GEOPHYSICS, VOL. 47, NO. 2 (FEBRUARY 1982); P. 177–195, 25 FIGS.

Field appraisal with three-dimensional seismic surveys offshore Trinidad

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ABSTRACT

A consortium comprising Texaco Trinidad Inc., Trinidad and Tobago Oil Company Ltd., and Trinidad-Tesoro Petroleum Company Ltd. commenced exploration in the South East Coast Consortium block offshore Trinidad in 1973. After four years of intensive exploration, a gas/condensate discovery was announced in early 1977 on the Pelican prospect. Later that year, in anticipation of the possible future need to site drilling/production platforms, a three-dimensional (3-D) seismic survey was recorded over the prospect. This survey resulted in improvements in seismic record quality, multiple attenuation, and fault resolution. A coordinated geologic-geophysical interpretation based on the 3-D seismic survey, a reevaluation of log correlations, and the use of seismic logs differed significantly from earlier interpretations. Because of this, it is anticipated that development of the field will need to be initiated in a different fault block from that previously envisioned.

A second 3-D survey contiguous to the Pelican survey was recorded in 1978 over the Ibis prospect. Results show significant data enhancement in the deeper part of the section and improved fault resolution relative to previous two-dimensional (2-D) control. The 3-D interpretation has revealed a much more complex fault pattern than originally mapped. Separate fault blocks will have to be individually evaluated, thus greatly increasing exploration risk.

INTRODUCTION

The republic of Trinidad and Tobago lies approximately eight miles off the northeast coast of Venezuela on the continental shelf of South America (Figure 1). Opposite Trinidad on the Venezuela coast is the delta of the Orinoco River.

The South East Coast Consortium was formed in 1973 to evaluate an offshore license (Figure 1) obtained from the Government of Trinidad and Tobago in that year. The Consortium comprises Texaco Trinidad Inc. (operator), Trinidad and Tobago Oil Company Ltd., and Trinidad-Tesoro Petroleum Company Ltd.

The license area lies approximately 30 miles off the southeast coast of Trinidad in the Galeota basin (Figure 2). This basin covers approximately 5000 square miles in which thick Pleistocene to Upper Miocene deltaic sandstones contain hydrocarbons in traps formed in gravity induced structures. Closures consist of large diapiric anticlinal ridges and rollover features developed downthrown to major growth faults. To date, four major oil fields and four major gas fields have been discovered in the basin and recoverable reserves have been estimated at one billion barrels of oil and 13+ trillion ft^3 of gas.

Exploratory drilling in the Consortium block was carried out between 1975 and 1977 with a total of 9 wells drilled on four separate structures. Of this total, six were drilled on the Pelican and Ibis prospects which form the basis of this paper. As a result of the exploratory drilling, a gas/condensate discovery was declared at Pelican in 1977. At Ibis, the presence of commercial quantities of hydrocarbons has not been confirmed in spite of the drilling of three productive wells on the structure.

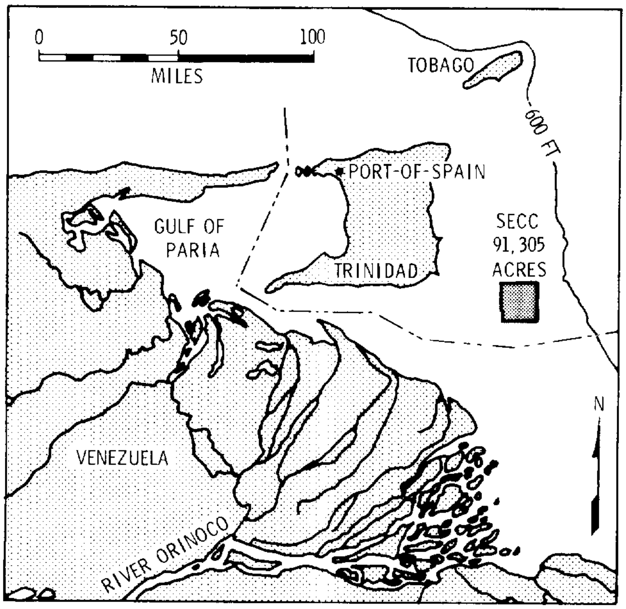

FIG. 1. Location of South East Coast Consortium block offshore Trinidad.

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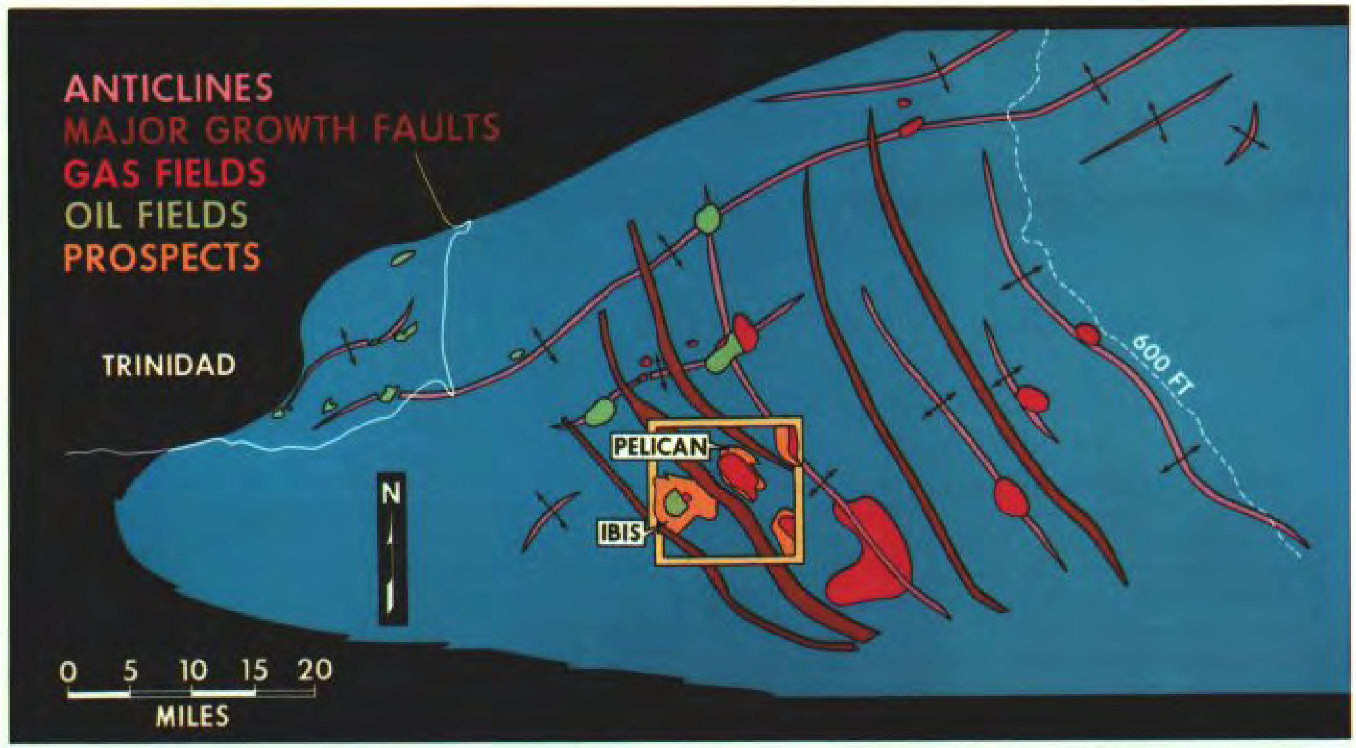

FIG. 2. Generalized structure of Galeota basin.

Thus in 1977, after four years of intensive exploration including the drilling of six wells and the recording of 1400 miles of seismic data, the Consortium was still faced with two major unanswered questions. These were: (1) Where should a development platform be located on Pelican? (2) Was the development of Ibis justified?

In seeking a solution to these problems, the Consortium engaged Geophysical Service Inc. to conduct a three-dimensional (3-D) seismic survey over the Pelican structure in 1977. Following this, the Ibis 3-D survey was recorded in 1978.

The value of 3-D migration in clarifying subsurface structure was vividly demonstrated in model experiments by French (1974). The problems of sideswipe energy which he discussed are considered to be particularly pertinent to the data recorded in the Pelican and Ibis areas.

Since 1976, 3-D surveys have been performed routinely on many prospects (Tegland, 1977; Bone, 1978; Hautefeuille and Cotton, 1979; Dahm and Graebner, 1982; and Johnson and Bone, 1980). Algorithms for 3-D migration were discussed by Schneider (1978), 3-D data collection and processing were reviewed by Selby (1978), and the design parameters for a successful 3-D survey were presented by Brown and McBeath (1980).

After the data from a 3-D survey have been migrated, numerous display options are available to the interpreter. Methods of 3-D data interpretation using these various displays were discussed by Brown (1978). The particular value of horizontal seismic sections has recently been reinforced by McDonald et al (1981).

THE PELICAN AND IBIS SURVEYS

Figure 3 shows the extent and orientation of the two 3-D surveys within the South East Coast Consortium block. The Ibis survey was recorded with the same parameters as the Pelican survey so that the data could be integrated during processing. In this way continuous 3-D coverage was obtained from one area to the other.

All data were recorded with 24-fold geometry along lines oriented southwest-northeast, the predominant dip direction over the block. The lines were 100 m apart, and the subsurface interval along each line was 33 m. The currents in the area were commonly 6–8 knots at right angles to the shooting direction, so the cable drift was high. Continuously recorded streamer tracking data provided the location of each depth point for each shot. A common-depth-point (CDP) set was then defined as those traces whose source-receiver midpoints fell within a bin 67 × 100 m.

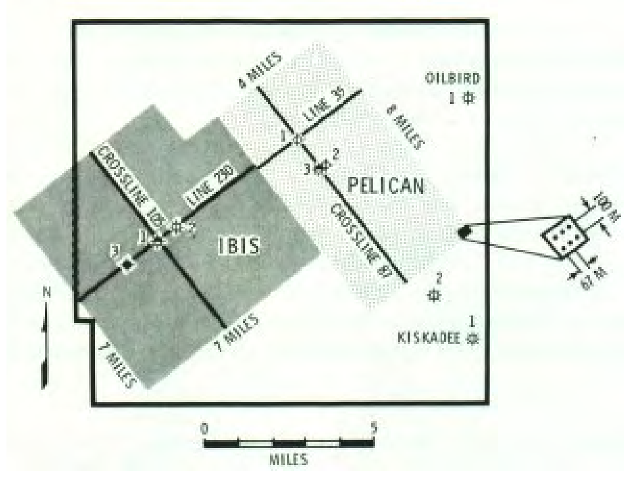

FIG. 3. Pelican and Ibis 3-D surveys and location of key lines.

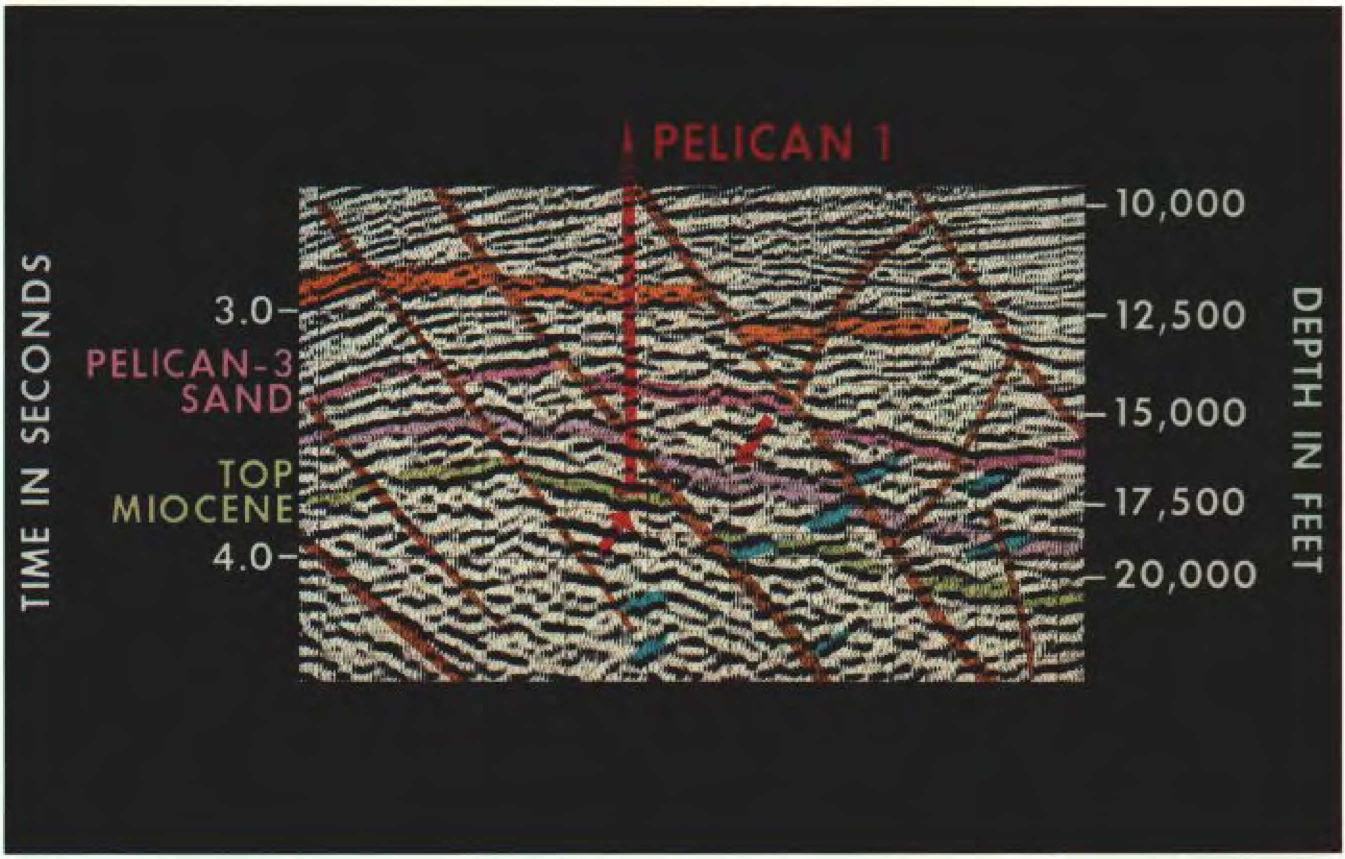

FIG. 4. Shot line 35, 2-D migration.

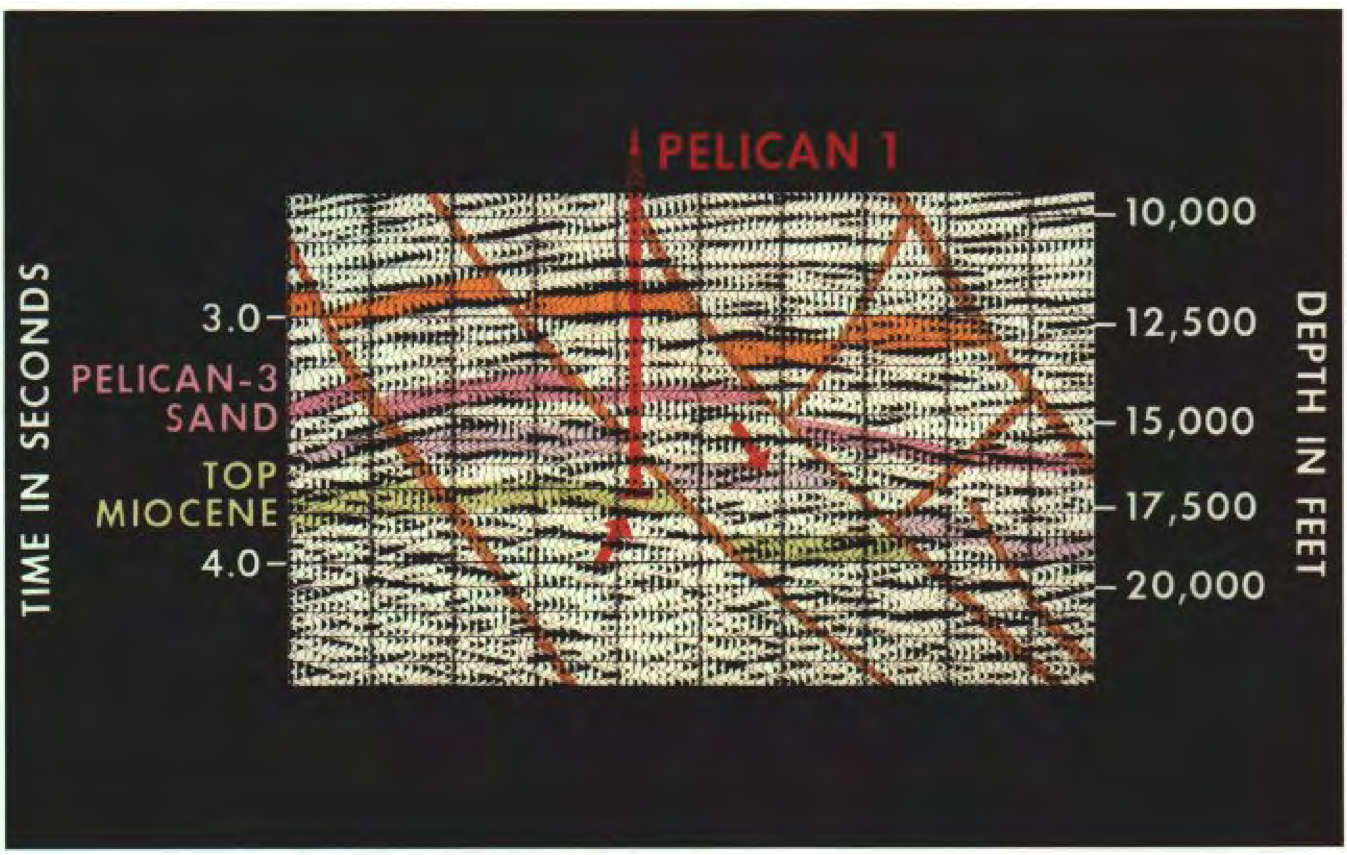

FIG. 5. Line 35, 3-D migration.

This limited the lateral subsurface smear to an acceptable level with a consequent improvement in the stack response.

After 3-D migration of the stacked data, the depth points at which migrated traces exist are spaced at 67 × 100 m as illustrated in Figure 3. The resultant data volumes at Pelican and Ibis were sliced to provide the basic displays for interpretation: lines, crosslines, and Seiscrop™ sections.

Figure 3 shows the location of the key lines that will be discussed below in order to examine the impact of 3-D recording and processing. Line 35 and crossline 87 will be examined at Pelican, and later line 230 and crossline 105 will be examined at Ibis.

PELICAN RESULTS

Figures 4 and 5 show the same portion of shot line 35 after two-dimensional (2-D) migration and line 35 after 3-D recording and processing. Several differences can be seen. However, in detailed comparison of individual features it must be remembered that they are not the same data. Because of dip in the crossline direction, data have moved into and out of the plane of line 35 during 3-D migration, in the manner illustrated in model experiments by French (1974) and in real data by Brown and McBeath (1980).

Certain comparisons are nevertheless justified. The general quality, continuity, and correlatability of the gold event is clearly improved on the 3-D section. This is attributed to the limitation of subsurface smear during stack as discussed in the previous section. Also, the fault definition is clearly enhanced.

At the positions of the red arrows in Figures 4 and 5, there is a reversal of interpreted dip. On the 2-D section, dip is definitely down to the northeast; on the 3-D section, dip is flat or slightly down to the southwest. The latter is confirmed by dipmeter logs in the Pelican-1 well. The change is explained as movement of data into and out of the plane of the section during 3-D migration.

Figures 6 and 7 demonstrate the effects of 3-D recording and processing on sections perpendicular to the direction of shooting. Figure 7 shows crossline 87 extracted from the 3-D data volume through the Pelican-1 and Pelican-3 wells. Figure 6 shows shot line 124, a 2-D line recorded at the same time as the 3-D survey in the same position as crossline 87.

The strong events between 1.5 and 2.0 sec on the northwest flank of the structure, that is on the left of the sections in Figures 6 and 7, are multiple generators. The multiple interference from these events occurs at a time coincident with the weak primary reflections from the reservoir section. The steeper multiple dip highlighted in blue on Figure 6 is clearly dominant on that section. This was the dip interpreted as primary on each of three previous conventional 2-D surveys. The gentler primary dip is, however, evident on crossline 87 (Figure 7).

The improvement in multiple attenuation in the 3-D data occurred during stack. The main reason for the improvement was more accurate velocities. In the 3-D processing the velocity analyses were run on binned data. Also, because the 3-D data were recorded in a direction close to strike on the northwest flank of the structure (northeast-southwest), there was less dip effect in the stacking velocity than for the 2-D data which were recorded northwest-southeast, the dip direction on this part of the structure. Furthermore, the stack multiplicity was increased from nominally 24 to nominally 48 by incorporating into one bin what would be an adjacent pair of depth points in conventional 2-D processing.

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Figure 8 shows the interpreted map at Top Miocene level when the 3-D survey was undertaken; it incorporates several generations of 2-D data. Figure 9 shows the map at the same level interpreted from the 3-D data. The most important difference is on the north flank of the structure, northwest of the Pelican-1 well. The dip between the well and the northwestern boundary of the 3-D survey area was mapped to be 2000 ft on the 2-D data (Figure 8). After the primary reflections had been correctly identified by using the 3-D data, less than 1000 ft of dip were mapped on the north flank (Figure 9). This decrease in dip has increased the interpreted hydrocarbon-bearing area under closure by approximately 20 percent, thus significantly affecting reserve estimates and development economics.

The prime reservoir in the Pelican area is the Pelican-3 sand. Figure 10 shows the interpreted map at this level before the 3-D survey. Figures 11 and 12 show two alternative interpretations from the 3-D survey data. A similar difference in northwest dip exists at this level as was mapped at Top Miocene, but the principal difference between pre- and post-3-D interpretations concerns the faulting.

Initial interpretation of the logs from Pelican-1 and Pelican-3 wells indicated different water levels in the Pelican-3 sand. This was explained by a cross-fault separating the two wells (Figure 10). The 3-D data precluded the possibility of this cross-fault. Instead, the growth fault has been interpreted farther northeast, thus separating the two wells at the Pelican-3 sand. The impact of this on the interpreted position of the reserves is shown in Figure 11. The recommendation based on the 3-D interpretation would therefore be to initiate development drilling in a different fault block from the one proposed prior to the acquisition of 3-D control. This change in interpretation has probably saved the South East Coast Consortium the expense of at least one dry hole and possibly the cost of mislocation of a development platform.

The water level in the Pelican-3 sand in the Pelican-3 well is near 13,800 ft. The contour at this level is shown by a dashed line in Figure 11. This is 200 ft deeper than the structural spill point of 13,600 ft, which, on the basis of structural closure alone, would control the downdip extent of the gas (Figure 11). An alternative interpretation which honors the water level in the well is shown in Figure 12. This invokes a stratigraphic reservoir boundary on the southeast. The validity and nature of this boundary are discussed in the next section.

THE STRATIGRAPHIC RESERVOIR BOUNDARY

The seismic section along crossline 87 (Figure 7) shows a very marked character change at the Pelican-3 reservoir level southeast of the well. It is probable that this indicates the position of the stratigraphic boundary.

This character change is evident on seven crosslines which intersect the boundary, and also on several Seiscrop sections. The two Seiscrop sections at 3260 msec (Figure 13) and 3276 msec (Figure 14) clearly show the high-amplitude positive (black) event outside the reservoir in the southeast part of the prospect area. The full sequence of Seiscrop sections intersecting the boundary, of which Figures 13 and 14 are two examples, was used to map its position as indicated in Figure 12.

The G-LOG™ process was used to investigate the nature of the stratigraphic reservoir boundary. A G-LOG function is a log generated by rigorous wave-equation inversion of the seismic trace (Graebner et al, 1980; Hays et al, 1980). A synthetic seismogram from a subsurface model is compared to the seismic trace, and an error is computed. Revisions are then made to the model iteratively until the error ceases to reduce. The residual

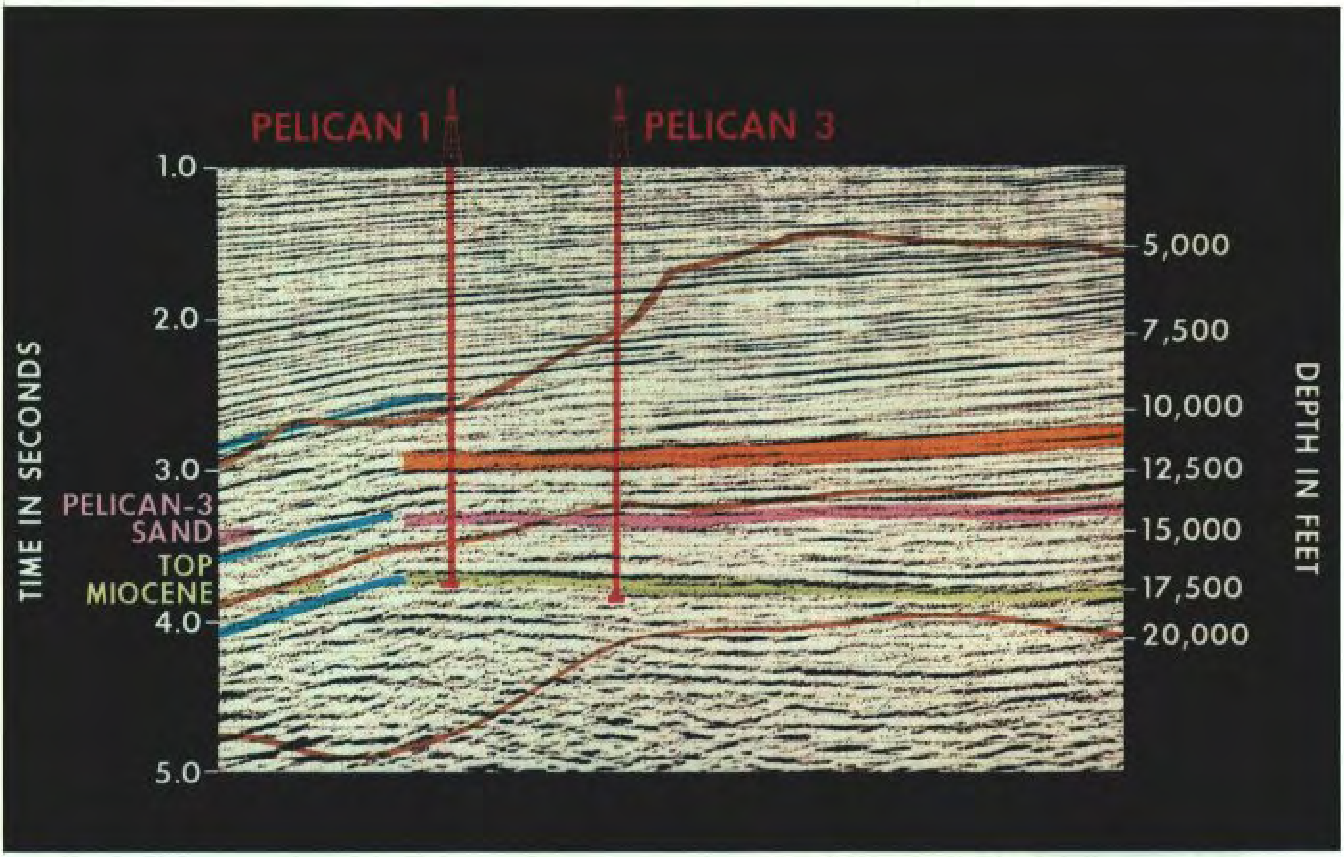

FIG. 6. Shot line 124, not part of 3-D survey but in same position as crossline 87.

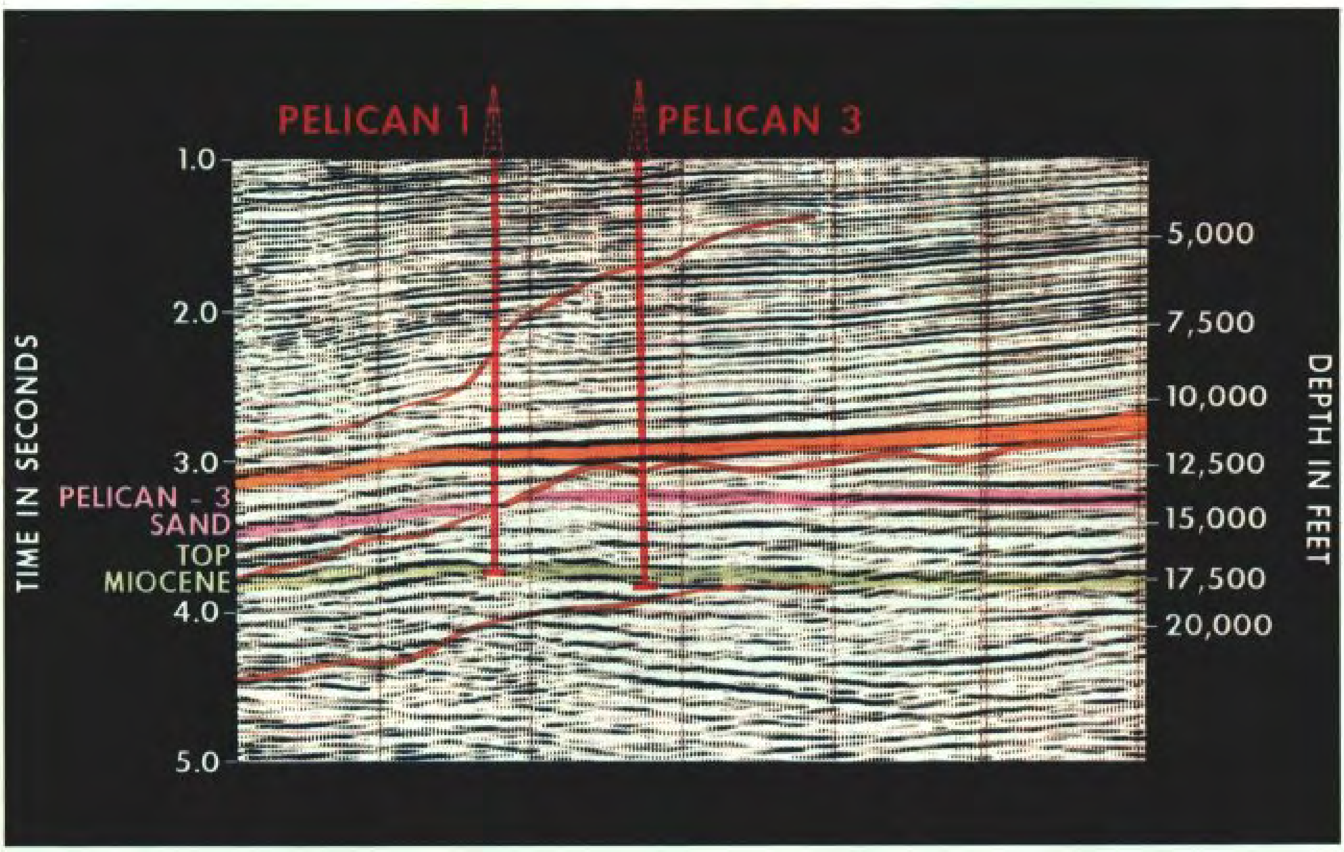

FIG. 7. Crossline 87, 3-D migration.

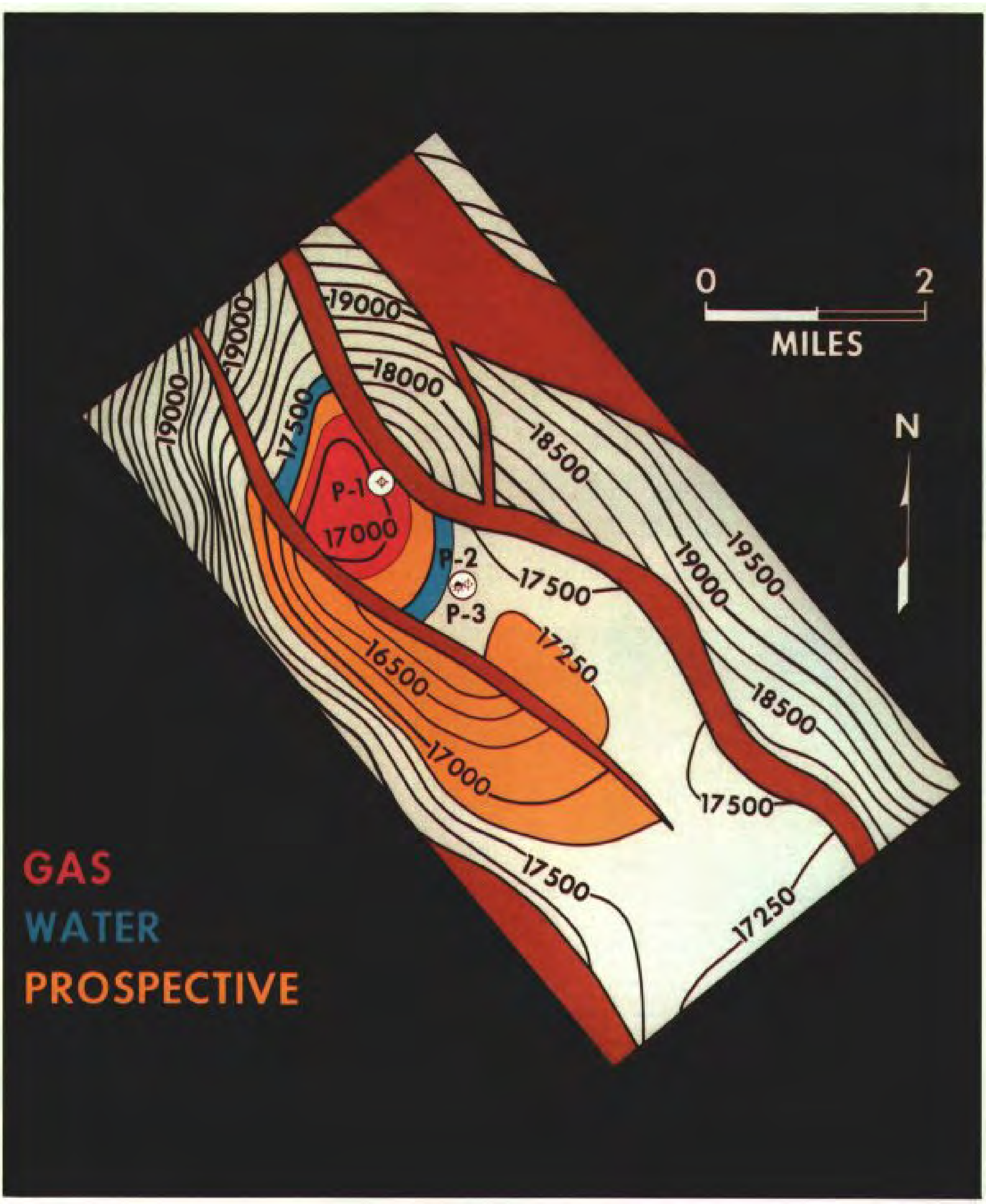

FIG. 8. Map of Top Miocene from 2-D data. Contour interval 250 ft.

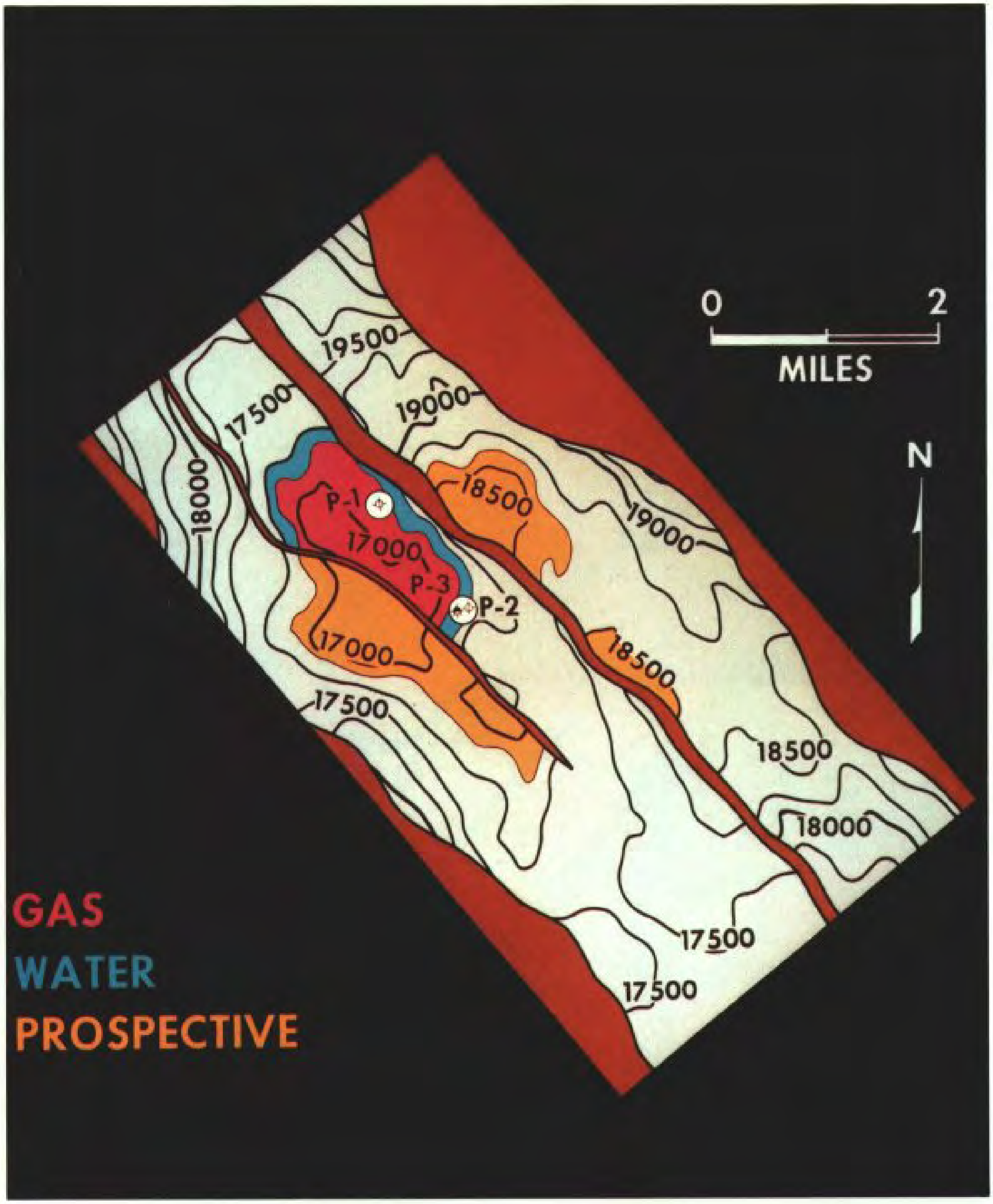

FIG. 9. Map of Top Miocene from 3-D data. Contour interval 250 ft.

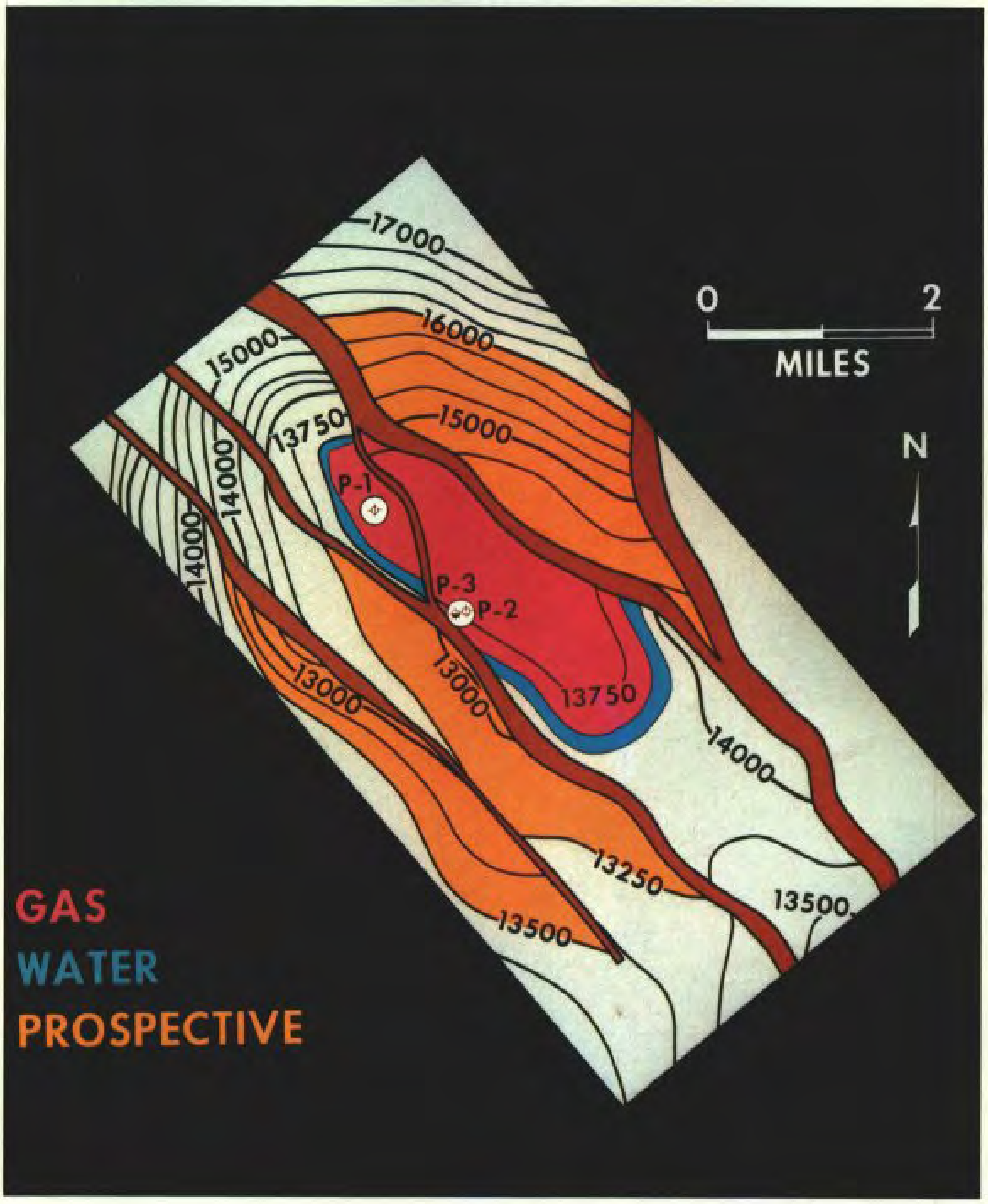

FIG. 10. Map of Pelican-3 sand from 2-D data. Contour interval 250 ft.

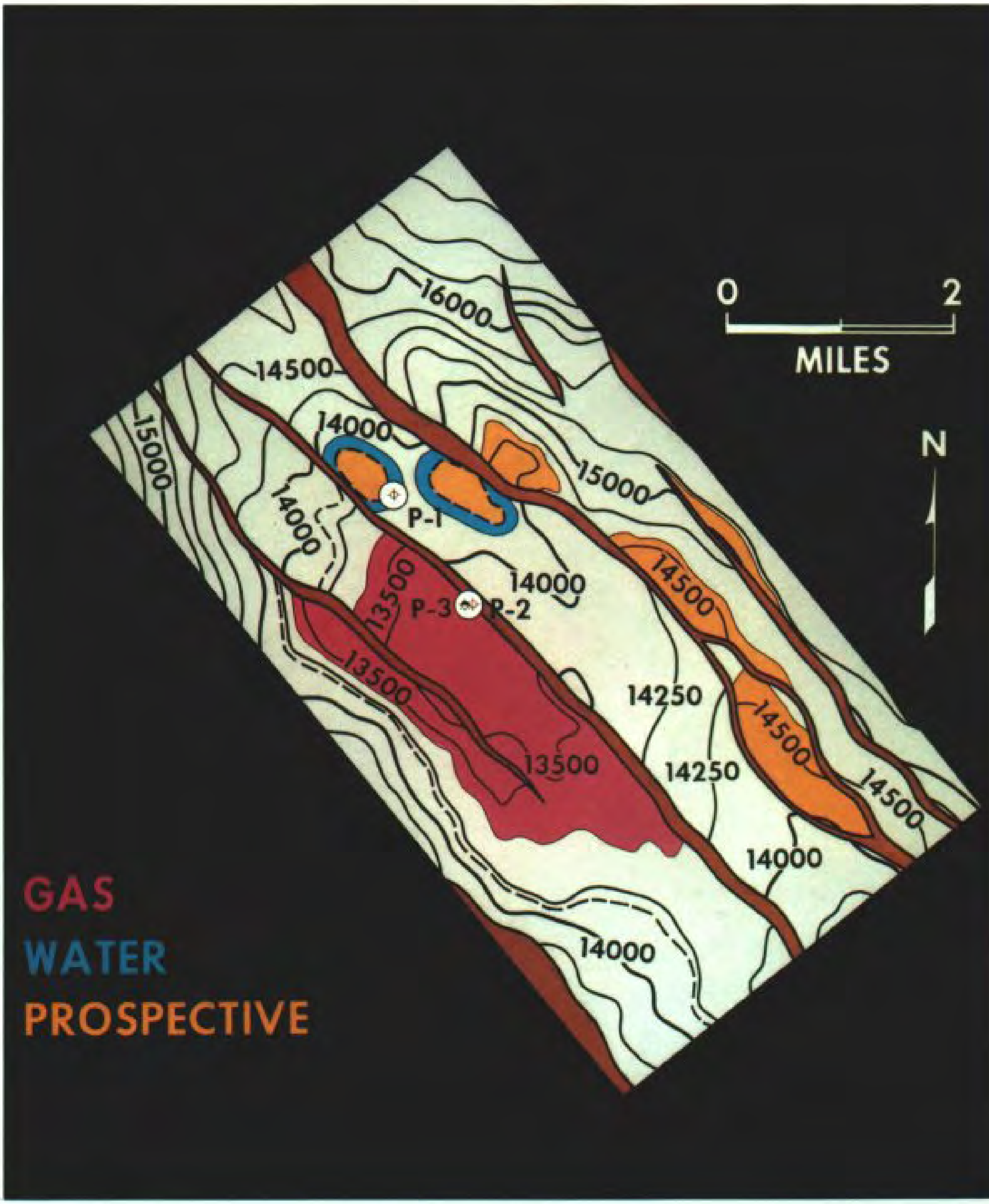

FIG. 11. Map of Pelican-3 sand from 3-D data with southeastern structural boundary. Contour interval 250 ft.

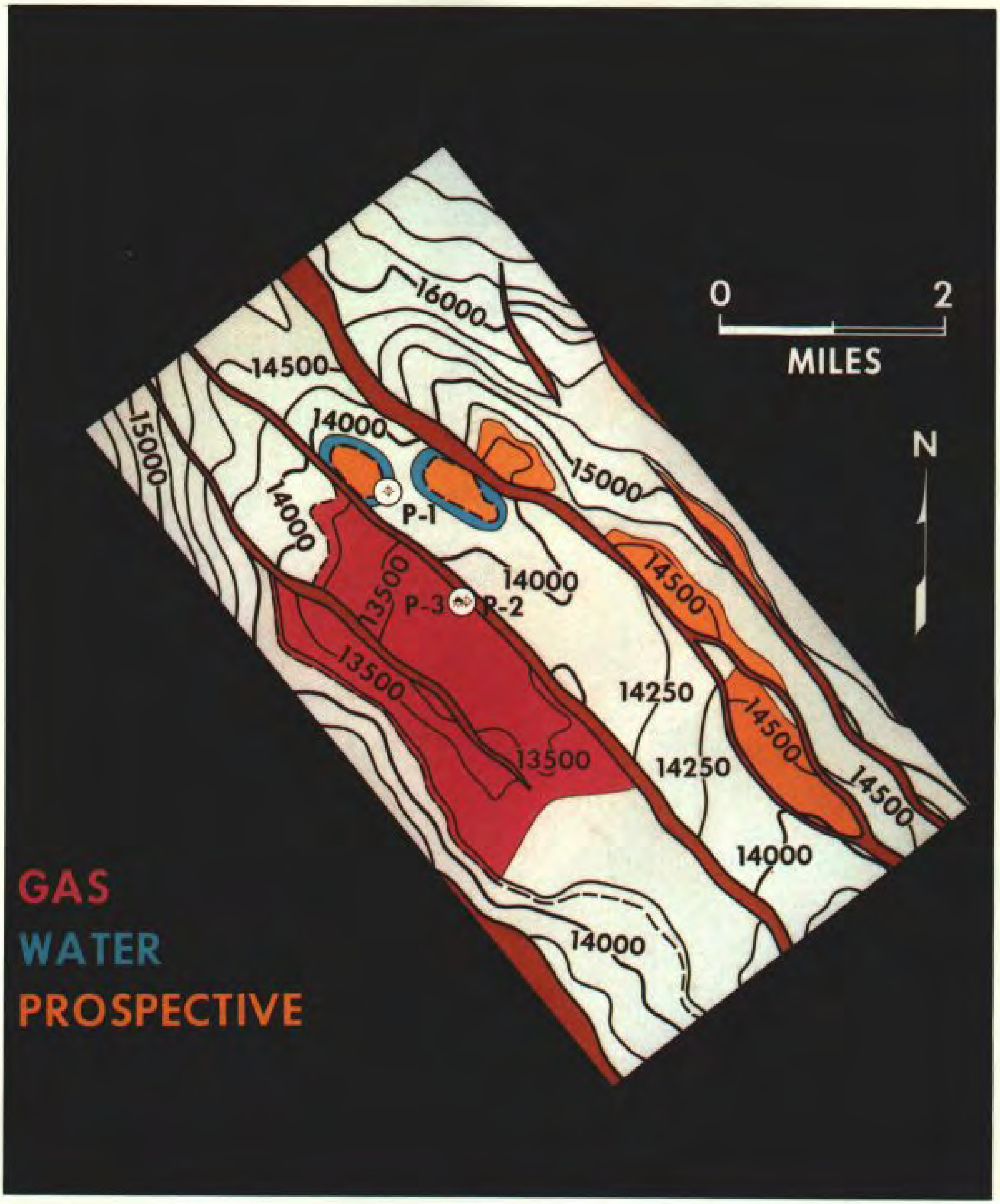

FIG. 12. Map of Pelican-3 sand from 3-D data with southeastern stratigraphic boundary. Contour interval 250 ft.

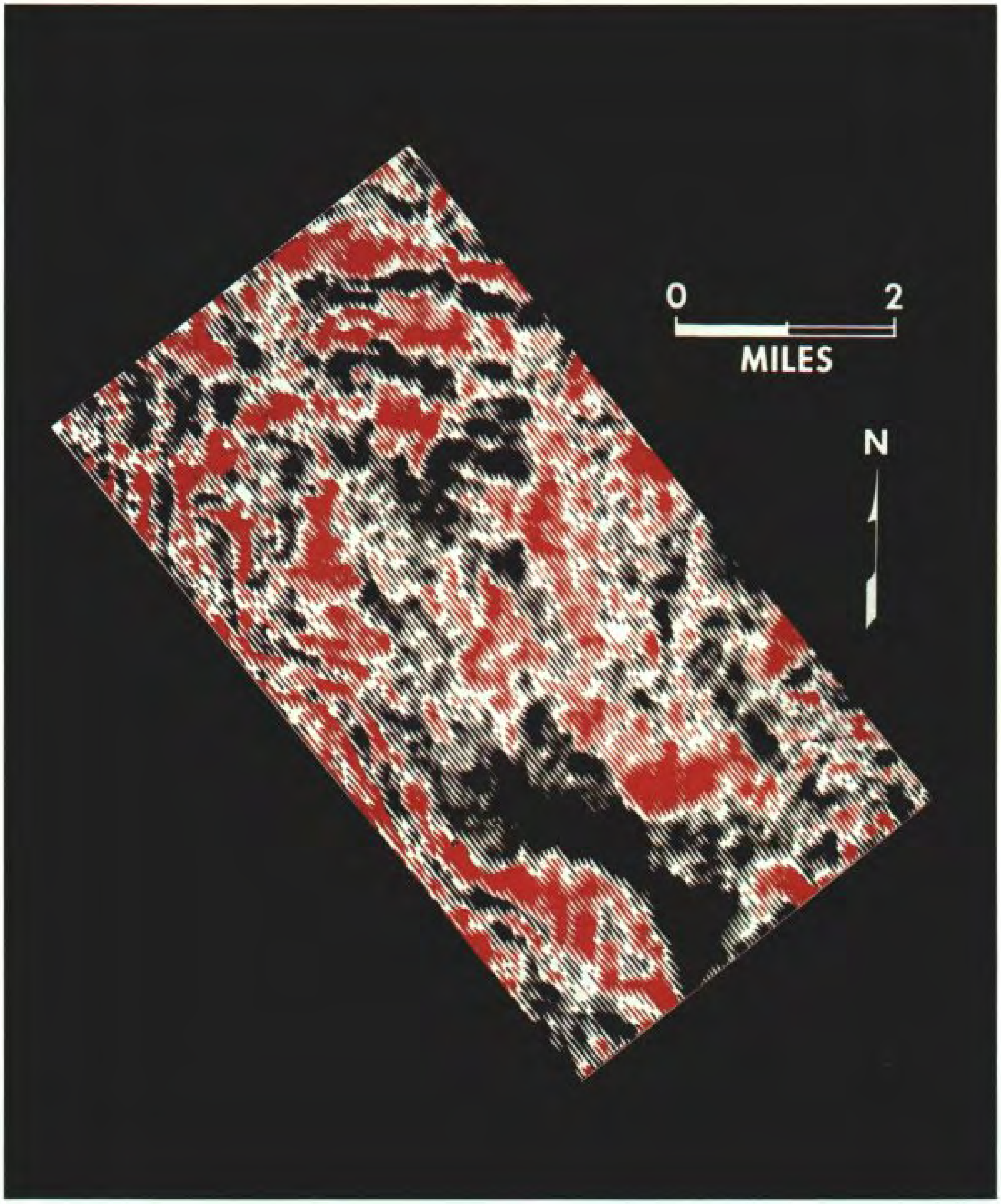

FIG. 13. Seiscrop section at 3260 msec, approximately 13,890 ft.

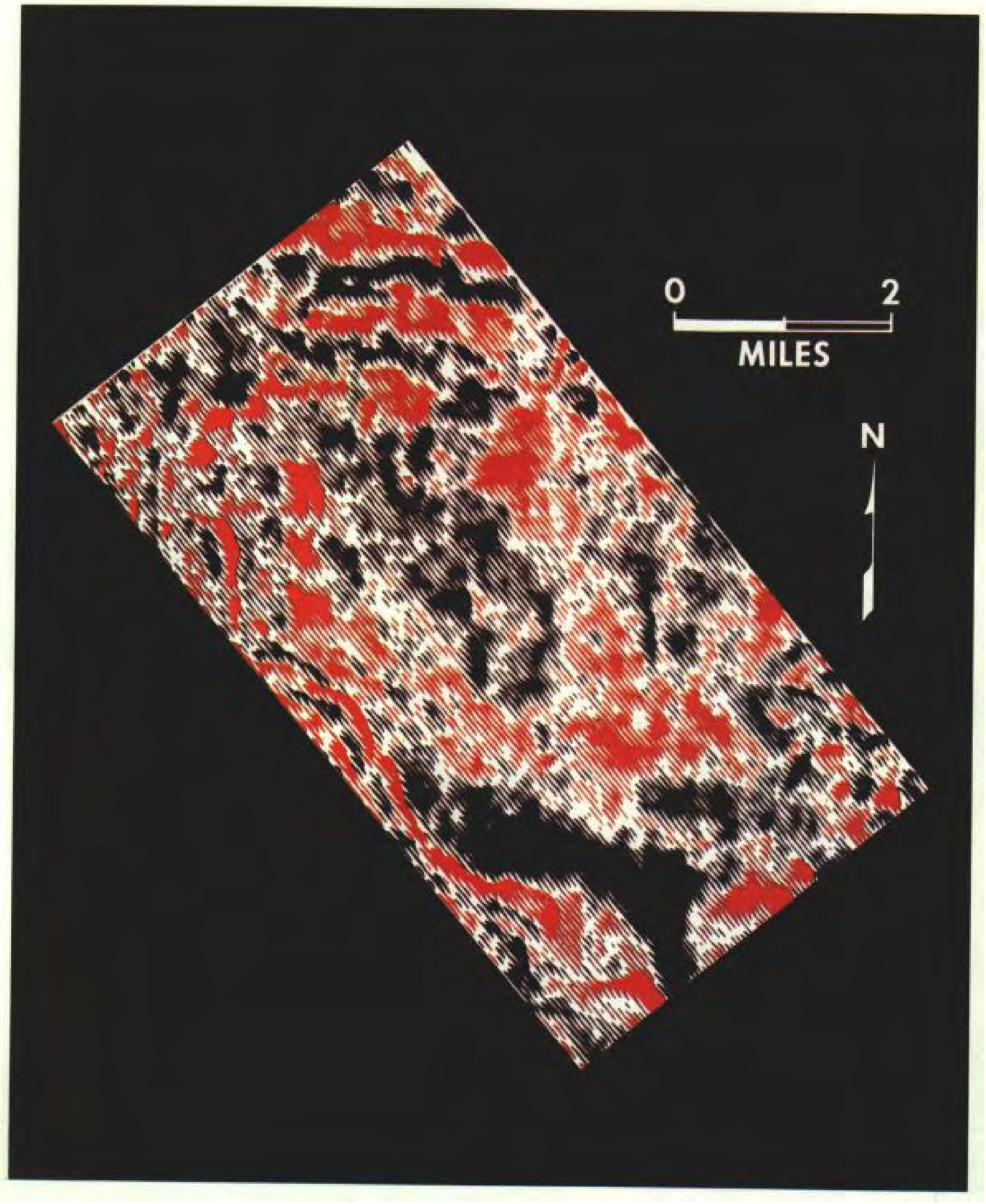

FIG. 14. Seiscrop section at 3276 msec, approximately 13,990 ft.

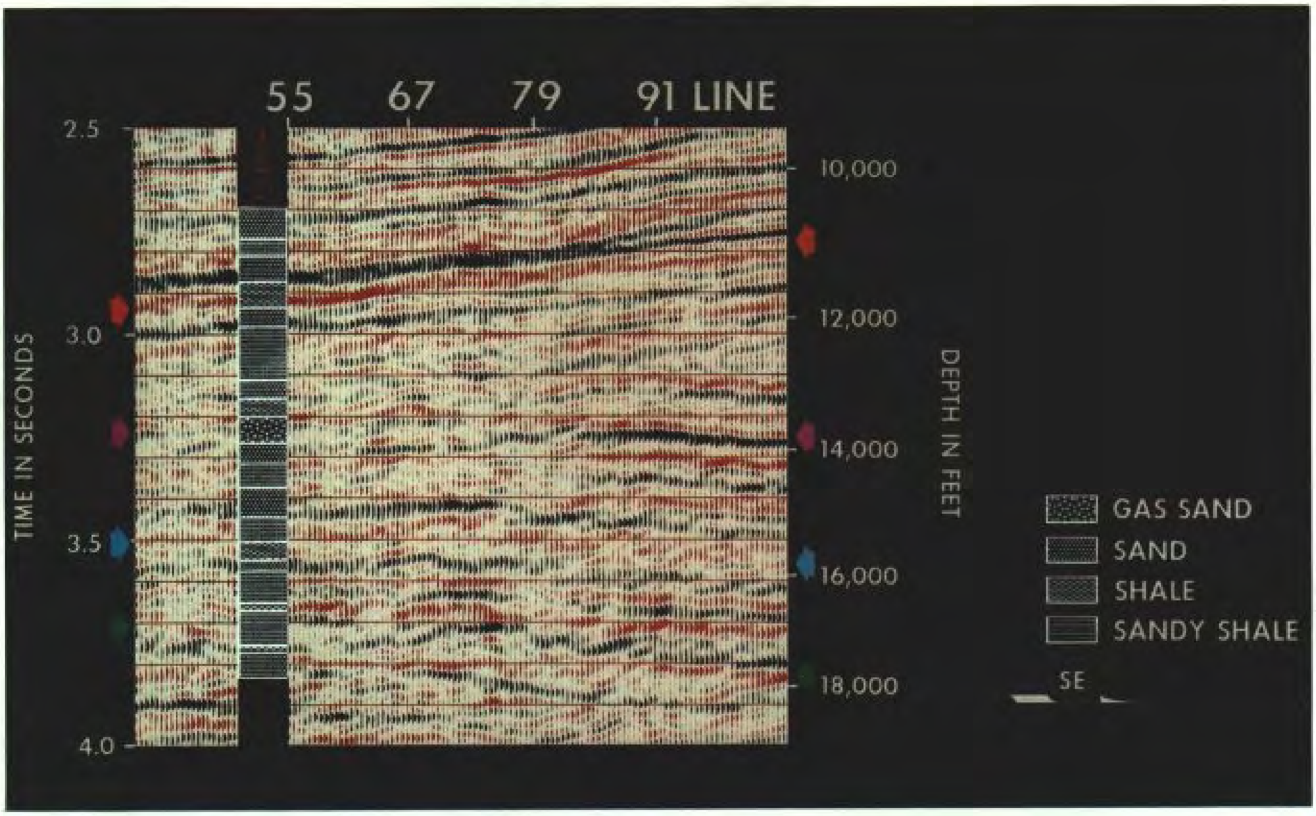

FIG. 15. Portion of crossline 87 corresponding to G-LOG section of Figure 17.

error and the manner in which it varies with other system parameters indicate the extent to which the data fit the assumptions of the G-LOG process. Thus the residual error provides an indication of the validity of the resultant G-LOG functions as a representation of subsurface properties. The poststack G-LOG process was carried out on every second trace along crossline 87. The performance of the residual error indicated that the resultant G-LOG functions were valid.

Figure 15 shows a portion of crossline 87 displayed in dual polarity. Four G-LOG functions and the full G-LOG interval velocity section in color for the same portion of crossline 87 are shown in Figures 16 and 17. A low-velocity shale above the reservoir is marked in gold in Figure 16. The continuity of this low-velocity feature is seen across Figure 17 in yellow. Generally, the higher velocities correspond to the sands and the lower velocities to the shales. Cyclical sand-shale deposition is evident above 3.0 sec on Figure 17. Two events below the reservoir are marked in blue and green in Figures 15 and 16 for correlation purposes.

At the reservoir level, Figure 16 shows that the two G-LOG functions outside the interpreted reservoir exhibit higher velocities than the two within. This is demonstrated on the continuous G-LOG section in Figure 17. The simplified lithology in the well shows the Pelican-3 gas sand between 3.20 and 3.26 sec; the lithological log actually demonstrates some sand/shale layering within this zone. Because there is very little dip at the reservoir level, the high velocity in the same time zone to the right of the section represents the Pelican-3 sand outside the reservoir. The abrupt lateral velocity change is interpreted as the stratigraphic reservoir boundary.

Close examination of the transition on the G-LOG section suggests layering: in the upper portion of the reservoir the transition occurs at line 70, in the next layer at line 79, and in the lower half of the reservoir at line 73. The magnitude of the velocity contrast across the boundary is approximately 600 ft/sec. It is concluded that this lateral change from low to high velocity indicates the change from a porous gas-filled sand to a tight sand, in which the pores are filled with cement which is probably clay.

IBIS RESULTS

The Ibis 3-D survey produced improvements in data quality similar to those obtained at Pelican. The most significant aspect of data enhancement is in the definition of faults.

Line 230 (Figure 18) is in the dip direction and shows the large number of faults cutting the structure. Crossline 105 (Figure 19) is in the strike direction through Ibis-1 well. The major fault which separates the Pelican and Ibis structures (Figure 18) has over 10,000 ft of throw at the top of the Miocene. The deep structure between 4.0 and 5.0 sec was not recognized on any of the previous 2-D surveys.

Fault definition was further enhanced on some key lines by using dual polarity displays. Peaks and troughs are both displayed as positive numbers on the sections, with peaks shown in black and troughs shown in red. This is the same convention as used for the Seiscrop sections. Figures 20 and 21 show the dual polarity display of line 230 uninterpreted and interpreted. Dual polarity

FIG. 16. G-LOG functions for traces indicated in Figure 15.

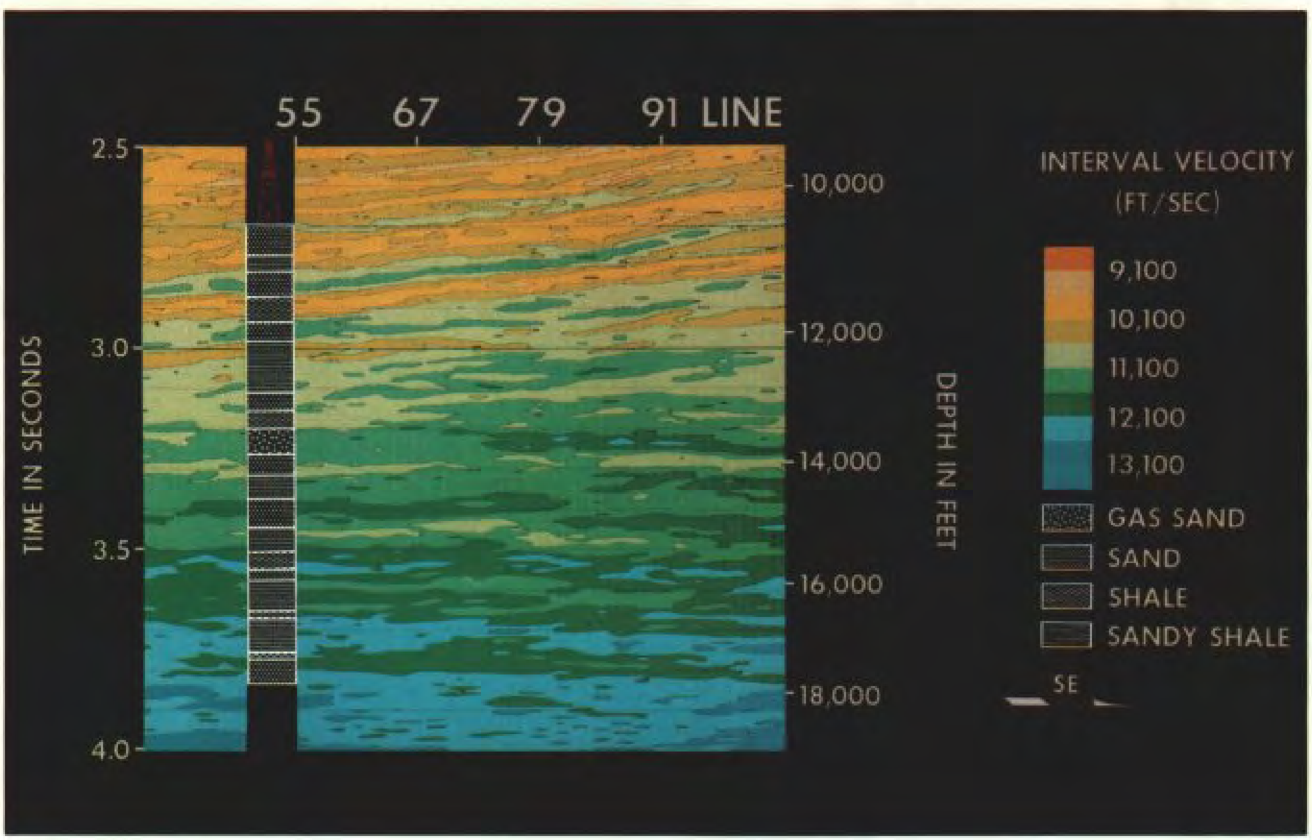

FIG. 17. G-LOG section crossline 87, showing velocity transition across inferred southeastern reservoir boundary.

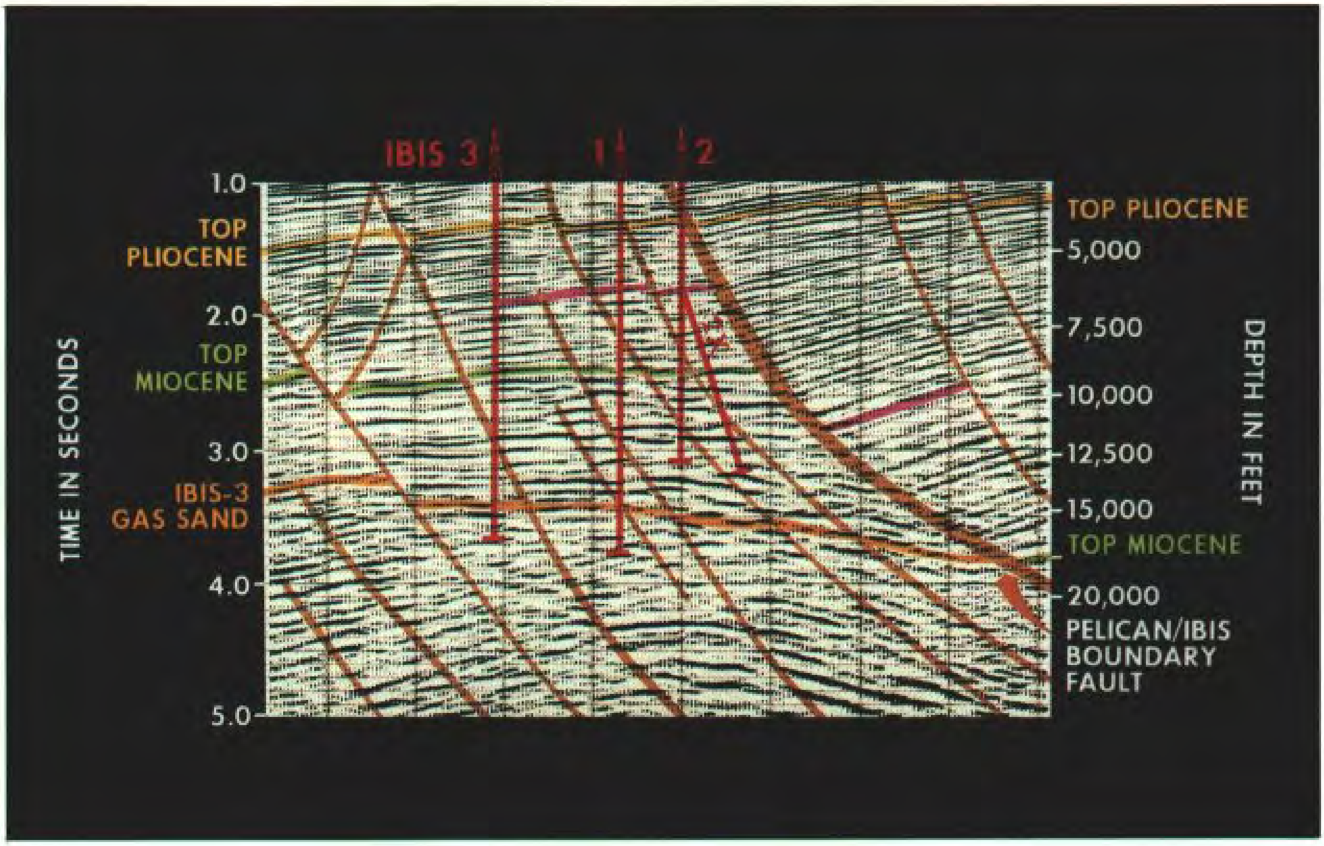

FIG. 18. Line 230 (Ibis), 3-D migration.

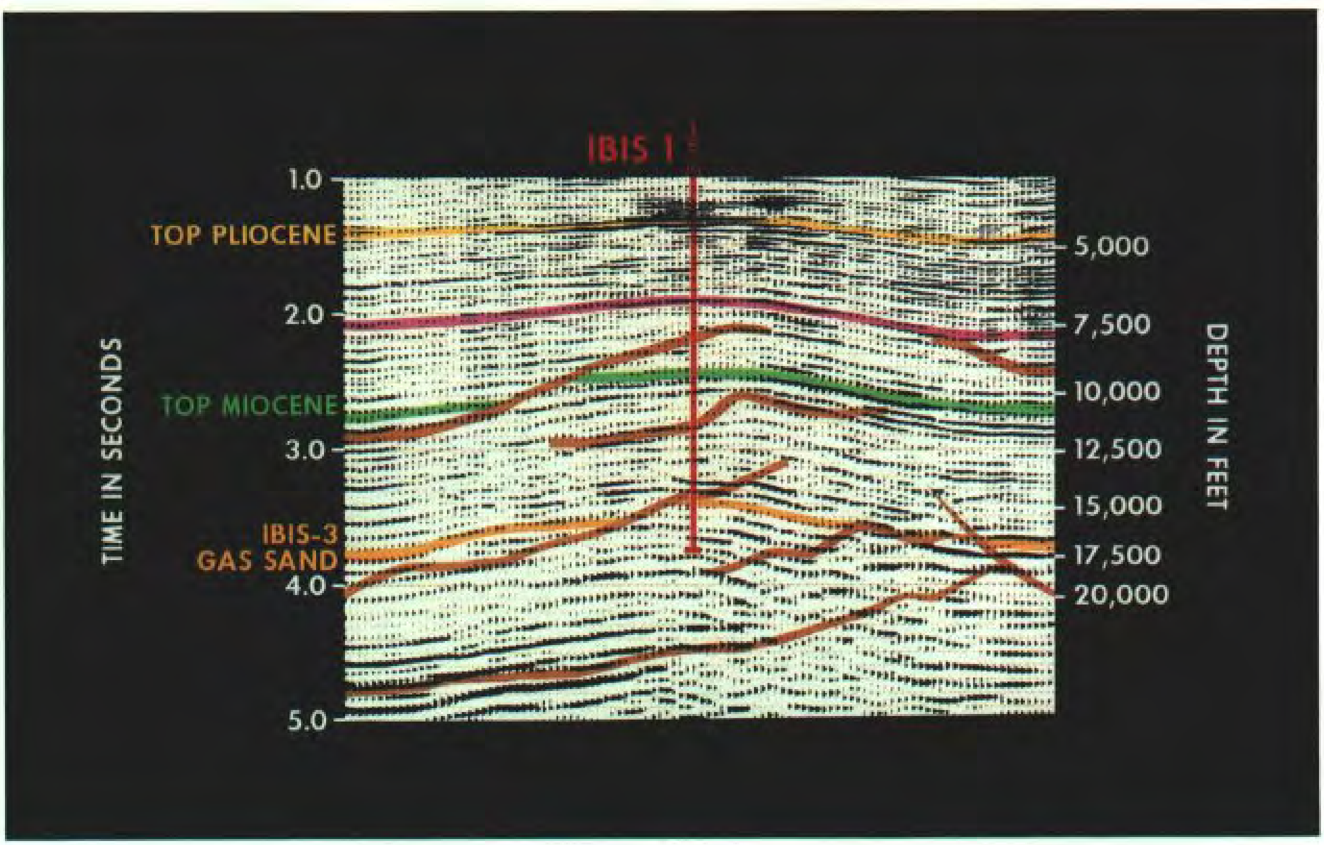

FIG. 19. Crossline 105 (Ibis), 3-D migration.

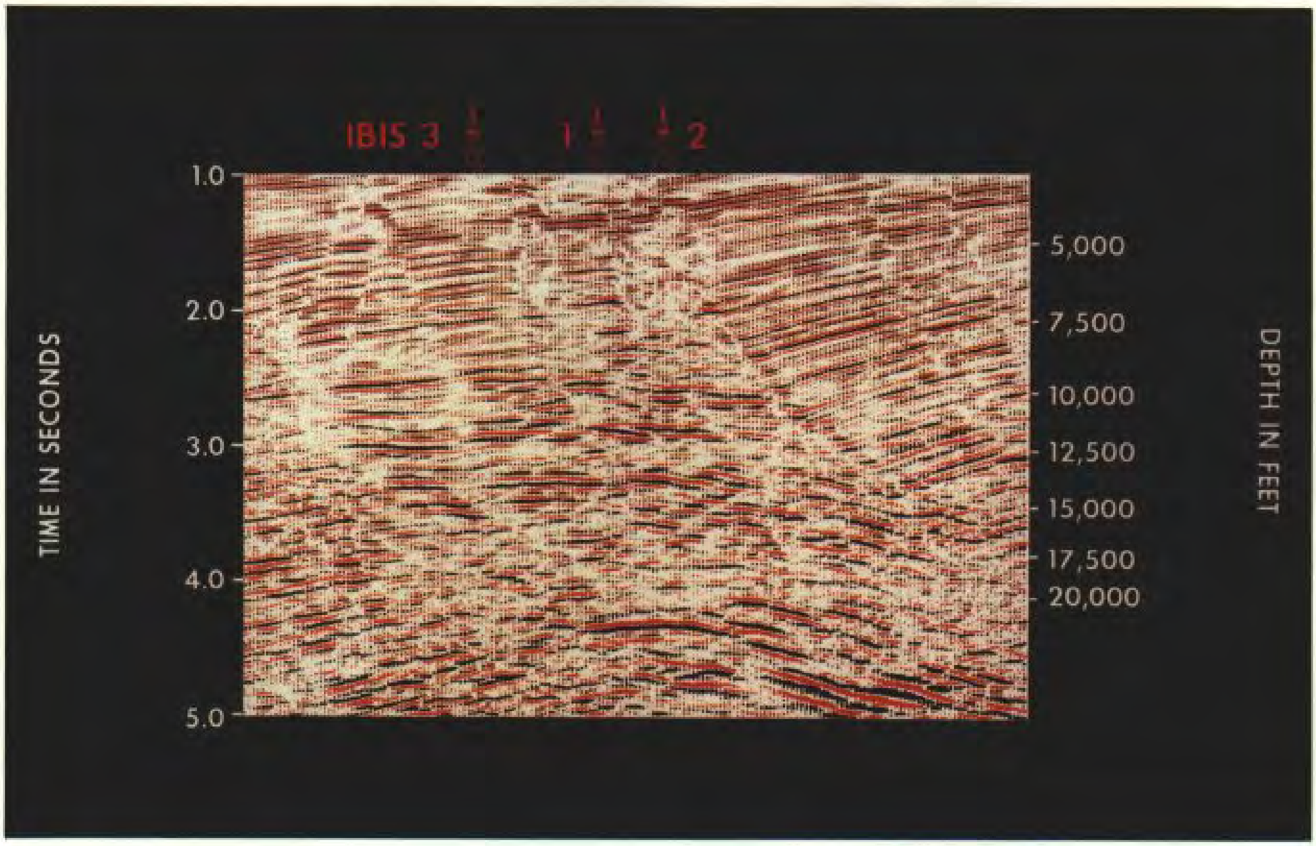

FIG. 20. Line 230, 3-D migration, showing enhancement of fault definition by dual polarity display.

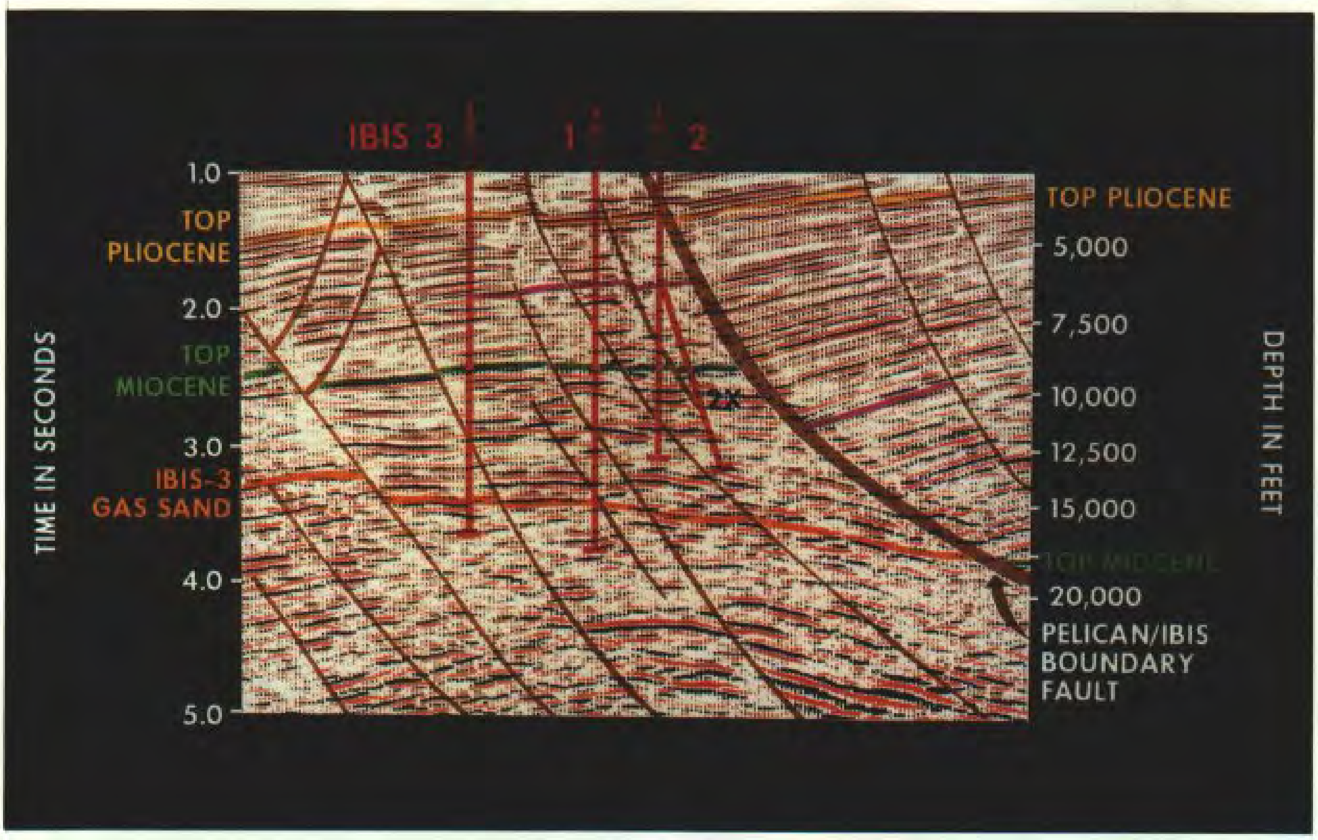

FIG. 21. Line 230, 3-D migration, interpreted dual polarity section.

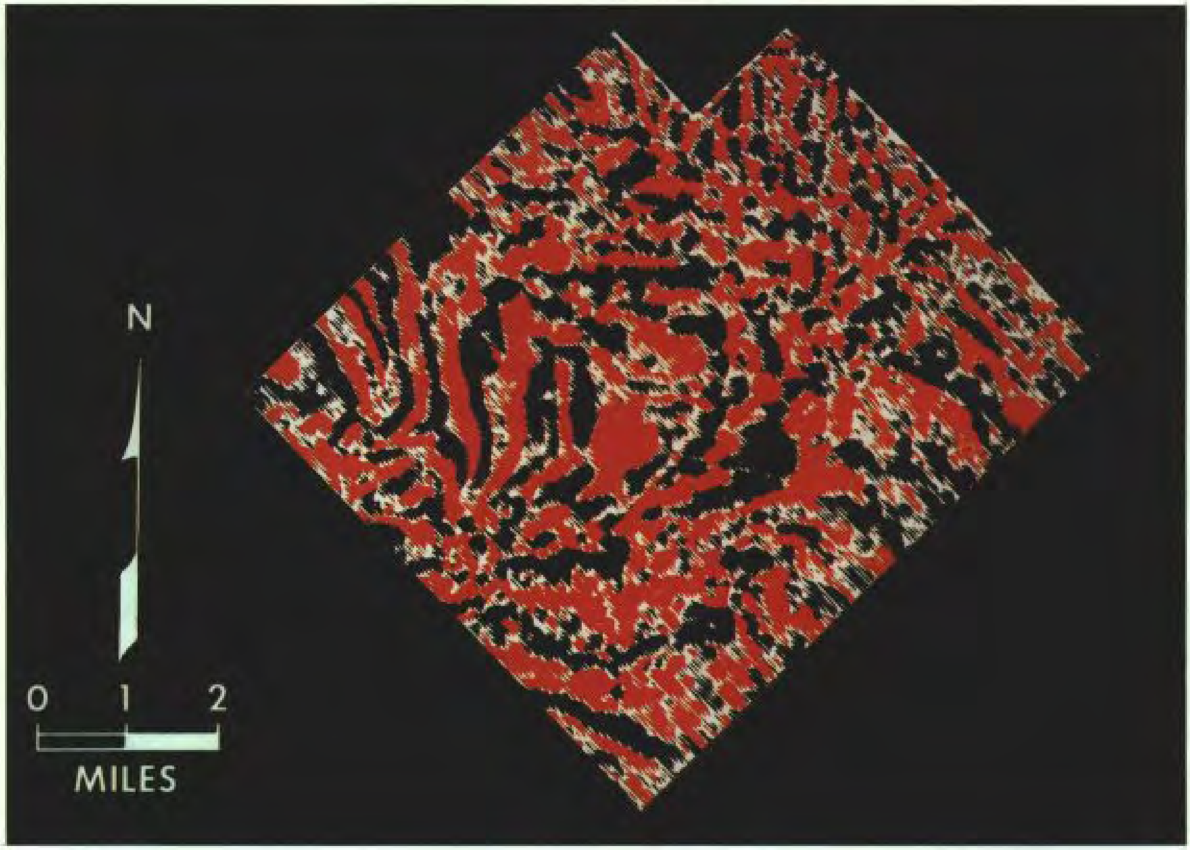

FIG. 22. Seiscrop section at 3400 msec, approximately 15,000 ft.

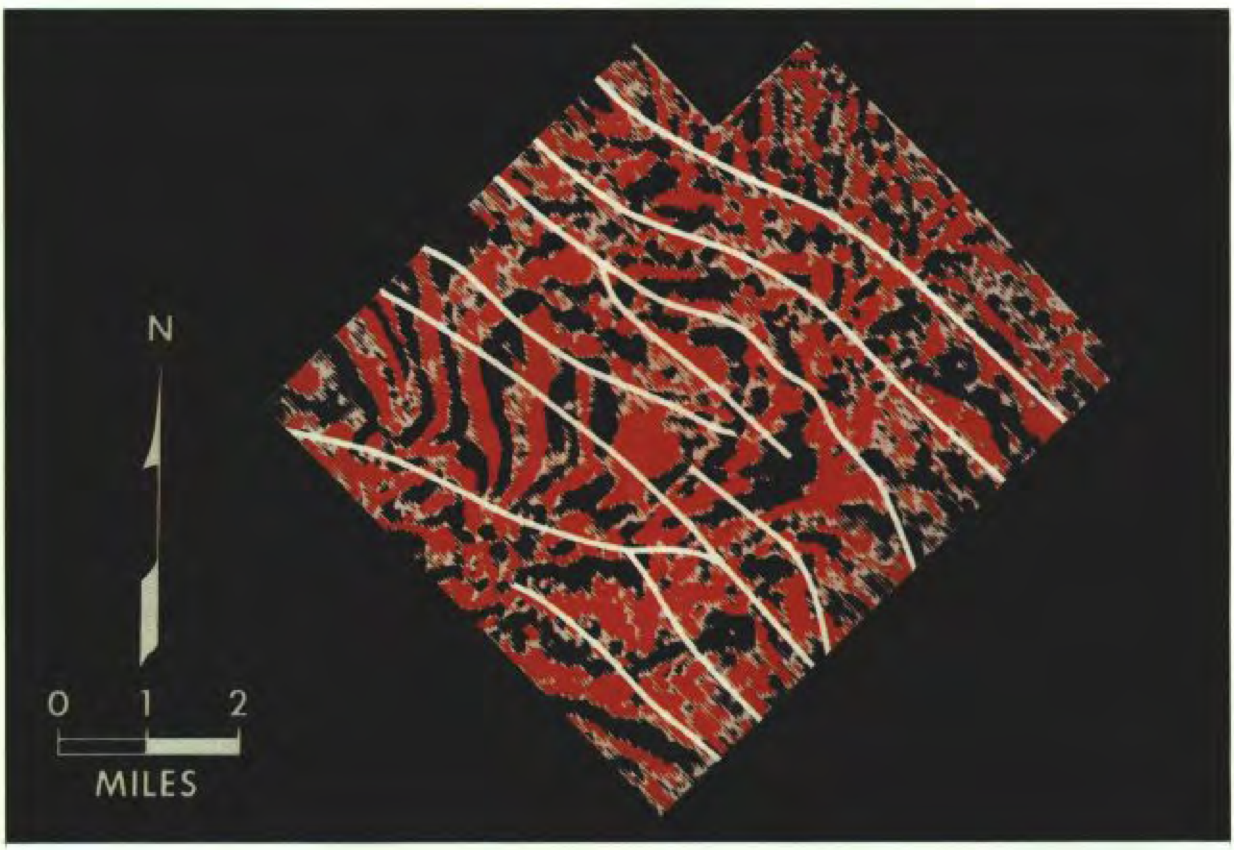

FIG. 23. Seiscrop section at 3400 msec, showing interpretation of faults.

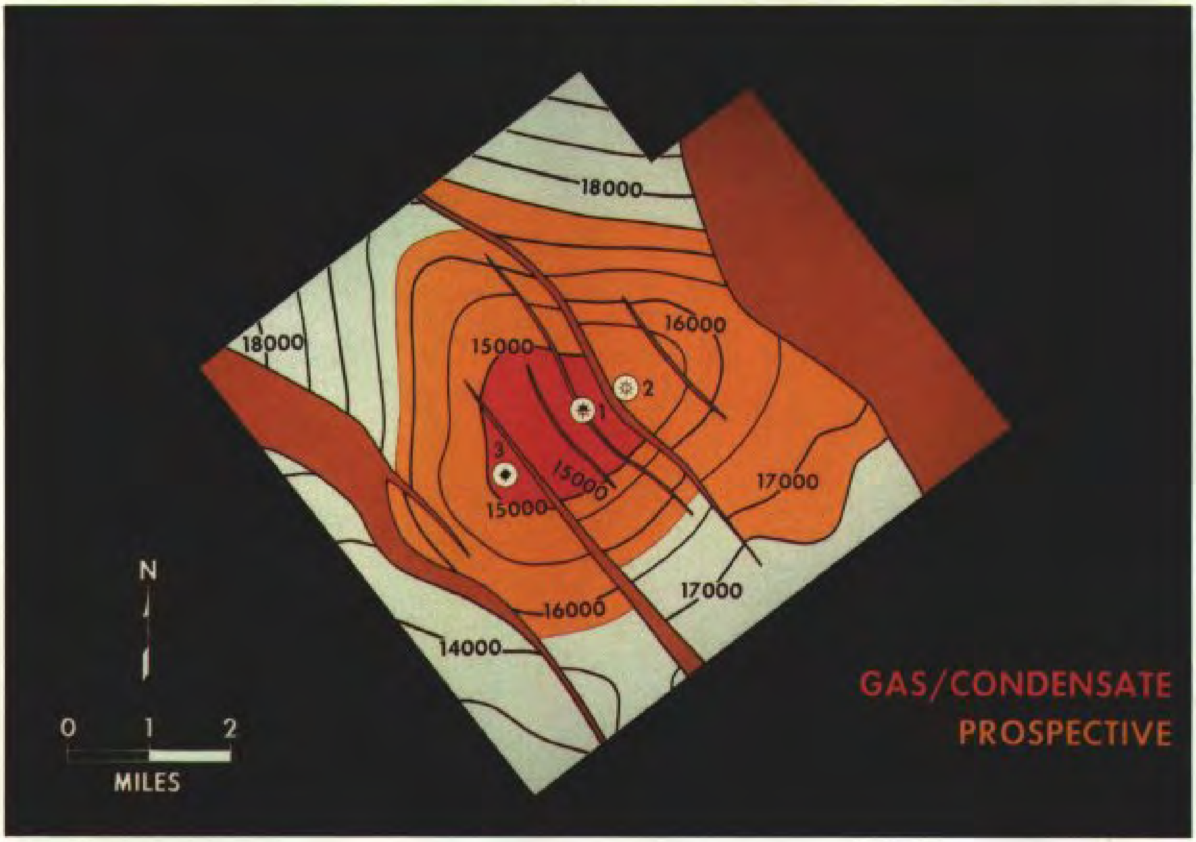

FIG. 24. Map of Ibis-3 gas sand from 2-D data. Contour interval 500 ft.

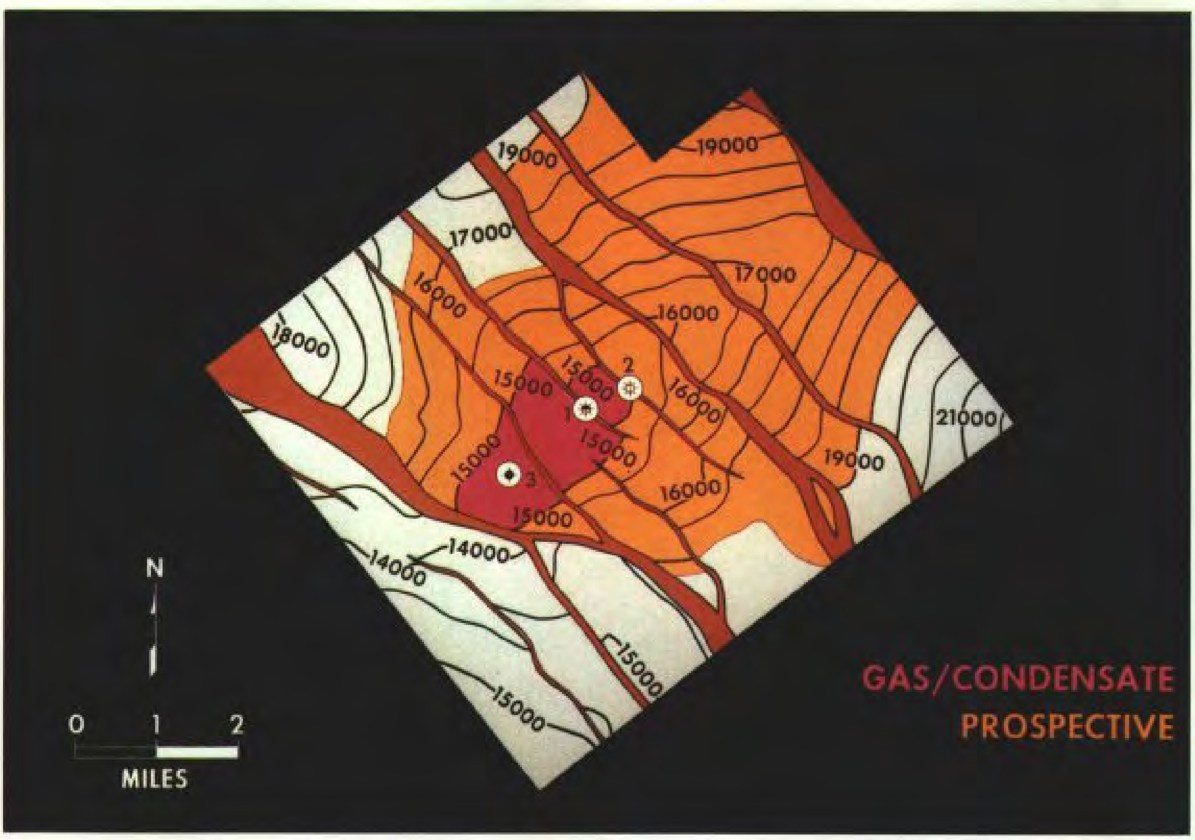

FIG. 25. Map of Ibis-3 gas sand from 3-D data. Contour interval 500 ft.

effectively doubles the number of event terminations at a fault plane, thus making precise fault definition easier.

The dome shape of the Ibis structure is visible on the Seiscrop section at 3400 msec, approximately 15,000 ft (Figure 22). Much of the faulting is also evident; all the faults interpreted at this level are marked on this Seiscrop section (Figure 23). Figures 21 and 23 together illustrate well the complex nature of the Ibis structure.

Figures 24 and 25 show the interpreted structure of the Ibis-3 gas sand before and after the 3-D survey. Major differences exist. The map based on the 3-D data is much more complex than the earlier interpretation. Ibis has been broken into many different fault blocks, each of which must be taken into account in development planning.

CONCLUSIONS

Data quality has been improved on both prospects. Processing took into account cable drift, a major problem offshore Trinidad, thus limiting subsurface smear during stack. Some deep primary events have been observed for the first time. Because of increased data density, fault definition is excellent. Structural interpretations are more reliable with removal of energy from outside the plane of the section. The flexibility which permits an interpreter to generate lines in any direction is a significant benefit. The probable containment of the principal Pelican reserves by a stratigraphic reservoir boundary to the southeast has been substantially validated after a detailed study of its nature.

The 3-D results have caused major changes in the development plans for both prospects. At Ibis, the structure is highly faulted and much more complex than originally interpreted. Separate fault blocks will have to be evaluated on an individual basis, which greatly increases the risk factor.

At Pelican, on the other hand, the interpreted area under closure has been increased. The possibilities of drilling an initial dry hole and mislocating a development platform have been reduced due to improved reliability of the coordinated geologic-geophysical interpretation based on the 3-D seismic survey and a reevaluation of log correlations. This has had a positive effect on development economics.

The 3-D seismic method has proved to be a useful tool for field appraisal in this area offshore Trinidad and will be considered over other prospects prior to commitment to expensive offshore development programs.

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