GEOLOGICAL VALUE OF DIGITAL SEISMIC TECHNOLOGY

by

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Introduction: The geologist, in exploring for petroleum, has two basic technologies that he uses to develop prospects. One basic technology encompasses all the scientific regimes developed to collect and interpret data from below the surface of the earth, primarily from wells. The other basic technology encompasses all the geophysical methods developed to collect and interpret data from surface measurements. The information gained from subsurface measurements is the most fundamental because the well data supplies the basic information concerning structure, stratigraphy, accumulation and economics. To collect and interpret the detailed information obtainable from measurements made in wells has required the development of a large number of sophisticated and interrelated technologies ranging from electric well logging to palynology. The geologist thus has a tremendous amount of detailed information available from a very localized and relatively small portion of the subsurface. To become an explorationist, the geologist assimilates all the pertinent data from a number of wells and predicts the subsurface conditions existent between and beyond the wells. If anomalous conditions can be predicted, an exploration project may develop. At this point the explorationist calls upon the geophysicist to obtain additional information, derived from surface measurements, to further delineate the anomalous conditions predicted from the subsurface measurements.

The explorationist is faced with the problem of relating data, from geophysical measurements, to quite different data from well measurements. Ideally, the objective of the surface geophysical methods should be to obtain data that can be directly related to well data and preferably in the same format as the information from the wells.

The reflection seismograph has more resolution than any other geophysical method and seismic data can most nearly be used interchangeably with well data. However, a problem still exists in correlating the seismic traces with the well logs because in the reflection seismograph system the desired seismic representation of the subsurface has been modified by many factors not related to subsurface conditions. To eliminate these non-diagnostic variables, improvements in seismic technology are required. In this paper, the ability of digital seismic technology to achieve the requirements of the explorationist will be examined.

The Problem Definition-Problem Solving Approach: A popular and effective approach to the achievement of an exploration objective by the seismic method is to describe the objective in seismic terms and then to describe or predict all of the seismic problems that must be solved before the objective can be achieved.

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This is the problem definition. The next step is to devise a system that will solve these problems so that only the diagnostic seismic data remains. This is the problem solution.

The first step in the problem definition-problem solving approach is to define the exploration objective in geologic parameters. The explorationist, from studies of all the available data, such as well logs of all types (including continuous

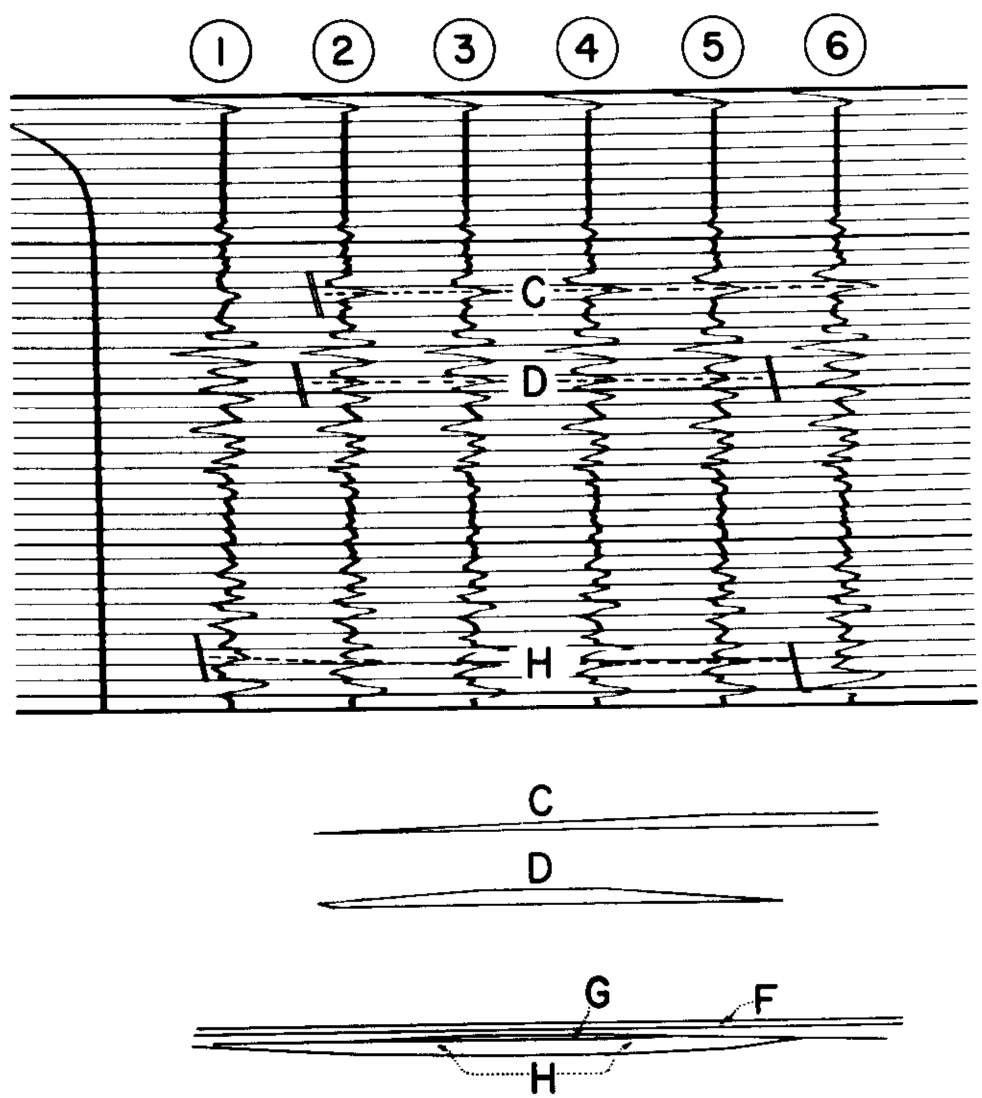

FIGURE 1. *Synthetic seismogram — stratigraphic trap model.*

velocity or sonic logs), cross-sections and maps, and from exchange of ideas with the geologist and geophysicist, defines the objectives.

An example of this approach is shown in Figure 1. In this Rocky Mountain area the objective is to find where sand "C" pinches out or where the sand "D" build-up occurs. The deeper sedimentary complex "F", "G" and "H" needs to be delineated and described. The explorationist in working up his prospect postulates that these stratigraphic conditions exist in the area, that they are economic objectives and that they do manifest themselves on sample and electric logs.

The geophysicist must represent these postulated stratigraphic conditions in seismic terms. The second step in the problem definition sequence then is to modify the continuous velocity, sonic or other logs to show the postulated sedimentary changes on a suite of logs. A multiple-free synthetic seismogram is then made from each of these logs. The six synthetic seismograms shown on the top of Figure 1 were made from synthetic logs that modeled the stratigraphic conditions shown on the bottom of the figure. These synthetic seismograms include a source function that was band limited zero to one hundred cycles per second. Thus, they are rich in high frequencies. The pinchout of sand "C" between synthetics 1 and 2 is discernible. The change in acoustic impedance associated with sand "D" is minor and its effects obscured by an earlier event. Thus, it is probably not possible to find the build-up in sand "D". The "FGH" complex can be seen on sample and electric logs, and with careful work can be resolved. However, the complex is not diagnostically displayed by acoustic contrasts on continuous velocity logs, and as a result, the variations in this complex are not displayed on the synthetic seismograms.

The suite of synthetic seismograms in Figure 1 is the seismic representation of the objectives. The pinchout of sand "C" can probably be mapped if the synthetic seismograms can be matched by field seismic records obtained in the prospect area. One requirement is that the field contains considerable high-frequency energy.

Evaluation of Ability of Seismic Method to Achieve Exploration Objective:

The extent to which prior shooting achieved the objective can be evaluated by a comparison with the synthetic examples. In general, such a study will show wherein the objective was not achieved. Changes in reflection character from shot to shot or from a profile may be attributable to variations in the shot pulse, shot environment, ghost reflections or reverberations in the near-surface layering. Quite often the variations from record to record due to these factors strongly over-ride the diagnostic subsurface variables. Thus, a study of prior shooting will indicate to what extent these variables must be eliminated.

Short period reverberations, of the type often encountered in marine work, and the longer period section multiples may completely obscure the objective reflections. These signal-like events may be discernible on the previous shooting, *but generally the records were obtained with automatic gain control or on* short spreads in a manner that makes definite analysis of the problem difficult.

If the exploration objective cannot be achieved by a reanalysis of prior shooting, one may conclude that the reflection quality, as well as its diagnostic content, must be appreciably improved. This requires a much better signal-to-noise ratio in the field recorded data and greater sophistication in subsequent processing.
The characteristics of the organized source-generated noise may be definable from prior shooting of "noise" or "micro" spreads, but generally the noise is complex and apparently random and non-coherent and thus difficult to analyze, and special field and processing techniques may be required.

At this stage in the evaluation or description of the seismic problem we have used synthetic seismograms to describe the exploration objective and thus gain an idea of the diagnostic seismic signal that must be developed; and we have some understanding of the source-generated noise.

Design of the Seismic Exploration System: From previous shooting it is generally possible to draw a block diagram depicting the components that enter into the total seismic problem or system. (See Figure 2). To solve this problem

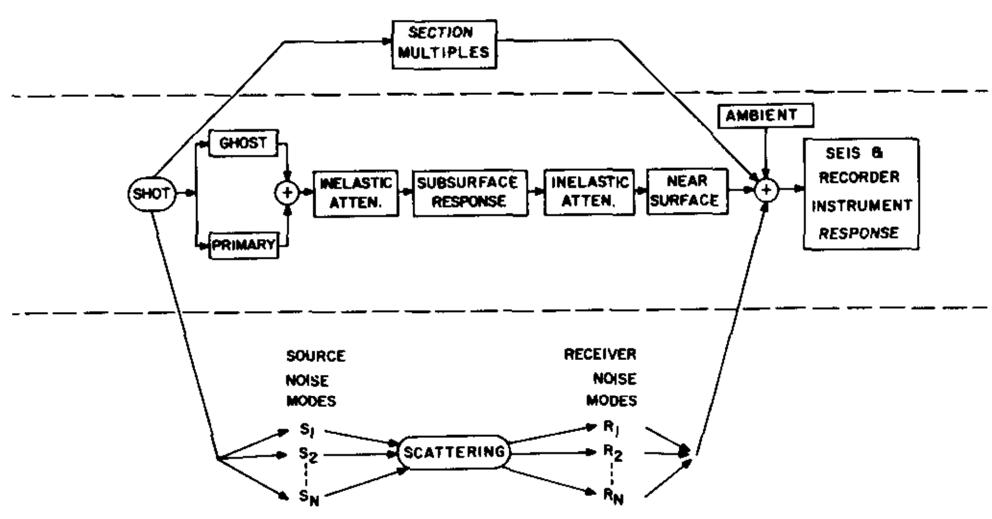

FIGURE 2. *Land seismic system.*

we need to determine the specific contribution of each of these components in the prospect area. This requires investigative, well controlled field measurements. For example, the source characteristics can be ascertained from shots of various sizes, at various depths, and in different environments, to see the effect of these controllable factors upon the source noise and upon frequency content of the record. The characteristics of the various noise modes, their generation and propagation, are determined from analysis of noise spread data. An understanding of the multiple reflection problem can be gained from analysis of velocity profiles (expanding spreads) and from comparison of multiple-free synthetic seismograms with synthetics made to depict various postulated multiple mechanisms.

Example of Seismic System Design: In the area described by the synthetic seismograms of Figure 1, the field records must contain considerable high-frequency energy because the relatively thin sand members are represented by sharp, high-frequency impulses. Thus, a first requirement is to develop a field system that generates and records broad frequency spectra. In this area, shots of various sizes and various depths were analyzed, using digital methods, to obtain the effect of variations in shot conditions upon frequency content of the record. In this analysis the primary interest is in the variation of the source signal function and not the variation in noise generation or in ghosting. Thus, the first digital process applied was the optimum wide band vertical stack or deghost program. This eliminated the ghosting phenomena, even if complex, without effecting the frequency content of the record. (See **Geophysics,** Vol. XXIX, No. 5, page 783, Schneider et al). The next digital process was the elimination of coherent noise using wide band velocity filtering, the Pie Slice process. Once again it is important to remove the noise without removing any of the signal frequencies. Thus, a wide band process is required. **Geophysics,** Vol. XXVIII, No. 6, page 948, Embree et al.) The ghost-free low-coherent-noise record is then analyzed to determine the power spectra, Figure 3 shows the relative power density as a function of frequency for an early portion of the record (0.3 to 0.8 seconds) and for a later portion (1.5 to 2.0 seconds). As would be expected, the shallower reflections have a higher frequency content, with considerable power in frequencies as high as 80 cycles per second. The deeper reflections have a much narrower frequency spectra with much less power in the frequencies above 50 to 60 cycles. It is interesting to note that the high-frequency content in the early record gate drops off at the rate of 0.2 db per cycle, whereas in the later gate the drop-off is a much more rapid 0.4 db per cycle.

In the prospect area, the subsurface strongly filters the high frequencies in the seismic signal. To overcome this, the source should be as rich in high frequencies as possible, and special care must be taken in the use of multiple shots and seismometers to avoid cancellation of high frequencies. The spectra analysis also suggests that special digital processes will be required to recover the high frequencies.

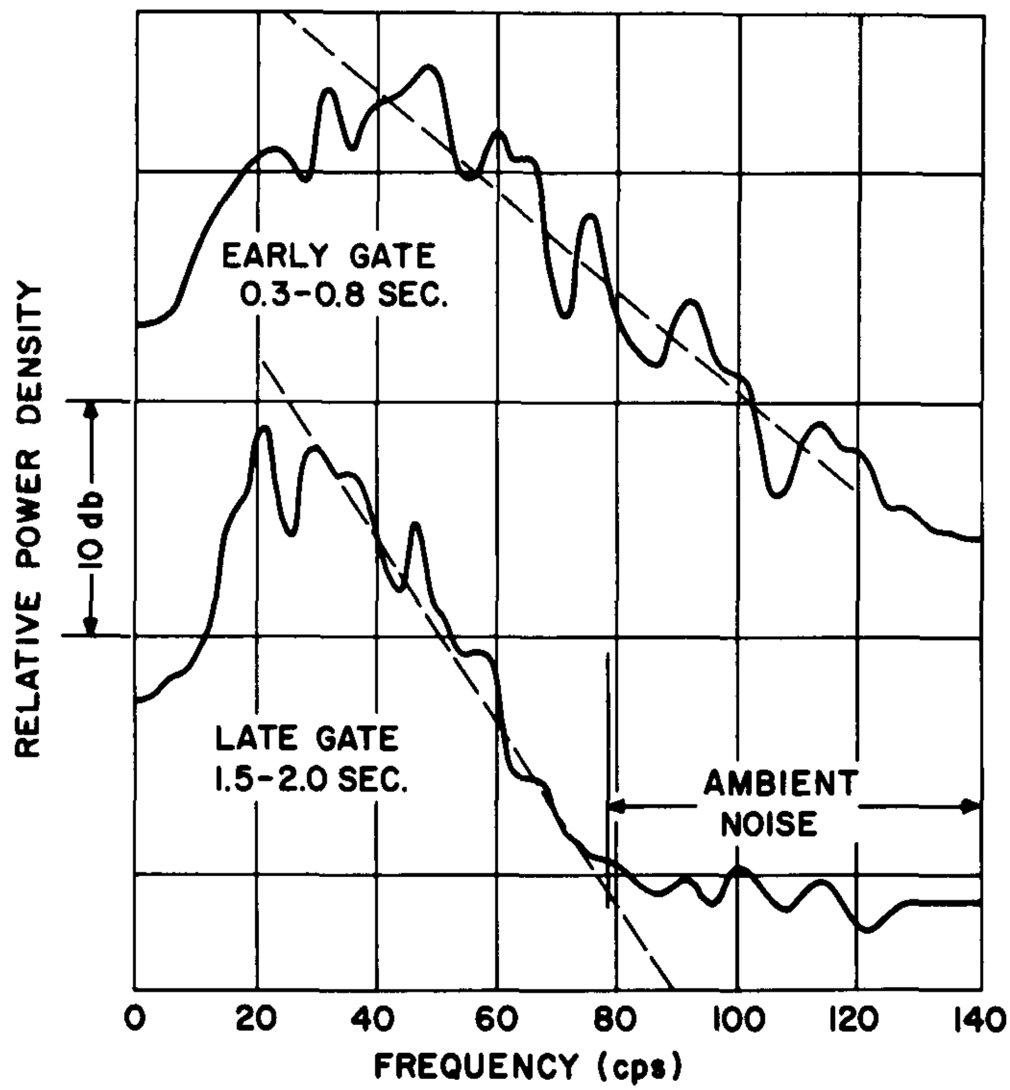

FIGURE 3. *Spectra estimates from deghosted, Pie Sliced record.*

The design of shot patterns and multiple seismometer arrays to eliminate source-generated noise is made much easier if the noise characteristics are represented on a frequency wave-number plot such as Figure 4. In this example the noise spread data were analyzed by digital processes to obtain the noise power as a function (F) and wave number (K). (Note that wave number in cycles per foot is the reciprocal of wave length in feet per cycle.) The apparent velocities represented on the F-K plot range from 833 feet per second to infinity. The dominate coherent noise trains are shear waves, velocity 2000 feet per second, and Rayleigh waves, velocity 800 to 1200 feet per second. The contours show the relative levels of the noise in db.

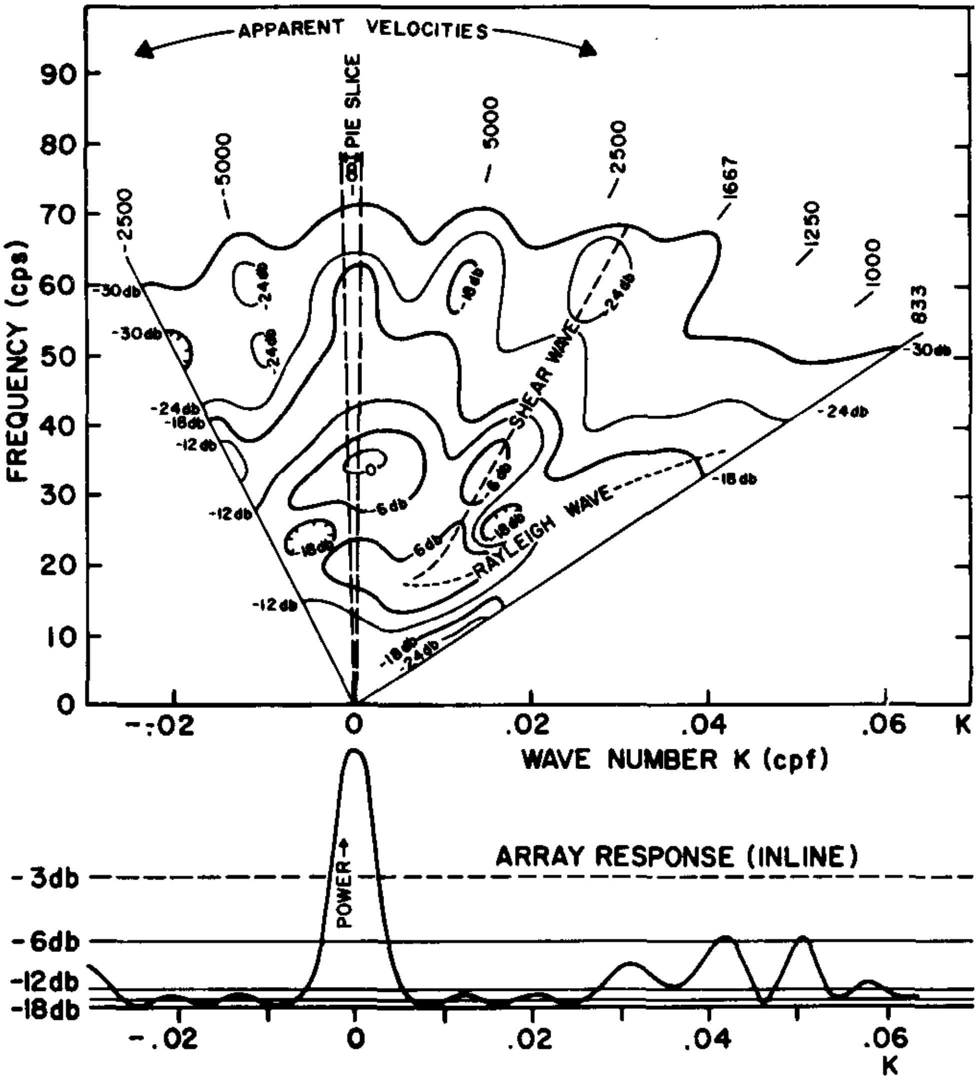

FIGURE 4. *F, K plot of noise power.*

The response of an inline array of seismometers is shown on the bottom of Figure 4. This array will reduce all inline noise in the 0.01 to 0.03 wave-number range by 12 db, which will take care of much of the noise. However, there is considerable zero wave-number noise remaining in the 15 to 40 cycle-per-second range. This indicates that considerable broadside noise is present and areal arrays instead of only inline arrays are needed. This was verified by a similar analysis of data from a cross-spread.

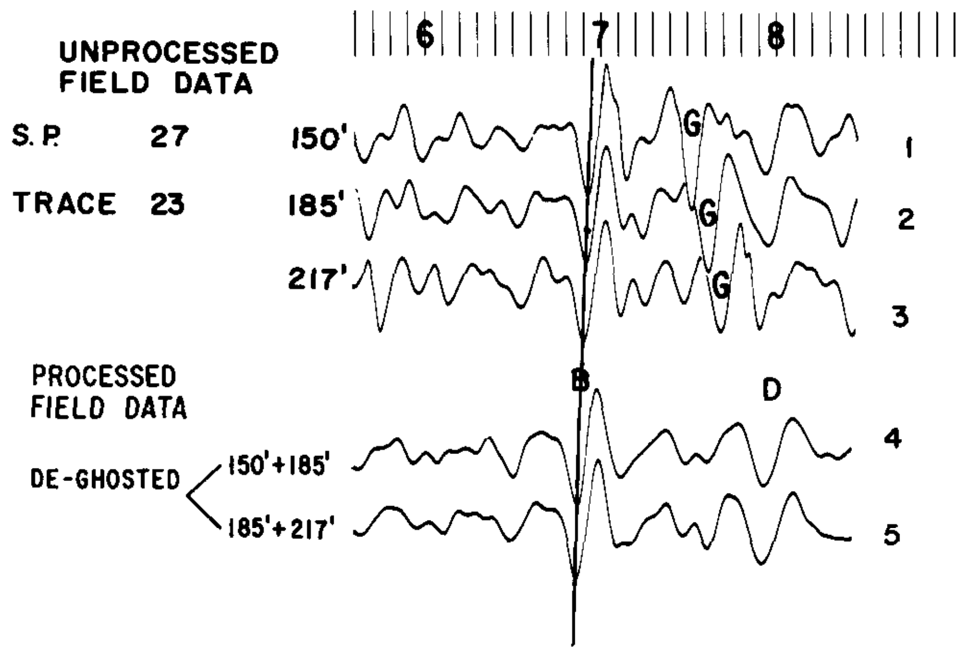

FIGURE 5. *Deghost filtering.*

The ghosting phenomena can be evaluated by shooting shots at different depths. In many areas there is considerable difference in reflection character between shot points and between shots in the same hole. In Figure 5, Trace 23 from S.P. 27 is shown for shot depths 150, 185, and 217 feet. In this example, from Western Canada, the "B" reflection needs to be developed as a reference and diagnostic information is required between the "B" and "D" reflections. It is apparent that variation from shot to shot is great and would obscure the diagnostic subsurface variation. In the digital process known as optimum wide band vertical stack, two or more shots at different depths are filtered with different filters and the output of pairs of filters is summed to obtain a deghosted record. Shots at 150' and 185' are individually filtered and combined to obtain trace 4 in figure 5. The 185' and 217' shots are likewise combined to obtain trace 5. The degree of duplication of traces 4 and 5 provides an evaluation of the process. In this case, reflection "D" is well developed and the effect of ghosting upon the weak reflection between "B" and "D" has been removed. This study shows that field shooting techniques must provide data for ghost elimination.

Evaluation of Seismic System in Prospect Area: At this stage in the program the frequency content of the record has been ascertained. The synthetic seismogram has shown the need for generating and recording a wide frequency spectrum. The noise has been analyzed and the recording and shooting geometry devised. The need for ghost elimination has been demonstrated. The next step is to evaluate

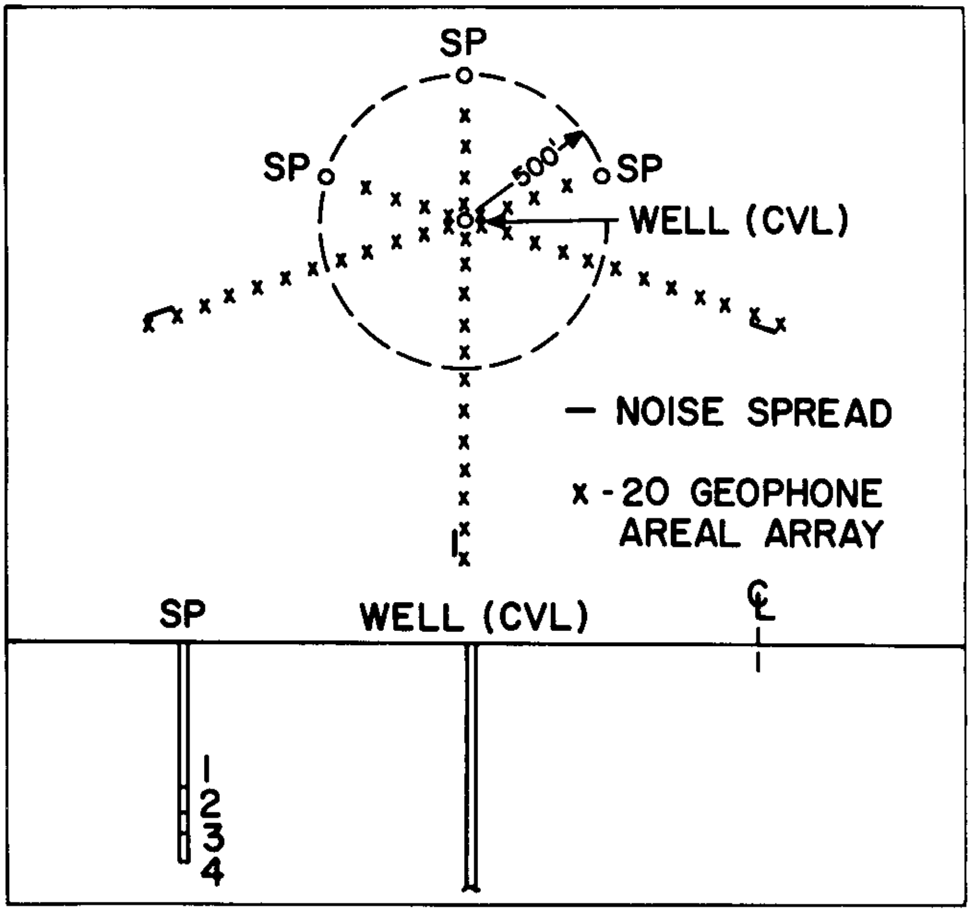

FIGURE 6. *Test shooting plan.*

the system in the prospect area at one or more wells where the objective can be described by synthetic seismograms. The purpose of the evaluation is to ascertain if all spurious and non-diagnostic information can be eliminated. If the end product duplicates the synthetic seismograms, it should be possible to map the exploration objective.

To evaluate the digital seismic system in the Rocky Mountain prospect where the objectives were described by the synthetics in Figure 1, a well was selected from which a diagnostic synthetic seismogram could be made. Three profiles were shot so that they have a common depth point at the well as shown in Figure 6. The traces on these three profiles having a common subsurface were selected and displayed in Figure 7. These traces duplicate reasonably well for some reflections, but in the zone of interest, 1.4 to 1.6 seconds, the duplication is poor. In this example the field records were digitally processed to achieve True Ampli-

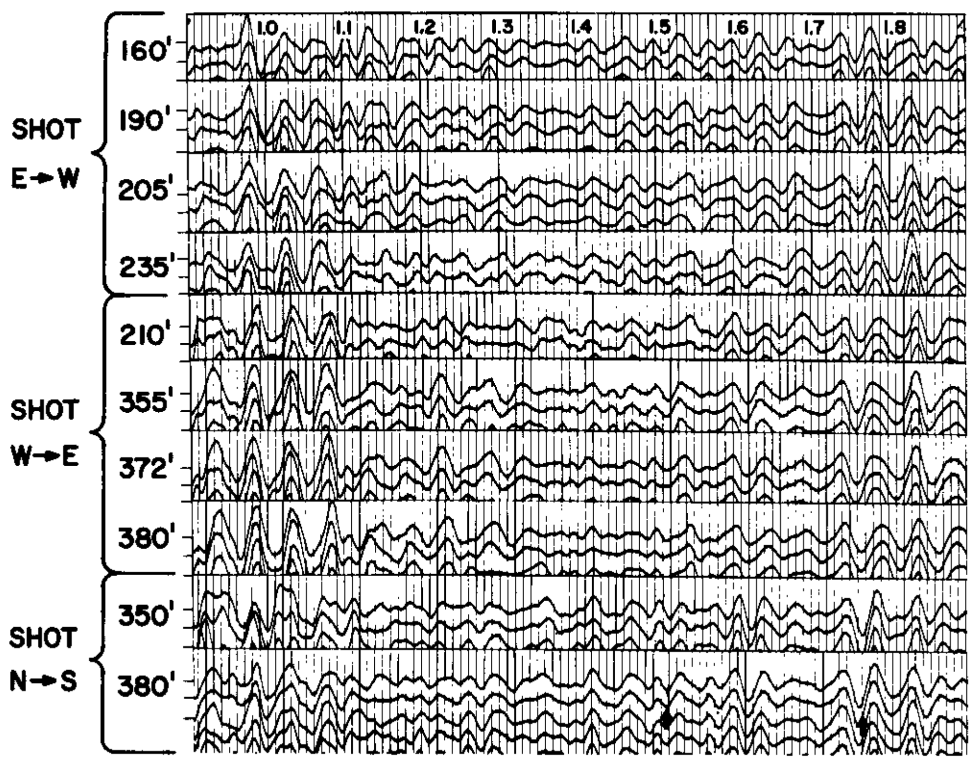

FIGURE 7. *Uphole test shots — T.A.R.*

tude Recovery (T.A.R.). This compensates for spherical divergence, inelastic attenuation and for program gain.

The results from additional digital processing are shown in Figure 8. The deghost process has been applied to pairs of shots to remove the shot variable due to ghosts, and the coherent noise was eliminated by velocity filtering. The traces from pairs of shallow and deep shots and from the three profiles now duplicate quite well. Since the traces all duplicate, it is now permissible to sum or composite the data on the top five traces to obtain the best average seismic representation of the subsurface, as shown on the third trace from the bottom.

The synthetic seismogram on the bottom trace shows a number of objective horizons "A" through "H". At this point there is very poor duplication between the synthetic from the well and the composite trace from surface seismic measurements. The synthetic has been filtered with a time varying filter of 0.5 db per cycle to see the effect of inelastic attenuation. In this case the filtering was probably too severe and probably over-compensated for loss of high frequencies due to travel through the subsurface.

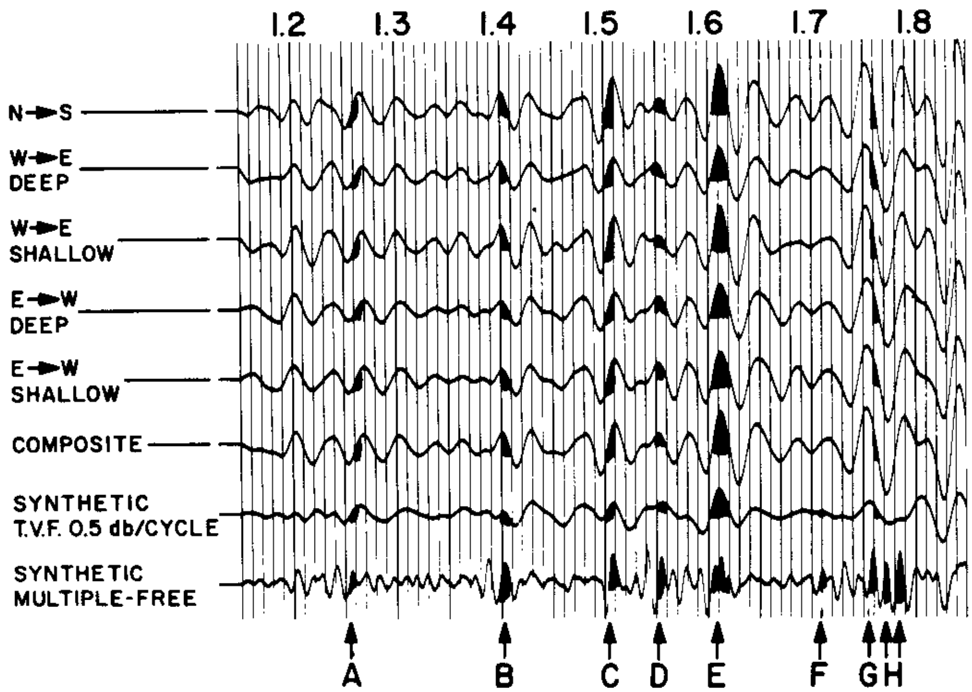

FIGURE 8. *Test shots — T.A.R., deghost, Pie Slice.*

The traces shown in Figure 9 have been individually developed to compensate for remaining variations in character not related to ghosting and to compensate for some of the lack of high frequencies. The individual traces now duplicate very well, and the composite of the five top traces compares quite favorably with the deconvolved synthetic on the seventh trace. The loss of high frequencies resulting from the time varying filtering of 0.5 db per cycle has been recovered by the deconvolution process and the composite, filtered synthetic and synthetic now all agree quite well except for the events at 1.7 seconds.

The results from each step in the digital data processing are summarized in Figure 10. The top trace, which represents the field data with True Amplitude Recovery, shows very little agreement with the synthetic seismogram. Trace 2 shows the application of deghost filtering and Pie Slice velocity filtering to remove the coherent noise. This eliminated most of the shot variable and developed better record character duplication. The third thrace shows the deconvolution data, which now agrees very well with the synthetic seismogram.

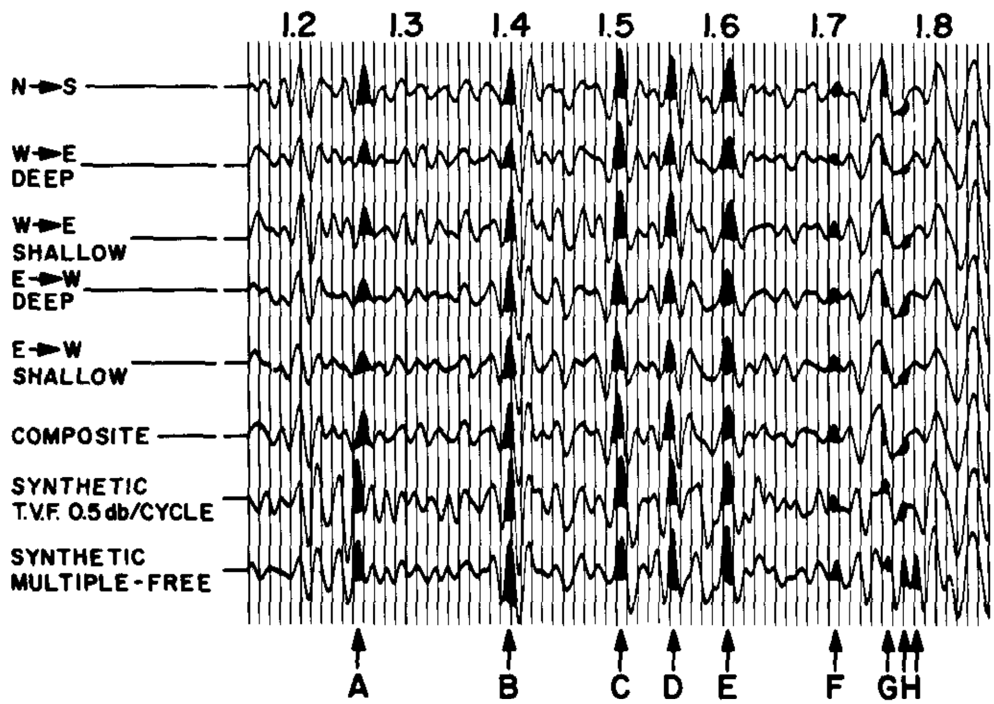

FIGURE 9. *Test shots — T.A.R., deghost, Pie Slice deconvolution.*

Diagnostic Value of Digital Seismic System: The comparison between Trace 3, developed from seismic surface measurements, with Trace 4, developed from subsurface well data shows that events B, C, D and E can probably be mapped reliably. Events F, G and H cannot be mapped. The geophysicist would conclude that subsurface acoustic interfaces causing events B, C, D and E can be mapped by surface seismic measurements and sophisticated data processing. However, referring back to Figure 1, it appears that only event "C" is diagnostic of a sand pinchout and that the acoustic contrasts depicting the other sands are too weak or obscured by other contrasts so that diagnostic events do not appear on the synthetic seismogram. The conclusion is, therefore, that only event "C" truly represents an exploration objective. The sand "D" probably falls somewhere between "D" and "E" reflection events which in themselves are not necessarily diagnostic of changes in sand "D". The "FGH" complex is not diagnostically shown on the synthetic or in the deconvolved record. Thus, this exploration objective cannot be achieved.

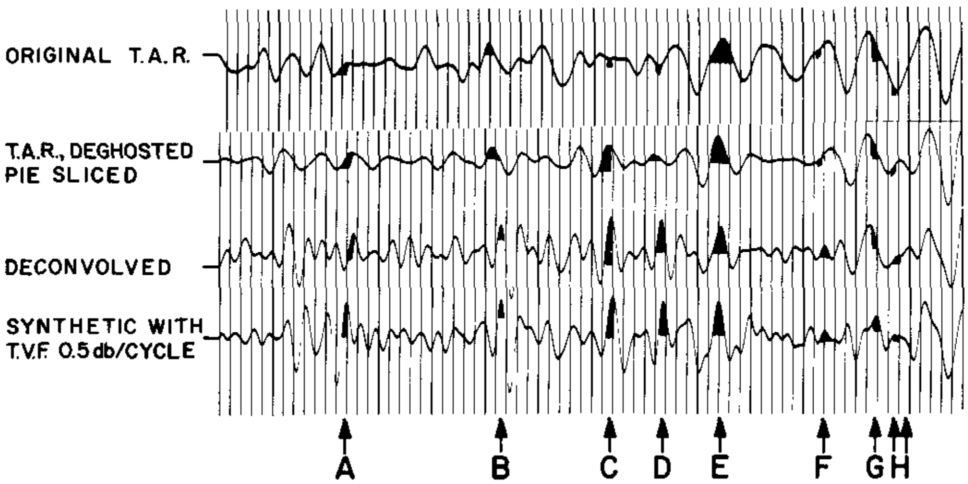

FIGURE 10. *Processing summary.*

At this point in the program the explorationist is assured that sand "C" can be mapped if the results at the test location are diagnosic. It appears that the other objective cannot be achieved. In this example, however, the explorationist decides that sand "C" was an economic objective and production shooting was initiated. Control lines between wells were shot, additional synthetic examples were computed, and the seismic system was periodically modified to compensate for variations in the surface and subsurface conditions.

Geological Value of Digital Seismic Technology: The digital computer and digital technology, including means for recording seismic data in computer format and means for displaying the computer output in a format most readily correlated with subsurface information, provides a significant new tool or capability for the explorationist. A fundamental, step-by-step approach to the solution of the exploration problem can now be applied. These steps can be briefly stated:

I. Describe the exploration objective by synthetic logs based on existing well data.

II. Describe the objective in seismic terms, converting well data into acoustical data and into synthetic seismograms.

III. Compare synthetic seismograms with synthetic logs to see to what extent the exploration objective is represented on the synthetic seismogram. Define the seismic objective.

IV. Evaluate ability of prior shooting to define the seismic objective.

V. Describe the seismic problems that tend to obscure the seismic objective, using prior shooting, specially recorded digital data and analytical digital processes.

VI. Design the over-all seismic system including field recording techniques and digital processing.

VII. Evaluate seismic system in prospect area at several control points.

VIII. Optimize the seismic system to achieve seismic objective in most economical manner.

IX. Shoot several lines between control points to evaluate production system.

X. Continually modify seismic system to accommodate changing field conditions or unpredicted changes in exploration objective and to encompass improvements in digital technology.

It is now basically possible, using digital technology, to obtain seismic results from surface seismic measurements that are essentially identical to synthetic seismic results obtained from well data. The degree to which this can be done in each prospect area can be predicted from a definitive analysis of the seismic problems and by application of the optimum seismic system at several control points in the prospect area.

The long trem objective, in the development of digital technology, is to obtain a well log equivalent from surface seismic measurements. When this becomes possible, the exploratory well will be replaced by a seismic surface measurement and only development wells will be drilled. Thus, funds in drilling budgets will be transferred to seismic budgets and the ratio of dry holes to producing wells significantly reduced.