

UTILIZATION OF SEISMIC EXPLORATION TECHNOLOGY FOR HIGH RESOLUTION MAPPING OF A GEOTHERMAL RESERVOIR

Final Report

P. L. Goupillaud
J. T. Cherry

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April 1977

Under Contract No. EY-76-C-1249
(Formerly E(04-03)-1249)

PREPARED FOR THE
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Systems, Science and Software
P. O. Box 1620
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BIBLIOGRAPHIC DATA SHEET	1. Report No.	2	3. Recipient's Accession No.
4. Title and Subtitle UTILIZATION OF SEISMIC EXPLORATION TECHNOLOGY FOR HIGH RESOLUTION MAPPING OF A GEOTHERMAL RESERVOIR			5. Report Date April 1977
7. Author(s) P. L. Goupillaud and J. T. Cherry			6.
9. Performing Organization Name and Address Systems, Science and Software P. O. Box 1620 La Jolla, California 92038			8. Performing Organization Rept. No. SSS-R-77-3176
			10. Project/Task/Work Unit No.
			11. Contract/Grant No. EY-76-C-1249
12. Sponsoring Organization Name and Address U.S. Energy Research and Development Administration 20 Massachusetts Avenue, N.W. Washington, D.C. 20550			13. Type of Report & Period Covered Final Report
			14.
15. Supplementary Notes			
16. Abstracts A seismic reflection survey using the "Vibroseis" technique and a combination of both compressional and horizontally polarized shear waves has been successfully completed over the East Mesa geothermal field. The interpreted results of the survey clearly demonstrates that: 1. The compressional waves have the resolving power to detect anomalous conditions such as faults and fracture zones of critical importance in geothermal reservoir investigations. 2. The shear waves have penetrated to the target depth but the lower quality of the data, thus acquired renders its processing and interpretation more difficult and less reliable. However, it also contains information which may prove essential for lithological discrimination, such as estimating the ratio V_p/V_s of the velocities.			
17. Key Words and Document Analysis. 17a. Descriptors Imperial Valley East Mesa Geothermal Reservoir Exploration Seismic Reflection Compressional Waves Shear Waves "Vibroseis" Technique V_p/V_s Ratio			
17b. Identifiers/Open-Ended Terms			
17c. COSATI Field/Group			
18. Availability Statement		19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 58
		20. Security Class (This Page) UNCLASSIFIED	22. Price

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
I.	INTRODUCTION.	1
II.	THE EAST MESA GEOTHERMAL AREA	3
III.	DESCRIPTION OF THE TEST	9
IV.	DATA INTERPRETATION	42
V.	CONCLUSIONS AND RECOMMENDATIONS	51
VI.	ACKNOWLEDGEMENTS.	53
REFERENCES		55

<u>Figure</u>	LIST OF ILLUSTRATIONS	<u>Page</u>
1.	Location of earthquakes in the Imperial Valley region with respect to major faults and geothermal anomalies	5
2.	Seismic reflection lines and geothermal well locations	7
3.	Vibrator position numbers and locations on Lines 1, 2 and 3.	10
4.	Configurations of P and SH Noise Test showing vibrator positions (VP), geophone positions (GP) and details of the geophone spread	11
5.	Results of the P wave noise test	12
6.	Results of the SH wave noise test.	14
7.	CDP diagram for P and SH reflection surveys.	15
8.	Vibrators and geophone group patterns used in the P and the SH reflection surveys	16
9.	Line 1P - Straight Stack	19
10.	Line 2P - Straight Stack	20
11.	Line 3P - Straight Stack	21
12.	Line 1S - Straight Stack	22

LIST OF ILLUSTRATIONS (continued)

<u>Figure</u>		<u>Page</u>
13	Line 2S - Straight Stack	23
14.	Line 1P, RAP Section, polarity normal.	24
15.	Line 1P, RAP Section, polarity reversed.	25
16.	Line 2P, RAP Section, polarity normal.	26
17.	Line 2P, RAP Section, polarity reversed.	27
18.	Line 3P, RAP Section, polarity normal.	28
19.	Line 3P, RAP Section, polarity reversed.	29
20.	Line 1P, migrated section.	30
21.	Line 2P, migrated section.	31
22.	Line 3P, migrated section. . . . , ...	32
23.	Guide SH velocity (suggested).	33
24.	Line 2S, section stacked with guide SH velocity.	34
25.	Line 2S, depth section	35
26.	Line 2S, depth section using VELAN SH velocities	36
27.	Line 2S, depth section using VELAN picks based upon guide velocity. Polarity normal.	37
28.	Line 2S, depth section using VELAN picks based upon guide velocity. Polarity reversed	38
29.	P velocity profile along Line 2P	40
30.	SH velocity profile along Line 2S.	41
31.	Line 2P, fractured zone noted on straight stacked section.	43
32.	Line 2P, RAP section, polarity reversed, clear evidence of fracture zone by lack of reflecting power.	44
33.	Line 2P, depth section interpreted	45
34.	Line 2S, depth section interpreted	46

I. INTRODUCTION

The geothermal reservoirs in the Imperial Valley of Southern California are convective hydrothermal systems which are tectonically controlled. The water is heated by a deeply buried igneous heat source, ascends along fault zones and circulates within the reservoir (Elders, et al., 1972; Department of the Interior, East Mesa Test Site Status Report, 1974).

The subsurface location and dimensions of the fault zone which control the reservoir must be established prior to the economic development of the resource. Furthermore an estimate of fracture porosity within the producing zones would improve prediction of flow rates and the useful life-time of the geothermal reservoir.

Our objective was to determine if state-of-the-art seismic reflection technology could locate these fault/fracture zones. The East Mesa Reservoir was chosen for the test and an intensive "Vibroseis" ® reflection survey was conducted over the reservoir.

Both compressional (P) and horizontally polarized shear (SH) reflection profiles were obtained. These profiles provide a detailed seismic view of a North-South cross-section of the East Mesa reservoir.

The survey required the coordination of two "Vibroseis" crews. Western Geophysical Company acted as subcontractor for the entire P acquisition using vertical vibrators and vertical geophones. Continental Oil Company (Conoco) contributed, free of charge, the horizontal vibrators, horizontal geophones and personnel required for the SH test.

We are very encouraged by the results of the survey. The reflection profiles (P and SH) and variations in the

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velocity ratio (V_p/V_{SH}) have identified an anomalous region in the East Mesa field. This region is interpreted as a fracture zone which could be highly significant in terms of its geothermal potential.

It appears that the "Vibroseis" reflection technique can furnish very valuable subsurface information in the Imperial Valley. This conclusion can be substantiated and quantified by conducting more extensive reflection surveys. These surveys should be coordinated with all available geophysical, geological and production data from the resource.

In the remainder of this report we present the details of the planning, execution and interpretation of the reflection survey. Section II discusses the tectonics of the Imperial Valley and the local geologic environment of East Mesa. Section III describes the planning and execution of the reflection survey. In Section IV we present the interpretation of the reflection data and the lithologic significance of V_p/V_{SH} . Section V gives our conclusions and recommendations.

II. THE EAST MESA GEOTHERMAL AREA

The site selected for the test was the East Mesa Geothermal Area which contains a large reservoir well documented through the development work of the Bureau of Reclamation. A description of the geological and tectonic setting of this reservoir will provide useful information for a correct interpretation of the results of the test.

The East Mesa site is in the Imperial Valley of Southern California. The Imperial Valley is a major topographic and structural feature characterized by a deep trough producing elevations several hundred feet below sea level as demonstrated by the Salton Sea. This trough is located at the northern end of the larger Salton trough, which is the landward extension of the Gulf of California into North America.

According to the theory of plate tectonics, the Gulf of California is a part of the active boundary between the North American and Pacific plates [Biehler, et al., 1964; Anderson, 1973; Elder, et al., 1972; Clarke, 1976].

The active nature of this plate boundary is demonstrated by patterns of magnetic and thermal anomalies, together with strike-slip faulting and recent volcanism. These processes suggest that the continental crust in this region is rifting apart, as part of the dynamic system that includes the southern part of the San Andreas and related faults in the Salton trough.

Within the framework of the plate tectonic hypothesis, the portion of California to the west of the San Andreas fault which disappears under the trough's recent sediments just east of the Salton Sea is on the North American plate which moves in a northwestern direction and rotates clockwise to accommodate the spreading taking place within the trough. According to this theory, the San Andreas is a strike-slip fault which produces large earthquakes when locking takes place at some points

along it [Anderson, 1973]. As one reaches the Imperial Valley, the seismicity, shown in Figure 1, changes in character as large earthquakes rarely occur but are replaced by smaller and more frequent earthquake swarms usually associated with spreading centers [Hill, et al., 1975; Combs and Hadley, 1975 and 1977].

The Imperial Valley trough is filled with recent sediments deposited by the Colorado River. These sediments are predominately erosional deposits from the Colorado Plateau at the time of the cutting of the Grand Canyon and the uplift of the Kaibab Plateau. They have been deposited over the past four or five million years. It is believed that they rest on a thin basaltic basement, indicative of an oceanic crust as would be expected for the Pacific plate. Where they have reached high enough temperatures and pressures, they underwent mineralogic changes which caused lithification [Muffler and Doe, 1968; Muffler and White, 1969].

The basement-sediment interface is probably very irregular, as evidenced by its outcrop in the Painted Canyon east of the Salton Sea. This basement irregularity should also be expected from the high seismicity shown in Figure 1 which indicates the presence of a large number of active faults in the area.

Having set the East Mesa site in its regional geological setting, we will now describe its local environment and the pertinent knowledge resulting from its present development. The Bureau of Reclamation lease is located east-southeast of Holtville near the corner of Townships 15S and 16S and Range 16E and 17E just north of Interstate 8 and immediately east of the East Highline Canal. To the north of the lease is another lease owned by Republic Geothermal while to the southwest is another one owned by Magma Power.

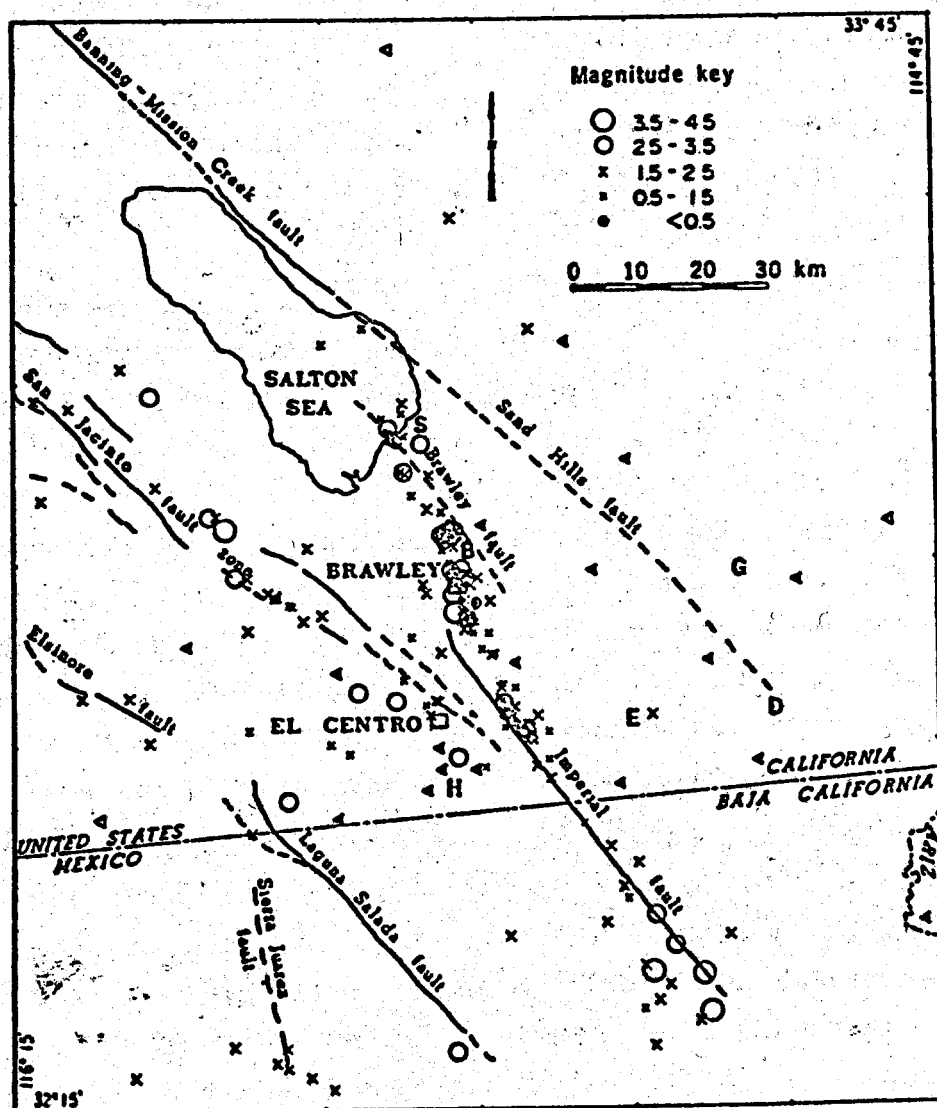


Figure 1. Location of earthquakes in the Imperial Valley region with respect to major faults and geothermal anomalies. Solid triangles represent locations of seismograph stations in the Imperial Valley network; open triangles correspond to locations of Caltech regional seismograph stations. Known geothermal resource areas are indicated by capital letters as follows B, Brawley; D, Dunes; E, East Mesa; G, Glamis; H, Heber and S, Salton Sea. Taken from Hill, *et. al.*, 1975.

A total of ten geothermal wells have been completed over these leases of which five belong to the Bureau of Reclamation who generously supplied us with their sonic logs. Most of the wells terminate between five and six thousand feet which appears to be the average depth necessary to reach conditions proper for geothermal potential.

The wells drilled by the Bureau of Reclamation were aimed at evaluating their merit for producing fresh water by desalinization of the hot brines. The five wells drilled by both Republic Geothermal and Magma Power on the contrary are targeted for electrical power generation.

In addition to the wells, the Bureau of Reclamation made available to us all the seismic reflection data in its possession. This consisted of some seven lines of six-fold data originally shot in 1966 by GSI for American Petrofina. The original data was being reprocessed by Western Geophysical Company in Denver and early results appeared encouraging. Mr. Walter Ortel of the Bureau of Reclamation continuously updated our information with these results and we reciprocated with him by communicating all of our results.

Figure 2 shows the location of the geothermal wells completed by Republic Geothermal, Magma Power and the Bureau of Reclamation. Also shown in the figure are the "Vibroseis" P and SH reflection lines, which are the subject of this report, and the seven American Petrofina lines shot in 1966 by GSI.

This old seismic data had been shot with dynamite at a shot point spacing of 500 feet. The lines were along directions approximately 45° east and west of north. Today's improved roads, on the other hand, are all along section lines extending N-S or E-W. In the present test the vibrator trucks were not suitable for operation in the loose, off-road sand encountered at the site. Therefore the vibrator positions were restricted to section line roads.

EAST MESA GEOTHERMAL FIELD

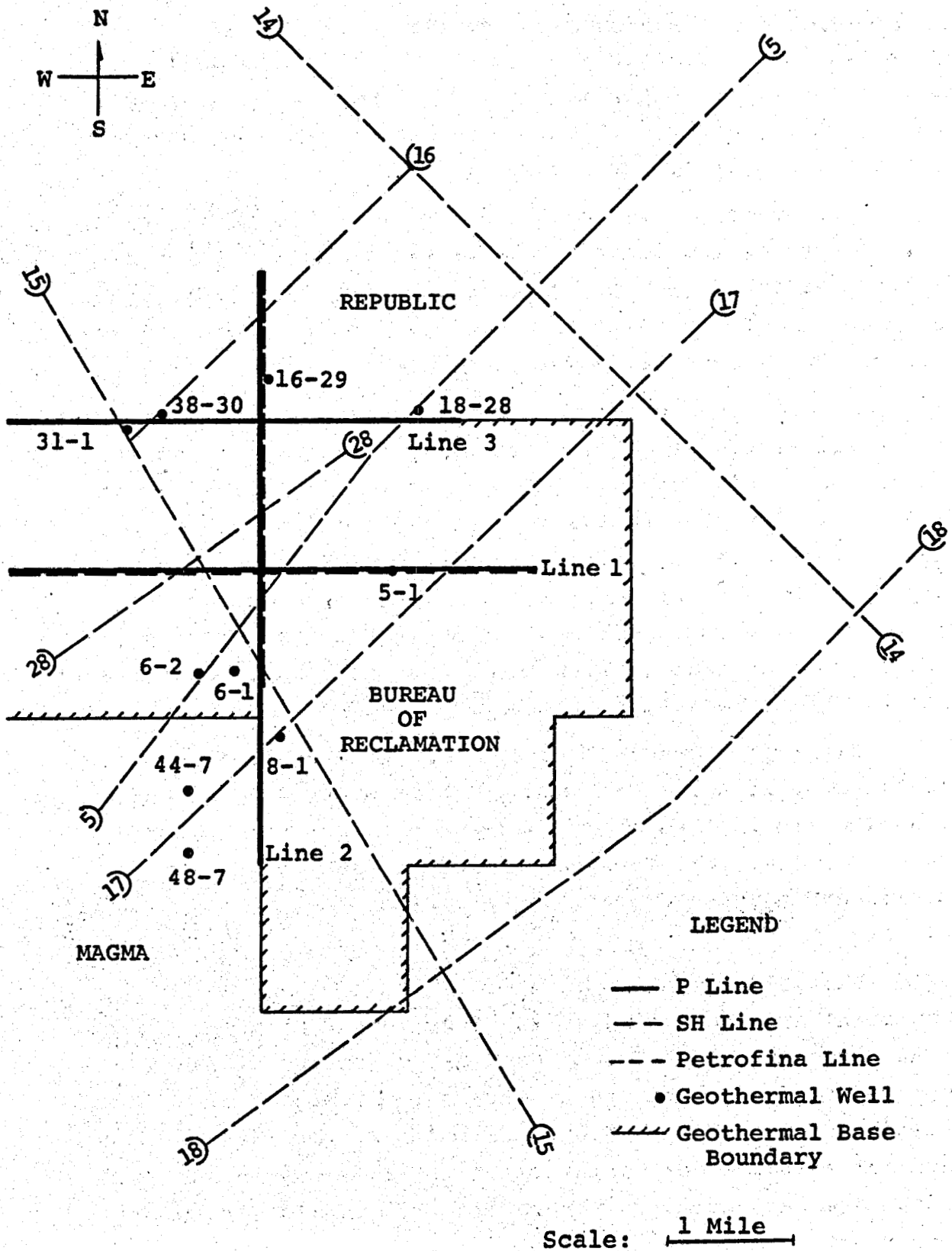


Figure 2. Seismic reflection lines and geothermal well locations.

Our lines, combined with the Bureau of Reclamation lines, provide a rather dense coverage of the central portion of the East Mesa Geothermal Reservoir.

III. DESCRIPTION OF THE TEST

The test took place from December 4 through December 16, 1976. The equipment available consisted of one complete Western Geophysical Company "Vibroseis" P-wave seismic crew, party V-6, and an experimental research SH-wave skeleton crew contributed at no cost by Continental Oil Company (Conoco). The Conoco crew consisted of two SH vibrators, nearly 3,000 SH-geophones, two vibrator operators and supervisory personnel.

Some 530 Vibrator Positions (VP's) were shot using either horizontal (SH) or vertical (P) vibrators. Over 10.5 miles of basement were covered with the P vibrators and more than 6.5 miles were shot with the SH vibrators. The location of the P and SH lines and the VP's are shown in Figures 2 and 3. In addition both P and SH "noise" tests were conducted at the start of the project to determine appropriate values for the offset and geophone coverage to be used for the reflection surveys.

The purpose of the noise test was to measure the velocities and amplitudes of the slowly traveling waves which can interfere and mask the target reflections. Figure 4 shows the details of the P and SH noise tests. The P test covered two (2) miles while the SH test covered one (1) mile. This difference in coverage gives equivalent interference times due to the slower velocities of the SH waves.

Figure 5 shows the result of the P noise test. For two-way reflection travel times of two (2) seconds and less, the major interference is caused by the P-wave refraction which travels across the spread at approximately 6600 ft/sec. The predominant frequency of the refraction was approximately 35 Hz. Therefore the surface wave length of the refracted energy is 190 feet. This formed the basis for choosing a geophone spread of 220 feet for the P reflection survey.

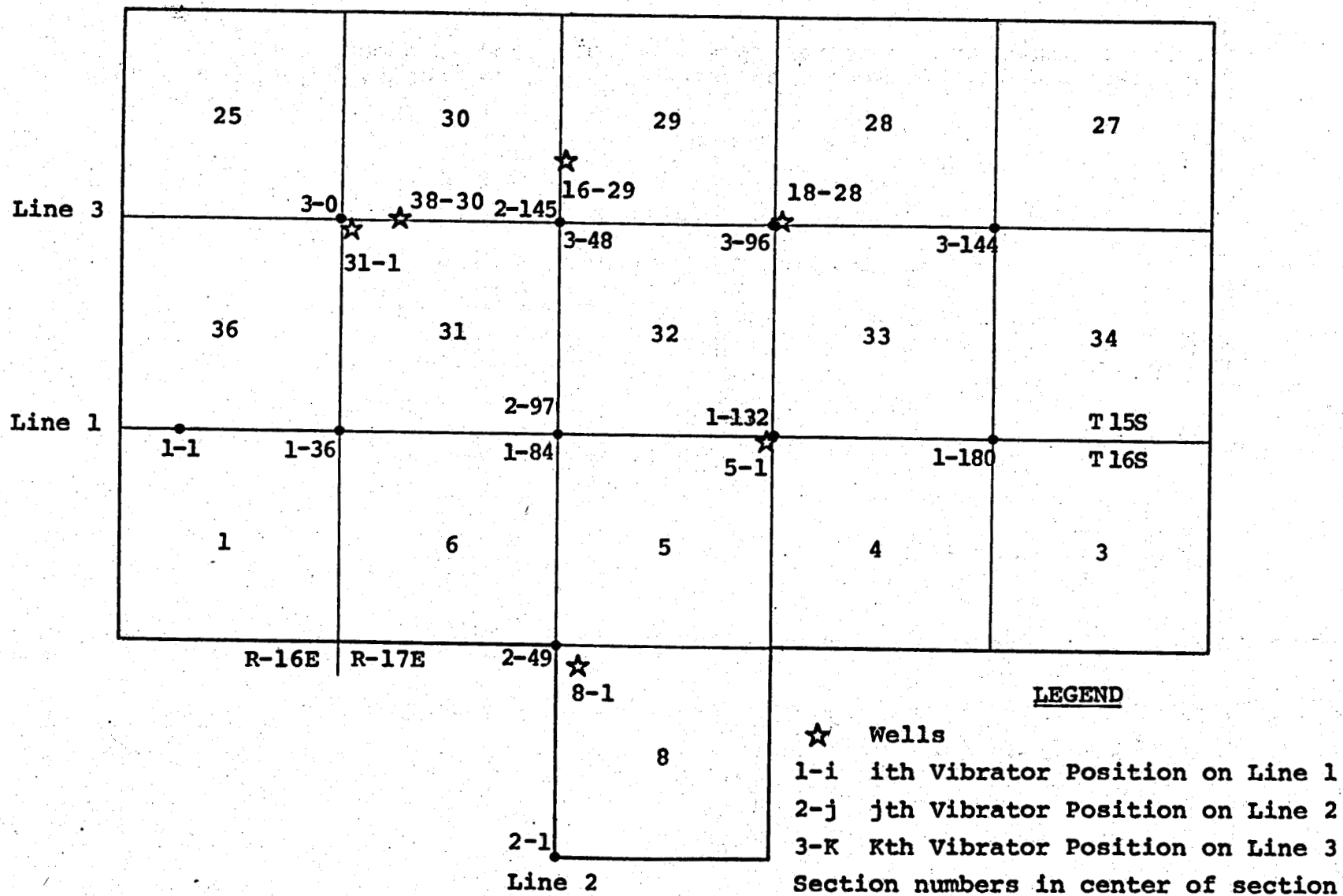


Figure 3. Vibrator position numbers and locations on Lines 1, 2 and 3.

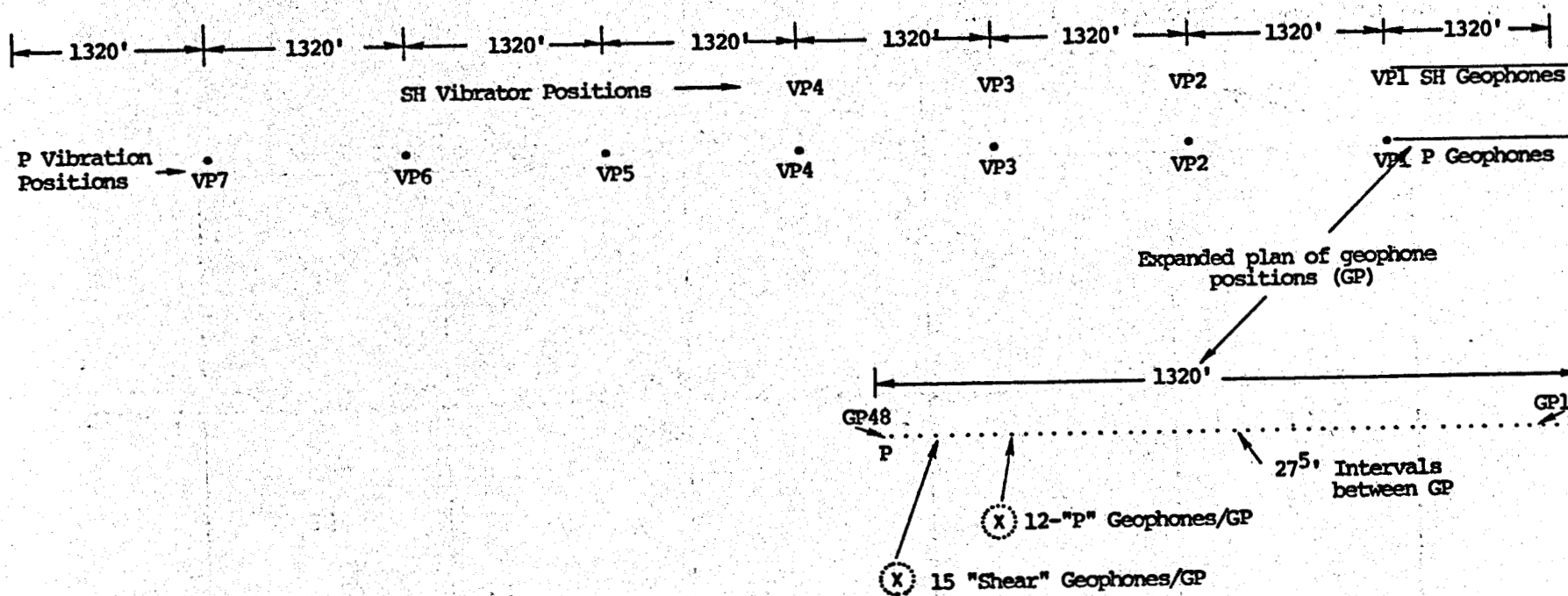


Figure 4. Configurations of P and SH Noise Test showing vibrator positions (VP), geophone positions (GP) and details of the geophone spread.

Figure 6 shows the result of the SH noise test. The expected SH reflection two-way travel time is from three to four seconds. Notice that for offset distance up to one (1) mile the interference from the strong SH refraction falls squarely in the middle of the spread. However because of the refractors low velocity (2500 ft/sec), this interference should be reduced by 220 feet of surface geophone coverage. Nevertheless, these noise tests indicate that we should expect more difficulty obtaining good SH reflections than P reflections.

The reflection P data was shot CDP 24-fold (see Figure 7) with a spacing of 110 feet using four vibrators transmitting 10 sweeps of 16 second duration extending from 56 Hz down to 10 Hz. There were two strings of twelve geophones at each nest, making 24 geophones per group extending over 220 feet. The geophone density in P was an average of one every 4.6 feet.

The reflection SH data was shot CDP 20-fold with the same spacing of 110 feet using the two Conoco SH-vibrators transmitting 20 sweeps of 16 second duration extending from 28 Hz down to 5 Hz. Each nest had four strings of 15 SH-geophones each covering the 220 feet. With the 100 percent overlap, the average SH-geophone density was one every 1.86 feet. Figure 8 describes the vibrator and the geophone patterns used in the P and SH surveys.

In the P mode, the spread extended from 660 feet to 5,830 feet, while in the SH mode it extended from 600 feet to 4,950 feet. Overall, seven days were devoted to the horizontal shear wave effort and six days to the compressional. Over 6.75 miles were surveyed in shear and 11.88 miles were surveyed in P, indicating a yield of nearly a mile/day in shear and nearly two in P, in spite of the very large effort being used.

1.0 Distance (miles) 0.5

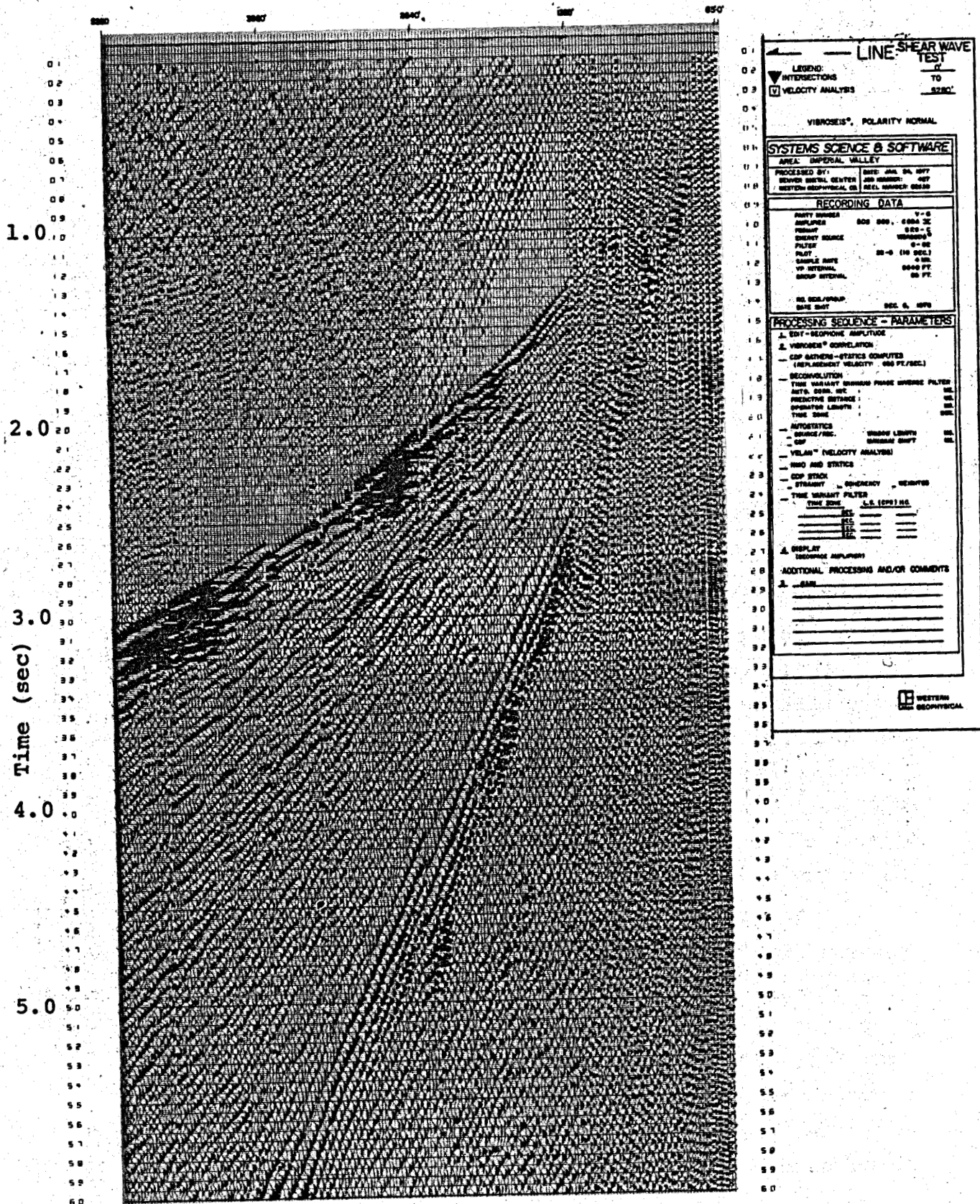


Figure 6. Results of the SH wave noise test. The first arrival is a refracted SH wave traveling across the spread with a velocity of 2500 ft/sec. The second distinct arrival has a velocity of 750 ft/sec and may be the direct SH wave.

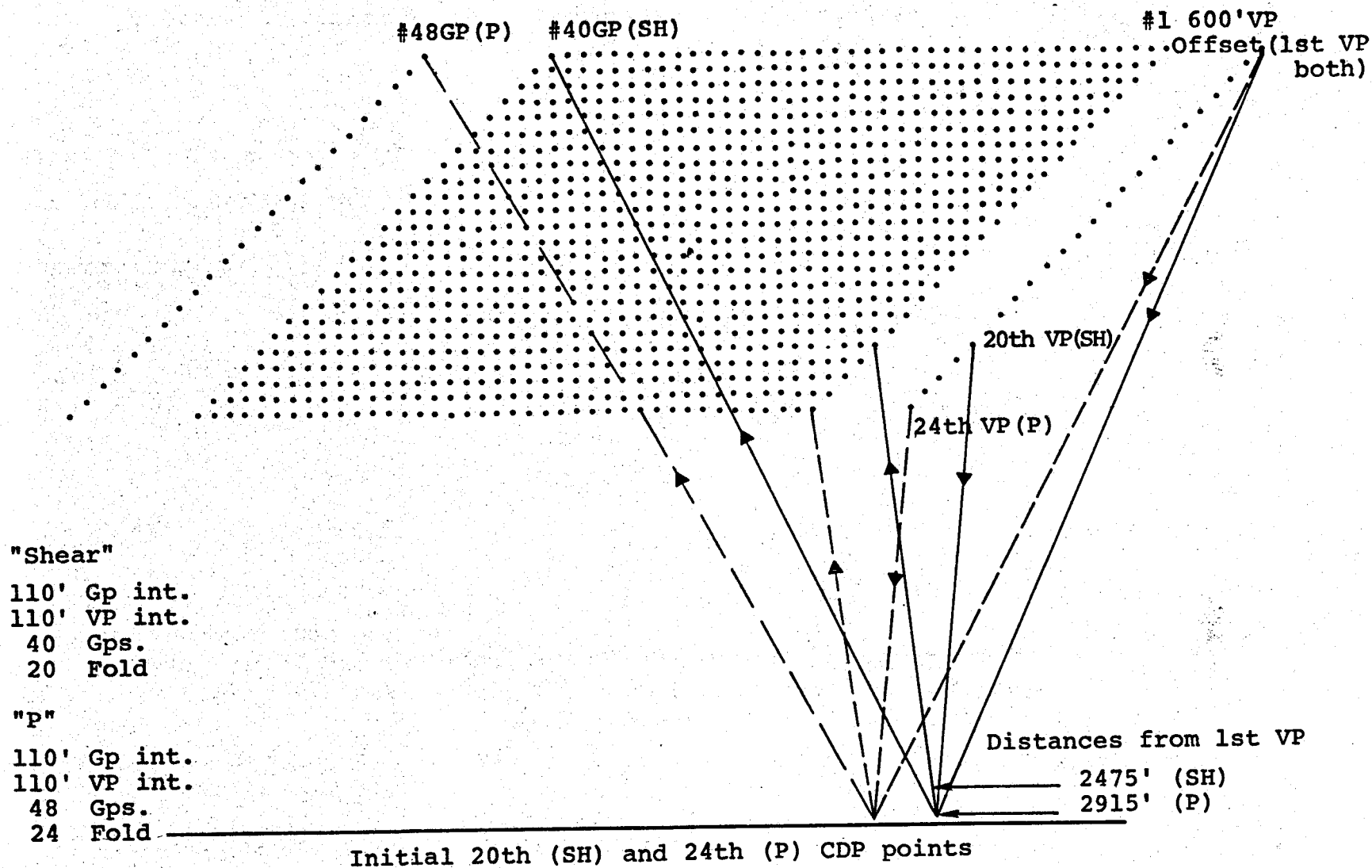
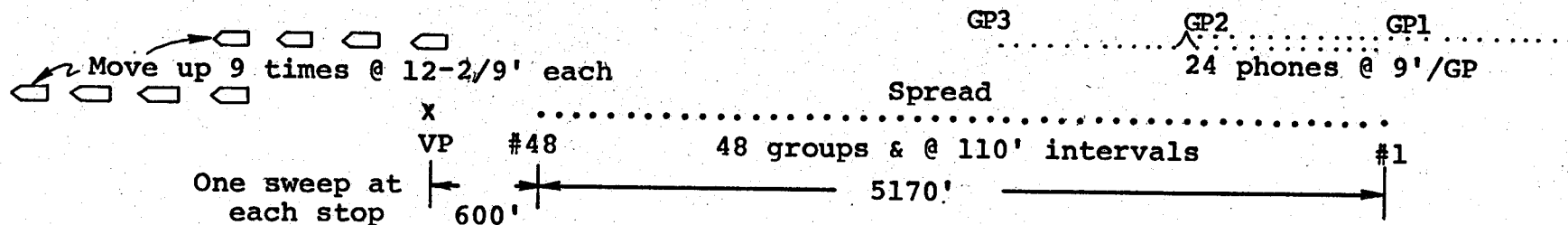


Figure 7. CDP diagram for P and SH reflection surveys. The P reflections at the 1st and 24th VP are dashed. The SH reflections at the 1st and 20th VP are solid.

"P"

P Vibrator Pattern:



"Shear"

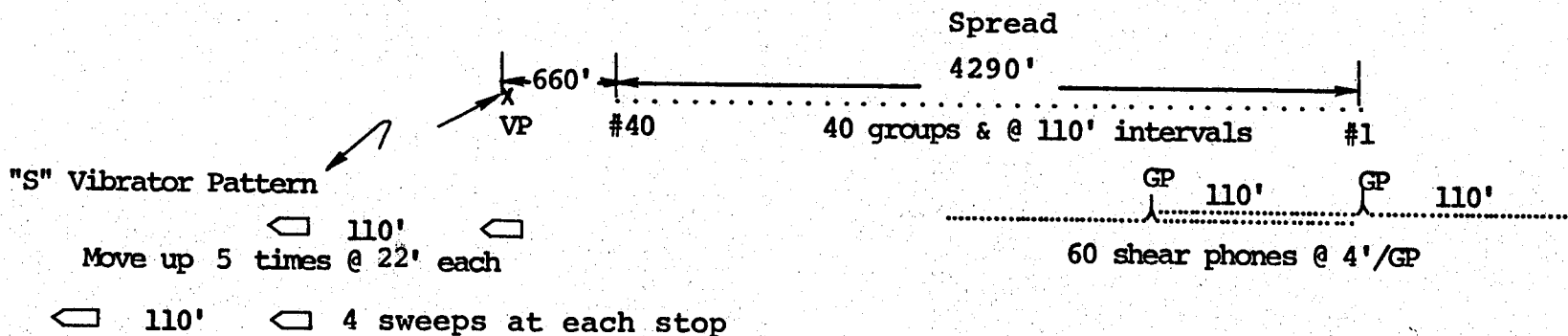


Figure 8. Vibrators and geophone group patterns used in the P and the SH reflection surveys.

It is important to note at this point the difference in effort between the P and the SH work. The P-work had the advantage of using four simultaneous vibrators and of using enough geophones to obtain the full 24-fold. In the SH-case, there were only two vibrators and the number of geophone strings available restricted the folding to 20 for maintaining an acceptable efficiency. This difference in effort may explain a large part of the quality contrast between the two sections.

All the data was recorded by Western Geophysical Company on a 48-channel DDS-COBA II recording system, including a Schmidt 48-channel correlator providing the field monitoring necessary for quality control. All the individual VP's were diversity summed during acquisition, then correlated and displayed on a paper record. Diversity summing is a scheme through which traces are weighted according to their power or signal/noise ratio and then summed.

The data was recorded digitally on 1600 BPI tapes which were sent to the Western Geophysical office in Denver, Colorado for processing. Attempts at obtaining preliminary straight stack results of the SH data before final completion of the work were unsuccessful, primarily because of airline freight transfer problems. Accordingly, the entire data acquisition was conducted without the benefit of having a chance to remedy a poor choice of shooting parameters. The results indicate that the original choice was proper.

The data was processed as described below.

1. Editing, demultiplexing and amplitude restoration.
2. Correlation with sweep reference signal.
3. Preprocessing and deconvolution: common depth grouping and deconvolution with a 144 ms operator with predictive distance of 69 ms used for the SH data, and correspondingly 132 ms with predictive distance of 32 ms with P. Geometrical spreading compensation and trace power balancing.

4. Automatic static correction with MISER (Modular Iterative Static Evaluation Routine).
5. Velocity analysis using groups of six common depth families.
6. Using the velocities, correct for NMO and stack the CDP producing equalized stacked sections (Figures 9 through 13).
7. The three P lines were processed with RAP (Relative Amplitude Processing) to get true amplitude sections (Figures 14 through 19).
8. The three P lines were migrated to check on diffraction effects, using the finite difference wave migration method (Figures 20 through 22).

At this stage, the poor quality of the SH data indicated that the big problem was that of determining a good estimate of the shear velocities. Only a few of the SH velocity determinations gave unambiguous information and the two sections stacked with the VELAN derived velocities were extremely poor, Line 2 displaying a slight advantage. (VELAN is Western Geophysical Company's trademark for their velocity analysis program.)

Concentrating then on Line 2, a guide SH velocity function (see Figure 23) was produced using the few good VELAN available and combining the P velocity knowledge with reasonable estimates of the V_p/V_s ratio. Using this velocity, an improved stacked section of Line 2 emerged (see Figure 24) and a corresponding depth section (see Figure 25) displayed clear improvements when compared to the depth section obtained with the VELAN velocities (see Figure 26).

Encouraged by this development, an attempt was made to reinterpret the poor VELANS with the guide velocity to produce still another depth section of Line 2 which again showed definite improvements (see Figures 27 and 28). This depth section was produced with both polarities for comparison with the P depth section.

West

1.0

2.0

Time

Figure 11. Line 3P - Straight Stack.

W—LINE: 3P

LEVEL: VP 8
INTERSECTIONS: VP 70
VELOCITY ANALYSIS: VP 80
SHELL FLOOR: SEA LEVEL
8400% VIBROSEIS, POLARITY NORMAL

SYSTEMS SCIENCE & SOFTWARE
AREA: SPERIAL VALLEY
PROCESSED BY: DATE: JAN 04, 1977
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SEVEN GUYOT CENTER

RECORDING DATA

PORT NUMBER: 000 000, 4 000 00
AMPLIFIER: 000 000, 4 000 00
RECORD: 000 000, 4 000 00
RECORD NUMBER: 000 000, 4 000 00
FILTER: 00 10 00 00 00
PULSE: 00 10 00 00 00
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PROCESSING SEQUENCE - PARAMETERS

1. GUY - RESPONSE AMPLIFIER
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ADDITIONAL PROCESSING AND/OR COMMENTS

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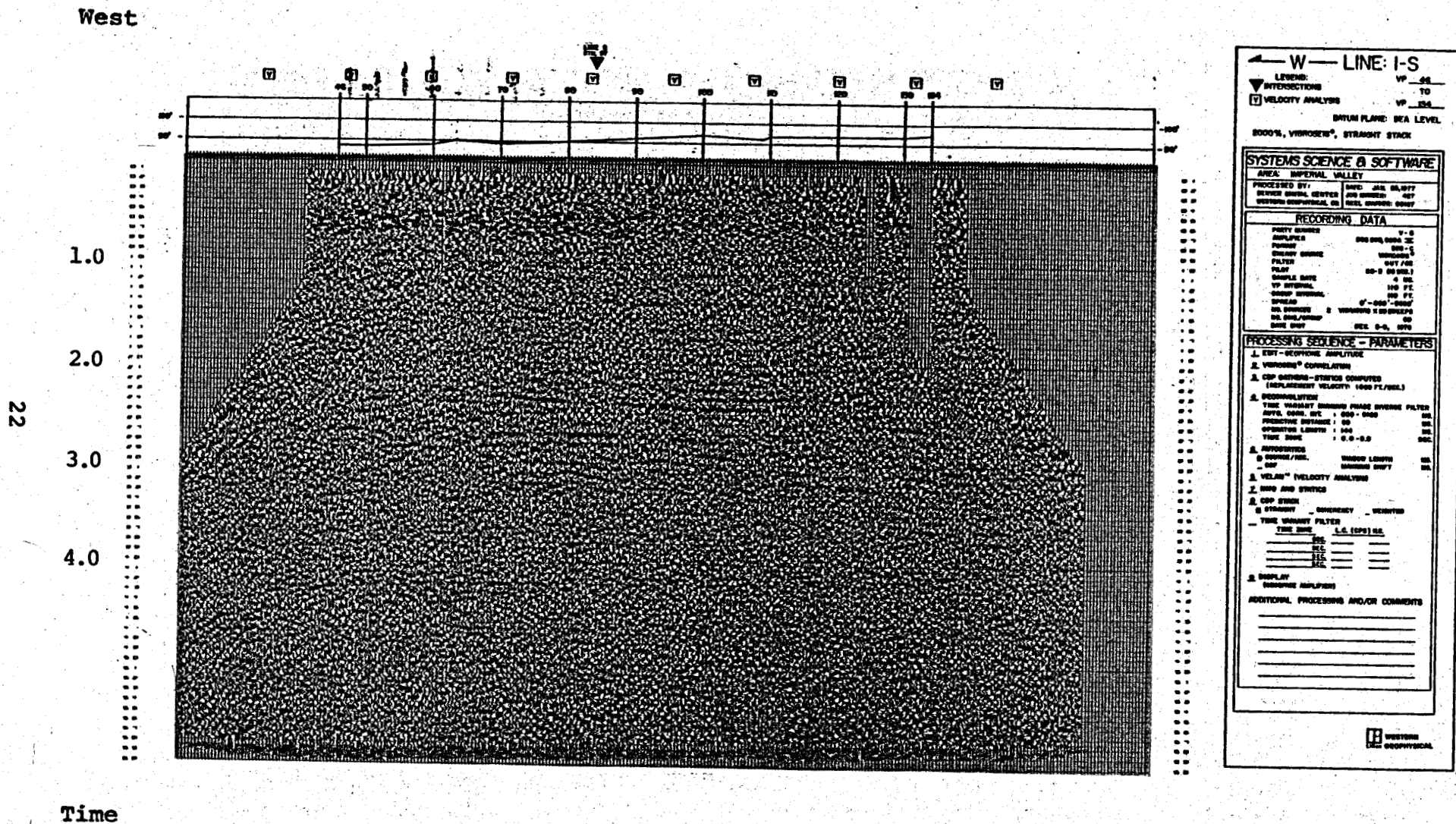


Figure 12. Line 1S - Straight Stack.

23



Figure 13. Line 2S - Straight Stack.

24



Figure 14. Line 1P, RAP Section, polarity normal.

RAP

SECTION

← W —

LEADS

☒ INTERROCTIONS

☒ VELOCITY ANALYSIS

LINE: IP

WP _____

TO _____

SPRINT PLANE: SEA LEVEL

2400'S, VIBROSON'S, POLARITY REVERSED

SYSTEMS SCIENCE & SOFTWARE

AREA: SAFETY, VALLEY

PROJECTED BY: _____

DESIGNED BY: _____

DESIGNED BY: _____

INFO PER: 8-1077

AND REVISION: 001

DATE: 0000-0000

RECORDING DATA

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SAMPLED	000 000, 0000 000
TIME	000-00
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PLATE	U.S. 600' V 60-60
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DEPTH NUMBER	00 00
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NO. SILENCE	00
DATE END	000-10-00 0000

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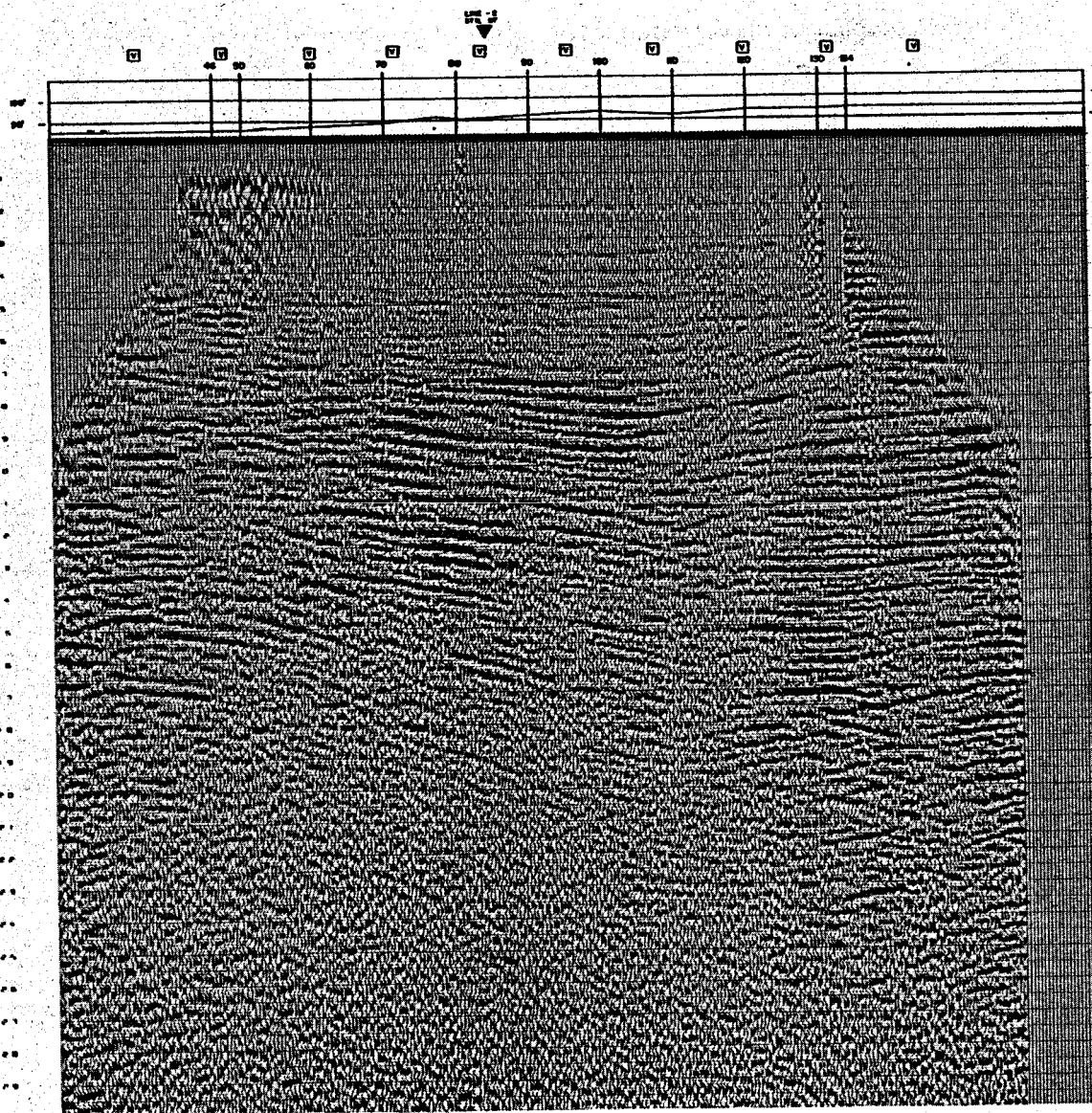


Figure 15. Line 1P, RAP Section, polarity reversed.

RAP SECTION

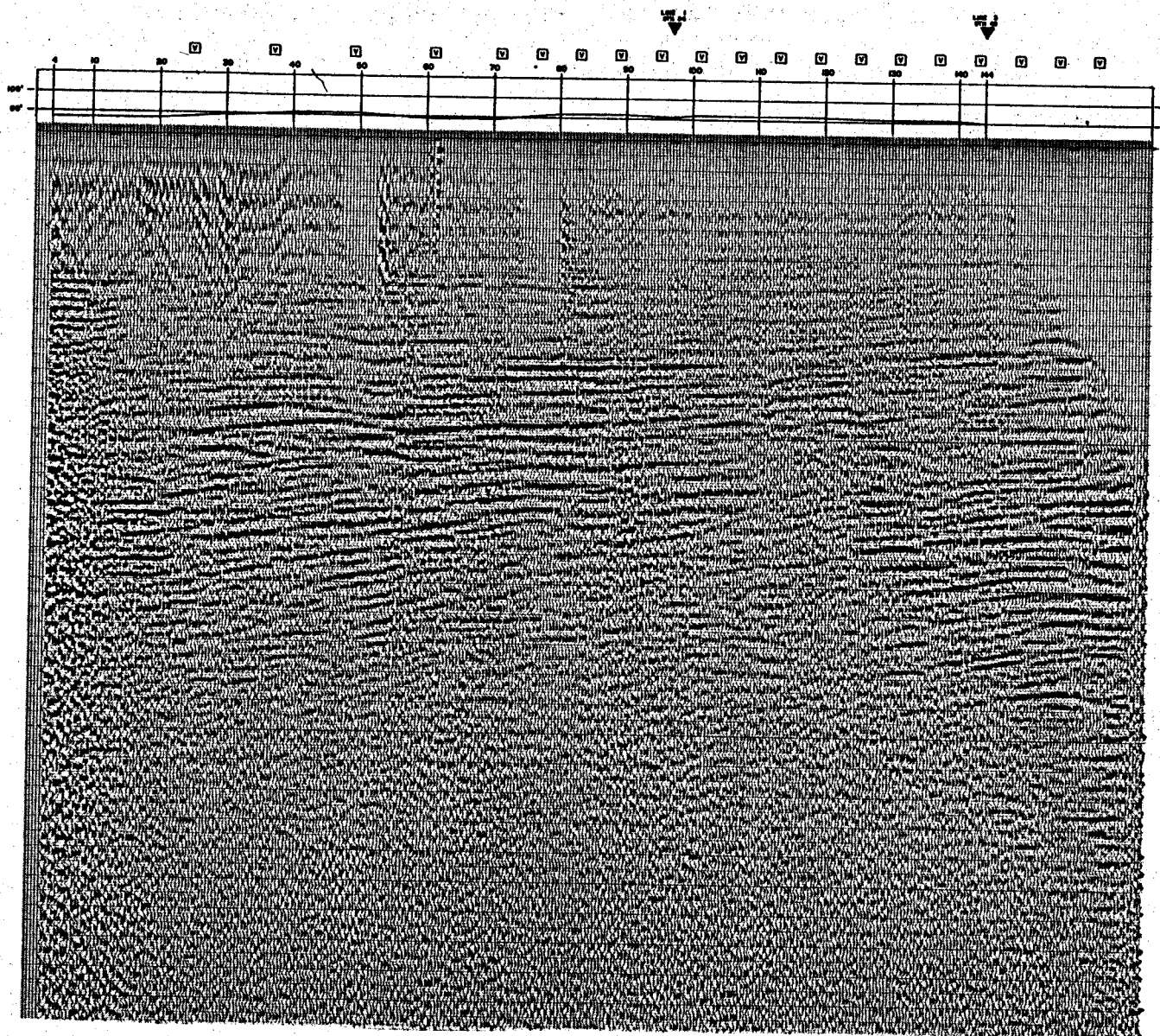
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Figure 16. Line 2P, RAP Section, polarity normal.

South

RAP
SECTION

S — LINE: 2P

LEADER: VP 1

INTERSECTIONS: VP 144

VELOCITY ANALYSIS: VP 144

DATA PLANE: SEA LEVEL

2400'S, VIBROSEIS*, POLARITY REVERSED

SYSTEMS SCIENCE & SOFTWARE

AREA: IMPERIAL VALLEY

PROJECTED BY: J. L. L. 10/10/80
 REVIEWED BY: J. L. L. 10/10/80
 DESIGNED BY: J. L. L. 10/10/80

RECORDING DATA

PORTY GEODES: 0-5
 INFLUENCE: 0-5
 POWER: 0-5
 PLANT: 0-5
 FILTERS: 0-5
 SAMPLE RATE: 0-5
 VP: 0-5
 SPREAD: 0-5
 NO. STATIONS: 0-5
 NO. STATIONS: 0-5
 DATE: 0-5

PROCESSING SEQUENCE - PARAMETERS

1. DATA - VIBROSEIS
 2. VIBROSEIS* CORRELATION
 3. CIP: GATHERING - STATION CORRELATION
 (LOCALIZATION VELOCITY: 0-5 FT/SEC.)

4. DECONVOLUTION
 TIME: 0-5
 AUTO. GAIN: 0-5
 OPERATING LENGTH: 0-5
 TIME: 0-5

5. FILTERING
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ADDITIONAL PROCESSING AND/OR COMMENTS

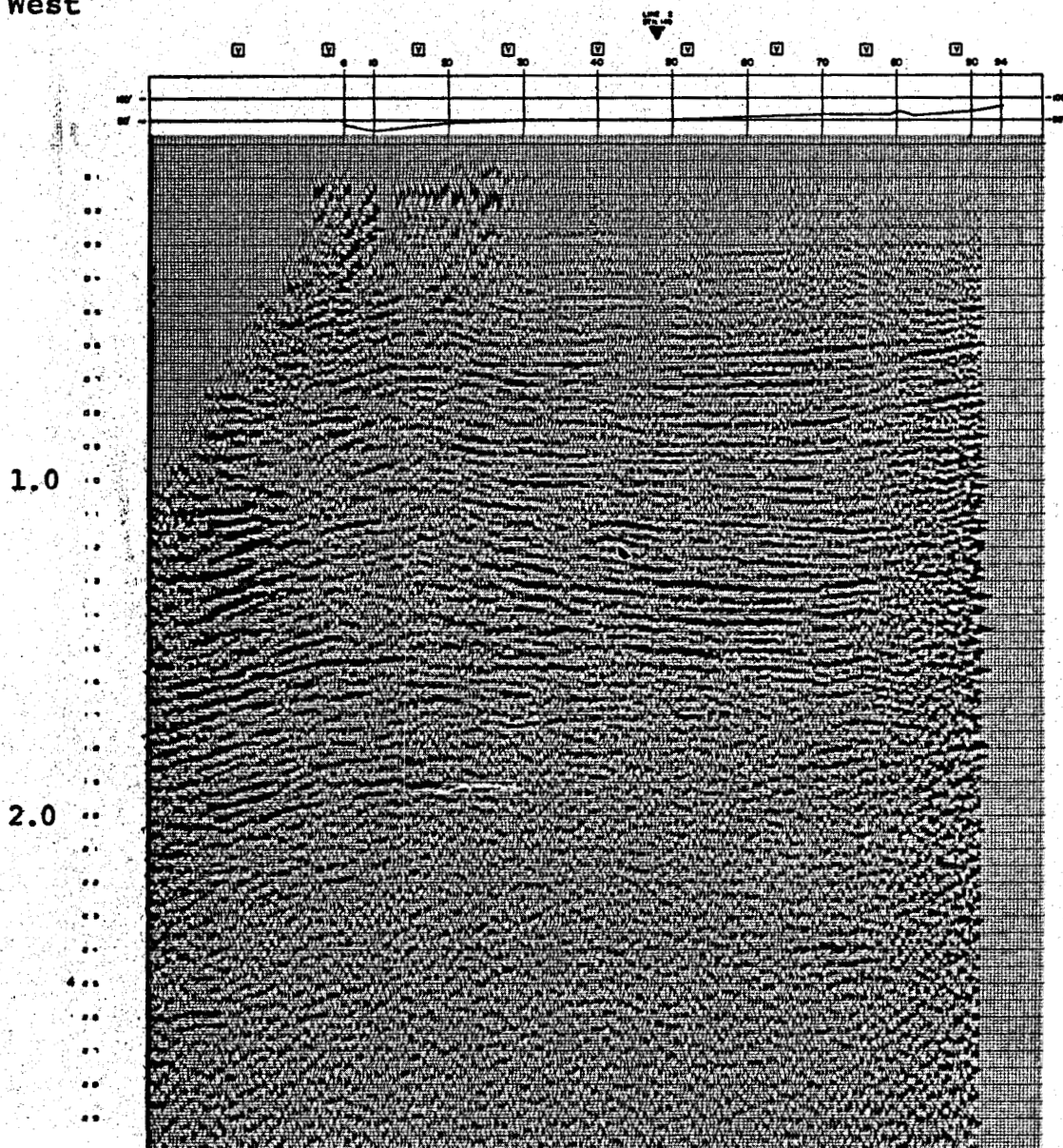
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Figure 17. Line 2P, RAP Section, polarity reversed.

W — LINE: 3P
LANDING:
INTERSECTIONS: WP **TO**
V VELOCITY ANALYSIS WP **SE**
SETUP PLANE: SEA LEVEL
8400'S, VIBROSEIS®, POLARITY REVERSED

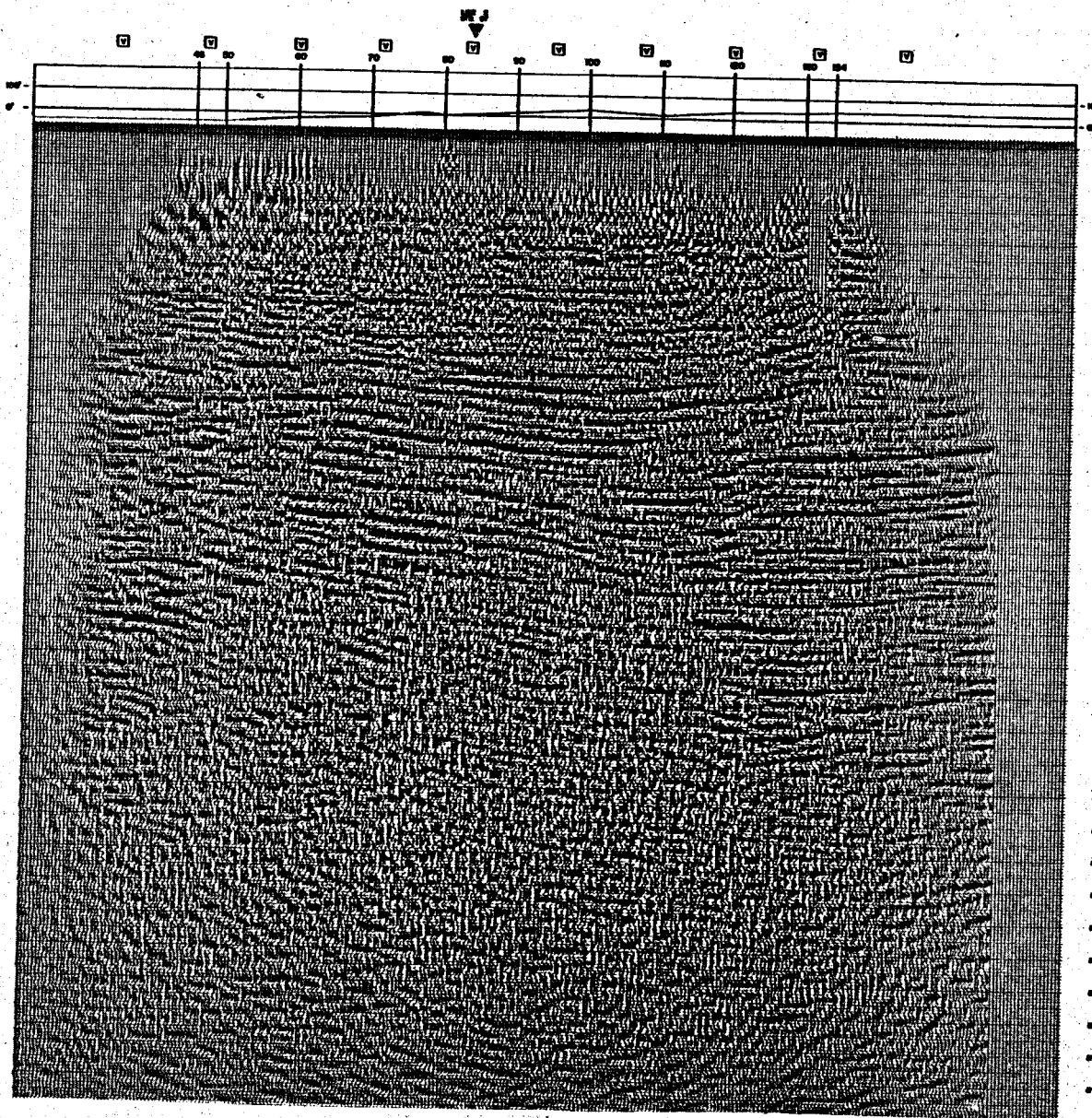
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29

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Time



← **W** — **LINE: IP**

LEVELS: VP 01
INTERSECTIONS: TO
☒ **VELOCITY ANALYSIS:** VP 01A

DATA PLAN: SEA LEVEL

2000%, VIRROSEN®, IMPIRATION

SYSTEMS SCIENCE & SOFTWARE

LOCAL REGIONAL VALLEY

PROCESSOR: **DATA:** JAN 10, 1977
 SERVER: **DATA CENTER** JAN 10/1977
 LOCATION: **INTERSECTION, 02** NCA, NUMBER: 00000

RECORDING DATA

PORTY BRANCH	V-0
ANALYSIS	000 000, 000000
NUMBER	010-0
BRANCH NUMBER	00000
FILTER	L.A. 0007 / R.S. 00
PLAN	20-10 00 0001
SCALE NAME	4 00
VP INTERNAL	110 FC
ORBIT	110 FC
ORBIT	0' 000 - 0000
ORBIT	VIRROSEN 2 00 00000
ORBIT	00000 2 00 00000
DATE	000 000 - 000

PROCESSING SEQUENCE - PARAMETERS

1. EDIT - SCOPING AMPLITUDE
2. VIRROSEN® CORRELATION
3. ORBIT - STATUS COMPUTED
 (COLLECTIVE VELOCITY TYPE FC/MS)
4. DECOMPOSITION
 TIME VELOCITY BRANCH PHASE INTERNAL FILTER
 DATA, 000, 000 - 000 - 000
 PASTING: 00000: 00
 BRANCH LENGTH: 0.0-0.0
 TIME 000
5. AMPLITUDE
 00000/MS.
 - 000
 BRANCH LENGTH
 BRANCH 000
6. VELAN™ VELOCITY ANALYSIS
7. INFO AND STATUS
8. ORBIT
 0 00000 - 00000 - 00000
9. TIME VELOCITY FILTER
 - TIME 000 L.A. 0001 00

10. DISPLAY
 (BRANCH ANALYSIS)

ADDITIONAL PROCESSING AND/OR COMMENTS

1. JOURNAL

18 SYSTEMS SCIENCE & SOFTWARE

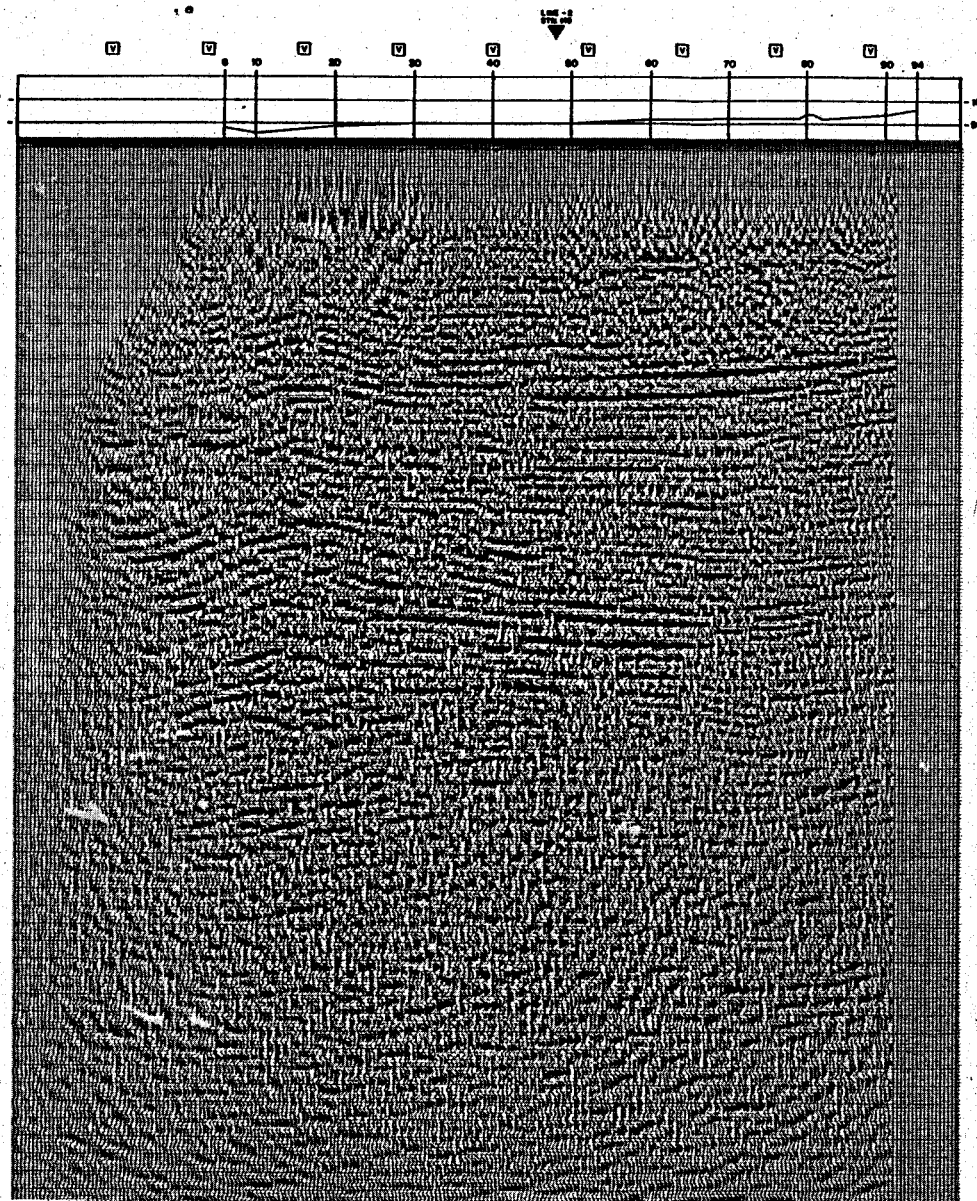
Figure 20. Line 1P, migrated section.

West

1.0

2.0

Time



W LINE: 3P

LENS: VP 8

INTERSECTIONS TO 10

VELOCITY ANALYSIS VP 24

DRUM FLAME: SEA LEVEL

2400% VELOCITY, IMMEDIATE

SYSTEMS SCIENCE & SOFTWARE

AREA: IMPERIAL VALLEY

PROCESSED BY: DATE: JAN 18, 1977

SEVEN DIGITAL CENTER AND FORMER: 007

SEVEN COMPUTERS, 60 KILL, 0000000000

RECORDING DATA

PORT NUMBER V-0

AMPLIFIER 000 000 0000 20

PHASE 00-1

DELAY SOURCE 00000

FLUX LA OFF / ALG 00

FLUX 00 - 00 00 00

SAMPLE RATE 4 00

VP SIGNAL 00 00

GROUP INTERVAL 00 00

WELL 00 - 00 00 00

NO. SOURCES 4 VELOCITY 0 00 0000

NO. SEGMENTS 00

DATE TIME 00 00-00 0000

PROCESSING SEQUENCE - PARAMETERS

1. CDP - GEOPHYSICAL AMPLIFIER

2. VELOCITY CORRELATION

3. CDP GATHERING - STEREO COMPUTER

(REPLACEMENT VELOCITY 0700 FT/SEC)

4. DECONVOLUTION

THE VARIANT SOURCE PHASE SOURCE FILTER

AUTO CORR. WFL 000 - 0000

RECURSIVE SOURCE 00

OPERATION LENGTH 100

TIME DUE 0.0 - 0.0

5. AUTOMATED

6. SOURCE / WFL

7. WFL

8. VELAN VELOCITY ANALYSIS

9. WFL AND STEREO

10. CDP STEREO

11. STEREO - WFL

12. VELOCITY FILTER

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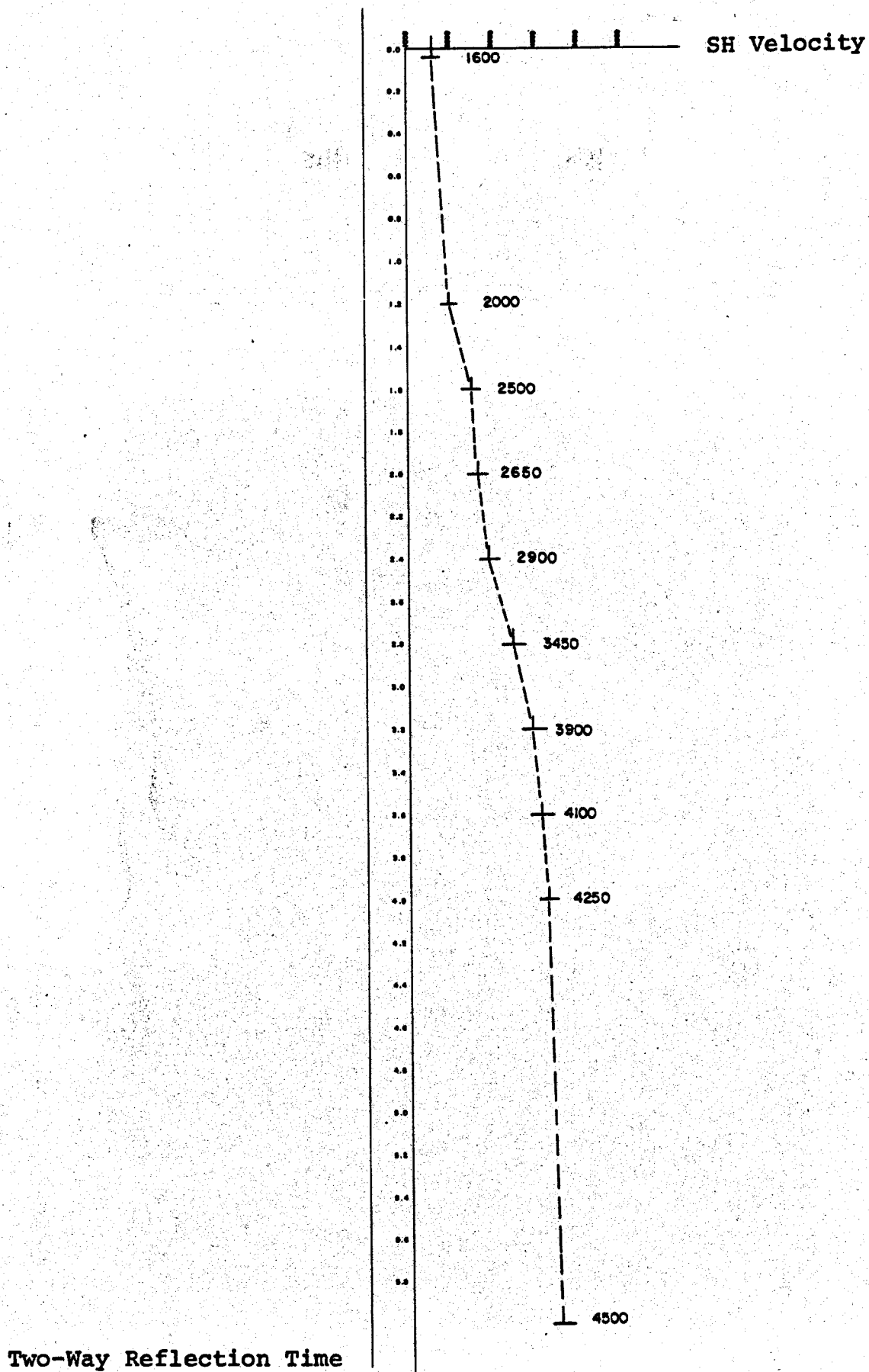
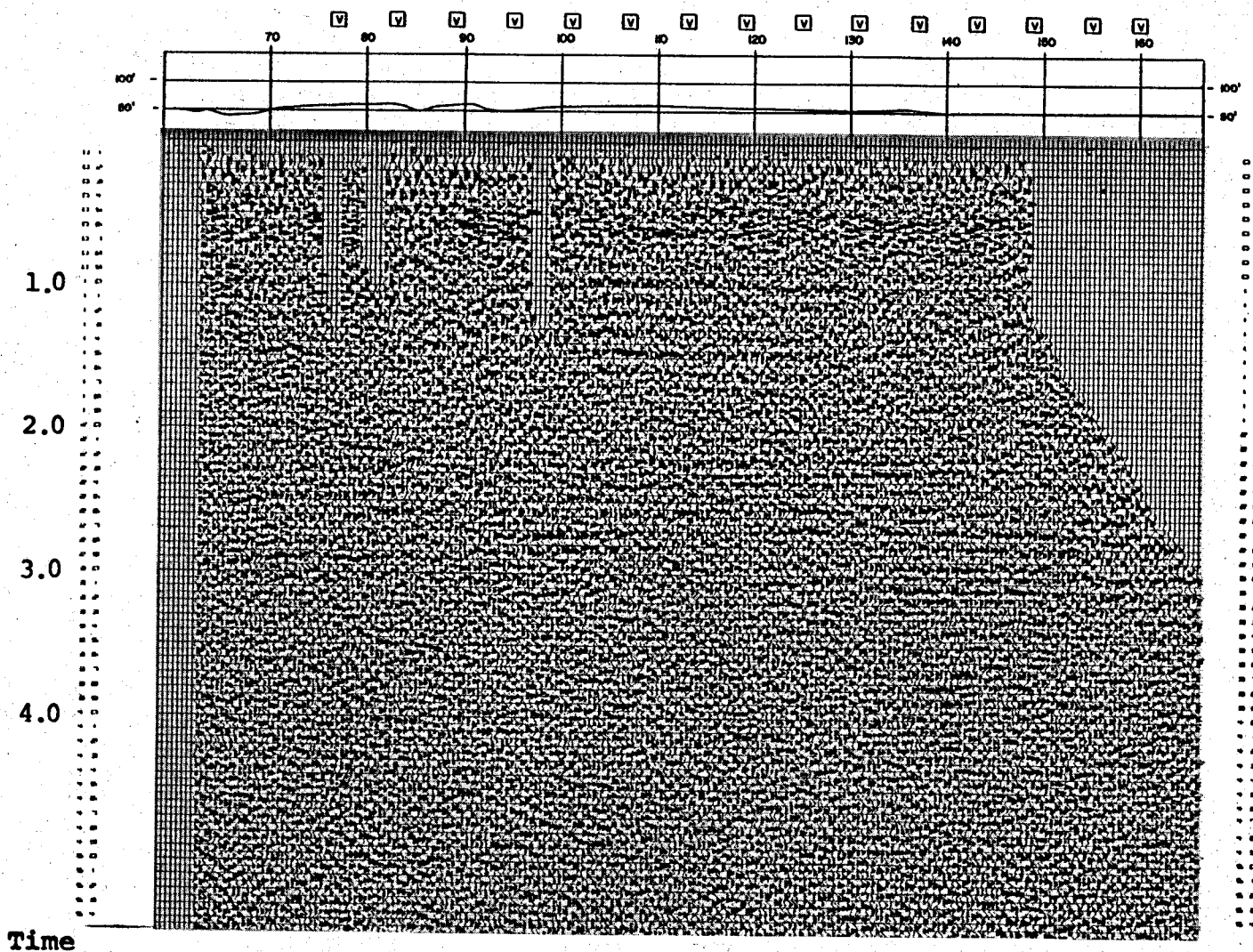


Figure 23. Guide SH velocity (suggested).

South



← S — LINE: 2S

LEGEND: VP 70
 INTERSECTIONS TO
 VELOCITY ANALYSIS VP 160

DATUM PLANE: SEA LEVEL
 2000%, VIBROSEIS®, POLARITY NORMAL

SYSTEMS SCIENCE & SOFTWARE
 AREA: IMPERIAL VALLEY

PROCESSED BY: DEWEY JARVIS CENTER DATE: JAN. 24, 1977
 WESTERN GEOPHYSICAL CO. JOB NUMBER: 427
 REEL NUMBER: 00411

RECORDING DATA

PARTY NUMBER V-2
 AMPLIFIER 993 999, CORA 33
 FORMAT 888 - C
 ENERGY SOURCE VIBROSEIS®
 FILTER 007 / 02
 PLOT 20-5 (16 SEC.)
 SAMPLE RATE 4 MS.
 VP INTERVAL 110 FT.
 GROUP INTERVAL 110 FT.
 SPREAD 0'-200'-200'
 NO. SOURCES 2 VIBRATORS X 20WHEELPS
 NO. REEL/GROUP 60
 DATE SHOT DEC. 9-11, 1976

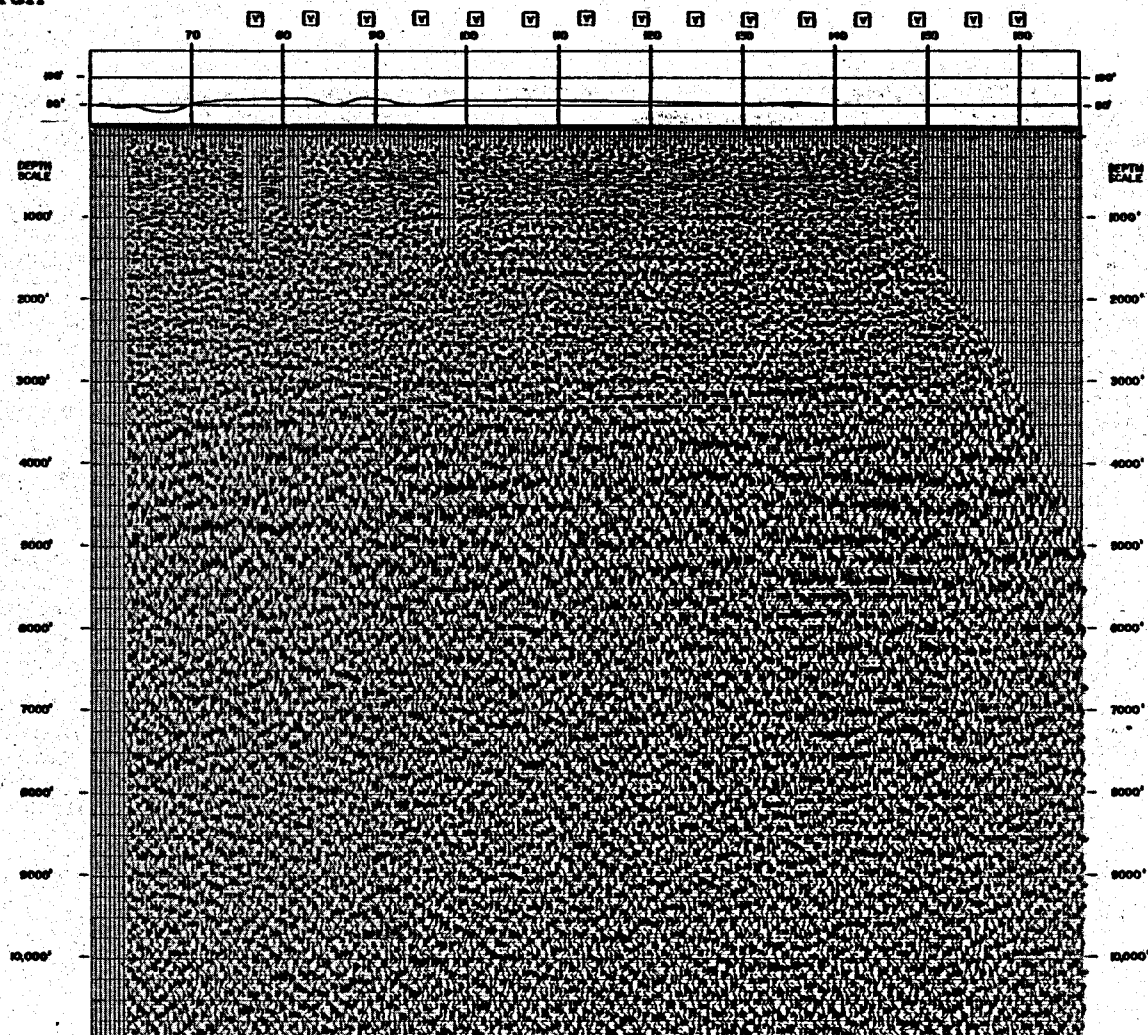
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1. EDIT - GEOPHONE AMPLITUDE
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 3. CDP GATHERS - STATICS COMPUTED
 (REPLACEMENT VELOCITY: 1600 FT./SEC.)
 4. DECONVOLUTION
 TIME VARIANT MINIMUM PHASE INVERSE FILTER
 AUTO. CORR. INT. 600-2000 MS.
 PREDICTIVE DISTANCE: 60 MS.
 OPERATOR LENGTH: 144 MS.
 TIME ZONE: 0.0-6.0 SEC.
 5. AUTOSTATICS
 SOURCE/REC. WINDOW LENGTH MS.
 CDP MAXIMUM SHIFT MS.
 6. VELAN™ (VELOCITY ANALYSIS)
 7. NMO AND STATICS
 8. CDP STACK
 STRAIGHT COHERENCY WEIGHTED
 TIME VARIANT FILTER
 TIME ZONE L.C. (CPS) H.C.
 SEC. _____
 SEC. _____
 SEC. _____
 SEC. _____
 9. DISPLAY
 (GEOSPACE AMPLIFIER)
 ADDITIONAL PROCESSING AND/OR COMMENTS
 STACKED WITH CLIENT PICKED
 VELOCITIES

WESTERN
 GEOPHYSICAL

Figure 24. Line 2S, section stacked with guide SH velocity.

South



Time

— S — LINE: 2S

LEGEND: VP TO TO
 INTERSECTIONS TO
 VELOCITY ANALYSIS VP 150

DATUM PLANE: SEA LEVEL

2000%, VIBROSEIS®, DEPTH SECTION

SYSTEMS SCIENCE & SOFTWARE

AREA: IMPERIAL VALLEY

PROCESSED BY: DATE: JAN 04, 1977
 DENVER DIGITAL CENTER JOB NUMBER: 007
 WESTERN GEOPHYSICAL CO. WELL NUMBER: 00001

RECORDING DATA

PARTY NUMBER V-0
 AMPLIFIER 000 000, 0000 0
 FORMAT SEC. 0
 ENERGY SOURCE VIBROSEIS®
 FILTER 007 / 000
 PLOT 00-0 (10 SEC)
 SAMPLE RATE 4 SEC
 VP INTERVAL 100 FT
 GROUP INTERVAL 100 FT
 OFFICIAL 0'-000'-0000
 NO. CHANNELS 2 VIBROSEIS 2.00 CHANNELS
 NO. VIBROSEIS/CH 00
 DATE SHOT SEC. 0-11, 1975

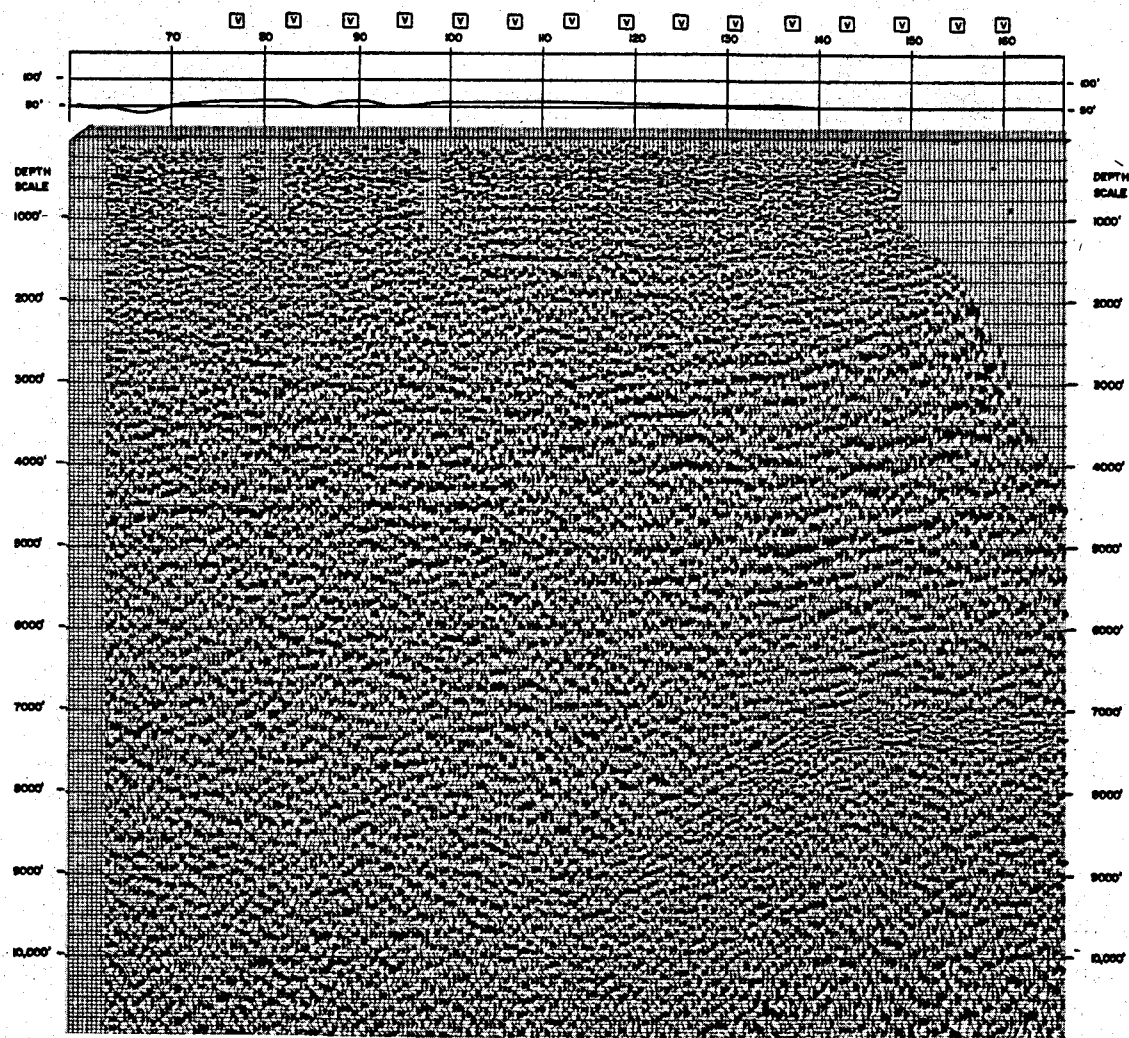
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 2. VIBROSEIS® CORRELATION
 3. CDP GATHERS - STATICS COMPUTED
 (REPLACEMENT VELOCITY: 1600 FT/SEC.)
 4. DECONVOLUTION
 TIME VARIANT WIDENING PHASE INVERSE FILTER
 AUTO. CORR. MET. : 000 - 0000
 PREVENTIVE DISTANCE: 00
 OPERATOR LENGTH: 100
 TIME ZONE: 0.0 - 0.0
 5. ALPHABETICS
 6. SOURCE/RECE. WIDEN LENGTH
 - CDP MAXIMUM SHIFT: 00
 7. VELAN™ (VELOCITY ANALYSIS)
 8. NMO AND STATICS
 9. CDP STACK
 10. STRAIGHT - CORRECTION - WEIGHTS
 - TIME VARIANT FILTER
 TIME ZONE: 1.0 (SPS) SEC.
 SEC. SEC. SEC.
 10. DISPLAY
 (GEOPHONIC AMPLIFIER)
 ADDITIONAL PROCESSING AND/OR COMMENTS
 a. DEPTH CONVERSION
 CONVERTED FROM CLIENT
 PICKED VELOCITIES

WESTERN GEOPHYSICAL

Figure 25. Line 2S, depth section.

South



Time

S — LINE: 2S

LEGEND:
 ▽ INTERSECTIONS VP TO
 V VELOCITY ANALYSIS VP TO

DATUM PLANE: SEA LEVEL

2000% VIBROSEIS, DEPTH SECTION
 FOR REFERENCE ONLY

SYSTEMS SCIENCE & SOFTWARE

AREA: IMPERIAL VALLEY

PROCESSED BY: DATE: JAN. 24, 1977
 SENIOR DATA CENTER JOB NUMBER: 407
 SYSTEMS GEOPHYSICAL CO. REEL NUMBER:

RECORDING DATA

PARTY NUMBER V-0
 AMPLIFIER 00000, C004 2C
 PUMPT 000-C
 ENERGY SOURCE VIBROSEIS
 FILTER OUT / IN
 PLOT 00-0 (0 SEC.)
 SAMPLE RATE 1 SEC.
 VP INTERNAL 10 FT.
 GROUP INTERNAL 10 FT.
 SPREAD 0' - 000' - 000'
 NO. CHANNELS 2 VIBROSEIS 2 DOCKERS
 NO. REEL/REEL 00
 DATE SHOT JAN. 9-11, 1976

PROCESSING SEQUENCE - PARAMETERS

1. EDIT - SEISMOGRAPH AMPLITUDE
 2. VIBROSEIS CORRELATION
 3. CDP SATELITE - STATION COMPUTED
 (REPLACEMENT VELOCITY: 0700 FT./SEC.)

4. DECONVOLUTION
 TIME VARIANT MINIMUM PHASE INVERSE FILTER
 AUTO. CORR. WTC 000 - 0000 SEC.
 PHASE TIME DELAY: 00 SEC.
 OPERATOR LENGTH: 10-4 SEC.
 TIME ZONE: 0.0 - 0.0 SEC.

5. AUTOCORRELATION
 6. SOURCE / REC. GROUND LENGTH SEC.
 CDP GROUND DEPTH SEC.

7. VELAN (VELOCITY ANALYSIS)

8. WMO AND STATION

9. CDP STACK
 10. STRAIGHT SLOPEMENT WEIGHTED

11. TIME VARIANT FILTER
 TIME ZONE 1.0 (0.0) SEC.
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 SEC. SEC.
 SEC. SEC.

12. DISPLAY (REVERSE AMPLIFIER)

ADDITIONAL PROCESSING AND/OR COMMENTS

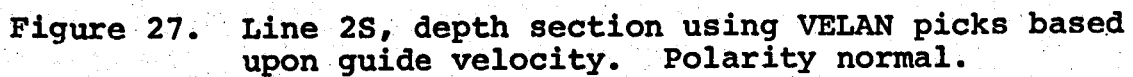
13. DEPTH CORRELATION (REMOVED)
 WITH VELAN PAVED VELOCITIES

14. VELOCITY ANALYSIS IS BLENDED

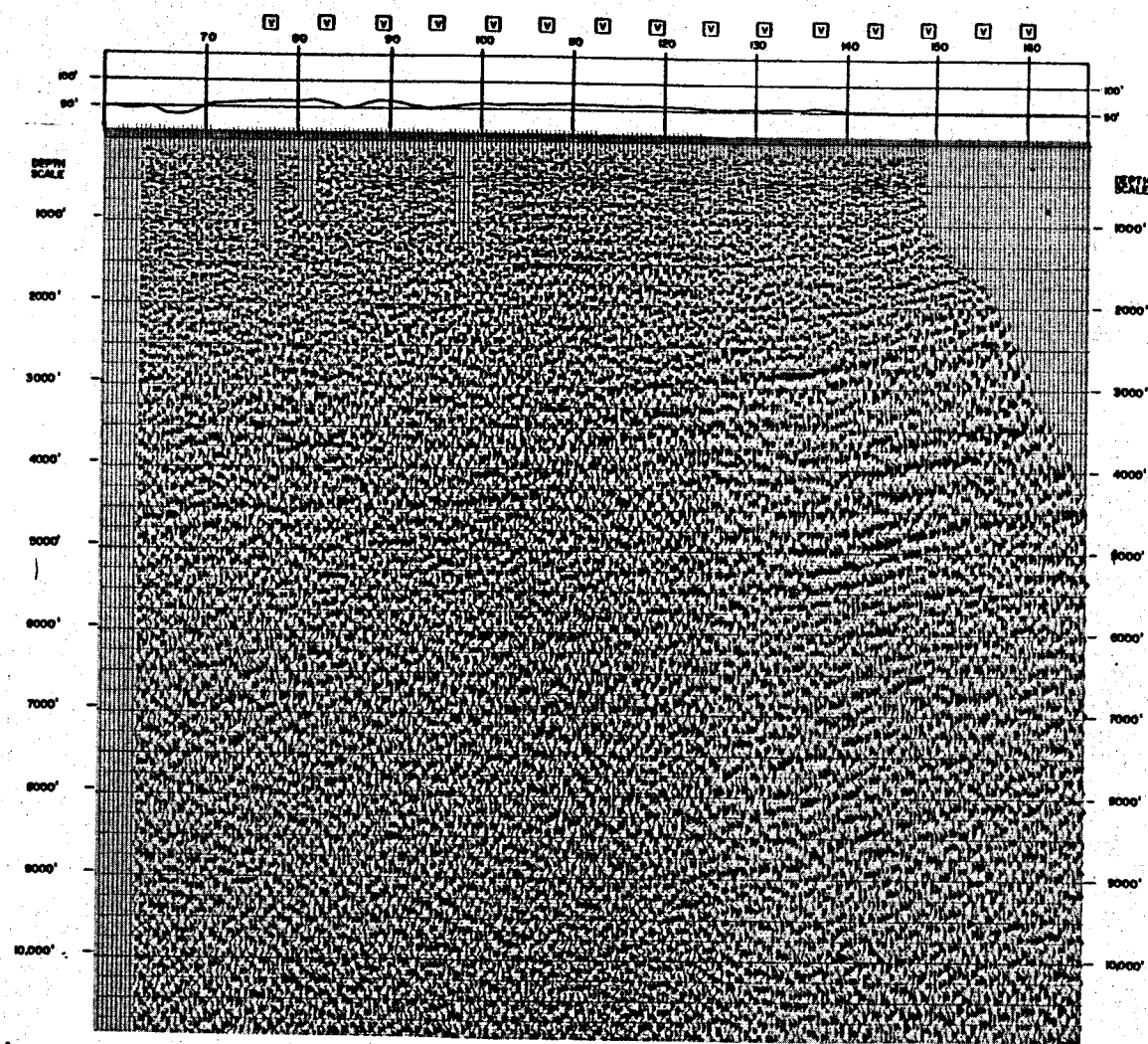
WESTERN
 GEOPHYSICAL

Figure 26. Line 2S, depth section using VELAN SH velocities.

37



South



Time

S — LINE: 2S

LEGEND:
 ▽ INTERSECTIONS VP TO
 □ VELOCITY ANALYSIS VP NO

DATUM PLANE: SEA LEVEL
 2000%, VIBROSEIS®, DEPTH SECTION
 POLARITY REVERSED

SYSTEMS SCIENCE & SOFTWARE

AREA: IMPERIAL VALLEY

PROCESSED BY: DATE: FEB. 10, 1977
 DENVER BRITL CENTER JOB NUMBER: 457
 WESTERN GEOPHYSICAL CO. REEL NUMBER: 16742

RECORDING DATA

PARTY NUMBER V-8
 AMPLIFIER 906 946, C08A 2C
 PUMPT 866-5
 ENERGY SOURCE VIBROSEIS
 FILTER OUT/IN
 PLST 20-0 04 SEC
 SAMPLE RATE 4 SEC
 VP INTERVAL 50 FT
 GROUP INTERVAL 10 FT
 SPREAD 0'-600'-900'
 NO. SOURCES 8 VIBROSEIS 25 SWEEPS
 NO. CHL/GROUP 60
 DATE SHOT DEC. 9-11, 1976

PROCESSING SEQUENCE - PARAMETERS

1. EDIT - GEOPHONE AMPLITUDE
 2. VIBROSEIS® CORRELATION
 3. CDP GATHERS - STATICS COMPUTED
 (HIGH-VELOCITY VELOCITY 1500 FT/SEC.)
 4. DECONVOLUTION
 TIME VARIANT INVERSE PHASE INVERSE FILTER
 AUTO. CORR. SEC 1.000 - 0.000
 PREDICTIVE DISTANCE: 00
 OPERATOR LENGTH: 100
 TIME ZONE 1 0.0 - 0.0
 5. AUTOSTATICS
 6. SOURCE/REC. VIBROSEIS LENGTH 00
 7. VELAN™ (VELOCITY ANALYSIS)
 8. NMO AND STATICS
 9. CDP STACK
 10. STRAIGHT COHERENCY WEIGHTED
 TIME VARIANT FILTER
 TIME ZONE L.C. (0.0) SEC
 SEC
 SEC
 SEC
 11. DISPLAY
 VIBROSEIS AMPLIFIER
 ADDITIONAL PROCESSING AND/OR COMMENTS
 12. DEPTH CONVERSION
 CONVERTED USING VELAN PICKED
 VELOCITIES BASED UPON CLIENT
 SPECIFICATION

WESTERN GEOPHYSICAL

Figure 28. Line 2S, depth section using VELAN picks based upon guide velocity. Polarity reversed.

Comparing the P and the SH depth sections, a high degree of resemblance becomes quite apparent, removing any doubt one may have whether the shear wave energy did penetrate down to the objective.

Both a P and an SH velocity profile along Line 2 were computed from the velocity information (see Figures 29 and 30). The P velocity information is quite accurate and reliable. Clearly, we cannot say the same for the SH. However, the major trends must contain valid information of possible lithological significance.

This completes the description of how the data was processed but we believe that still further improvements of the shear data is possible with a finer analysis of the shear velocities.

VELOCITIES FOR LINE 2P SSS

South

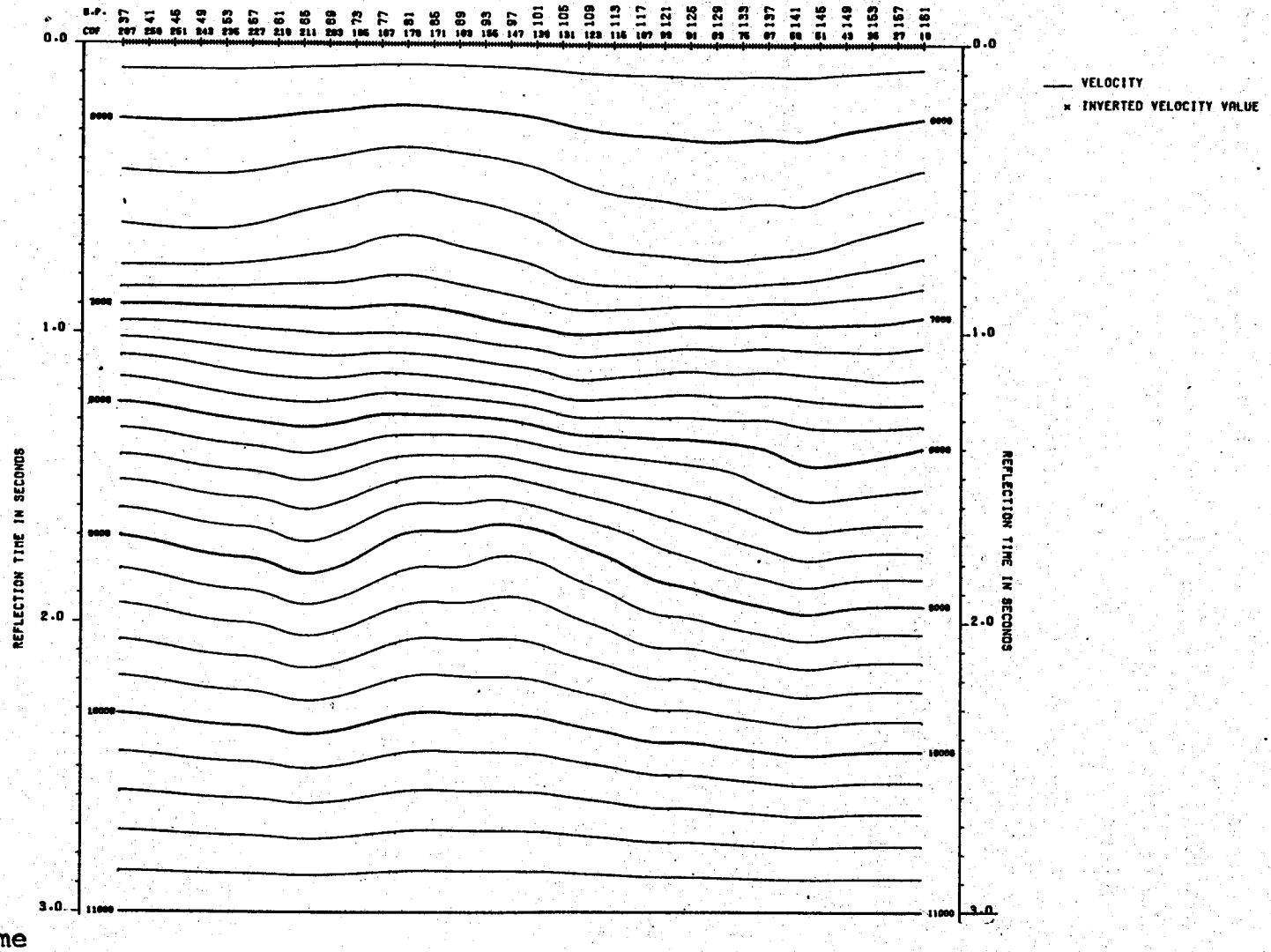


Figure 29. P velocity profile along Line 2P.

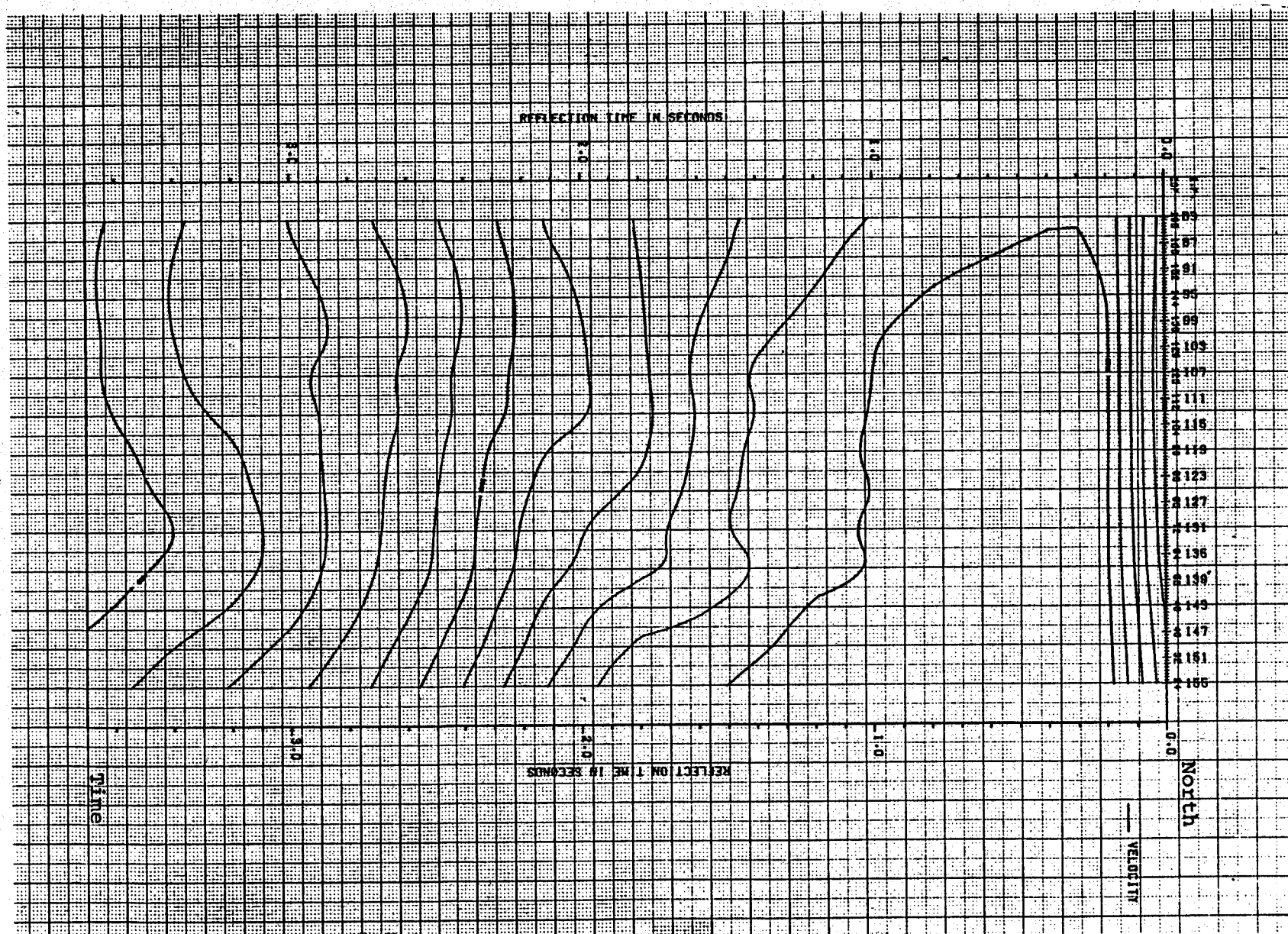


Figure 30. SH velocity profile along Line 2S.

IV. DATA INTERPRETATION

The objective of this project was to determine if state-of-the-art seismic reflection technology could locate the fault/fracture zones controlling the circulation of fluid in the East Mesa reservoir. Our interpretation of the data has been restricted to Line 2 (Figure 2). This line proved extremely interesting from the P data. Therefore it was the only line where both P and SH data has been completely processed. Consequently, this discussion relates only to that line and our conclusions are based only on this limited amount of data.

On the preliminary straight stack P section (see Figure 31) a zone about VP-90 to VP-120 displays a noticeable lack of coherency on Line 2. Upon RAP processing which preserves the real reflecting power of the various events, this anomalous zone became prominent in displaying an almost complete lack of reflectivity (see Figure 32). Its behavior at the shallow depth of about 3,000 feet displays the same lack of reflectivity shown by the rest of the line below 5,000 to 6,000 feet, the normal depth of the geothermal reservoir. Some diffraction draping visible at the end of some of the reflecting events suggests that this anomalous zone may be terminated rather abruptly by the presence of major fractures or faults. Overall, the evidence suggests that the entire zone may be a fracture zone where the absence of reflectivity is due to the scattering effect of the fractures. The presence of this fracture zone can also be detected on both the P and the SH depth sections (see Figures 33 and 34). The SH data, while poorer, supports the evidence produced by the P and strengthens its validity. However, these are not the only facts in favor of our hypothesis of the existence of a fracture zone.

This interpretation is also supported by the results of the velocity analysis conducted on Line 2-P between SP-89

△△

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Time

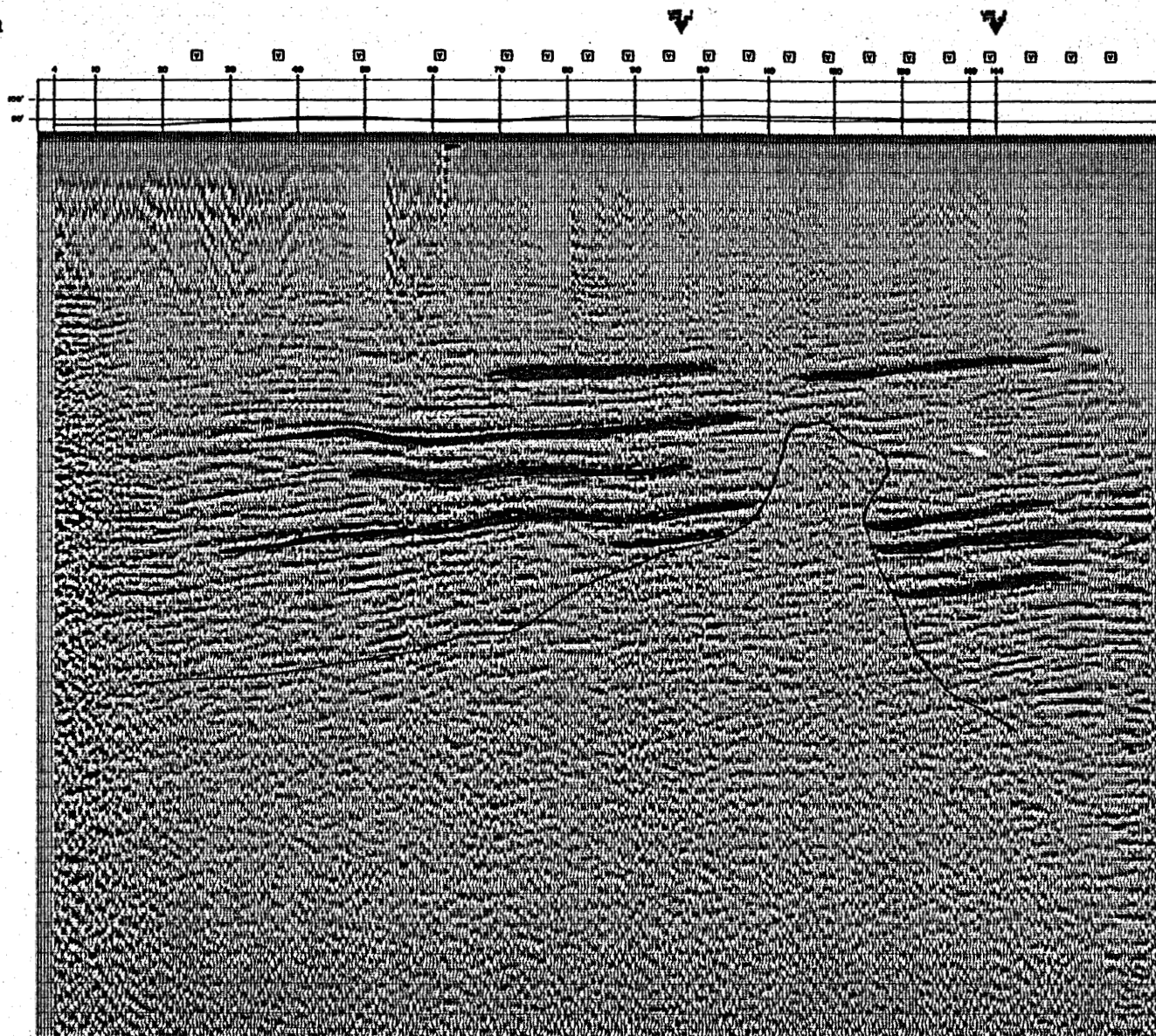
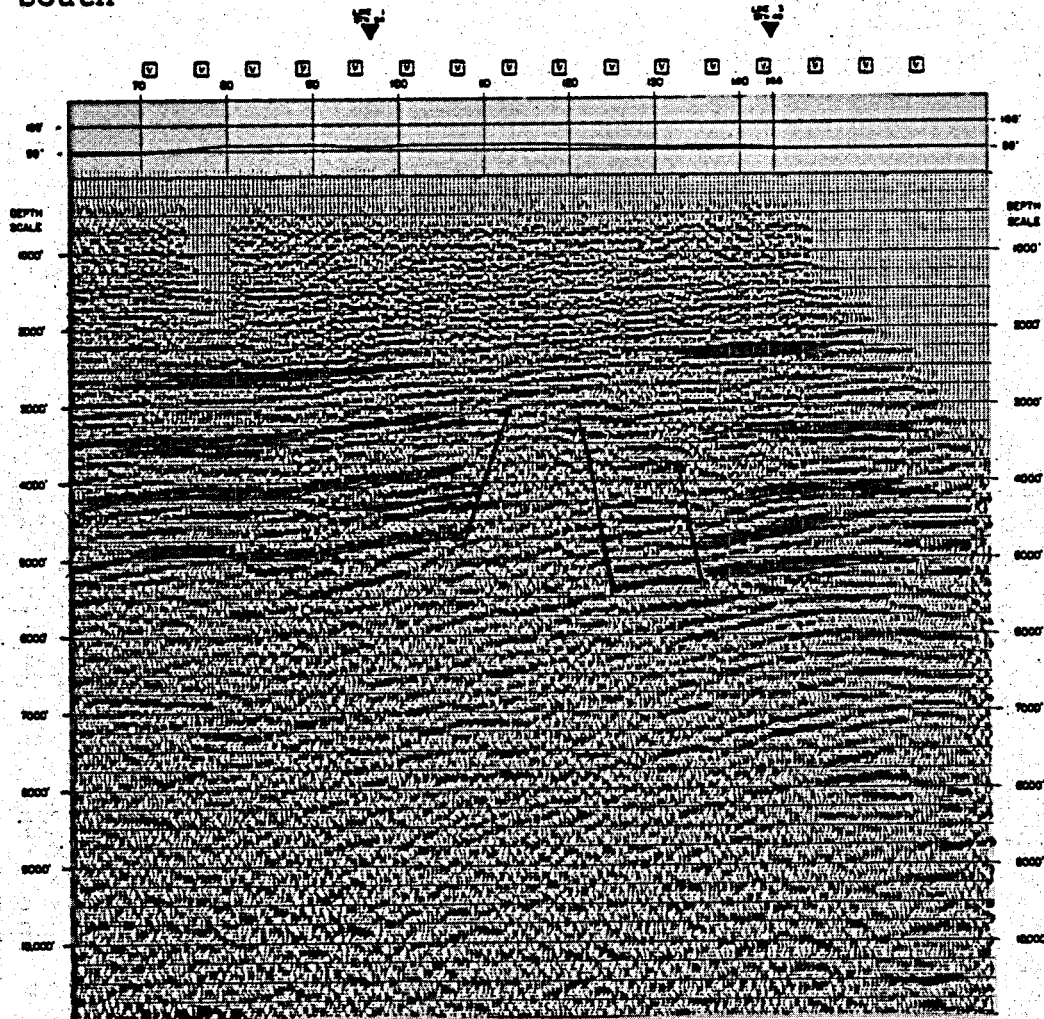
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Figure 32. Line 2P, RAP section, polarity reversed, clear evidence of fracture zone by lack of reflecting power (outlined by thin line).

South



Depth

LINE 2P

LEGEND
☒ INTERSECTIONS
☒ VELOCITY ANALYSIS

BOTTOM PLANE SEA LEVEL

3400'S. VIBROLOG'S, DEPTH SECTION

SYSTEMS SCIENCE & SOFTWARE

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 SYSTEM: [blank] DATE: [blank] FILE: [blank]

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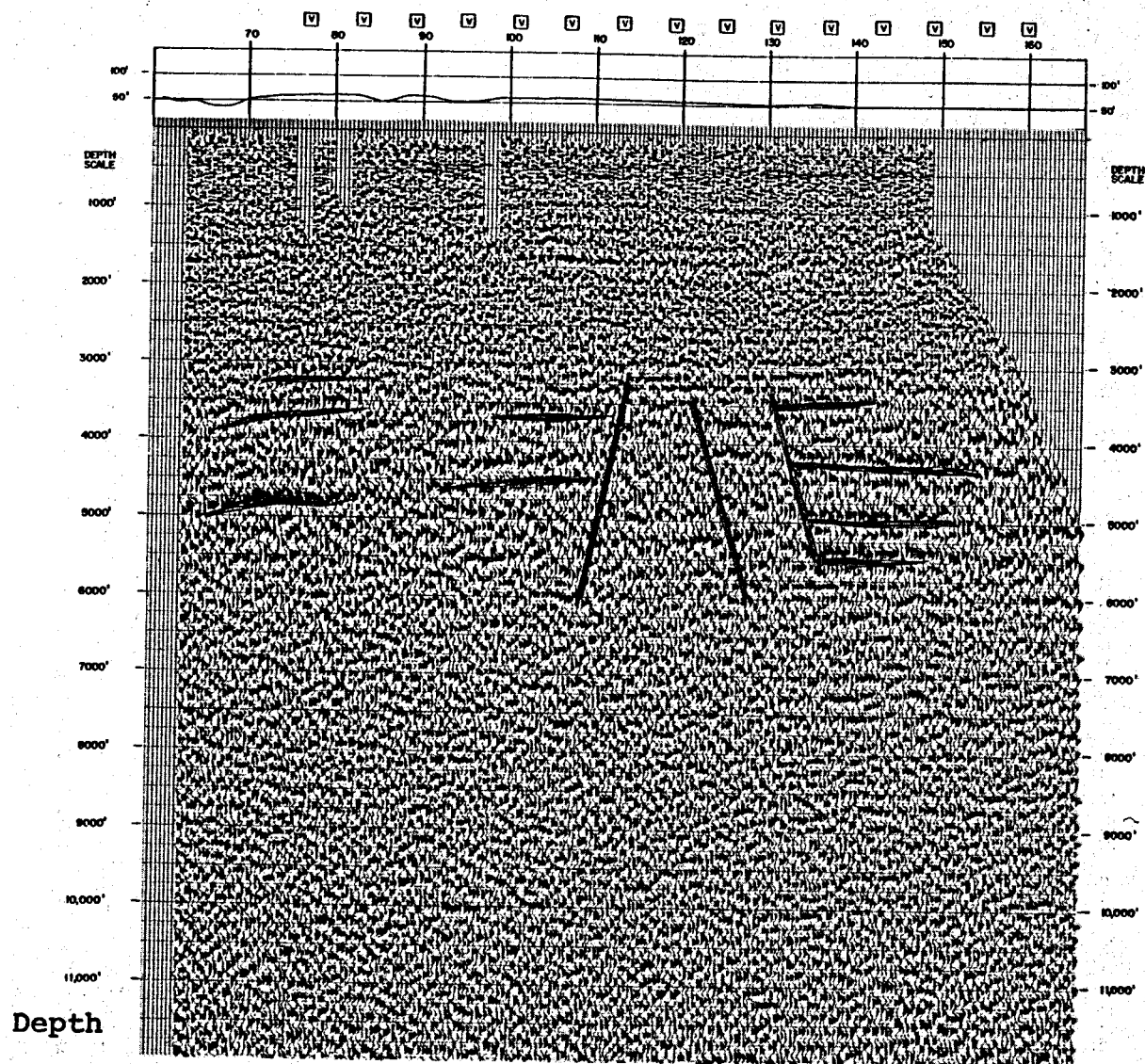
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SYSTEMS SCIENCE & SOFTWARE

Figure 33. Line 2P, depth section interpreted.



← S — LINE: 2S

LEGEND: VP TO
 INTERSECTIONS TO
 V VELOCITY ANALYSIS VP 150

DATUM PLANE: SEA LEVEL

2000%, VIBROSEIS®, DEPTH SECTION

SYSTEMS SCIENCE & SOFTWARE	
AREA: IMPERIAL VALLEY	
PROCESSED BY:	DATE: JAN. 24, 1977
SEVENIER DATA CENTER	JOB NUMBER: 007
WESTERN GEOPHYSICAL CO.	FILE NUMBER: 00001
RECORDING DATA	
PARTY NUMBER	V-0
AMPLIFIER	800 000, 0000 2
TUNING	100-10
ENERGY SOURCE	VIBROSEIS®
FILTER	OUT / 60
PLAY	50-0 (10 REELS)
SAMPLE RATE	4 00
VP INTERVAL	100 FT
GROUP INTERVAL	100 FT
SPREAD	0'-600'-800'
NO. SOURCES	8 VIBROSEIS 1.00 DEEPS
NO. REELS/FORM	00
DATE SHOT	DEC. 9 - 11, 1976
PROCESSING SEQUENCE - PARAMETERS	
1. EDIT - GEOFONE AMPLITUDE	
2. VIBROSEIS® CORRELATION	
3. CDP GATHERS - STATICS COMPUTED (REPLACEMENT VELOCITY: 1000 FT/SEC.)	
4. DECONVOLUTION	
TIME VARIANT WINDOW PHASE INVERSE FILTER	
AUTO. CORR. INT.	1000 - 5000
PRESUMED DISTANCE	0.0
OPERATOR LENGTH	144
TIME ZONE	10.0 - 6.0
5. AUTOSTATISTICS	
SOURCE / RES.	WINDOW LENGTH
CDP	WINDOW SHIFT
6. VELAN™ (VELOCITY ANALYSIS)	
7. NMO AND STATICS	
8. CDP STACK	
S TRAINT	COHERENCY
TIME VARIANT FILTER	
TIME ZONE	L.C. (CPS) K.C.
SEC.	
SEC.	
SEC.	
SEC.	
10 DISPLAY (RECORDS AMPLIFIER)	
ADDITIONAL PROCESSING AND/OR COMMENTS	
9. DEPTH CONVERSION	
CONVERTED TO US CLIENT	
PICKED VELOCITY	

WESTERN
GEOPHYSICAL

Figure 34. Line 2S, depth section interpreted. Note similarity to the 2P depth section in Figure 33.

and SP-145. Starting from the north end, very good analysis extend from SP-145 to SP-125 but the qualities of those at SP-119, SP-113, SP-107 are very poor or poor and further south they return to fair. Considering the broader view of all the velocity analysis made over the geothermal reservoir, it is interesting to note that almost all the velocity analysis, even the best ones, abruptly deteriorate at a definite depth which seems to coincide with the depth at which most geothermal wells have been terminated. This might suggest that the reflective power is quite strongly coupled to the conditions existing where geothermal potential exists, such as the degree of consolidation and amount of fracturing which are important hydrodynamic parameters.

In view of the relative quality of the velocity analysis, a velocity profile along Line 2-P has been computed and transformed to depth (see Table 1). It should be noted that the V_p RMS obtained along the line remain within a narrow range of values and that all their variations remain within their standard deviation at all depths.

A similar analysis of the shear velocities (see Table 2) shows more variations and, in particular, it can be noted that a substantial anomaly exists at the velocity analysis performed around VP-113. There, the results indicate an abnormally rapid increase of the shear velocity with depth when it is compared to that estimated at the other shot points. The discrepancy is well beyond the standard deviation and can therefore be considered significant.

Using both the V_p RMS and the V_{SH} RMS profiles, the V_p/V_{SH} ratio profile was computed (see Table 3). Again, it can be noted that this ratio behaves in a similar fashion (within the standard deviation) all along the line with the exception of VP-113). The ratio there is substantially larger near the surface (depth < 4,000 feet) than anywhere

TABLE 1 (TOP) AND TABLE 2 (BOTTOM)

<u>V_pRMS</u> <u>Versus</u> <u>Depth</u>	<u>155</u>	<u>149</u>	<u>143</u>	<u>137</u>	<u>131</u>	<u>125</u>	<u>119</u>	<u>113</u>	<u>107</u>	<u>101</u>	<u>95</u>	<u>89</u>	<u>Average and</u> <u>Standard</u> <u>Distribution</u>
1000'	5,930	6,044	5,963	6,004	5,957	5,939	5,989	6,019	6,049	6,066	6,082	6,160	6016.7±68.5
2000'	6,244	6,373	6,218	6,295	6,206	6,268	6,268	6,325	6,382	6,414	6,445	6,592	6329.1±120.5
3000'	6,811	6,797	6,655	6,774	6,716	6,834	6,668	6,684	6,699	6,769	6,838	6,998	6779.0±102.1
4000'	7,306	7,264	7,152	7,329	7,329	7,408	7,163	7,165	7,167	7,222	7,276	7,516	7291.0±115.2
5000'	7,615	7,731	7,682	7,824	7,802	7,845	7,687	7,685	7,683	7,716	7,748	8,128	7774.5±143.7
6000'	7,917	7,933	8,097	8,084	8,127	8,275	8,321	8,244	8,166	8,276	8,386	8,587	8189.3±206.9
7000'	8,277	8,389	8,449	8,362	8,294	8,604	8,648	8,635	8,622	8,755	8,888	9,022	8555.5±250.8
Slope	2.474	2.510	2.273	2.360	2.295	2.137	2.116	2.190	2.266	2.182	2.102	2.037	2.245±0.147
Intercept	-13,709	-14,122	-12,307	-13,085	-12,533	-11,620	-11,336	-11,877	-12,435	-11,969	-11,512	-11,424	-12,327±907
<u>V_sRMS</u> <u>Versus</u> <u>Depth</u>	<u>155</u>	<u>149</u>	<u>143</u>	<u>137</u>	<u>131</u>	<u>125</u>	<u>119</u>	<u>113</u>	<u>107</u>	<u>101</u>	<u>95</u>	<u>89</u>	<u>Average and</u> <u>Standard</u> <u>Distribution</u>
1000'	1,751	1,924	1,809	1,973	1,892	1,970	1,850	1,725	1,934	1,900	1,974	1,913	1884.6±84.4
2000'	1,969	2,481	2,152	2,253	2,336	2,368	2,318	2,115	2,523	2,409	2,279	2,366	2294.9±156.7
3000'	2,518	2,632	2,644	2,733	2,636	2,718	2,718	2,618	2,778	2,879	2,723	2,754	2695.9±92.8
4000'	2,956	3,040	3,084	3,156	3,176	3,123	3,031	3,083	3,058	3,292	3,074	3,163	3103.0±86.5
5000'	3,256	3,379	3,468	3,513	3,522	3,434	3,367	3,486	3,398	3,628	3,382	3,546	3448.3±99.4
6000'	3,489	3,645	3,799	3,776	3,826	3,703	3,673	3,848	3,707	3,650	3,567	3,745	3702.3±106.1
7000'	3,712	3,769	4,076	3,930	4,029	3,871	3,955	4,178	3,992	3,794	3,737	3,948	3915.9±143.9
Slope	2.834	3.174	2.547	2.833	2.690	3.039	2.873	2.384	3.017	2.910	3.210	2.844	2.863±0.240
Intercept	-3,956	-5,463	-3,653	-4,635	-4,230	-5,197	-4,584	-3,171	-5,218	-4,959	-5,509	-4,707	4607±735

TABLE 3

V_{P_RMS}/V_{S_RMS} Versus Depth	<u>155</u>	<u>149</u>	<u>143</u>	<u>137</u>	<u>131</u>	<u>125</u>	<u>119</u>	<u>113</u>	<u>107</u>	<u>101</u>	<u>95</u>	<u>89</u>	Average and Standard Distribution
1000'	3.38	3.14	3.30	3.04	3.15	3.04	3.24	3.49	3.13	3.19	3.08	3.22	3.20+0.14
2000'	3.17	2.57	2.89	2.79	2.66	2.65	2.70	2.99	2.53	2.66	2.83	2.79	2.77+0.18
3000'	2.70	2.58	2.52	2.48	2.55	2.51	2.45	2.55	2.41	2.35	2.51	2.54	2.51+0.08
4000'	2.47	2.39	2.32	2.32	2.31	2.37	2.36	2.32	2.34	2.19	2.37	2.38	2.35+0.07
5000'	2.33	2.29	2.22	2.23	2.22	2.28	2.28	2.20	2.26	2.13	2.29	2.29	2.25+0.05
6000'	2.27	2.18	2.13	2.14	2.12	2.23	2.26	2.14	2.20	2.27	2.35	2.29	2.22+0.07
7000'	2.23	2.23	2.07	2.13	2.06	2.22	2.19	2.07	2.16	2.31	2.38	2.28	2.19+0.10
Slope	-4.460	-5.843	-4.499	-5.876	-5.338	-6.724	-5.174	-3.824	-5.610	-4.421	-6.194	-5.477	-5.287+0.847
Intercept	15.820	18.508	15.215	18.380	17.018	20.620	16.920	13.703	17.647	14.800	19.759	17.920	17.193+2.045

else while at greater depth it becomes normal again. This behavior may reflect the presence of a fracture zone making the shear wave velocities abnormally low.

Considering the amount and quality of the data used to derive the evidence, caution is advisable in interpreting its meaning and evaluating its credibility. Only more data and more experience in its use will supply the answers. Having detected an anomalous behavior and determined its location, it would be most interesting to discover its true cause. This can be done only through the drilling of a test well to check whether its performance confirms or denies the existence of a fractured zone in this area.

It is also interesting to note that Line 28 of the Bureau of Reclamation which intersects Line 2 of this test at VP-115 also proved to be of very poor quality. Also, this line corresponds on the structural interpretation of the Bureau of Reclamation to a plunging nose coming from the northeast. Therefore, even structurally, it could be viewed as an interesting location.

V. CONCLUSIONS AND RECOMMENDATIONS

In view of the results presented above, we are able to answer several questions of substantial importance in geothermal exploration, questions which derive directly from the general objective of the project.

The geothermal objective was an evaluation of the merits of advanced exploration seismic methods in geothermal exploration. More particularly, this evaluation was restricted to the conditions encountered in the Imperial Valley where previous attempts appeared discouraging.

The results of the test clearly show that the seismic reflection method, as used in modern oil exploration, is a very useful tool for the investigation of the geothermal potential of the Imperial Valley.

More specifically, we can emphatically state that:

- The P (compressional) "Vibroseis" [®] technique, using a proper CDP folding, produces seismic data of sufficient quality to adequately furnish reliable subsurface structural and stratigraphic information, particularly that concerning parameters of high geothermal significance.
- The SH (horizontal shear) "Vibroseis" technique was also able to obtain energy penetration down to the objective. Its results can be used to support the P data and also to bring additional lithological discrimination which may prove to be very beneficial in terms of geothermal reservoir characteristics.

In view of these conclusions, we are also able to make the following recommendations:

- Conduct a more extensive P survey in the Imperial Valley in order to determine the economic trade-off between field effort and information quality.

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This trade-off study should be detailed enough to supply the basis for establishing a cost-effective exploration scheme designed to ascertain the overall geothermal potential of the Imperial Valley.

- Whereas the SH data quality in no way matches that of P, it is quite likely that it would yield further information in response to some additional and more detailed and intensive processing, particularly in the form of a finer velocity combing. This processing may enhance the quality and definition of the lithological and stratigraphic inferences which can be drawn. Consideration should be given to supporting this additional SH-data processing.
- Finally, if a real potential is demonstrated for the SH method, serious considerations should be given to the design and development of a combined P and SH seismic source. The conditions encountered at East Mesa restricted the survey to the network of improved roads. This is today one of the major obstacles severely impeding the future exploration of a substantial portion of the Imperial Valley. What is needed is a lighter and more mobile source than the extra heavy equipment we had at our disposal, equipment designed entirely for deep oil exploration. It must be capable of generating efficiently both P and SH seismic waves in the rather loose soil conditions encountered in the sand hill areas of the Imperial Valley.

VI. ACKNOWLEDGEMENTS

The successful completion of this project resulted from the concerted efforts of a large number of individuals to whom we would like to give public testimony of our appreciation.

First, we wish to acknowledge the enthusiastic support given to this project by the members of ERDA's Geothermal Division, more particularly Dr. Clayton Nichols, Program Manager, Larry Ball and Keith Westhusing. Next, our deepest thanks go to the management of Continental Oil Company for their contribution to the project. The project could not have been executed without their willingness to supply the shear wave equipment and expertise at no cost to the project. More specifically, we wish to take this opportunity to express our appreciation to Bill Laing, Jerry Ware and John Hopkins. Without their help our efforts would have been to no avail.

Our next thanks go to the management of Western Geophysical Company who also cooperated magnificently and, more specifically, to Charles Dix and R. I. Hsu who actively supported this project with unusual enthusiasm.

We also recognize the great assistance given to us by Dr. Shawn Biehler of the University of California at Riverside who gave us the benefit of his wide knowledge and extensive experience in the geophysical problems of the Imperial Valley.

We are also extremely grateful to Mr. Walter Ortel of the Bureau of Reclamation who contributed all of his seismic data and experience in the Imperial Valley. We also wish to thank the management of the test site at East Mesa and all their personnel for their excellent cooperation and the kind hospitality they demonstrated to the field crew.

Our thanks also go the management of Republic Geothermal who allowed us to run Line 3 over their new road.

We also extend our thanks to all the personnel involved on the field crew because the results actually depend to a large degree on the way they do their job.

Finally, we must express our deep appreciation to Ms. Darlene A. Roddy and Ms. M. Elyse Tessary who contributed so much to the final preparation of this report.

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