STRATIGRAPHIC TRAP EXPLORATION

by

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ABSTRACT

The field seismogram contains signals modified by distortive and additive noise. A variety of field and computer problem solving techniques are available to the geophysicist to transform the seismogram into a more readily interpretable form. A high resolution stratigraphic trap exploration system is a blend of field recording methods and computer processing techniques required by the conditions of the exploration problem. The system presented has achieved the expression of anomalies at frequencies near 100 hertz on Williston Basin and Rocky Mountain data.

INTRODUCTION

In stratigraphic trap exploration the ideal tool is the well log. It is, of course, impractical from a cost standpoint to drill wells at a space interval one would like from a purely interpretive point of view. It becomes necessary, therefore, to have recourse to indirect methods.

Perhaps the most successful indirect method for many years has been seismic. Exploring for stratigraphic traps by the seismic method is primarily an effort to obtain from surface observations equivalent information derived from subsurface well logs. In practice all operations subsequent to recording the seismogram are aimed at making each trace equivalent to a synthetic seismogram derived from an acoustic log at that location. The ultimate objective of the seismic method would be reached with the establishment of a one correspondence between the subsurface geology and the processed seismic trace.

In processing the raw seismogram to a more meaningful product a great deal of use is made of statistical communication theory. This derives from the fact that the seismic method represents a statistical communication system: there is a source (the seismic explosion), a

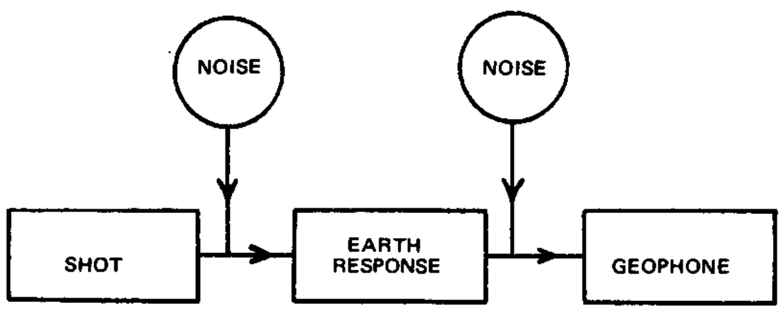

FIG. 1.—Seismic — a statistical communication system.

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transmission channel (the earth) and a receiver (a geophone group). Various types of noise are injected into the system at different points.

This is very similar to the familiar situation of a radio transmitter, the atmosphere and a radio receiver. The distinction is that the shot wavelet or outgoing signal is generally unknown and that "the medium is the message" rather than the outgoing wavelet.

As is well known the message recorded at the receiver is garbled by the mixing of source, earth and noise effects in a space-time variant sense. An independent measure on a variable cannot be taken, it is always modified by other surrounding variables. One measure can only be considered as one statistic. High tribute must be paid to the interpretive skill of the doodlebugger who, without the aid of seismic data processing, successful used the seismic method. During the past ten years digital recording and processing systems have significantly increased the ability of the geophysicist to reliably interpret seismic data on increasingly difficult exploration problems.

CREATION OF A SEISMOGRAM

Some of the barriers and limiting conditions which need to be attacked by a stratigraphic trap system are outlined in Fig. 2. To understand the space-time structure of the total problem, namely the processes involved in the creation of seismogram, it is useful to proceed through the sequence of boxes beginning with the shot. The pulse initially generated at the shot is a sharp time transient. It immediately suffers near surface effects. The first of these, the shot environment, broadens the wavelet in time and decreases its frequency bandwidth. The pulse undergoes a further broadening from the addition of ghost reflection and the reverberations generated in the near surface interfaces. The outgoing pulse greatly lengthened from the combination of near surface effects suffers a progressive loss of high frequencies due to frequency dependent attenuation as it propagates through the section. This high frequency absorption of seismic energy in the ground, due primarily to inelastic attenuation, is one of the most fundamental agents limiting the resolution of the reflection system. This frequency selective absorption imposes narrower limits on the bandwidth, and as a consequence, produces additional broadening of the shot pulse. The elongated shot wavelet is reflected from each of the subsurface acoustic impedance boundaries or reflectors. On the return path to the seismometer, the reflected events again experience this frequency dependent attenuation. Broadening of the waveform with travel time due to these losses occurs simultaneously, of course, with the reflection process. In the vicinity of the seismometer, the upward travelling signals again experience, in general, a different combination of near surface interfaces, generating its own peculiar set of reverberations. At the seismometer the ambient noise, coherent noise propagation modes, and long period section multiples are algebraically added to the reflection signals which have been shaped by the subsurface system response. The sum is then reshaped by the seismometer and recording instruments to give a field seismogram. The amplitudes on

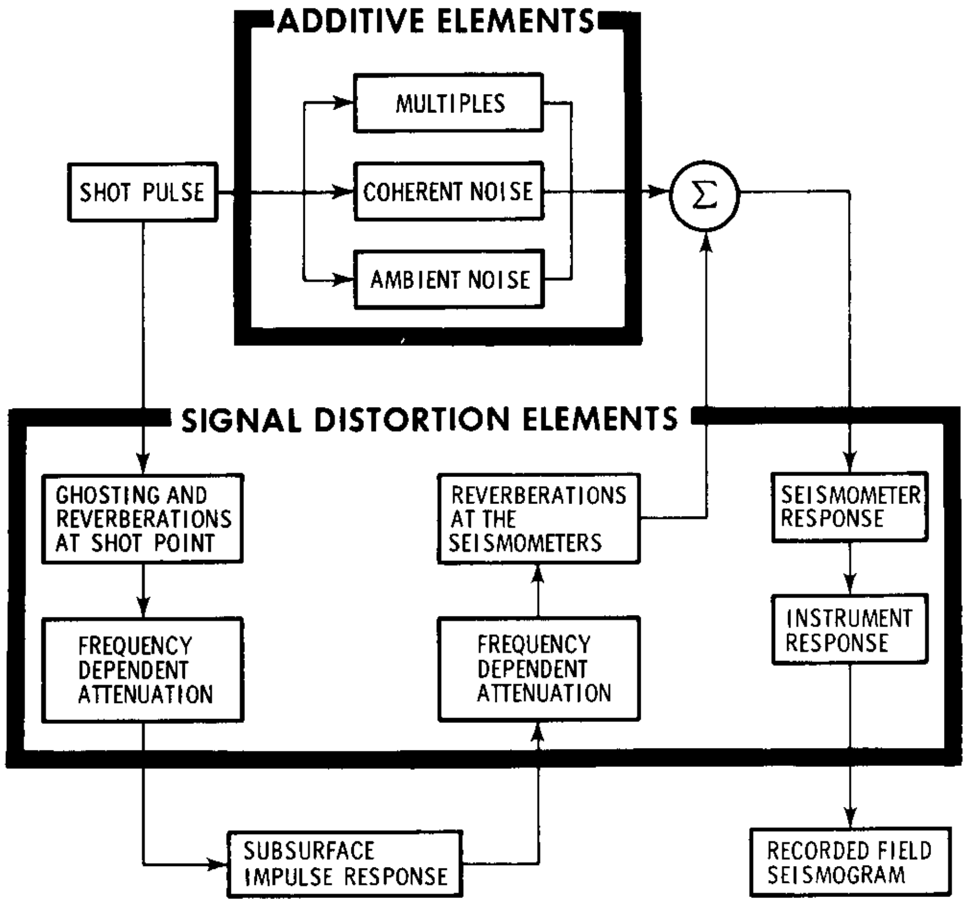

FIG. 2.—Processes involved in the creation of a seismogram.

the field seismogram then represent the desired signals which have been modified by

— the sequence of distortion elements and

— the additive elements generated by the shot pulse.

PROBLEM SOLVING TECHNIQUES

To deal effectively with seismograms the geophysicist has an array of field and computer problem solving techniques available to him. His choice of techniques must be based on a thorough understanding of the space-time variant nature of signal distortion and additive elements. See Fig. 3.

SPACE VARYING	TIME VARYING	PROBLEM-SOLVING TECHNIQUES: FIELD PROCEDURES	PROBLEM-SOLVING TECHNIQUES: COMPUTER PROCESSING
SHOT WAVELET VARIATIONS		$d_s > d_w$	DECONVOLUTION
GHOSTING		LINEAR CHARGES	MULTICHANNEL FILTERING (DEGHOSTING)
REVERBERATIONS			DECONVOLUTION
	FREQUENCY-DEPENDENT ATTENUATION	PREEMPHASIS FILTERING	TIME-VARIANT DECONVOLUTION
REFLECTION AMPLITUDE VARIATIONS	REFLECTION AMPLITUDE VARIATIONS	PROGRAMMED GAIN	TRUE AMPLITUDE RECOVERY
MULTIPLES	MULTIPLES	MULTIFOLD SHOOTING & LONG RECORDING SPREADS	MULTICHANNEL FILTERING (OPTIMUM STACK, CDP STACK)
COHERENT NOISE	COHERENT NOISE	SHOT & SEISMOMETER ARRAYS BANDPASS FILTERING	MULTICHANNEL FILTERING (VELOCITY FILTERING, MIXING) BANDPASS FILTERING
AMBIENT NOISE	AMBIENT NOISE	LARGE CHARGES MULTIFOLD SHOOTING & RECORDING BANDPASS FILTERING	MULTICHANNEL FILTERING (DIVERSITY STACKING, VERTICAL STACKING) TIME-VARYING BANDPASS FILTERING

FIG. 3—Classification of signal distortion and additive elements according to their space-time properties with corresponding field and computer problem solving techniques available.

The shot environment from one location to another frequently exhibits pronounced lateral changes. The most prevalent field technique is to attempt to place all the charges in the same shooting medium. This is usually accomplished by keeping the shot depth below the weathered layer. The processing technique used to stabilize the shot wavelet is deconvolution.

The effect of ghosting and reverberations from the near-surface interfaces can change rapidly not only from shot to shot but also from one seismometer group to another, since both are related to reflection coefficients of the highly changing interfaces. Ghosting may be attacked in the field with linear charges such as sausage powder, broomstick or delay caps. In the computer, ghost attenuation is accomplished using a multichannel filter which requires two or more shots per hole. Reverberations in general cannot be effectively handled in the field and, therefore, must be corrected in the processing. Again deconvolution is the most effective technique.

Frequency dependent attenuation, due chiefly to inelastic losses, can be considered primarily a space stationary effect. A field approach to the inelastic attenuation is a pre-emphasis filter which attempts to achieve a flat or white spectrum at some time on the seismogram. This is accomplished during the recording process by filtering off the low frequency at the same rate that the high frequency energy decays. However, since the high frequency decay is not time stationary, it is most effectively treated in the processing with a series of deconvolution filters. These filters vary in time in accordance with the changing frequency content of the seismogram.

Recovery of true amplitude relationships from the initial amplifier gain function is a space stationary condition; however, the amplitudes of the reflected events change along the line of profiles. The amplitude variations can be monitored in the field using programmed gain control (PGC) and in the computer with the true amplitude recovery process. This processing technique removes the recording gain function and compensates for the fact that the shot function is a point source rather than a plane wave.

The long-period section multiples and the coherent noise can be considered as both space and time varying. Multiple attenuation using multifold shooting and long spreads in the field to obtain sufficient differential NMO between the primary and multiple is the most common solution. The performance of the stacking process can be significantly improved by attacking the multiples with a series of the time variant multi-channel filters designed to attenuate events which exhibit the residual normal moveout characteristics associated with multiple energy. Coherent noise is usually handled in the field with shot and seismometer arrays combined with bandpass filtering. Problems beyond the capabilities of field procedures can again be tackled with a multi-channel filtering technique. Although mixing and velocity filtering are the most common, a number of more exotic techniques can be employed.

The amplitudes of the reflected events fall off with increasing travel time. For this reason, the signal to noise ratio, and particularly, the signal to ambient noise ratio, is a time variant phenomenon. To combat the ambient noise problem in the field, either large charges in dynamite shooting or high recording multiplicity in surface sources are used in conjunction with bandpass filtering. In the computer, both straight and diversity stacking are used. Straight stack yields a signal to noise ratio improvement equal to the square root of the number of element. The diversity stack combines the data in accordance with the signal to noise ratio of the individual inputs.

Two additional problems not illustrated in the flow chart must also be considered. These are velocity and statics. Reliable, continuous velocity control is necessary to obtain accurate normal moveout corrections, to properly align the common depth point traces for stacking, and to facilitate the determination of accurate static corrections. The static problem is particularly significant in strat trap work due to the subtle nature of most stratigraphic anomalies.

The problem of NMO and statics provides geophysics with a classic paradox: good static corrections require good NMO corrections and conversely good NMO corrections require good statics. Dynamic crosscorrelation analysis is a technique which will yield accurate velocity information in the presence of residual statics. This velocity determination technique measures the residual NMO of primary and/or multiple energy as a function of time on the record. The measurements are made using common depth point traces from a specified number of depth points along the line. Since the velocity is measured using the combined correlation statistics of several depth points instead of just one, the combined static variations take on the characteristics of a highcut filter. The effect of this filter is to attenuate the crosscorrelation peak; however, the time of the peak is not affected. Hence, the time of the crosscorrelation peak may be translated into an accurate measure of velocity in spite of the static problem.

With the NMO problem overcome, the static problem becomes easier to manage. Various automated static programs currently being used compute and apply a set of surface consistent shot and receiver static corrections based on the redundancy inherent in multifold shooting.

The field and computer techniques having been discussed, a stratigraphic trap exploration system is presented. The system is the blend of field recording methods and computer processing techniques required by the conditions of the exploration problem to achieve the sought for results. Three field examples are presented to illustrate the system. In every case a preliminary feasibility study was conducted by making multiple free synthetic seismograms from acoustic logs of wells in the respective areas. The expression of the anomaly in the ideal noise-free case shows the minimum bandwidth required to resolve the sought for anomaly and sets a reference against which the success of the system can subsequently be measured.

WILLISTON BASIN LINE 1

The first example is of data acquired in the Williston basin. It is an attempt to achieve coherent frequencies near 100 cycles per second from the seismic data and represents a severe test of the stratigraphic trap exploration system. Fig. 4 outlines the system used for this example. The following points should be noted:

Field:

—Three-fold splits provide 3/1 signal to ambient noise ratio and limited multiple attenuation.

—Deep holes improve the signal to coherent noise ratio.

—Two shots per hole will be used in the deghost process.

WILLISTON BASIN LINE 1

FIELD PARAMETERS

- SHOOTING
  - COVERAGE: THREEFOLD
  - SHOTPOINT INTERVAL: 880 ft
  - SHOT DEPTHS: 260 ft / 300 ft TOPS
  - CHARGES: 5 lb / 5 lb
- RECORDING
  - SPREAD: SPLITS
  - GROUP INTERVAL: 220 ft
  - SEIS ARRAY:
    - 4-ARM STAR
    - 6 SEISES / ARM
  - SEIS INTERVAL: 15 ft
- INSTRUMENTATION
  - FILTERS:
    - LOW CUT: OUT
    - HIGH CUT: 350 cps, 24 db / OCTAVE E
  - RECORD LENGTH: 3 sec
  - SAMPLE PERIOD: 1 ms

PROCESSING SEQUENCE

FIELD TAPE
↓
TRUE AMPLITUDE RECOVERY
↓
TIME-VARIANT DECONVOLUTION
↓
DEGHOSTING
↓
NORMAL MOVEOUT
↓
DATUM STATICS
↓
DYNAMIC CROSSCORRELATIONS FOR VELOCITY DETERMINATION
↓
RESIDUAL NORMAL MOVEOUT
↓
AUTOMATED RESIDUAL STATICS
↓
THREEFOLD COMMON DEPTH POINT STACK
↓
TIME-VARIANT DECONVOLUTION
↓
TIME-VARIANT DIGITAL FILTERING

FIG. 4.—Stratigraphic trap exploration system employed on Williston Basin data.

—Small charges yield a high frequency shot wavelet.

—Four-arm star provides better signal to coherent noise ratio for both in-line and broadside noise.

—Out -350 cps. filter and 1 ms. sampling achieve the broadband recording required for a solution.

Computer:

—True amplitude recovery maintains true amplitude relationships on the record.

—First time-variant deconvolution using long time gates provides shot wavelet stabilization, reverberation attenuation, and some compensation for inelastic attenuation losses.

—Deghost provides attenuation of ghost energy.

—Dynamic correlations provide detailed velocity control required to ensure proper stacking.

—Automated statics insure consistent static corrections.

—Three-fold stack provides better signal to ambient noise ratio and some multiple attenuation.

—Second time-variant deconvolution using short time gates compensates for inelastic attenuation losses.

—Time-variant filtering yields good signal to coherent noise and signal to ambient noise ratios.

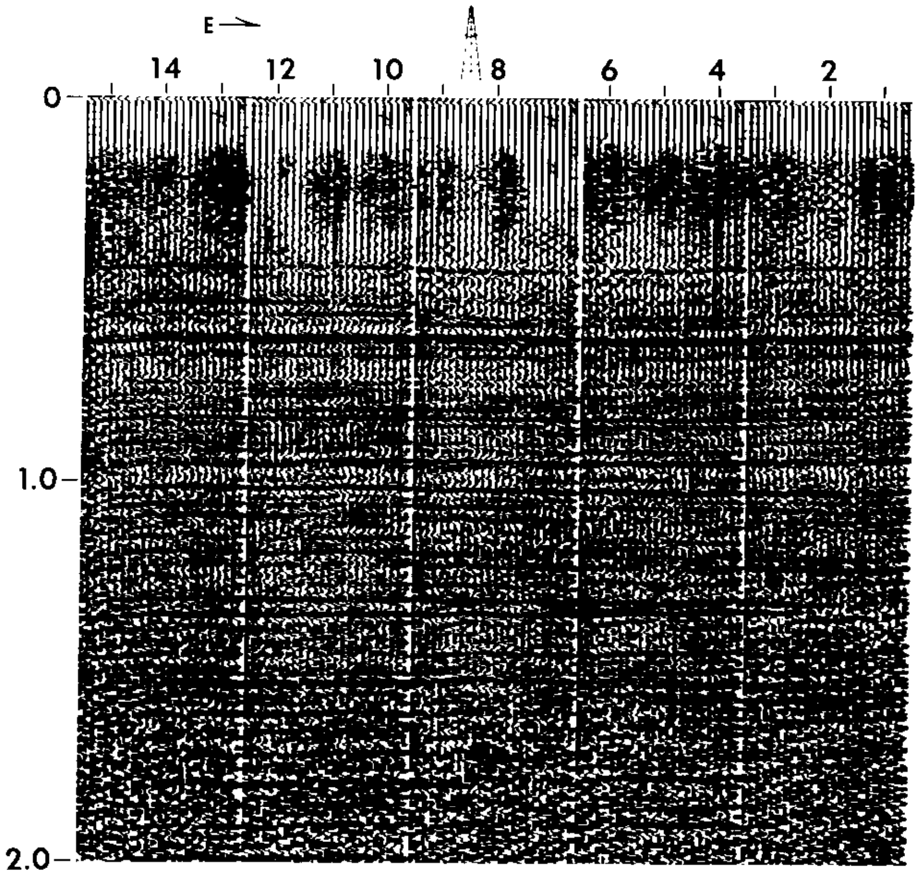

FIG. 5.—Williston Basin Line 1 — processed output of the system.

Fig. 5 is the processed output of this system. Although difficult to see in this mode of presentation, the required frequency content is present on the section. Two pinchouts, one at 0.5 sec. and one at 1.3 sec., are shown together with a very subtle unconformity at about 1.0 sec. Fig. 6 shows the continuity of the high frequency energy and the comparison of the processed seismic traces with the synthetic seismogram. The multiple-free synthetic was generated using a sonic log from a well near the line.

Fig. 7 is an enlargement of that portion of Fig. 6 outlined by a rectangle. The processing listed in Fig. 6 was used to obtain a single transformed seismic trace at each shotpoint to facilitate the detailed isochron measurements required in the survey. In examining the output traces of the velocity filter on both slides with regard to each other and the synthetic, it is important to remember that there are no common input traces between pie slice outputs. Each pie slice output is an independent sample of the seismic data. The continuity of the high frequency seismic energy is readily apparent on both figures. The period of many of the events is less than 10 ms. and this meets the sought-for frequency objective. However, the best measure of success or failure is the degree of correlation between the transformed seismic trace and the synthetic seismogram. In Fig. 7 the synthetic seismogram is almost indistinguishable from the seismic data, and indicates the success of the strat trap exploration system for this example.

ROCKY MOUNTAIN BASIN LINE 1

In the second example the objective is to 'tie' two sonic logs and achieve coherent energy near 100 cycles per second on the processed outputs of a line of Rocky Mountain Basin data. The system used in this example is shown in Fig. 8.

The techniques will again be briefly examined in view of the problems generally encountered.

Field:

—Three-fold splits provide a 3/1 signal to ambient noise ratio and limited multiple attenuation.

—Deep holes improve the signal to coherent noise ratio.

—Sausage powder provides for ghost attenuation.

—Four-arm star yields a better signal to coherent noise ratio for in-line and broadside noise.

—Out-168 cps. filter and 2 ms. sampling achieve the broadband recording required by the problem.

Computer:

—True amplitude recovery maintains true amplitude relationships on the record.

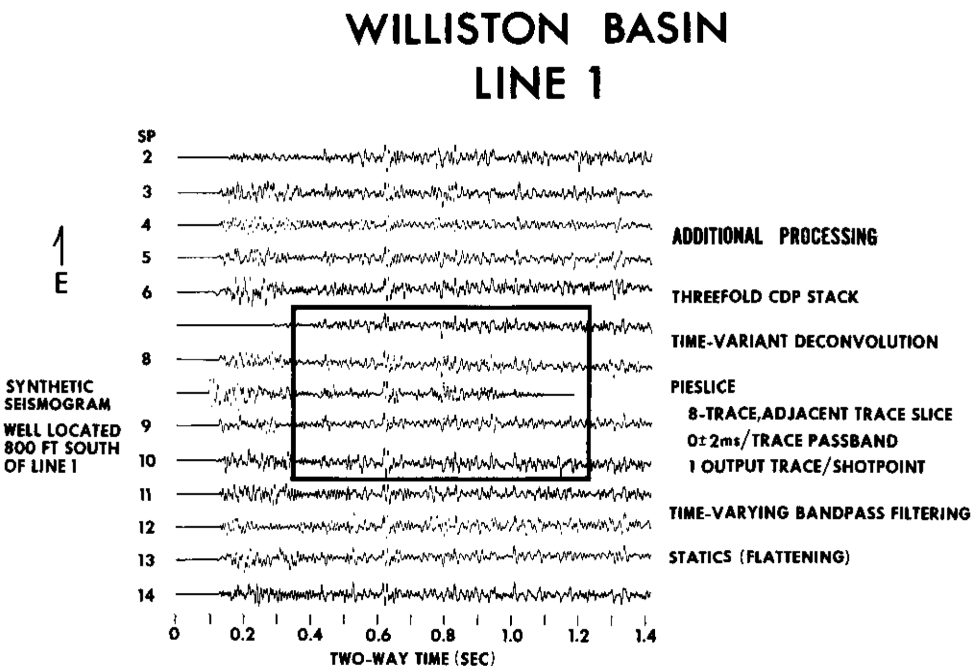

FIG. 6.—Synthetic to data match.

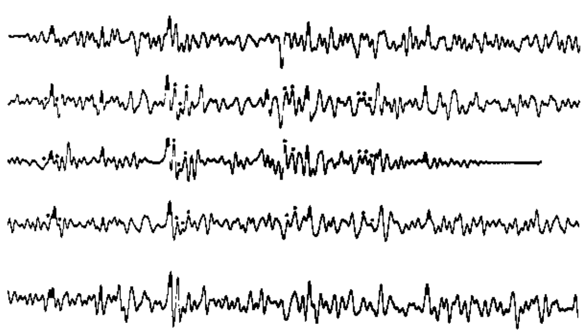

FIG. 7.—Detail of portion of Fig. 6 outlined by a rectangle.

ROCKY MOUNTAIN BASIN LINE 1

FIELD PARAMETERS

- SHOOTING
  - COVERAGE: THREEFOLD
  - SHOTPOINT INTERVAL: 880 ft
  - SHOT DEPTH: 155 ft TOP
  - CHARGE: 50 lb SAUSAGE
- RECORDING
  - SPREAD: SPLITS
  - GROUP INTERVAL: 220 ft
  - SEIS ARRAY:
    - 4-ARM STAR
    - 6 SEISES / ARM
  - SEIS INTERVAL: 30 ft
- INSTRUMENTATION
  - FILTERS:
    - LOW CUT: OUT
    - HIGH CUT: 168 cps, 24 db / OCTAVE
  - RECORD LENGTH: 4 sec
  - SAMPLE PERIOD: 2 ms

PROCESSING SEQUENCE

FIELD TAPE

TRUE AMPLITUDE RECOVERY

TIME-VARIANT DECONVOLUTION

NORMAL MOVEOUT

DATUM STATICS

DYNAMIC CROSSCORRELATIONS FOR VELOCITY DETERMINATION

RESIDUAL NORMAL MOVEOUT

AUTOMATED RESIDUAL STATICS

THREEFOLD COMMON DEPTH POINT STACK

TIME-VARIANT DECONVOLUTION

TIME-VARIANT DIGITAL FILTERING

FIG. 8.—Stratigraphic trap exploration system employed on Rocky Mountain Basin data.

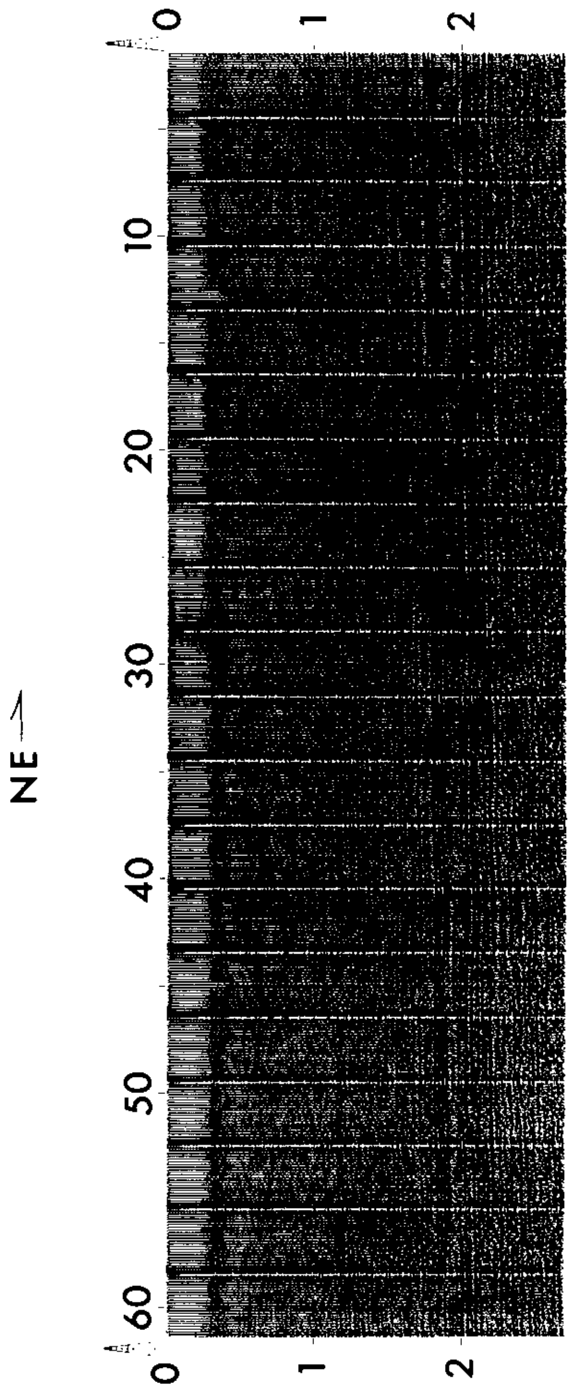

FIG. 9.—Rocky Mountain Basin Line 1 -- processed output of the system.

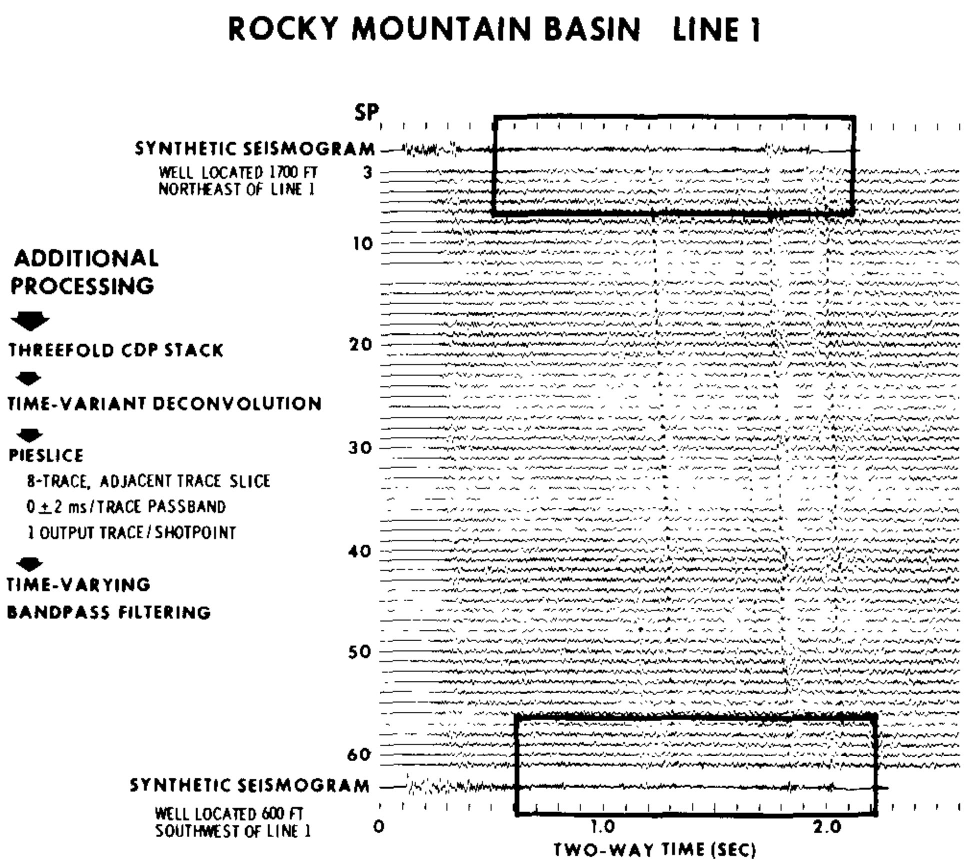

FIG. 10.- Synthetic to data match.

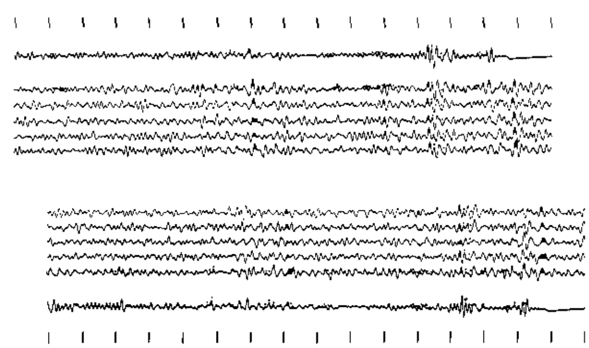

FIG. 11.—Detail of portions of Fig. 10 outlined by rectangles.

—First time-variant deconvolution using long time gates provides shot wavelet stability, reverberation attenuation, and some compensation for inelastic attenuation losses.

—Dynamic correlations provide the close velocity control required to align the traces properly in stacking.

—Automated statics insure consistent static corrections.

—Three-fold stack provides better signal to ambient noise ratio and some multiple attenuation.

—Second time-variant deconvolution using short time gates completes the compensation for losses due to inelastic attenuation.

—Time-variant filtering yields good signal to coherent noise and signal to ambient noise ratios.

Fig. 9 shows the output section of the system. The length of the line and the frequency content of the data detract from the presentation; however, the dip from right to left is apparent and the small slump in the section near shotpoint 40 can also be seen on this output. Fig. 10 more clearly demonstrates the high frequency continuity, the dip on the section, the structural anomaly near shotpoint 40, and the fit between the processed output traces and the synthetic seismogram at both ends of the line. Both synthetic seismograms were derived using only the sonic logs from the two wells near the line.

Fig. 11 is an enlargement of the two portions of Fig. 10 outlined by rectangles. As in the previous example, the additional processing was used to obtain a single processed trace at each shotpoint to facilitate both the accurate structural and isochron measurements needed for the prospect. The outputs of the pie slice are again independent samples of the processed traces. Both figures indicate the consistency and continuity of the high frequency data. Although not as white as the previous example, the majority of the reflection events exhibit good frequency content between 50 and 100 cps. As evidence of quality and quantity of the data at the high end of the frequency spectrum, the lowest high-cut filter used on this output had its 6 db down point at 95 cps. Success or failure of the system is still best determined through the fit between the synthetic seismogram and processed seismic trace. Fig. 11 shows the degree of correlation to be good at both ends of the line.

WILLISTON BASIN RECONNAISSANCE LINE 2

The third example is a Williston Basin reconnaissance line. This type of strat trap prospect requires a somewhat more conventional approach to the seismic problems. Fig. 12 shows the system used in this example. Points that should again be noted:

Field:

—Six-fold offset endovers provide multiple attenuation and good signal to ambient noise ratio.

—Deep holes improve the signal to coherent noise ratio.
—50 lb. sausage powder provides for ghost attenuation.
—*Four-arm star yields a better signal to coherent noise ratio for in-line and broadside noise.*
—12 cps. low-cut filter improves signal to coherent noise ratio.
—112 cps. high-cut filter improves signal to ambient noise ratio.

Computer:

—*True amplitude recovery maintains true amplitude relationships on the record.*

WILLISTON BASIN RECONNAISSANCE LINE 2

FIELD PARAMETERS

- SHOOTING
  - COVERAGE: SIXFOLD
  - SHOTPOINT INTERVAL: 660 ft
  - SHOTPOINT OFFSET: 165 ft INLINE
  - SHOT DEPTH: 155 ft TOP
  - CHARGE: 50 lb SAUSAGE
- RECORDING
  - SPREAD: OFFSET ENDOVERS
  - GROUP INTERVAL: 330 ft
  - SEIS ARRAY:
    - 4-ARM STAR
    - 6 SEISES / ARM
  - SEIS INTERVAL: 30 ft
- INSTRUMENTATION
  - FILTERS:
    - LOW CUT: 12 cps, 24 db / OCTAVE
    - HIGH CUT: 112 cps, 24 db / OCTAVE
  - RECORD LENGTH: 4 sec
  - SAMPLE PERIOD: 2 ms

PROCESSING SEQUENCE

FIELD TAPE
↓
TRUE AMPLITUDE RECOVERY
↓
SYSTEM DECONVOLUTION
↓
NORMAL MOVEOUT
↓
DATUM STATICS
↓
TIME-VARIANT DECONVOLUTION
↓
DYNAMIC CROSSCORRELATIONS FOR VELOCITY DETERMINATION
↓
RESIDUAL NORMAL MOVEOUT
↓
AUTOMATED RESIDUAL STATICS
↓
SIXFOLD COMMON DEPTH POINT STACK
↓
TIME-VARIANT DIGITAL FILTERING

FIG. 12.—Stratigraphic trap exploration system used on a basin reconnaissance line.

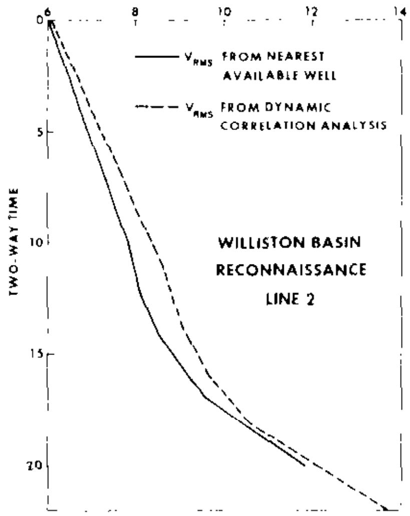

FIG. 13. Result of dynamic correlation velocity analysis.

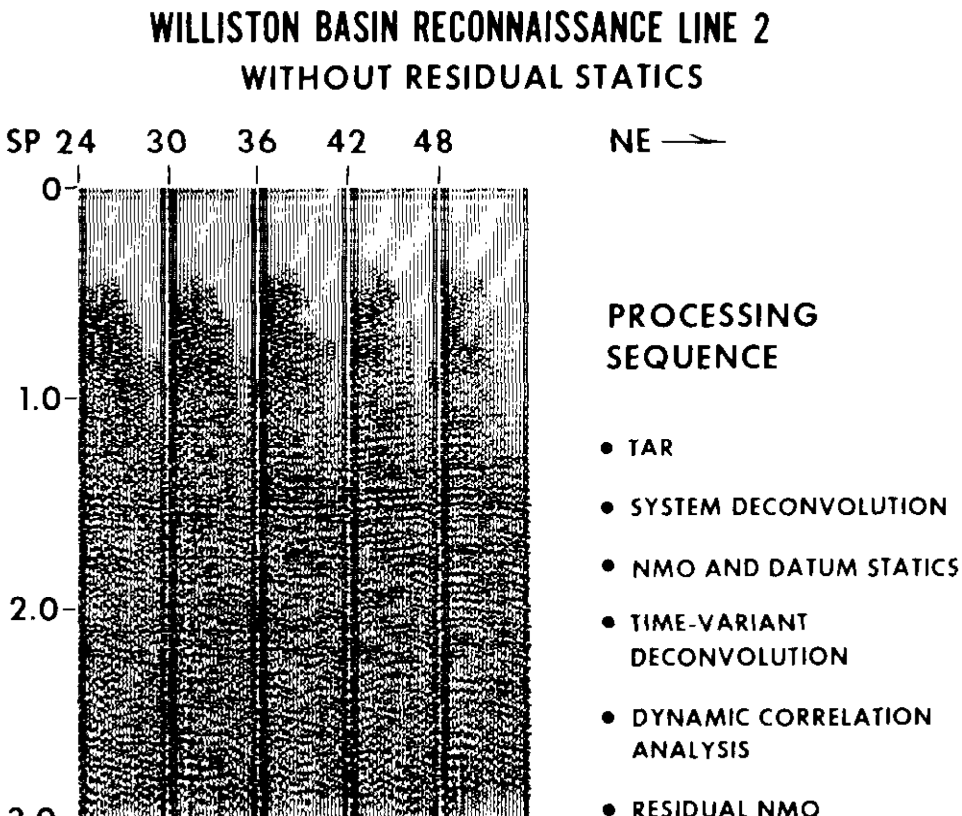

FIG. 14. Single-fold section without residual static corrections.

—Time-variant deconvolution using long time gates provides shot wavelet stabilization, reverberation attenuation, and some compensation for inelastic attenuation losses.
—Dynamic correlations provide for velocity control.
—Automated statics insure consistent static corrections.
—Six-fold stack provides for multiple attenuation and better signal to ambient noise ratio.

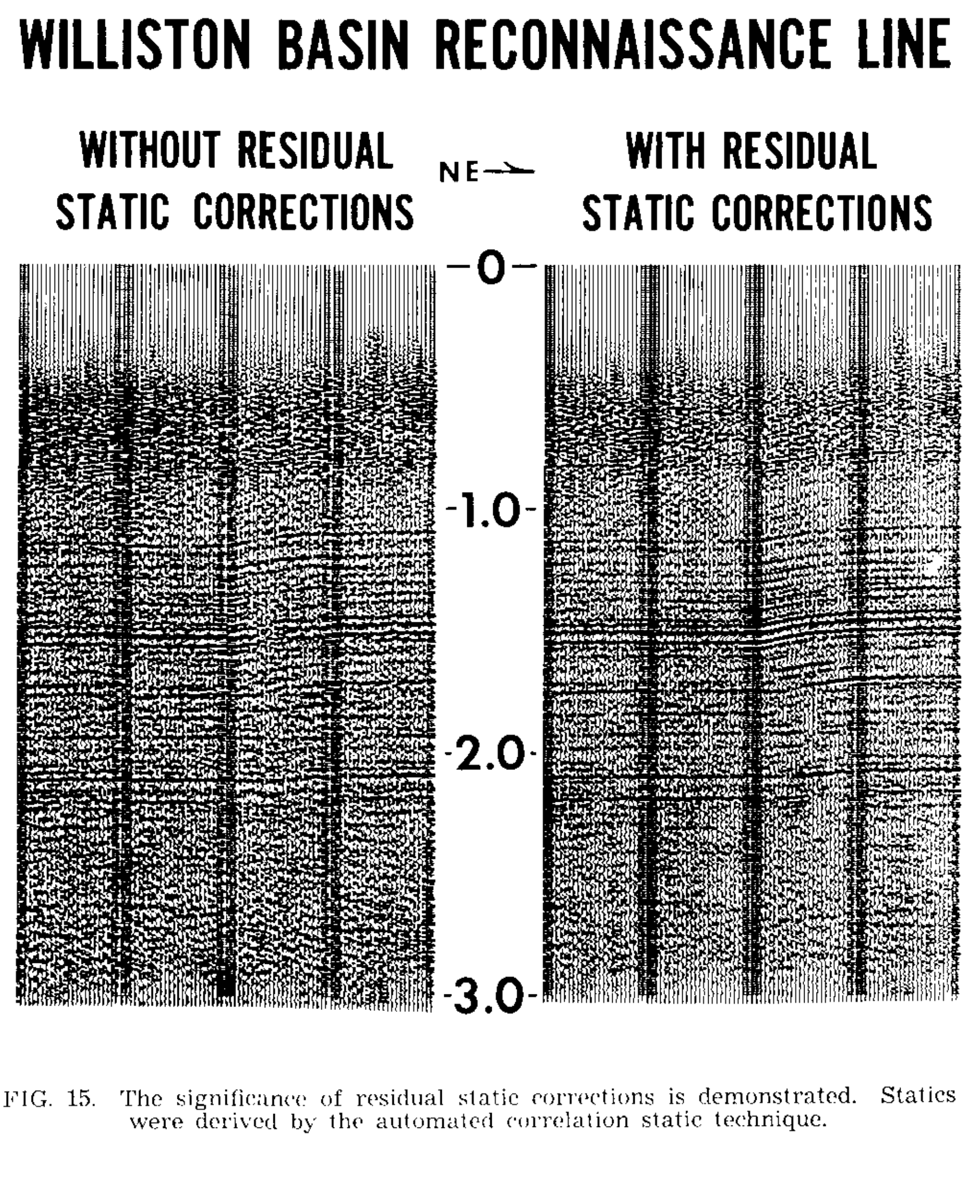

FIG. 15. The significance of residual static corrections is demonstrated. Statics were derived by the automated correlation static technique.

—Time-variant filtering yields good signal to coherent noise and signal to ambient noise ratios.

The problem of velocity control and static corrections were particularly acute in this example. By the very nature of a reconnaissance survey, the amount of velocity information available is quite limited. It was, therefore, necessary to extract the required velocity data from the seismic records. This was accomplished by means of the dynamic cross-correlations in spite of a severe residual static problem.

Fig. 13 shows the result of the velocity analysis determined over four stacked output records. The solid black line is RMS (Root Mean Square) velocity for NMO corrections from a well several miles northwest of the line. This velocity function was the initial estimate for the line of profiles. The dashed line is the result of the dynamic correlation analysis of the records. A close examination of the two curves reveals a marked similarity between the two velocity functions. The dashed line exhibits the same general shape as the well function. The breaks in velocity on the dashed line occur later in time and the derived function is somewhat faster, particularly from 0.5 sec. to 1.5 sec. in the section.

Fig. 14 is a single-fold section without residual static corrections. This section graphically illustrates the static problem which is the result of a highly variable near-surface condition and is aggravated by the large group intervals used in a reconnaissance survey.

The residual static problem alone can seriously affect the final product even when all other problems have been properly handled. Fig. 15 shows the result of the strat trap exploration system for this example with and without residual static corrections. The section on the right side of the figure is a significantly better product at all times on the section. From the shallow pick at 0.7 sec. to the deepest horizon at 2.1 sec., the continuity and high frequency content provide the interpreter with a far more diagnostic picture of the subsurface anomaly.

CONCLUSION

The total stratigraphic exploration system as presented in this paper is one in which subsystems consisting of field recording methods and processing techniques are carefully blended together to meet the conditions of the exploration problem to achieve the sought for results. The capability of existing tools to properly handle the great majority of the seismic problems encountered in stratigraphic trap exploration was demonstrated.

Recent processing developments that are key to successful stratigraphic trap exploration include time varying deconvolution, automated residual statics and dynamic correlation analysis. With these techniques the areas over which resolution of stratigraphic traps is feasible has been vastly expanded.

ACKNOWLEDGMENT

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