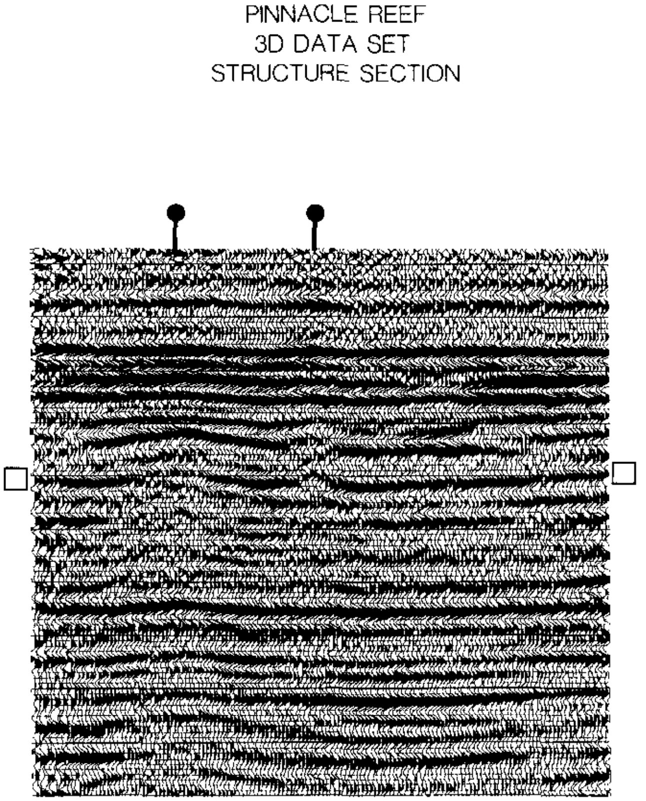


Fig. 23. A single unmigrated line, roughly coincident with the line in Figure 22, from a 3D data volume encompassing the two anomalies.

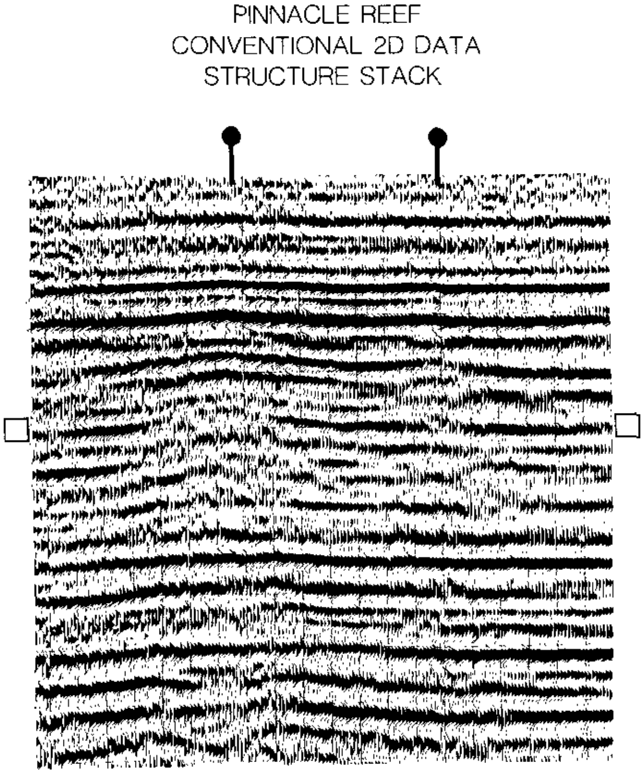


Fig. 22. A conventional unmigrated 2D line from a Dovenian Leduc reef area of central Alberta, showing two anomalies.

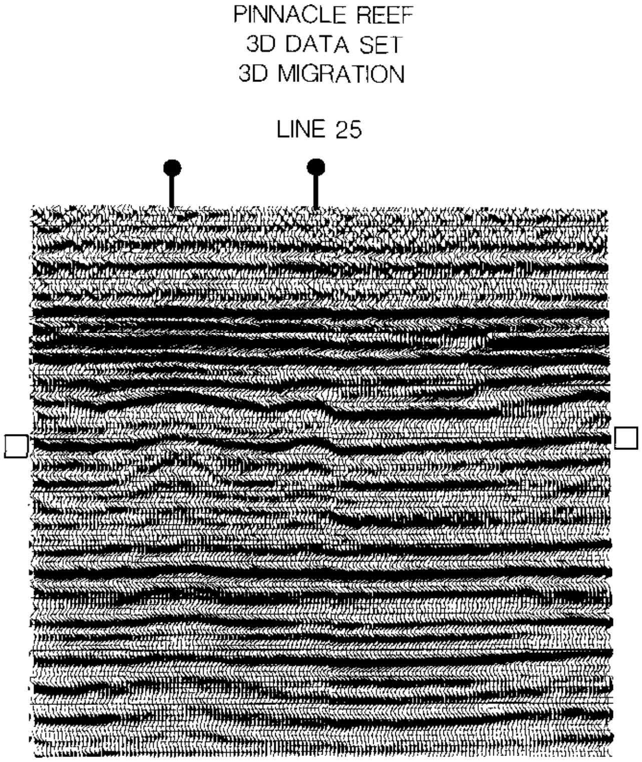


Fig. 24. The same line as in Figure 23, after 3D migration.

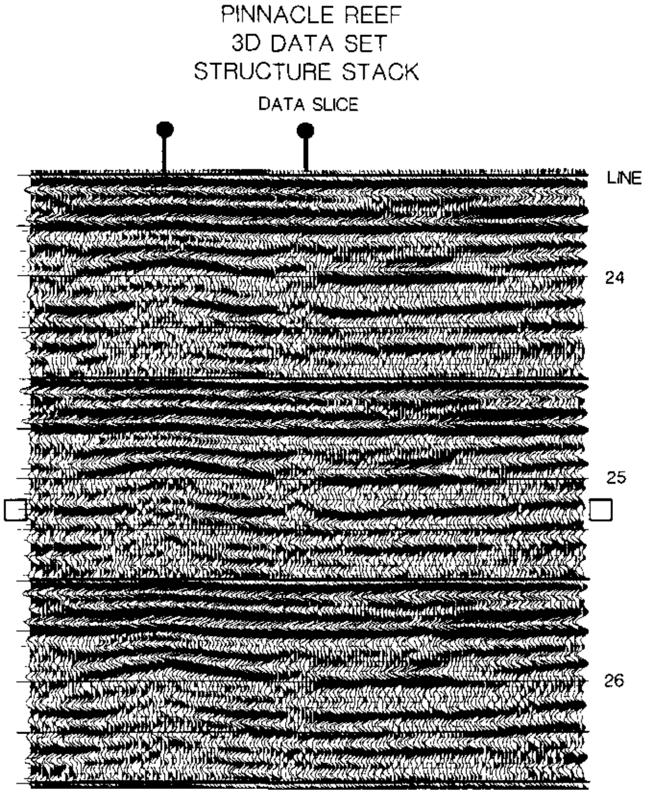


Fig. 25. Data-slice displays of three lines before migration, from the 3D data set over the anomalies.

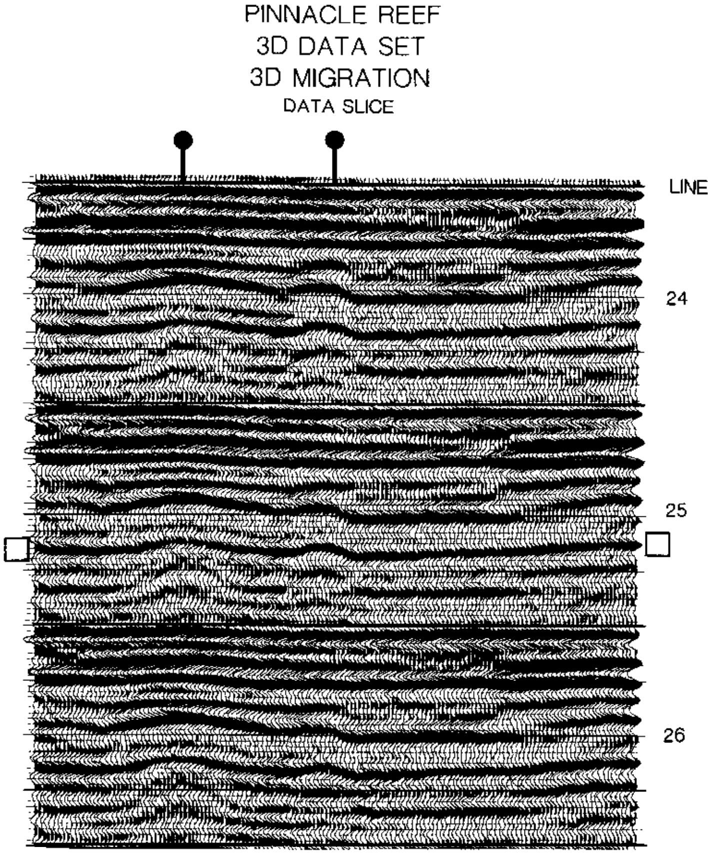


Fig. 26. The same sequence of data slices as in Figure 25, after 3D migration.

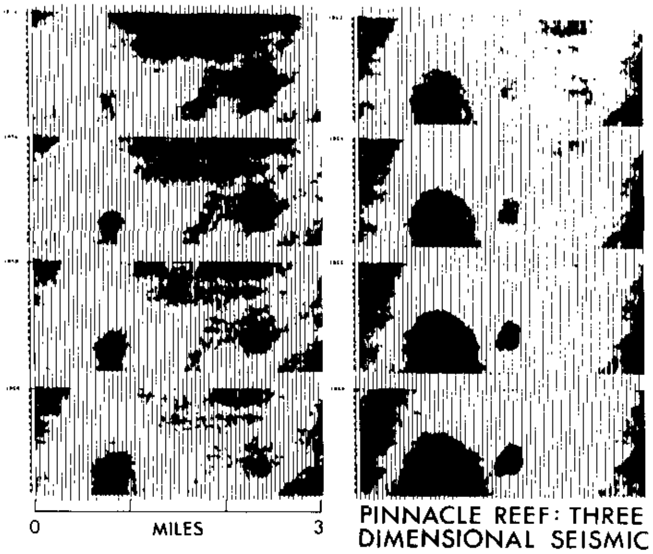


Fig. 27. Eight time-slice displays at the shale-marker level, illustrating the two anomalies.

(Fig. 25) and after migration (Fig. 26). The reef zone is two peaks below the marker indicated on the central line of each figure.

Figure 27 is a series of 8 time slices at the shale marker level illustrating the two reefs. The larger reef to the left has a maximum buildup 8 ms or approximately 50 ft higher than the smaller reef. In this second survey, then, the objective of finding hydrocarbons in a small area, using a cost effective method, has been met. The 3D data resolved the somewhat uncertain interpretation in a convincing and economical manner.

CONCLUSIONS

A method of acquiring and processing 3D seismic data has been presented. The main features of the method, as demonstrated in the application to two areas, are:

1) Conventional crews were used, with conventional instruments.

2) Low environmental impact was achieved by using existing cut lines.

3) Data processing was accomplished largely by using conventional 2D techniques (even migration).

4) The resulting 3D data offered considerably improved interpretability over previous conventional 2D data.

5) The total costs of each survey compared very favourably (approximately 1/10) with drilling costs in the region.

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