PAPER B

CROSSWELL SEISMIC IMAGING IN CARBONATE ROCKS OF A WEST TEXAS 1-ACRE 5-SPOT

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ABSTRACT

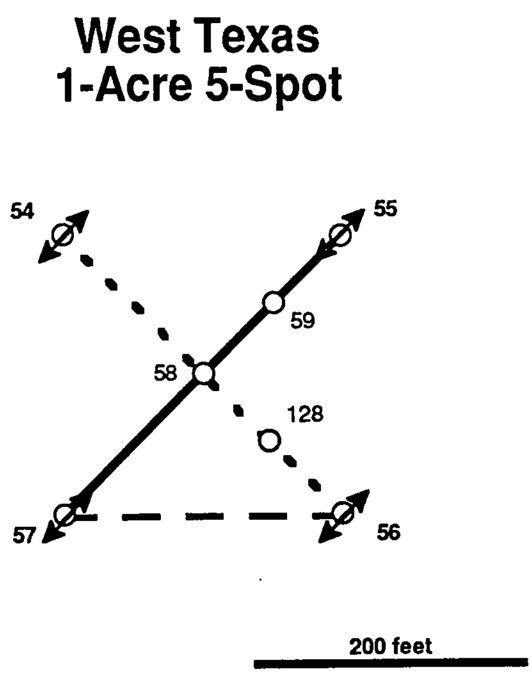
Three crosswell seismic surveys were run across the two diagonals and bottom edge of a 1-acre 5-spot in a West Texas, Permian Basin oilfield. The tomograms show the flat-lying structure of the reservoir and point to variations in reservoir quality. In the upper part of the tomograms there is a southwest to northeast increase in the slowness values, i.e., a decrease in velocities that may be attributable to waterflood effects.

OBJECTIVES

Crosswell traveltime tomography has been applied successfully to estimate seismic velocities between wells. Although much of the tomography has been used for purposes of monitoring enhanced oil recovery (EOR), the goal in this study was to image the reservoir interval to look for indications of barriers to fluid flow and to test the development of high frequency tomography in the Permian Basin environment. Specifically in West Texas, our interest was to image the reservoir interval within the Grayburg formation to look for variations in reservoir quality in otherwise flat-lying, continuous reservoir horizons.

SITE DESCRIPTION

Three crosswell surveys were conducted between four wells, each located at a corner of a 1-acre, 5-spot pattern (Figure 1; North is towards the top of the page). Survey 1 was along the 5-spot's NE-SW diagonal between Wells 57 and 55. Survey 2 was along the NW-SE diagonal between Wells 56 and 54. Survey 3 was along the 5-spot's southern edge between Wells 56 and 57. The well heads are 297.0, 298.5 and 210.6 feet apart in surveys 1, 2 and 3, respectively.



	Survey #	Source Well	Receiver Well	Well-to-Well Distance	No. of Sources	No. of Receivers
———	1	57	55	297.0 feet	70	69
‒ ‒ ‒	2	56	54	298.5 feet	77	81
— —	3	56	57	210.6 feet	72	75

Figure 1: Three crosswell surveys were conducted between four wells, each located at a corner of a 1-acre, 5-spot pattern.

The primary targets in this study were reservoir horizons of the Permian-aged Grayburg formation. These horizons (S2, D4 and S3) are located within the payzone, which occurs between depths 4,130 and 4,250 feet, and dip roughly 3 degrees to the southeast. From logs, the dolomites (D1-D5) have typical P-wave velocities of 18,000-20,000 feet/sec and porosities around 5 percent. The sands (S1-S3) have P-wave velocities of 14,300-16,700 feet/sec and porosities of 10 percent or higher. Gas is known to exist above the payzone interval in this West Texas reservoir [Michael Stein, pers. comm., 1991].

In 1982 Amoco Production Company conducted a water-after-gas (WAG) CO_2-injection pilot project within this 1-acre 5-spot. The payzone's S2, D4 and S3 units, located from 4130 to 4250 feet, were the target for this project [Michael Stein, pers. comm., 1991]. Wells 54, 55, 56, and 57 were all used as CO_2 and water injection wells. CO_2 injection ended in March 1982. After a two-month soaking period, water injection occurred from May to July 1982. Following the pilot the wells in this 5-spot were shut in. Finally in late 1982, water injection started in a well about 420 feet to the southwest of the pilot and floodwater was driven across the 5-spot area towards a production well located about 370 feet northeast of the pilot.

DATA ACQUISITION

The field survey used a piezoelectric cylindrical bender downhole source constructed for Stanford by Southwest Research Institute. A hydrophone array built for Stanford by Century Geophysical Corporation was used as receivers. A description of the data acquisition system can be found in Paper N of this volume. The source was driven with a 250 msec upsweep from 350 to 2350 Hz. Sixteen sweeps were stacked to form the seismic trace. The data were recorded at a sample interval of 0.1 msec. Recorded data were subsequently cross-correlated to produce the seismic record. A common receiver gather taken at a depth of 4110 feet in survey 1 is shown in Figure 2.

The data were recorded with six hydrophones spaced ten feet apart. The shooting pattern fixed the hydrophones at depth and scanned the source upwards past the hydrophones through an aperture of roughly ±50 degrees. The hydrophones were moved at 5-foot or 10-foot intervals through the targeted reservoir zone from nearly 4300 feet to about 4100 feet. The source-receiver spacing was 10 feet in survey 1 and 5 feet in surveys 2 and 3.

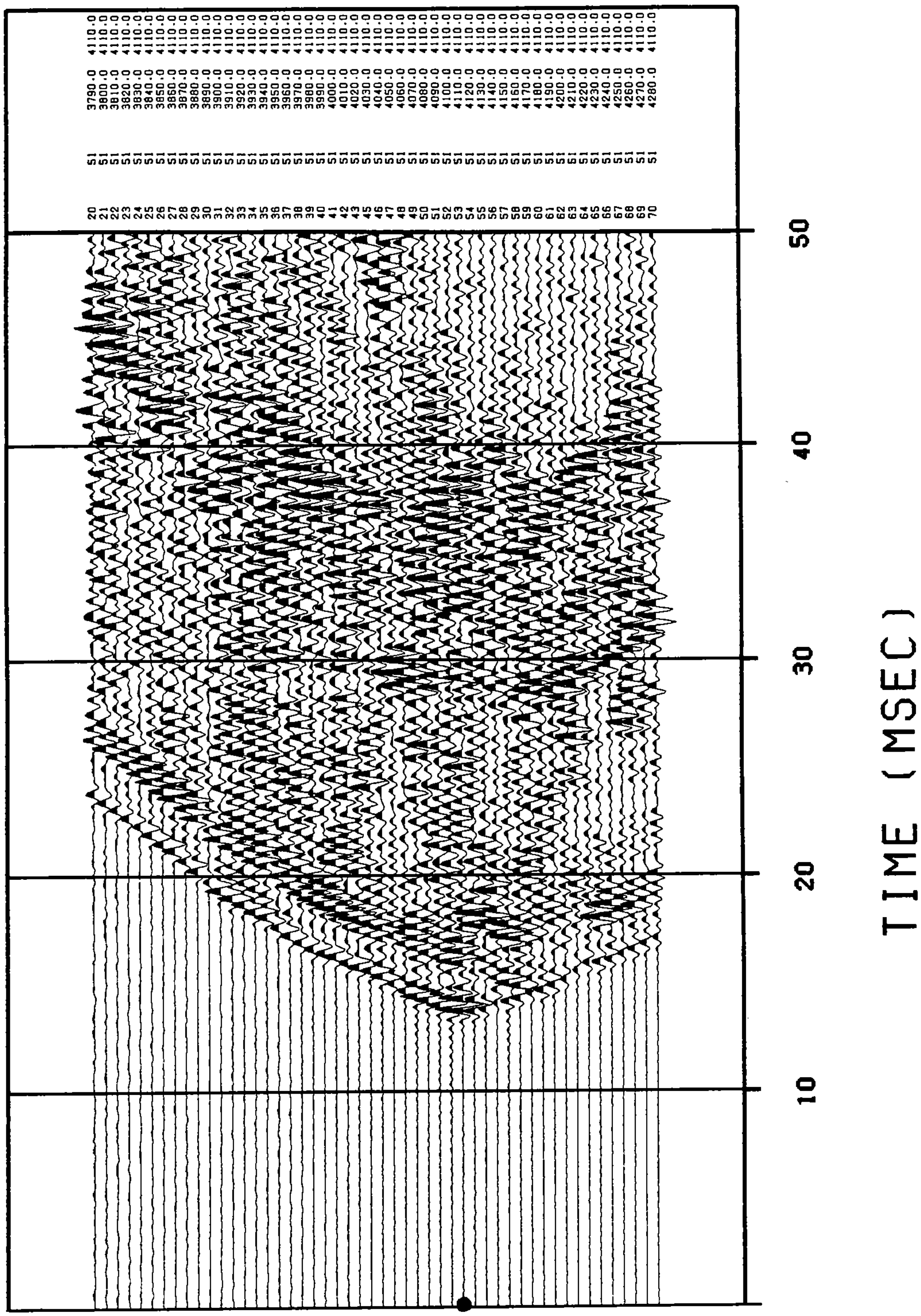


Figure 2: Common receiver gather 51 from survey 1. Receiver position is at depth 4110 feet. Each trace has been normalized to itself.

DATA PROCESSING AND INVERSION

P-wave traveltimes were picked from the cross-correlated seismic traces. Traces where reliable traveltime picks could not be obtained were ignored. Plots of the picks (which also show source-receiver coverage) are shown in Figures 3a, 3b, and 3c for surveys 1, 2, and 3, respectively.

Inversion of the traveltimes was performed using the iterative string method. This method uses two-dimensional ray tracing in an iterative backprojection scheme for matching calculated and measured traveltimes. Each data set was processed independently to produce a tomogram. The starting model for each was a smooth laterally interpolated version of the sonic logs. Twenty (20) ray trace iterations were performed on the each of the three data sets. [See Paper I for more details on string inversion processing.]

INTERPRETATION

Overall View of Tomograms

Tomograms covering depths from 3,900 to 4,300 feet are shown in Figures 4a, b and c. In each figure the receiver well is on the left and the source well is on the right. The tomograms are displayed in terms of slowness (µsec/ft); the warm colors (reds) indicate low slownesses or fast velocities and the cool colors (blues) indicate high slownesses or slow velocities. The low tomogram slownesses (high velocities) correlate with high sonic velocity, low porosity and very low permeability dolomites predicted from the well logs. The high tomogram slownesses (low velocities) correlate with lower sonic velocity, higher porosity and permeable sands. The overall flat-lying structure of the Grayburg formation is the dominant feature in the tomograms. The reservoir units are more or less continuous and are not disrupted.

Lateral Variations within Units

Lateral variations of slowness within the reservoir units may correlate with variations in reservoir quality. In West Texas reservoirs such variations in reservoir quality are caused by varying amounts of matrix material (e.g., detrital clay, fine-grained dolomite) and cement (e.g., anhydrite, dolomite). This matrix and cement occludes pore space and impedes fluid flow. Poor reservoir quality, that is, low effective porosities and permeabilities, usually occurs where there is an abundance of matrix and cements. High

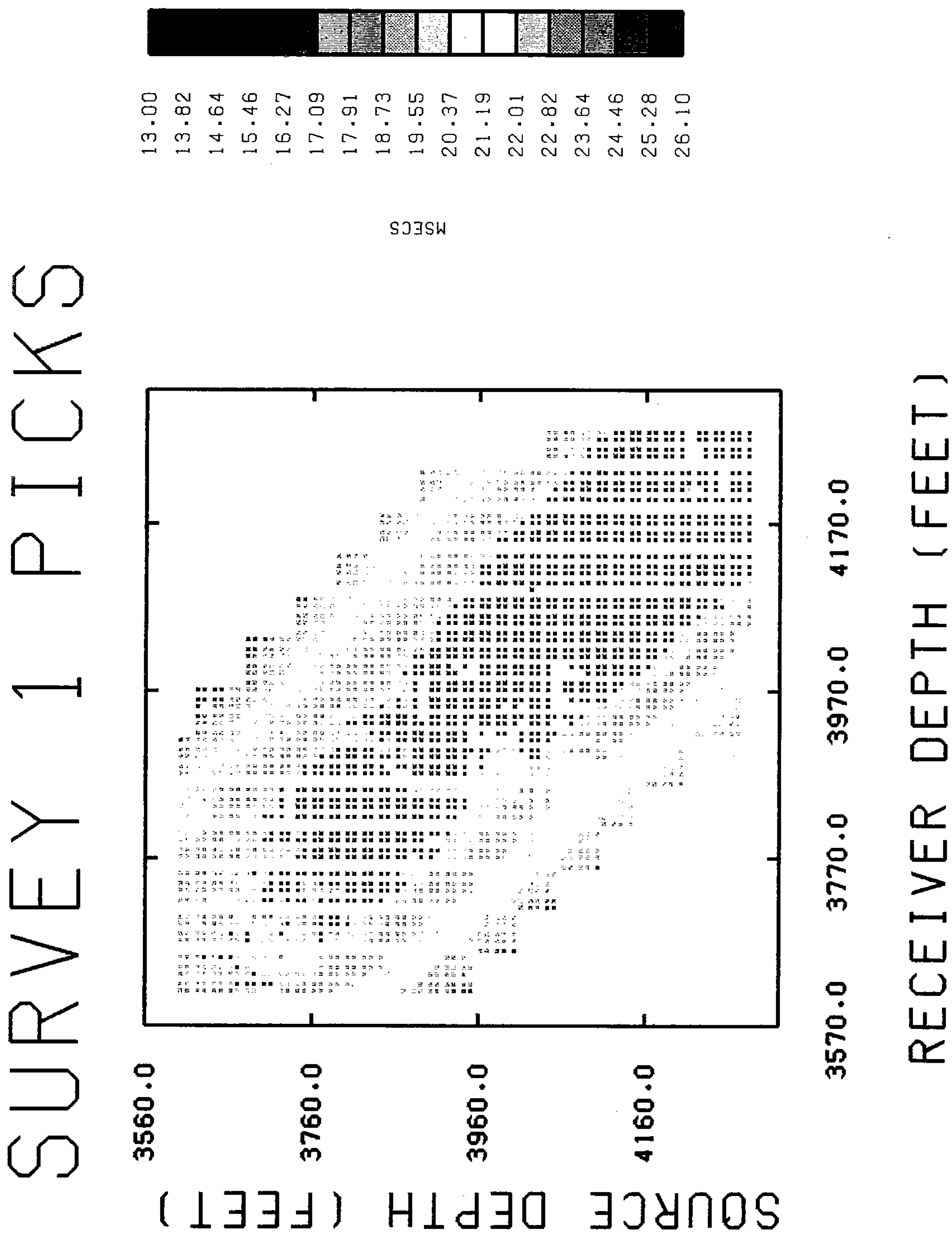


Figure 3a: Plots of picks for survey 1. The colors show the range of traveltimes (msec).

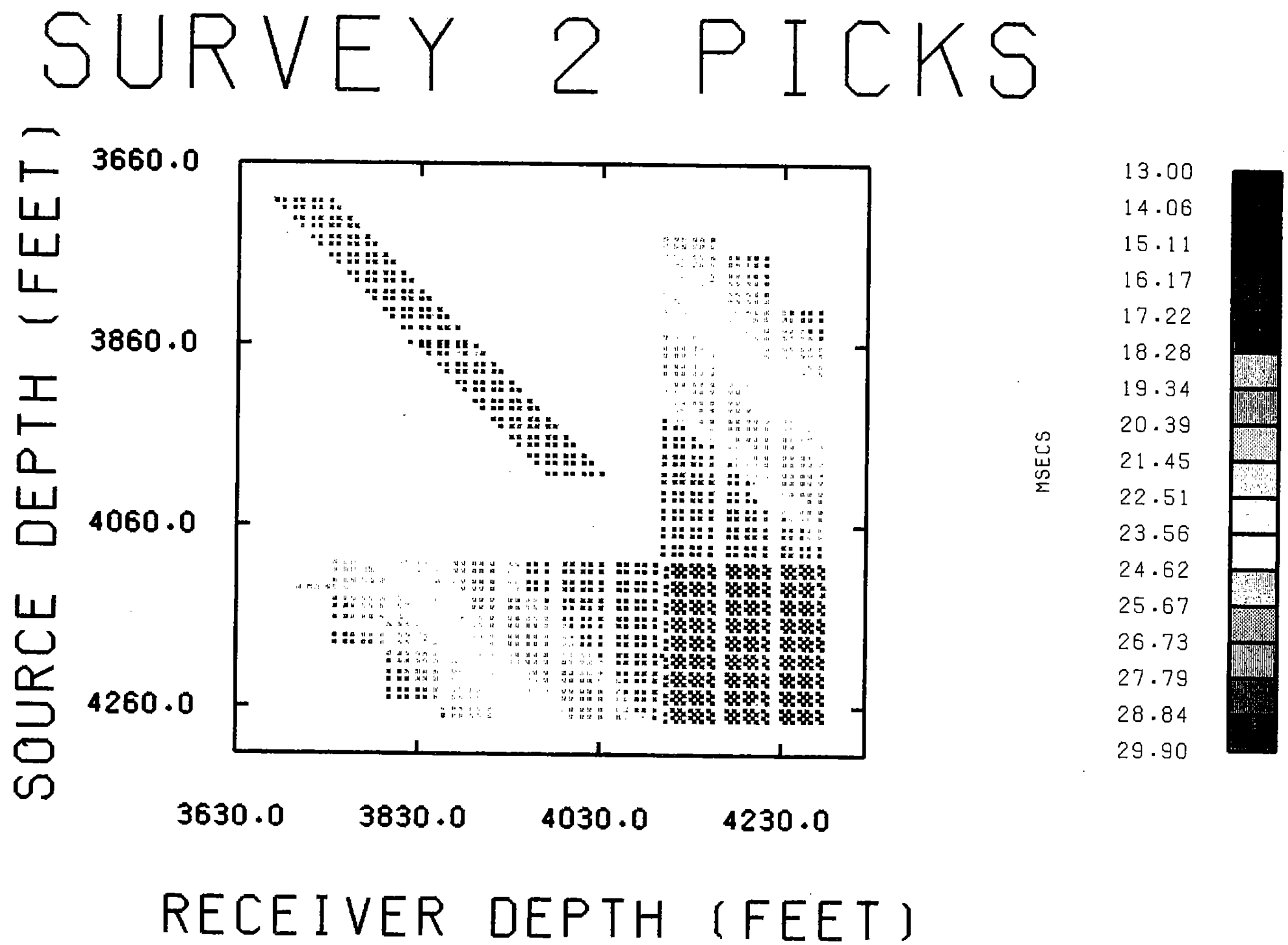


Figure 3b: Plots of picks for survey 2. The colors show the range of traveltimes (msec).

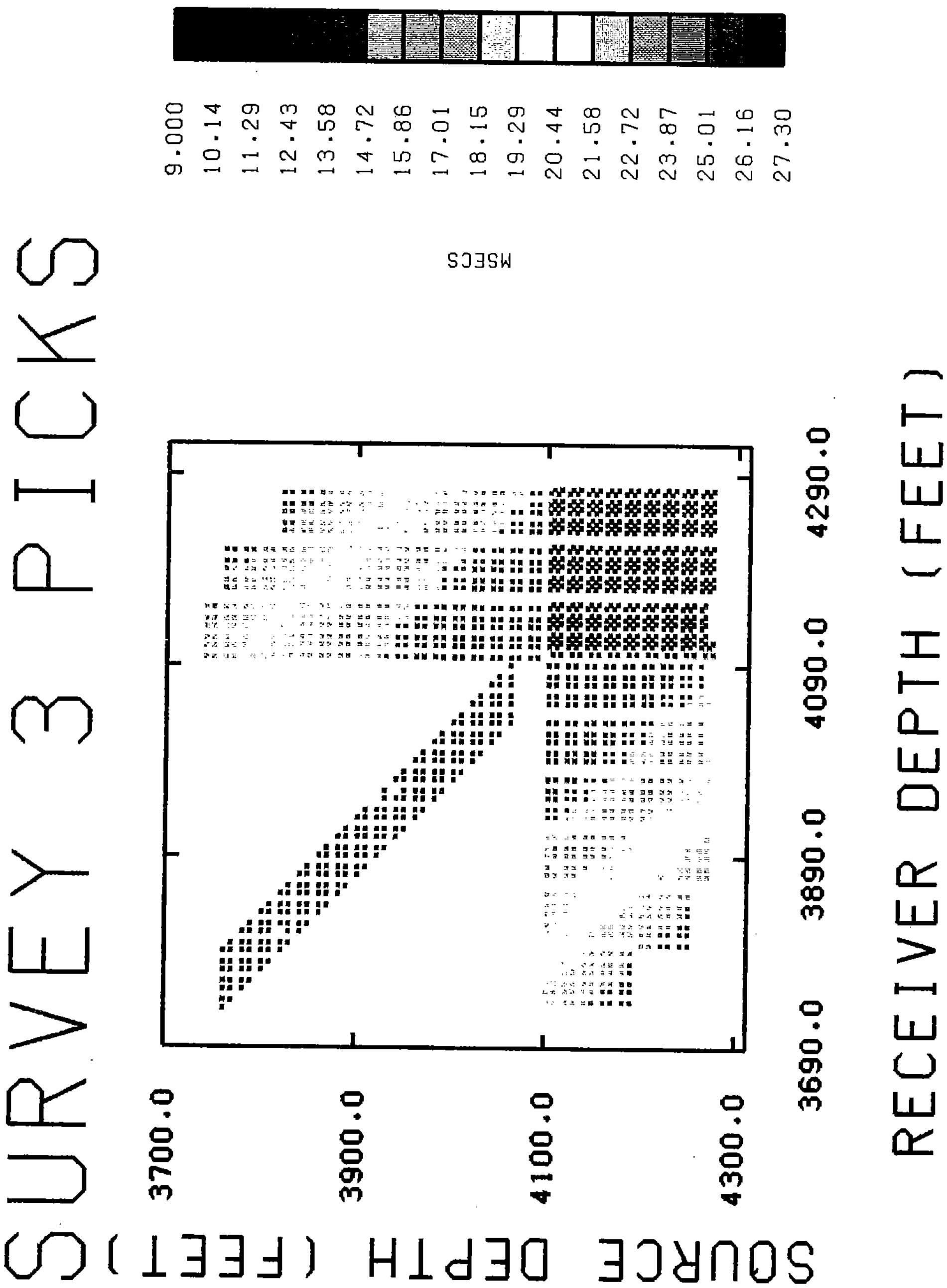


Figure 3c: Plots of picks for survey 3. The colors show the range of traveltimes (msec).

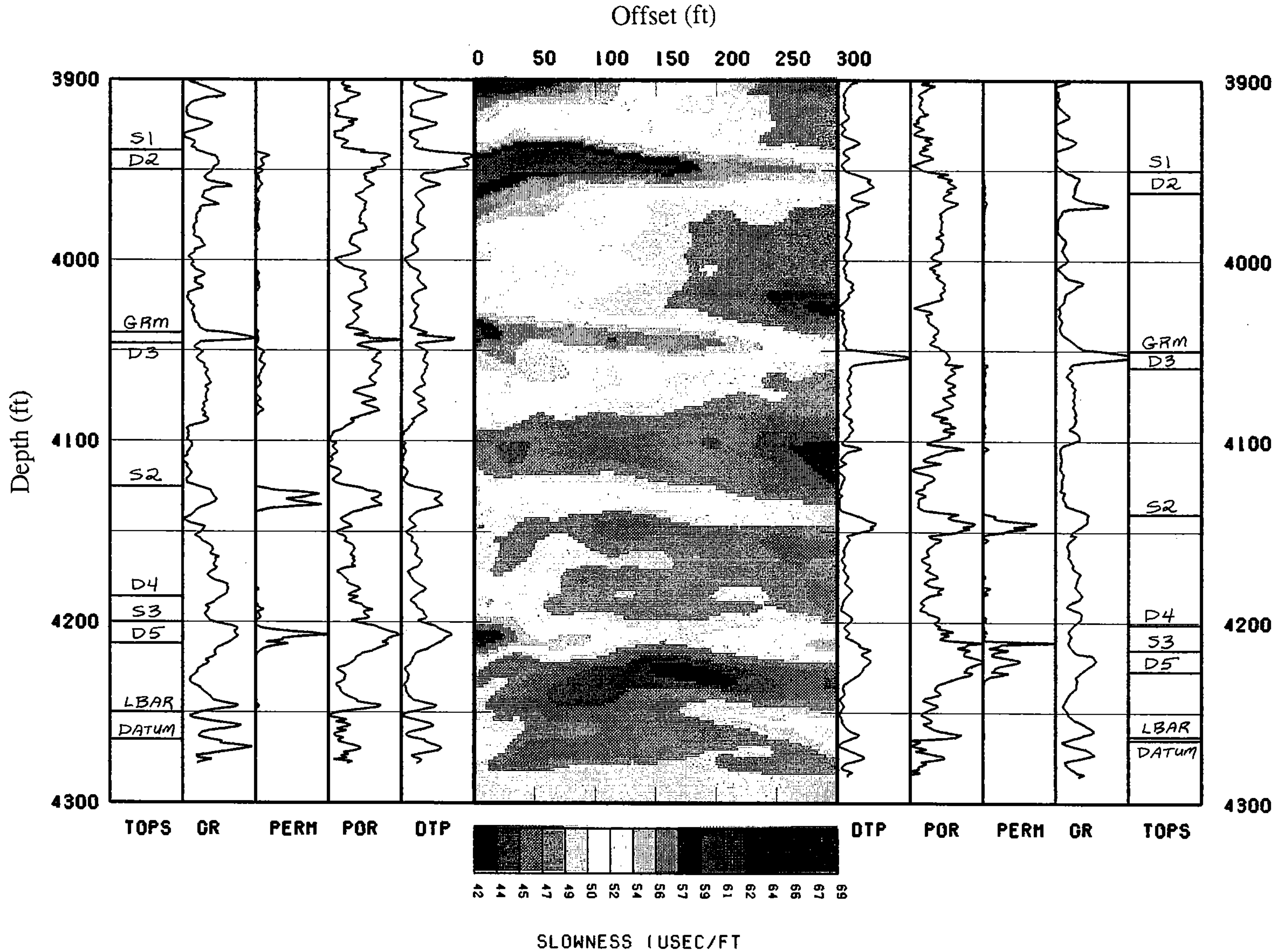


Figure 4a: Slowness tomogram for survey 1 covering depths from 3,900 to 4,300 feet. Panels on side, from outside to inside, show logs of stratigraphic tops, gamma ray, permeability, porosity, and sonic slownesses.

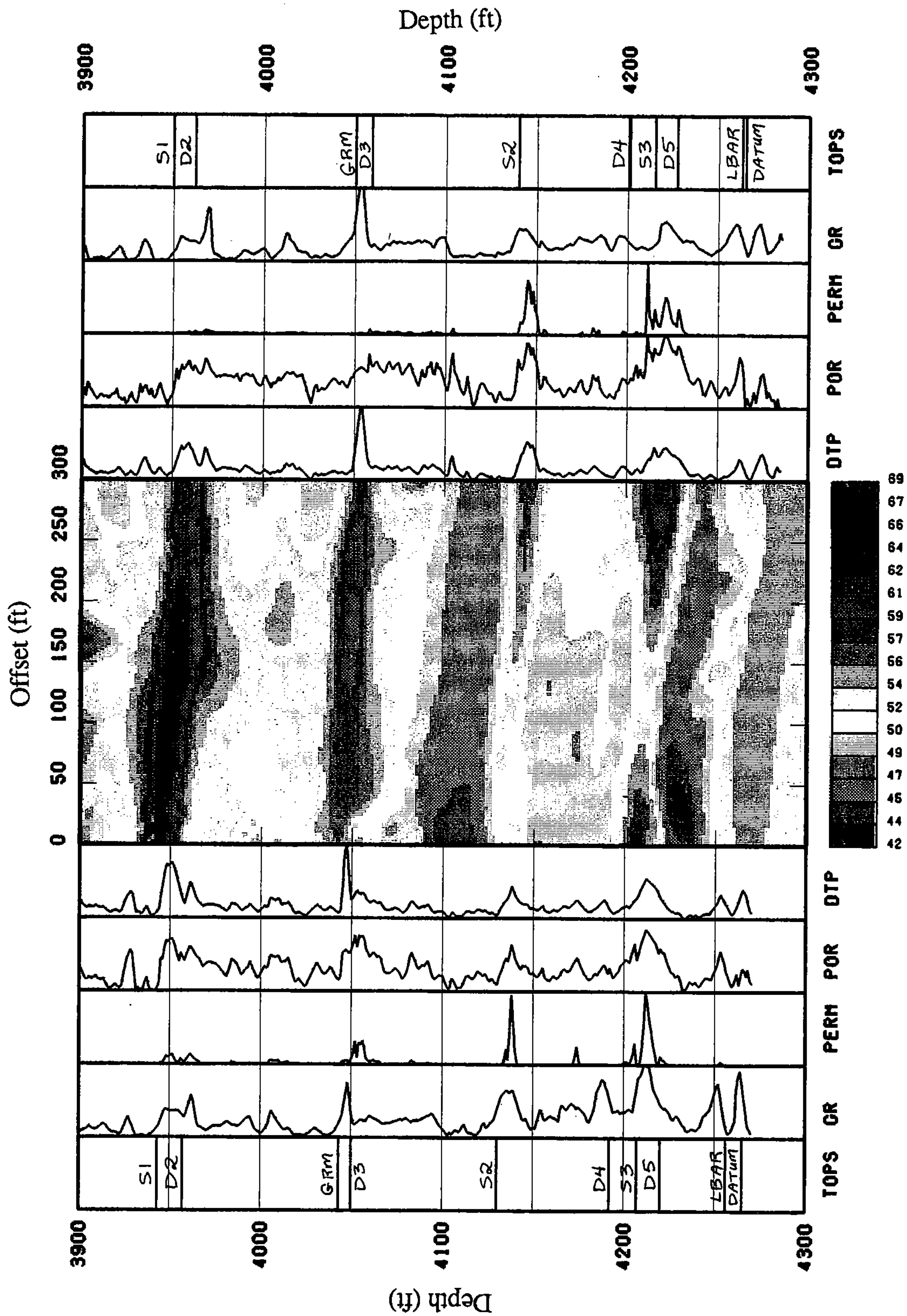


Figure 4b: Slowness tomogram for survey 2 covering depths from 3,900 to 4,300 feet.

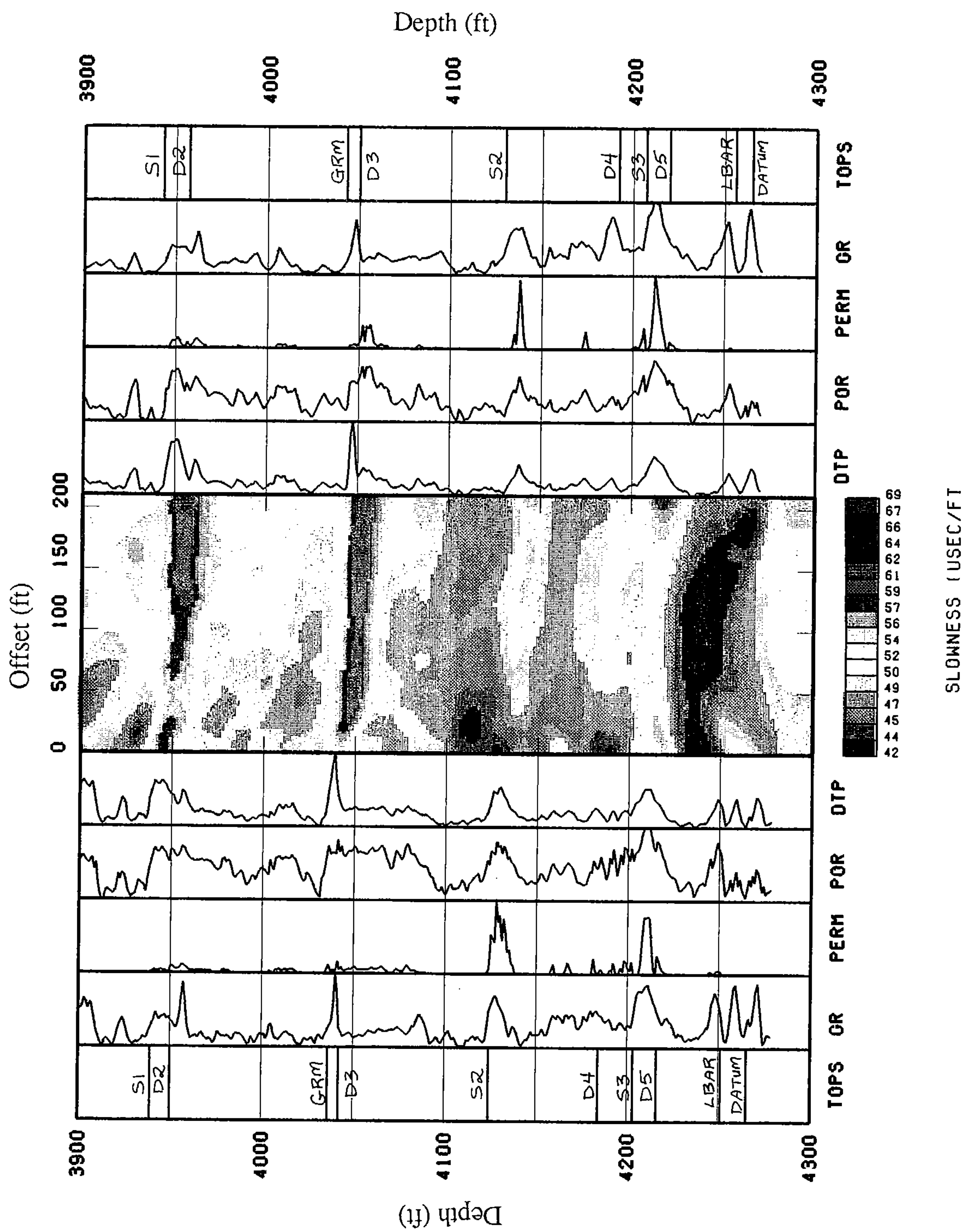


Figure 4c: Slowness tomogram for survey 3 covering depths from 3,900 to 4,300 feet.

seismic velocities would be expected in these parts of the tomograms. Conversely, good reservoir quality, that is, higher effective porosities and permeabilities, usually occurs where there is a low amount of matrix and cement. Lower seismic velocities would be expected to coincide with these zones.

Effects of Gas Above Reservoir

Another interesting feature is a SW-NE increase in slowness across the 5-spot in the upper part of the tomograms (Figure 5). Slownesses around Well 57 are lower than elsewhere in the 5-spot. Slownesses increase both to the east (Well 56) and to the north (Well 54) of Well 57. In survey 2 (Wells 56 to 54), the stratigraphic horizons in the 3,900-4,050 feet depth range have systematically higher slownesses than the lower payzone intervals. Taken all together, these observations suggest an increase in slowness from southwest to northeast in the 3,900 to 4,050 feet depth interval. This SW-NE increase in slowness may be explained by waterflooding effects on gas. This gas may occur either as residual CO_2 remaining from the WAG CO_2-injection pilot project or as a gas cap above the payzone.

Within West Texas carbonate reservoirs, it is common practice to create hydraulic fractures in wells in order to expose the wells to large surface areas of the reservoir rock—hydraulic fractures in this field align in a generally WNW-ESE direction that is consistent with in situ stress orientation measurements in this region [Zoback and Zoback, 1980; Zoback and Zoback, 1989]. Waterfloods are engineered in line-drive patterns to sweep floodwaters in the direction perpendicular to these hydraulic fractures. This flow direction is generally NNE-SSW. It is possible for these floodwaters to escape from the payzone stratigraphic units and sweep through the upper or lower bounding units.

Residual CO_2

During the pilot project, CO_2 could have escaped into the units above the payzone through leaks behind casing, natural breaks in the reservoir seal (4080-4130 ft), or hydraulic fractures induced and propagated upwards through the reservoir seal during the CO_2 and water injection phases of the pilot. The tomograms may be showing the effects of floodwater sweeping from southwest to northeast and displacing residual CO_2. Water-saturated zones would show up in the tomograms having lower slownesses (higher velocities) than gas-saturated zones. Since CO_2 is miscible with water, within the payzone itself, it is more likely than not, given time, residual CO_2 from the pilot would be dissolved in the floodwaters and swept away.

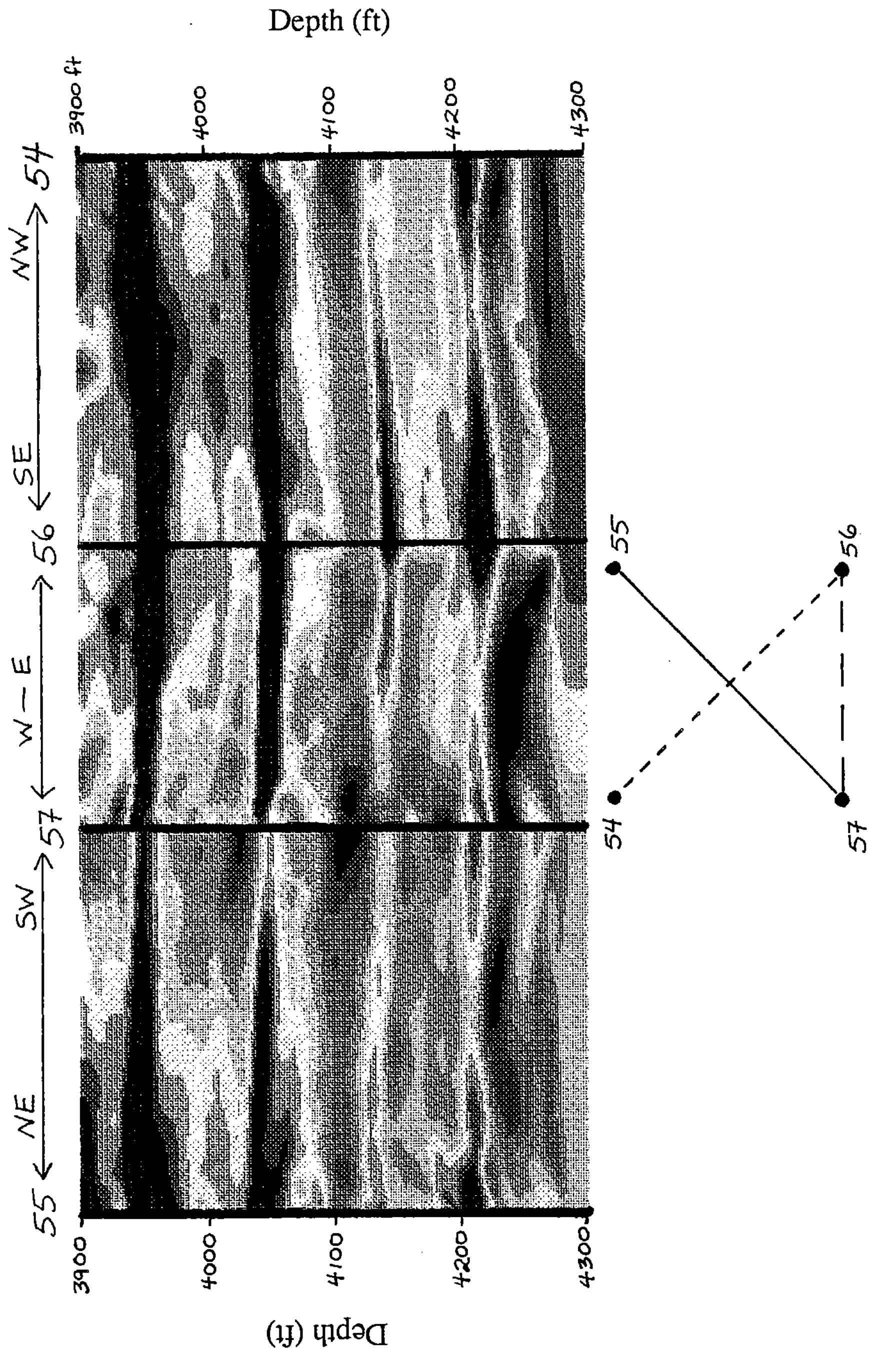


Figure 5: Slowness tomograms spliced together. Notice the SW-NE increase in slowness across the 5-spot, above 4100 feet in the tomograms. This might be explained by waterflooding effects on gas.

Gas cap above the payzone

Gas is known to exist above the payzone interval in this West Texas reservoir [Michael Stein, pers. comm., 1991]. The tomograms may be showing the effects of floodwater displacing this gas cap to the northeast. As before, water-saturated zones would show up in the tomograms having higher seismic velocities than gas-saturated zones.

FUTURE DIRECTIONS

The common receiver gather shown in Figure 2 shows several easily identified reflections. In addition, coherent S-wave arrivals are possibly visible. We see promise of extracting further information from these data.

We are planning to process these data further. Our plans are first to do reflection mapping [see Paper A in this volume], followed by reflection-constrained traveltime tomography, and finally use the results of this traveltime and reflection processing to do formation evaluation.

Although we see promise of extracting further information from these data, the vertical sampling interval (10 feet) creates spatial aliasing and difficulties with wavefield separation. In addition, the very wide-angle reflections (greater than 60°) at the top of the reservoir will create mapping complexities. Initial reflection mapping will aid us to design a more appropriate field experiment to incorporate reflection imaging with traveltime tomography at this West Texas site.

A critical need being addressed in the future is a better integration to the extensive core and log database available for the pilot site as well as an integrated interpretation using production and fluid flow data.

CONCLUSIONS

At this time, we cannot attach significance to an interpretation of lateral reservoir variations. The site has undergone significant fluid alteration due to waterflooding, WAG CO_2 injection, and continued waterflooding. A pervasive gas cap has existed in the area; so, our interpretation is complicated by the uncertain fluid dynamics of the five-spot region. We plan to map crosswell reflectors and upgrade the slowness image accordingly in order be able to give more significance and confidence to an interpretation. Further, we must work with a resident reservoir engineer in order to better understand the reservoir history and fluid distribution models acceptable for the five-spot region.

ACKNOWLEDGEMENTS

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REFERENCES

Zoback, M. L., and Zoback, M. D., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, **85**, 6113-6156.

Zoback, M. L., and Zoback, M. D., 1989, Tectonic stress field of the continental United States, *in* Pakiser, L. C., and Mooney, W. D., Ed., Geophysical framework of the continental United States: Geological Society of America, Memoir 172, 523-539.