DOE/BC/14649--12

# ANALYSIS AND EVALUATION OF INTERWELL SEISMIC LOGGING TECHNIQUES FOR RESERVOIR CHARACTERIZATION

**Contract No. DE-AC22-90BC14649**

**Southwest Research Institute**
**San Antonio, Texas**

**Contract Date: June 29, 1990**
**Anticipated Completion: December 1993**

**Government Award: $294,811**
**(Current Year)**

**Principal Investigator: Jorge O. Parra**

**Project Manager: Chandra Nautiyal**
**Bartlesville Project Office**

**Reporting Period: April 1 - June 30, 1993**

## DISCLAIMER

SOUTHWEST RESEARCH INSTITUTE

## OBJECTIVE

The objective of this three-year research program is to investigate interwell seismic logging techniques for indirectly interpreting oil and gas reservoir geology and rock physical properties. This work involves a balanced study of advanced theoretical and numerical modeling of seismic waves transmitted between pairs of reservoir wells combined with experimental data acquisition and processing of measurements at controlled sites as well as in full-scale reservoirs. This reservoir probing concept is aimed at demonstrating high-resolution measurements and detailed interpretation of heterogeneous hydrocarbon-bearing formations.

## SUMMARY OF TECHNICAL PROGRESS

### Task 3 - Data Processing and Analysis

#### A. *Preliminary Interpretation of Interwell Seismic Data from Wells 5-7 and 7-7 at the Gypsy Test Site*

This part of the project is a well log and seismic analysis of the geological cross section between wells 5-7 and 7-7 at the Gypsy test site. Figure 1 illustrates the location of the six wells at Gypsy. To investigate the seismic wave propagation between wells we selected the cross-section through the Dallas 9-7, 5-7, and 7-7 which contains the calculated lithology and the compressional wave velocity logs as shown in Figure 2. In this cross-section there are six selected intervals having high-degree of probability of being continuous. Five high-velocity (HV) zones and four low-velocity (LV) zones are correlated across the section. The Gypsy sandstone interval (HV4) is composed by stacked channel sands, mudstones, and siltstones which indicates an uncertain and very difficult correlation of individual sandstone units between wells. However, the integration of the geology and well logs with the crosswell data indicates the presence of two low-velocity sands to be continuous in the Gypsy sandstone interval at the depths of 935 to 970 feet (see Figure 3). These two sand units exhibit high porosity (30%) and high permeability (1 to 2 darcy). Also, Figure 3 illustrates gamma ray and density logs as well as a comparison between the vertical compression wave velocity log and the horizontal compressional wave velocity log determined from zero-vertical offset seismic waveforms. This comparison shows strong vertical velocity anisotropy in the shale, and weak anisotropy in the clean sands. Specifically, high gamma ray amplitudes are associated with clean sands in the Gypsy interval. That is, the gamma ray amplitudes are less for clay-filled sands than for brine-filled sands (observed in cores). The shales have gamma ray amplitudes similar to those amplitudes corresponding to dirty sands.

In order to better characterize the interwell seismic response of the target zones of interest the vertical and horizontal compressional wave velocity logs are plotted separate in Figure 4. In addition, the vertical compressional wave velocity log corrected for shale is shown in Figure 5. In general, the horizontal velocity log (see Figure 4) and the compressional wave velocity log corrected for shale (in Figure 5) have similar responses. In particular, the bottom low-velocity sand can be easily identified in both logs at the depth interval of

960 to 980 feet. In addition, when the source and detectors are located within this sand unit the measured interwell seismic waveforms exhibits dispersion characteristics associated with guided waves trapped in the low-velocity sand as shown in Figures 4 and 5. The connectivity of the clean sand beds between wells 5-7 and 7-7 have been already demonstrated by pulse test data acquired by BP Exploration at Gypsy. The results of these tests indicated that many of the sands are in pressure communication with many of the sands in the receiver well 5-7. In addition, the pulse test data have confirmed the existence of an impermeable barrier between the top and bottom sand units (Turpening et al., 1992).

In conclusion, since guided waves are observed in the interwell seismic logging data at Gypsy, seismic guided waves can propagate in heterogeneous sandstone reservoirs. Also, the correlation of the geological formations with well logs and seismic data indicates the origin of the waveforms associated with continuous and discontinuous bodies.

### B. *The Response of a Thin Layer in an Anisotropic Shale*

In this section the theoretical modeling capabilities developed in the first and second year of the project are used to calculate the seismic response of a hydrocarbon bearing formation at the Buckhorn test site in Illinois (Parra *et al.*, 1991 and Saito, 1991). Reverse VSP and interwell seismic experiments were conducted at the site for mapping geological structures and to determine rock physical parameters to characterize the Silurian Kankakee limestone formation, which is an oil producer in the Mt. Sterling area in Illinois. Reverse VSP and interwell seismic measurements together with log data have yielded information on the anisotropic characteristics of the shale and heterogeneities within the limestone associated with lateral changes in porosity. According to the exploration and production histories of the field, the oil reservoir is the porous zone of the Silurian Kankakee which is horizontally distributed at a depth of about 200 m, and has less than 8 m of thickness. The results of several logging measurements conducted just after drilling five boreholes indicate a good correlation of the formation from well to well. The Kankakee is considered as a thin high-velocity layer in the low-velocity background shale.

A three-dimensional view of the wells is shown in Figure 6. Two 24-element hydrophone arrays were used to conduct attenuation measurements and traveltime tomography using a 1000-joule arc discharge borehole seismic source. The source was placed in well A, at a depth of 180 m and hydrophone arrays were placed in wells D, B, and E. The rock physical parameters and structure determined from reverse VSP, interwell seismic data and well logs were used to construct a layered model. This model consists of a limestone-shale sequence formed by a thick isotropic limestone layer followed by an anisotropic low-velocity shale of thickness 60 m and an isotropic thin high-velocity limestone layer representing the Kankakee formation. This thin layer overlays the bottom half-space formed by a low-velocity shale having the same characteristics as those of the upper shale section. The rock physical parameters of this model are given in Table 1.

Figure 7 shows a pressure seismogram calculated for a horizontal point force signal centered at 600 Hz and located at a horizontal distance of 46 m from the source. The shale formation is characterized by large P-wave amplitudes followed by converted compressional and shear waves. The seismogram also shows the presence of the Kankakee limestone layer which attenuates the seismic waves observed by detectors within the thin layer. To check the synthetic seismogram, the corresponding observed field data recorded in well B is illustrated in Figure 8. The agreement between synthetic data and field data confirms the interpretation of well logs and crosswell seismic data which suggest a predominantly horizontal structure and an attenuated limestone. The model results compare very well with the raw field data except for the P-waves traveling in the Kankakee (a highly heterogeneous formation) and for the large amplitude tube waves which cannot be produced with the present program. However, the code can be modified for simulating seismic data containing tube waves. This can be done through the use of equivalent line mechanism representations for the source and receiver wells (Kurkjian, *et al.*, 1992)

## REFERENCES

Turpening, W.R., Chon, Y.T., Pepper, R.E., Szerbiak, R.B., Schultz, T.R., Thielmier, G.W., and Ballard, R.A., 1992, Detection of reservoir continuity using crosswell seismic data - A Gypsy Pilot Study: SPE Paper 24711.

Parra, J.O., Karisch, E.P., Bangs, J.H., and Zook, B.J., 1991, Demonstration of high-resolution reverse VSP for reservoir characterization applications, Task II - Full-scale field demonstration experiments, U.S. Dept. of Energy, Contract NO. DE-AC22-89-C-14473; SwRI Proj. 15-3200.

Saito, H., 1991, Anisotropic traveltime tomography at the Buckhorn test site in Illinois: 61st Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 123-126.

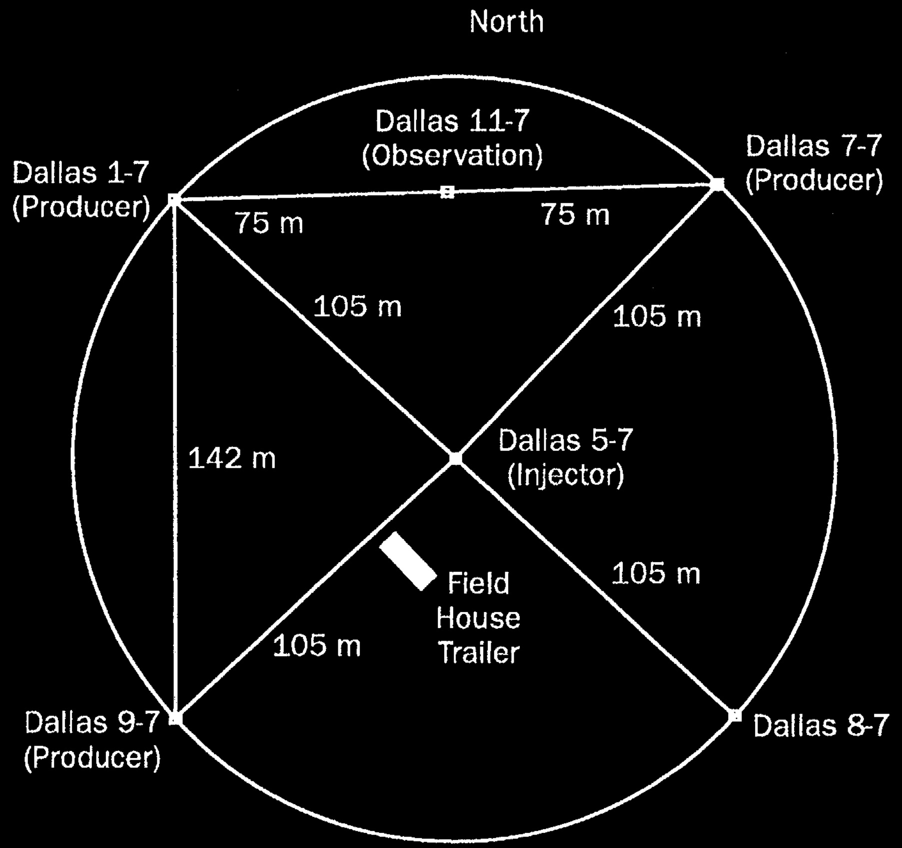
Kurkjian, A.L., Schmidt, H., Marzetta, T.L., and White, T.E., 1992, Numerical modeling of crosswell data: 62nd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 141-144.

**TABLE 1. Formation Parameters for a Limestone-Shale Layer Sequence**

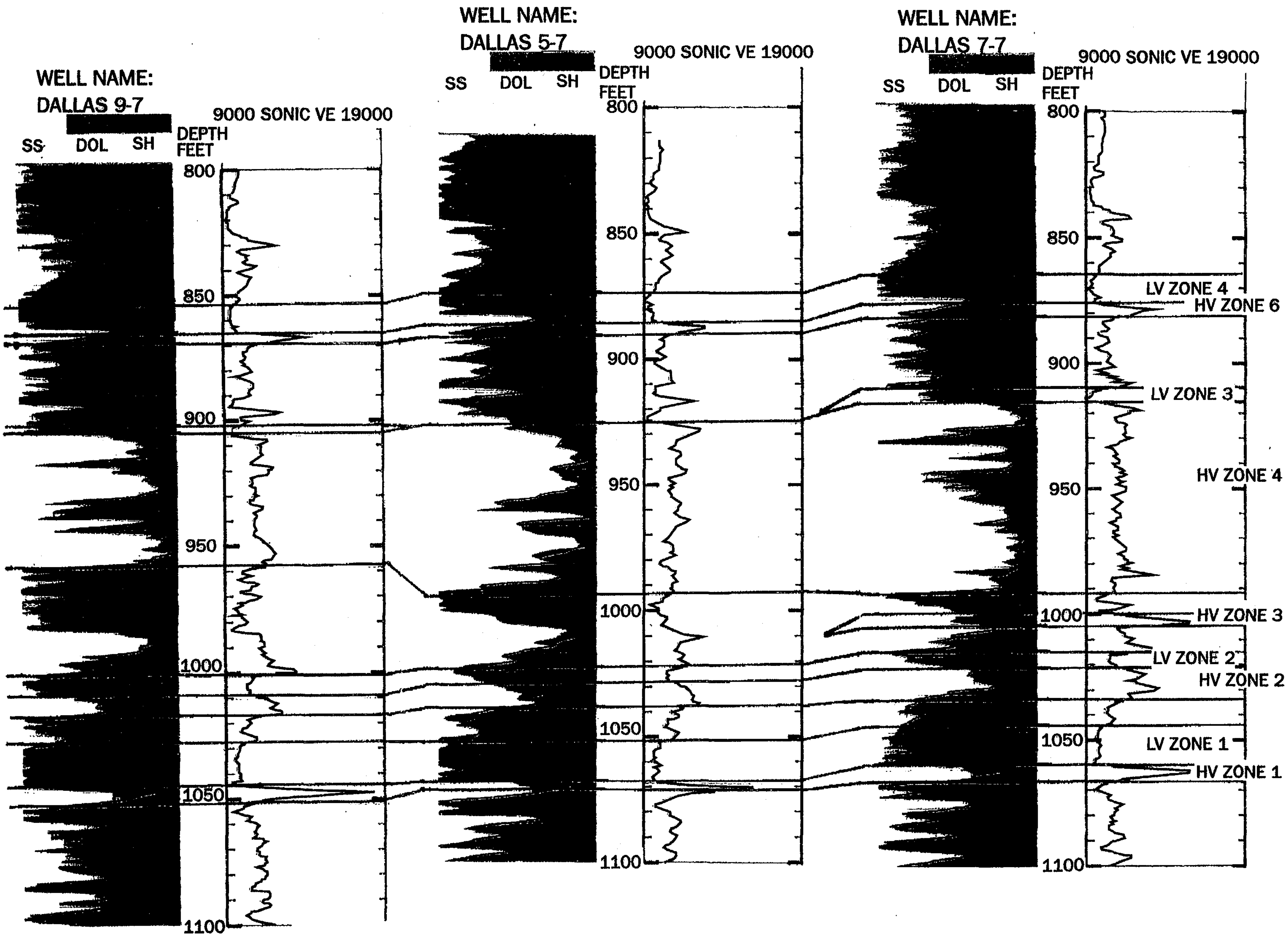
| Region | Thickness (m) | Density (g/cm$^3$) | $C_{11}$ (Ga) | $C_{13}$ (Ga) | $C_{33}$ (Ga) | $C_{44}$ (Ga) | $C_{66}$ (Ga) | Q |
|---|---|---|---|---|---|---|---|---|
| Limestone | 134 | 2.87 | 65.7 | 18.4 | 65.7 | 23.7 | 23.7 | 40 |
| Shale | 60 | 2.55 | 27.7 | 15.52 | 16.6 | 3.7 | 6.1 | 28 |
| Kankakee | 7.5 | 2.10 | 50.0 | 14.0 | 50.0 | 18.0 | 18.0 | 4.5 |
| Shale | ∞ | 2.55 | 27.7 | 15.52 | 16.6 | 3.7 | 6.1 | 28 |

# LIST OF FIGURES

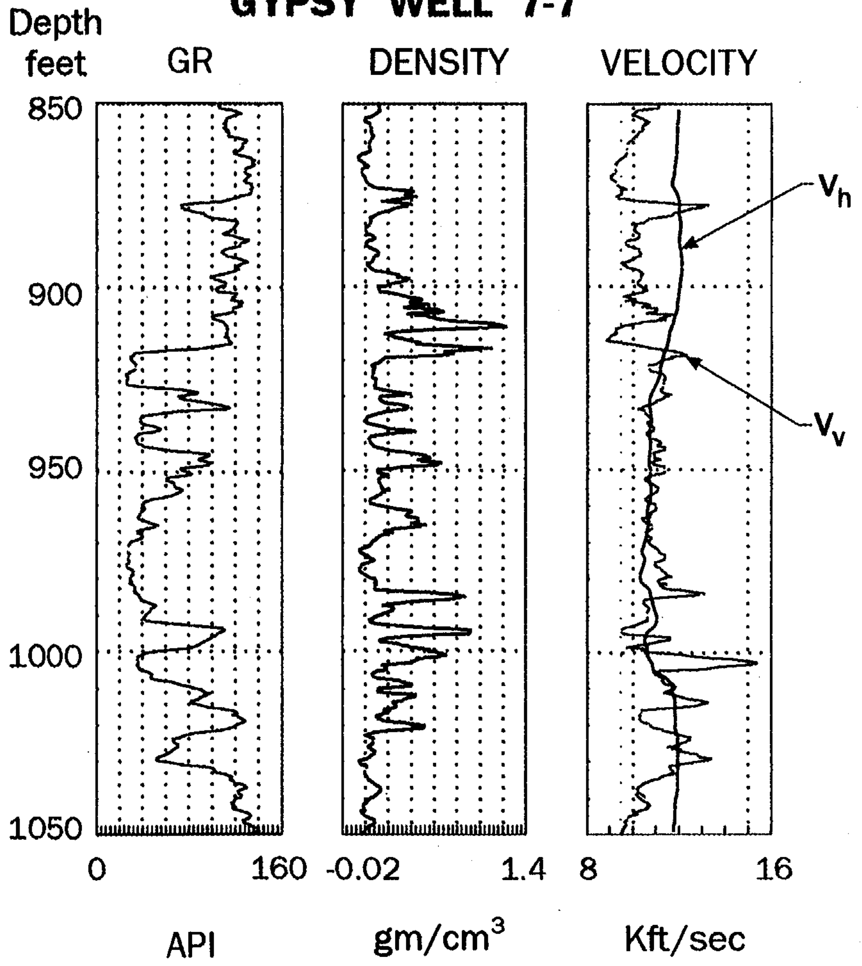
# GYPSY BOREHOLE TEST FACILITY
# CLEVELAND, OKLAHOMA



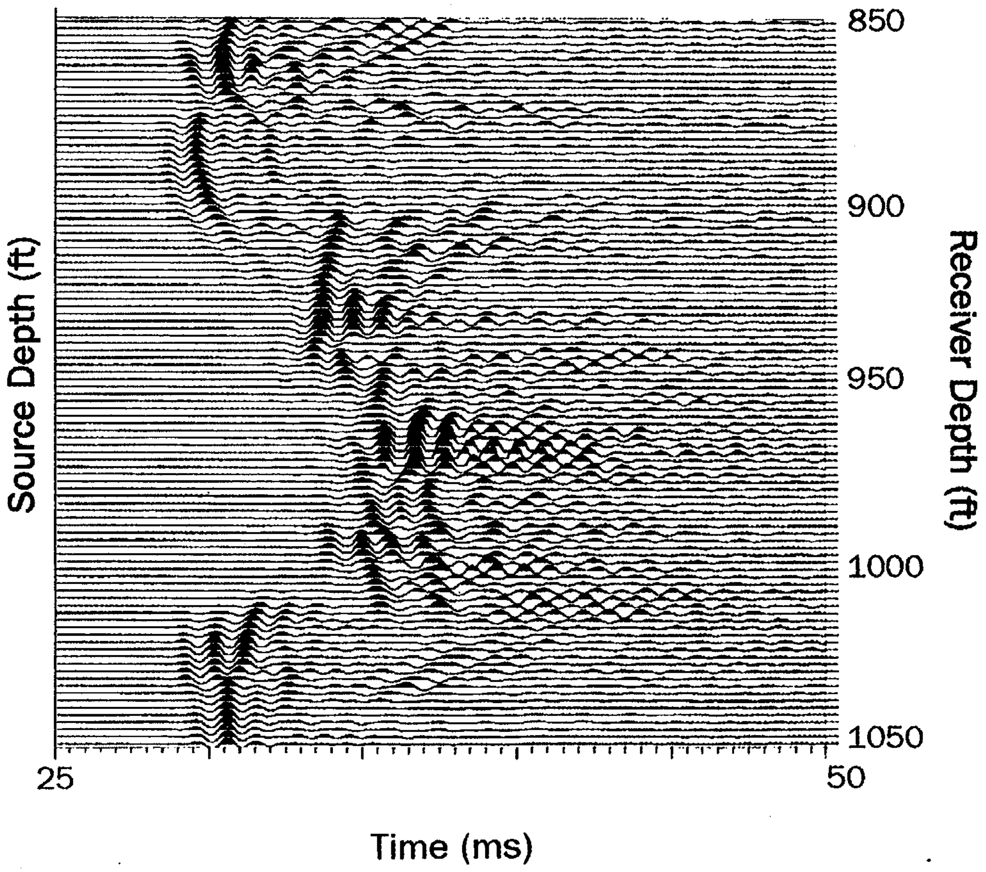
# CROSS-SECTION THROUGH THE DALLAS 9-7, 5-7, AND 7-7



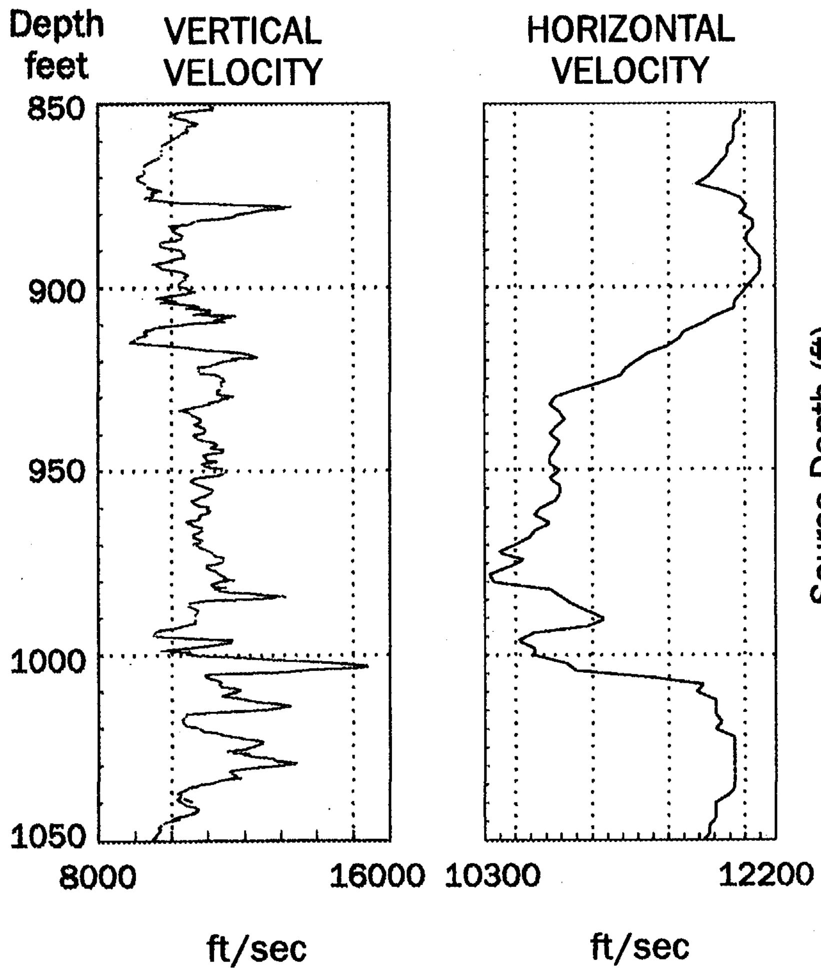
**GYPSY WELL 7-7**



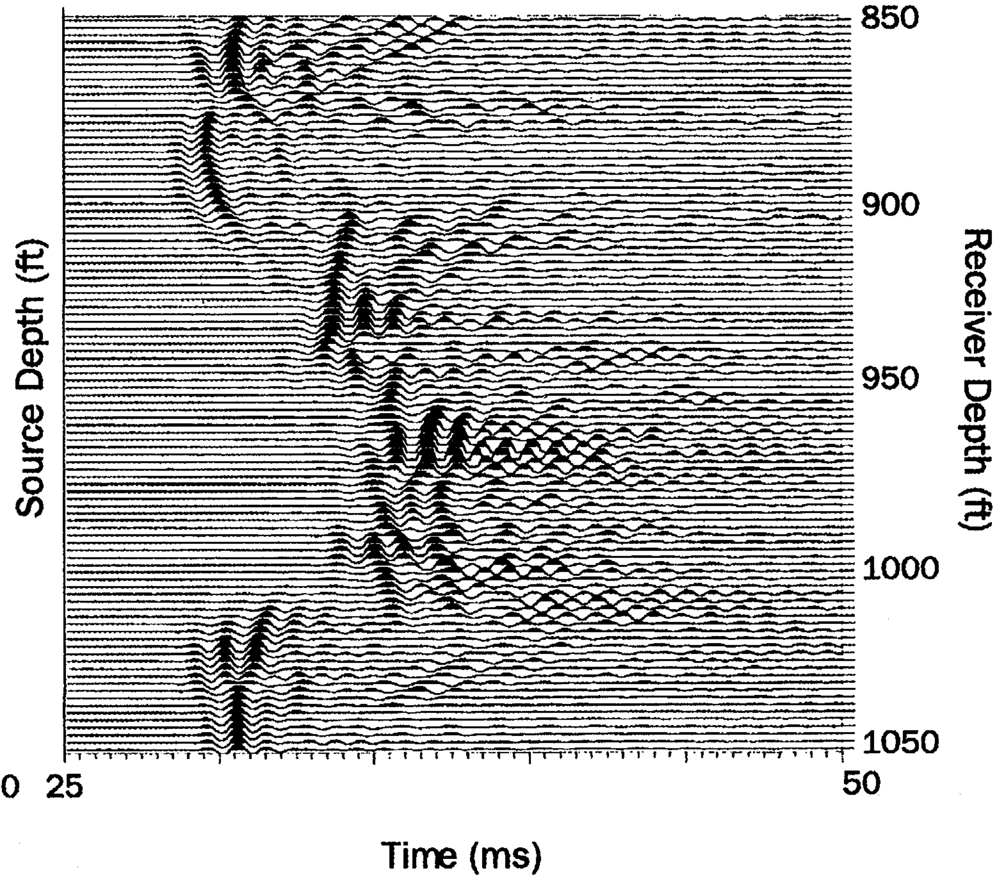
**ZERO VERTICAL OFFSET WAVEFORMS
IN WELLS SPACED 340 FEET**



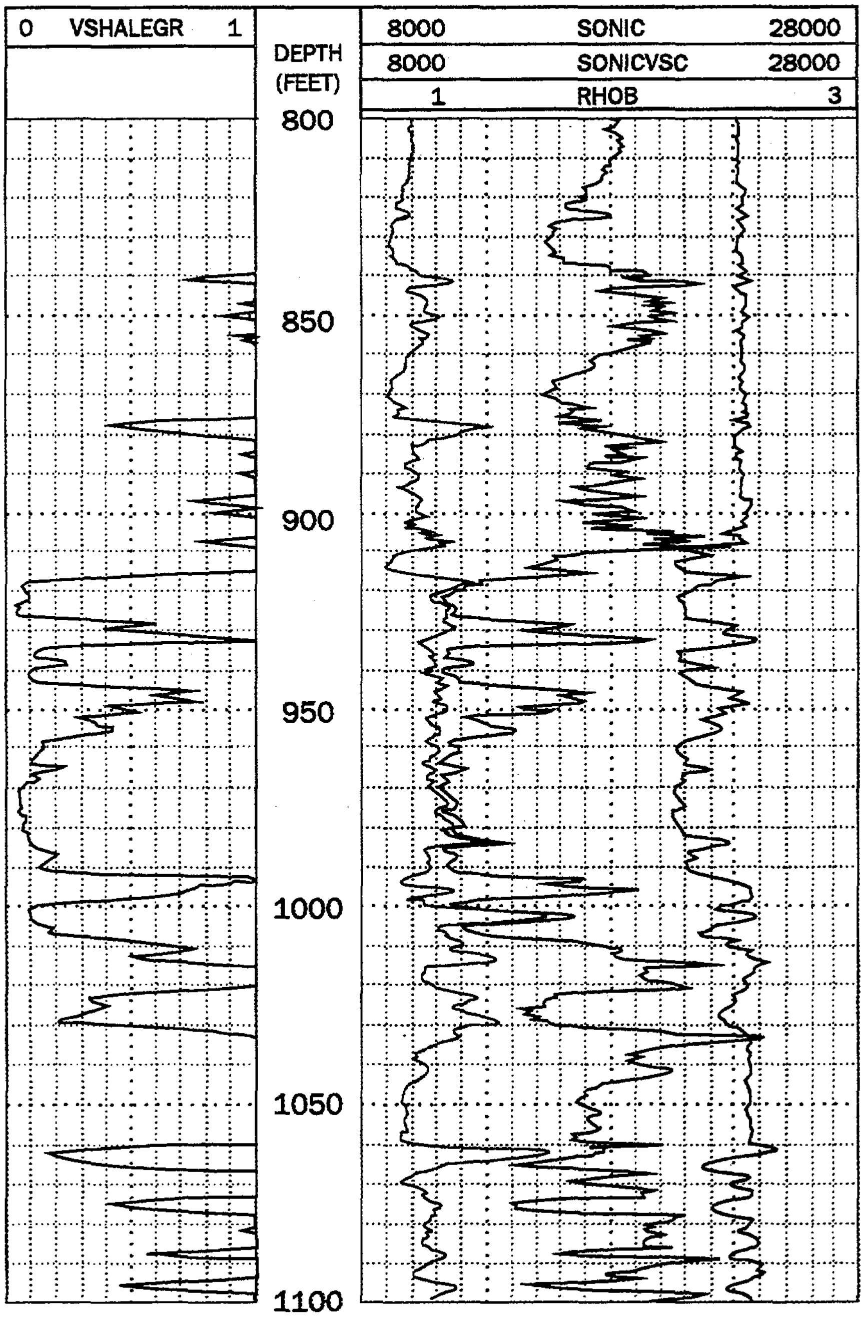
## GYPSY WELL 7-7



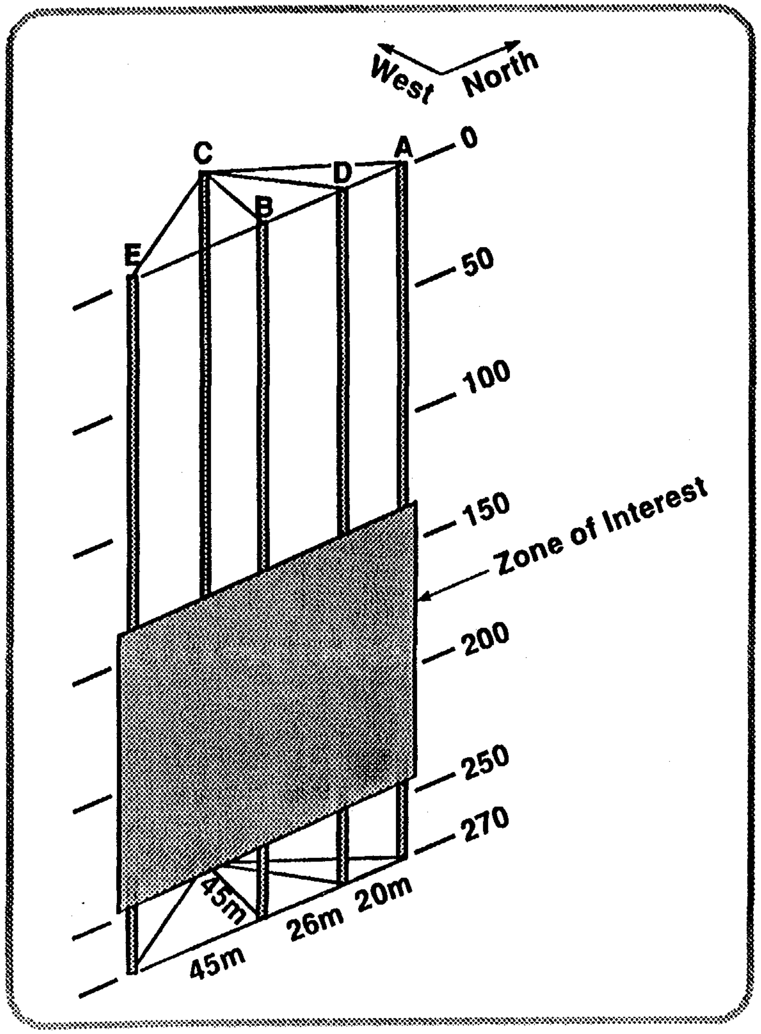
## ZERO VERTICAL OFFSET WAVEFORMS IN WELLS SPACED 340 FEET



VSHALEGR: volume of shale calculated from the gamma ray (%)
SONIC VE: velocity of the compression wave (feet/second)
SONICVSC: velocity of the compression wave corrected for shale
(feet/second)
RHOB: bulk density (grams/$cm^3$)
WELL Name: DALLAS 7-7

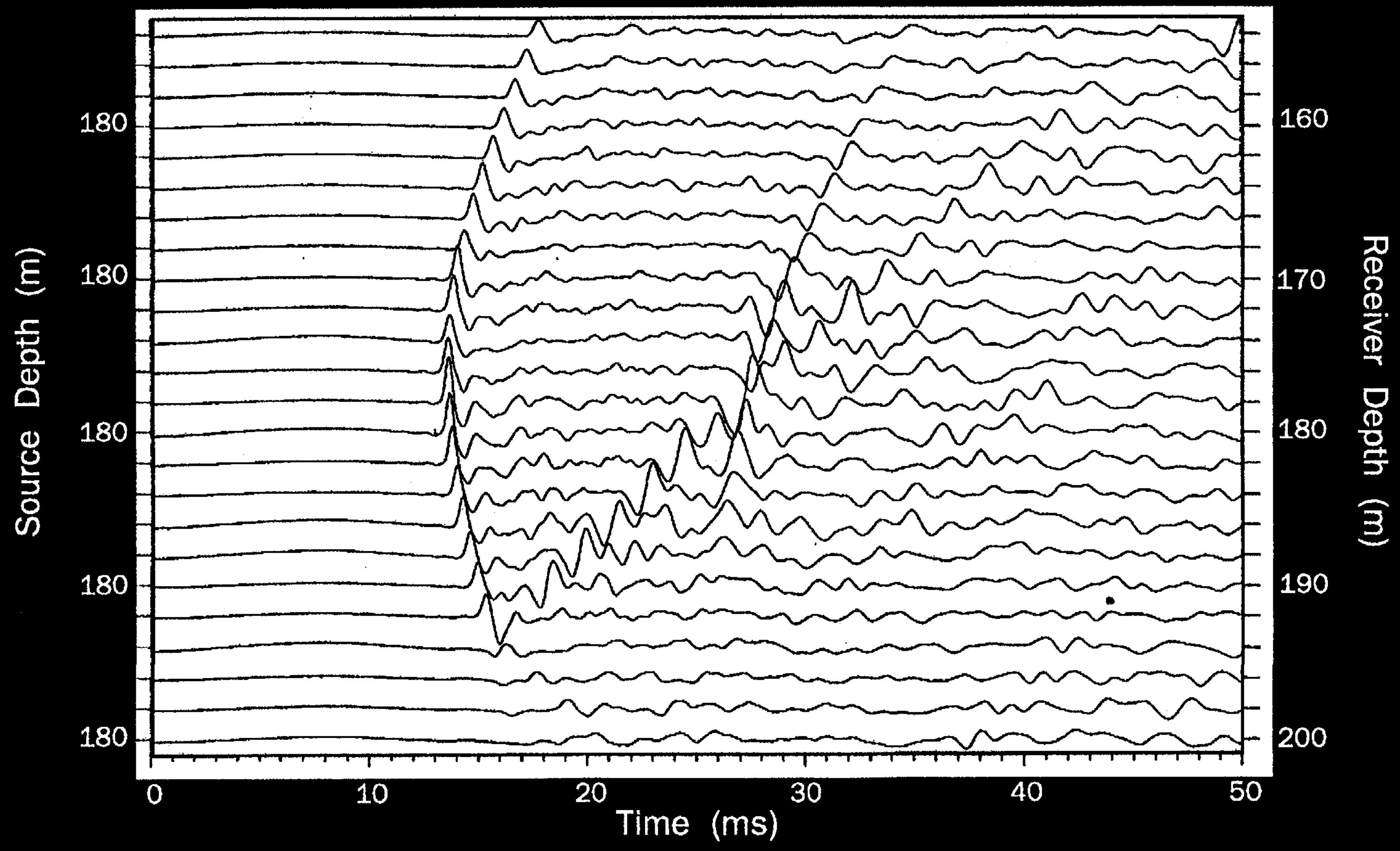


# THREE-DIMENSIONAL VIEW OF FIVE BOREHOLES AT THE BUCKHORN TEST SITE



# COMMON-SOURCE WAVEFORMS
# IN WELLS SPACED 46 m

## Arc Discharge



# PRESSURE SYNTHETIC SEISMOGRAM (600 Hz)

## Well Spaced 46 m