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GEOPHYSICS

# DEEP-HOLE GEOPHONE STUDIES*

FRANKLYN K. LEVIN† AND RALPH D. LYNN†

## ABSTRACT

Seismic surveys have been made in eight widely separated wells with two types of wall-coupled geophones. These geophones accurately detected and reproduced elastic waves traveling in the earth.

Both direct (initial) pulses from shots and reflection events were studied. The complexity introduced into the initial pulses by secondary reflections varied from well to well. Amplitude decayed as the negative 2.4 power of travel time. Pulse-broadening caused by selective absorption of high frequencies was found. Different wells showed amounts of broadening ranging from nearly complete to that indicating little absorption of high seismic frequencies.

Reflections from interfaces below the geophone were traced to their origin in the earth. At three wells, the same reflections were found on surface seismograms giving an identification of surface-detected reflections and of reflector depth. Multiple reflections were distinguished from direct reflections and were found to mask the latter at four wells. In one case, multiple reflections were identified with events on surface records.

Reflection coefficients found for direct reflections averaged 0.36.

Accurate velocity surveys of the wells resulted from this work.

## INTRODUCTION

Although understanding elastic pulse behavior in the earth is fundamental to exploration with the reflection seismograph, few investigators have studied the subject. Ricker (1953) and McDonal et al. (1958) examined pulses traveling through the relatively uniform Pierre shale. Jolly (1953) investigated pulses propagating through a more common type of earth section. With a special well geophone, he detected seismic pulses far below the surface. The present study is a continuation of Jolly's work. We shall report results from seven additional wells and shall describe a new type of geophone used in six of them. The location of the wells, the pertinent information about them, and the data for the well discussed by Jolly (Coleman Stephens No. 2) are given in Table I.

## INSTRUMENTS AND FIELD PROCEDURES

With a few exceptions, the instruments and procedures for this study were identical with those of Jolly. The major exception was the well geophone, two

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† Jersey Production Research Company, Tulsa, Oklahoma.

types of which were used. The first resembled that described by Jolly, but it differed in several respects. The principal difference lay in the lock-in section, which consisted of one motor-driven arm that could be retracted and extended from the surface. With this instrument, we could survey going down or coming up the well. Also, the variable reluctance detector of Jolly's original geophone was replaced with a 4-cps dynamic unit. Finally, the preamplifier design was changed to give improved high-frequency response. Two geophones of this type were

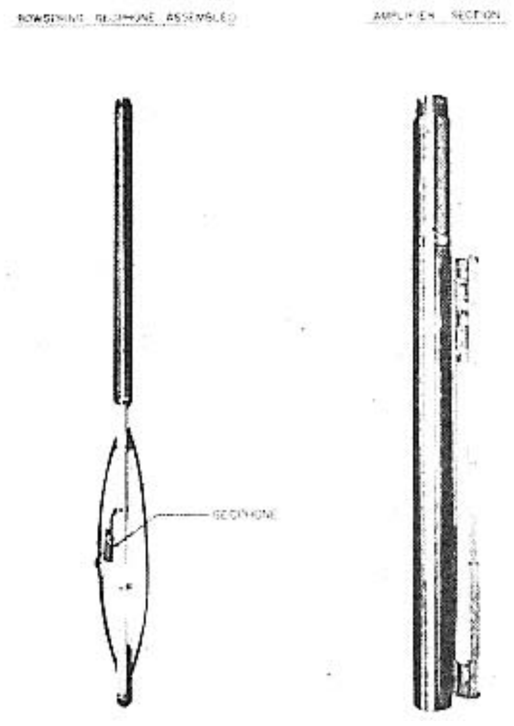

FIG. 1. Bow-spring deep-hole geophone.

built and run in tandem in one well (Walter Morris No. 1). Difficulty in locking the geophones at the desired depth and unduly long survey times led to the design of our present unit, the bow-spring deep-hole geophone.

Like the locking-arm geophones, the bow-spring deep-hole geophone consists of detector, lock-in and preamplifier sections (Figure 1). The detector is a 17-cps dynamic seismometer in a heavy case. It is carried at the center of one of two bow-springs and is coupled to the borehole wall at two points. A slip joint at each end of the bow-spring section provides mechanical decoupling from the remainder of the instrument. The preamplifier has an overall gain of about 275 and an output impedance of about 300 ohms. The frequency response is flat from about 17 to 500 cps. It is limited by the frequency of the seismometer and by the electrical capacity of the logging cable. The preamplifier is powered by mercury batteries and is controlled from the surface.

Either type of wall-coupled geophone accurately measures earth particle velocity amplitudes. Under identical conditions, locking-arm and bow-spring instruments give the same results. However, for operational ease, we favor the

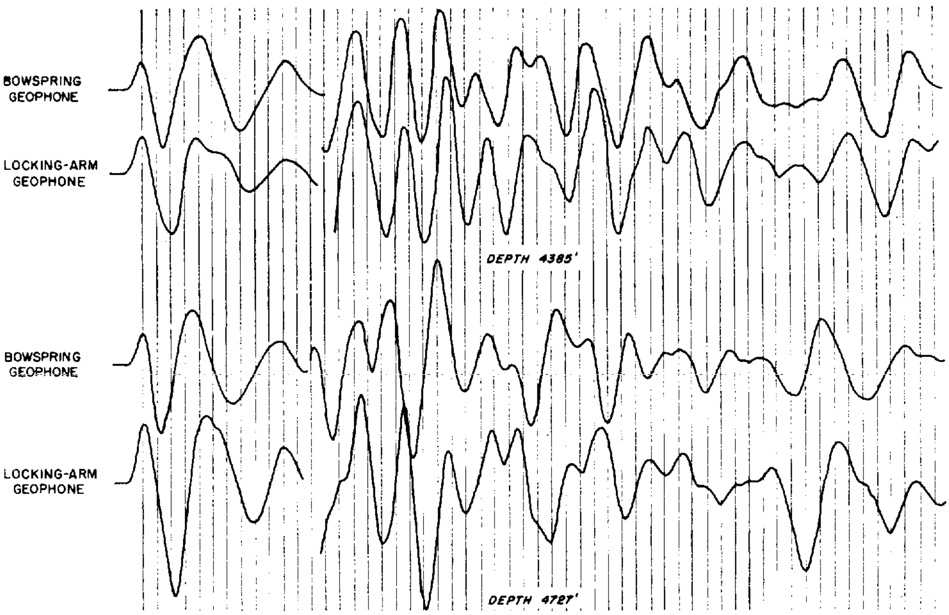


FIG. 2. Comparison of signals from bow-spring and locking-arm deep-hole geophones.

bow-spring geophone. Figure 2 is a comparison of signals from the two instruments. For the lower pair of traces, the charges were not at exactly the same depth; a corresponding time difference is apparent.

## THE INITIAL PULSE

Two types of data resulted from deep-hole geophone studies. By examining the initial shot pulses, we could determine how travel through an earth section modified simple seismic pulses. Also, we could detect reflections, track them to their source in the earth, and differentiate them from multiple reflections.

The initial pulses from shots detected in the wells of Table I changed shape in a regular manner with depth, but there were differences between pulses from different wells (Figures 3 to 11). Some pulses were simple and resembled Ricker wavelets (Figure 7) with their shape independent of detector depth. Others,

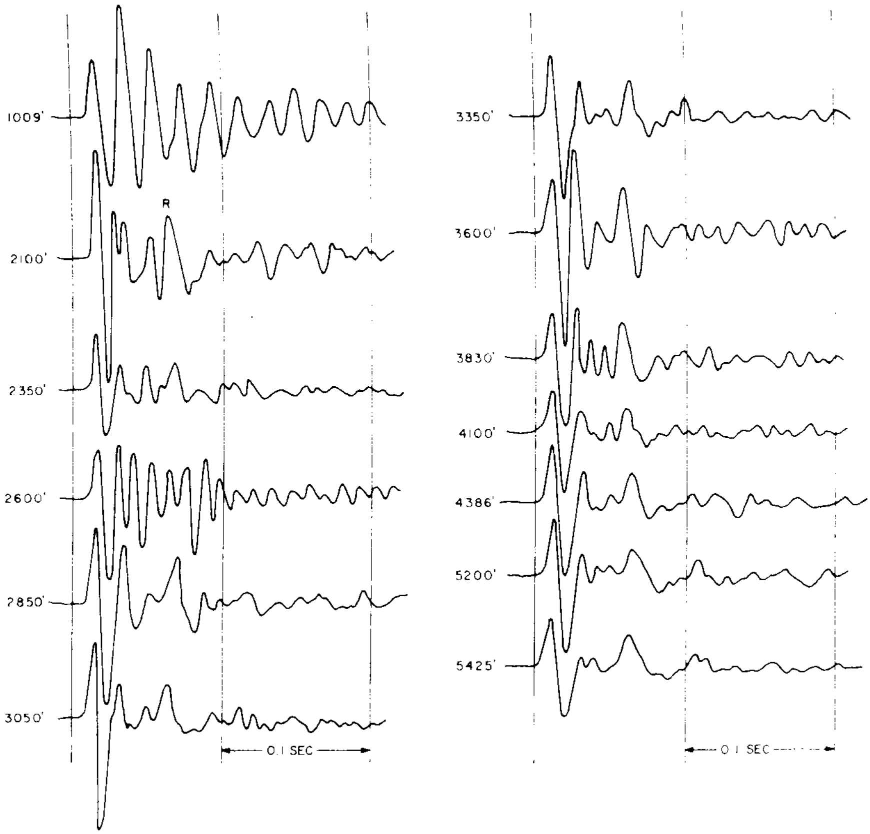


FIG. 3. Initial seismic pulses from hole shots—Coleman-Stephens No. 2.

initially simple, became complexes of several cycles (Figure 9). In addition, all pulse changes between these extremes occurred.

Two mechanisms contributed to the shape changes. First, high frequencies were attenuated more than low frequencies so that the pulses broadened. Secondly, the pulses added cycles or distinct secondary events. A principal source of secondary energy was the reflection from the surface. Van Melle and Weatherburn (1953) called this event the ghost reflection. Ghost reflections generated by reflection from the base of the weathered zone were not detected here, since we shot just below that depth. Surface-generated ghost reflections appear in Figures 3, 5, and 8, where they are marked with *R*. By far the most spectacular example occurred at the Navajo Tribe No. 1 (Figure 8). It was a perfect inverted image of the initial pulse, and its average amplitude was 0.85 that of the initial pulse. Since the effective initial pulse consisted of the actual initial pulse and the ghost reflection, reflections in the vicinity of the Navajo Tribe No. 1 were double.

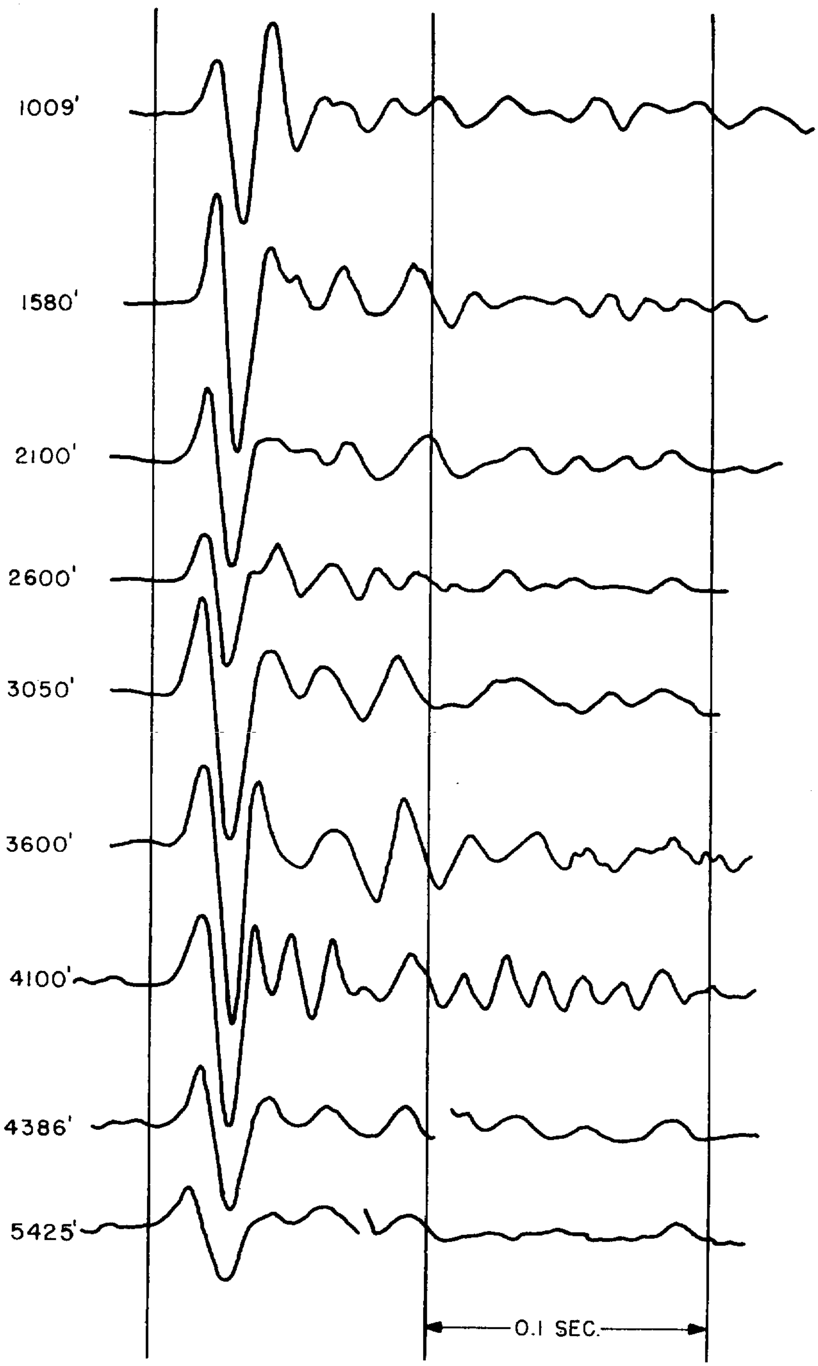


FIG. 4. Initial seismic pulses from air shots—Coleman-Stephens No. 2.

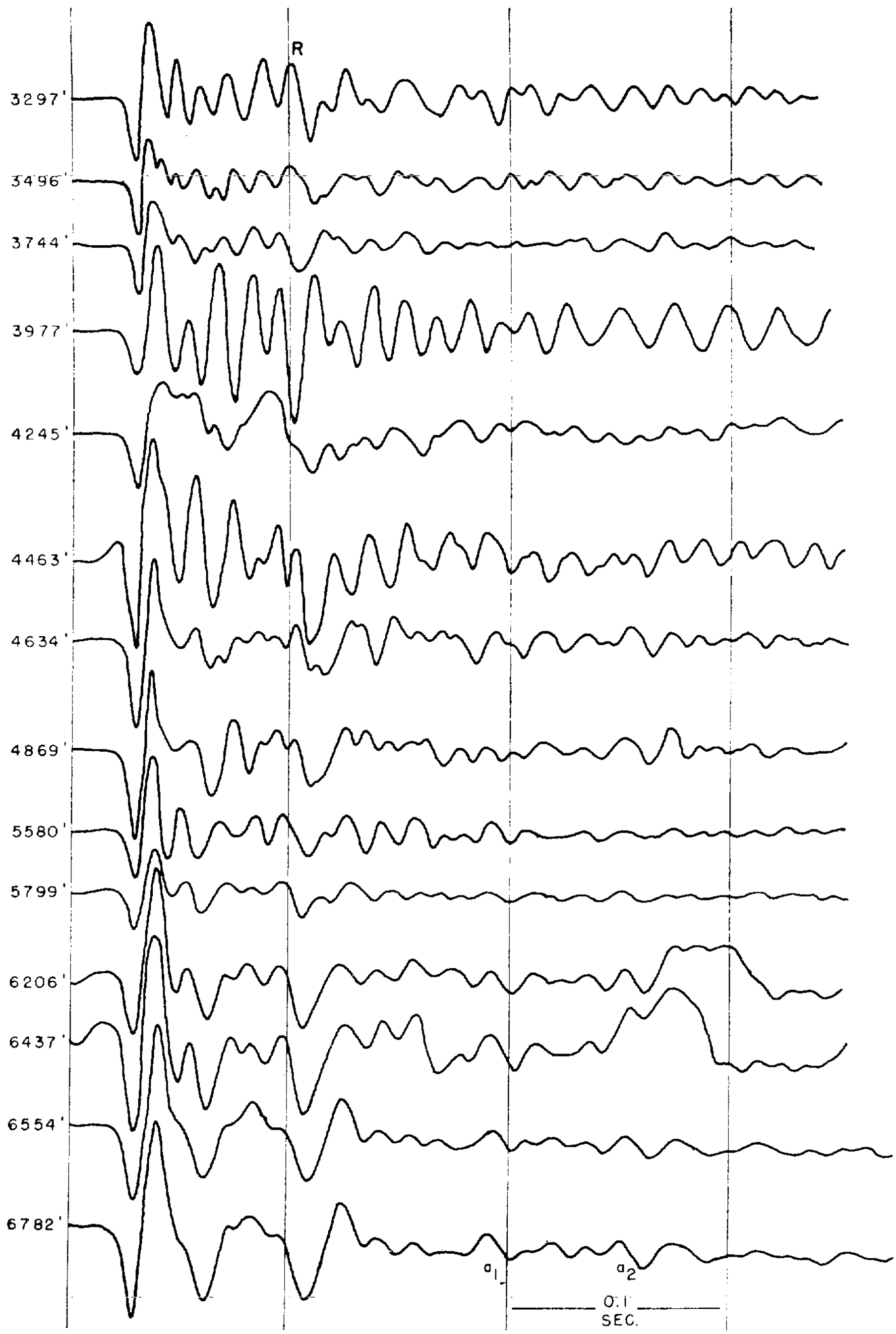


FIG. 5. Initial seismic pulses—Walter Morris No. 1.

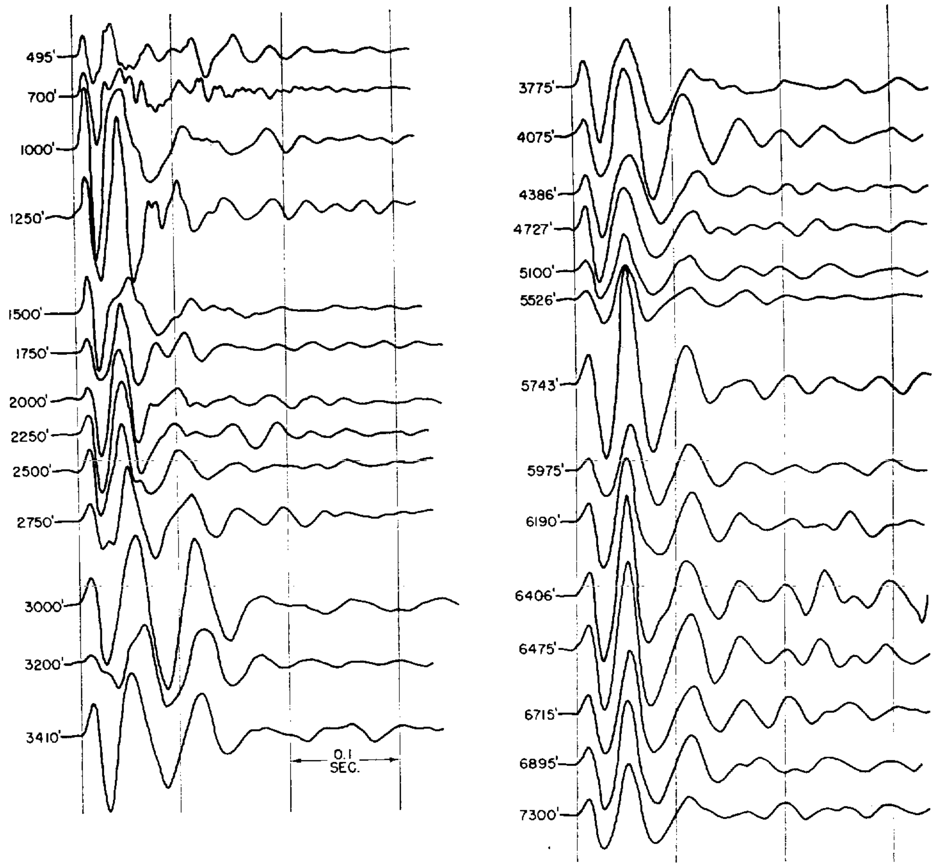


FIG. 6. Initial seismic pulses—Mayme Morrissey No. 1.

Ghost reflections at the other two wells (Figures 3 and 5) were smaller than those at the Navajo Tribe No. 1, the average ratio of ghost reflection amplitude to initial pulse amplitude being 0.46 and 0.44 respectively. Although the ghost reflections were less obviously inverted images of the initial pulses, in both cases the travel times were twice the uphole time. Air shots (Figure 4), as expected for sources above the surface, produced no ghost reflections.

In addition to ghost reflections, interbed and intrabed reflections affected the initial pulse shape by modifying and extending the initial pulse. The amount of complication introduced by interbed and intrabed reflections varied from well to well. At the Gothic Nose No. 1 (Figure 9), for depths greater than 2,000 ft, two distinct events (designated $a_1$ and $a_2$) appeared immediately following the direct arrival. The first of these was 0.50, the second 0.35 times as large as the initial pulse. Because of data scatter, the numerical values are not too significant. $a_1$ and $a_2$ arose as reflections within massive low-speed beds from 2,020 to 2,245 ft.

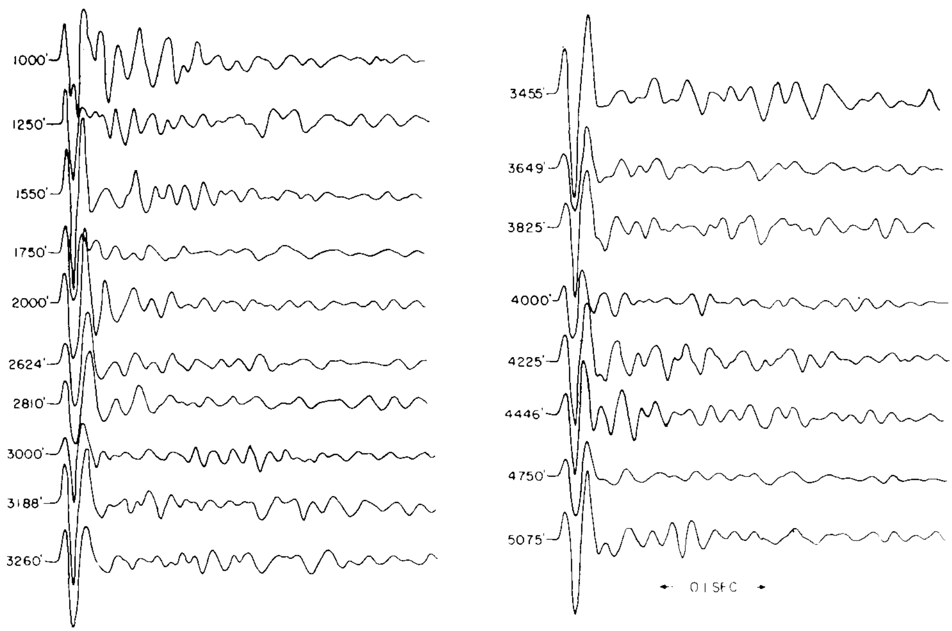


FIG. 7. Initial seismic pulses—Hurley No. 1.

In agreement with the theory of multiple reflections, $a_1$ and $a_2$ are erect and are separated from the initial pulse by twice the travel time through the beds involved. Wave forms from depths above 1,900 ft do not show $a_1$ and $a_2$ (see, for example, the 1,883-ft form of Figure 9). The large sizes of $a_1$ and $a_2$ are difficult to explain on the basis of reasonable velocity and density values.[1]

Although the largest secondary event at the Walter Morris No. 1 was the ghost reflection, there were minor secondaries, indicated as $a_1$ and $a_2$ on Figure 5. $a_1$ arose as a multiple reflection within a massive high-speed layer, predominantly limestone, dolomite, and anhydrite from 4,633 to 5,798 ft; $a_2$ is the corresponding event generated by the ghost reflection. As expected for multiple reflections, $a_1$ and $a_2$ have the same polarities as the initial pulse and ghost reflection respectively; and their time separation from their generating pulses, 0.15 sec, is twice the travel time through the massive layer. Also, both $a_1$ and $a_2$ disappear near the top of the layer. The ratios of amplitudes $a_1$ to the initial pulse and $a_2$ to the ghost reflection are 0.14 and 0.32. In theory, if the multiply reflected

[1] The persistence of events $a_1$ and $a_2$ at the Navajo Gothic Nose No. 1 emphasizes the atypical nature of two of the records, one recorded at 2,883 ft, the other recorded at 4,333 ft, on neither of which $a_1$ and $a_2$ appear. Poor coupling of the geophone to the borehole wall, presumably caused by hole washouts, was responsible for the record peculiarities. In later work, the well caliper log was used to avoid setting the geophone in washouts.

pulses were identical with their generators, the two ratios should be the same. However, the high frequency loss shown by the traces from 5,799 and 6,206 ft occurred within the massive layer. Since the ghost reflection had already lost high frequencies in the weathered zone, it was less affected than the initial pulse. Trapping of high frequencies within the massive layer is the probable cause of the phenomenon.

The effect of multiple reflections upon the initial pulse was most marked at the Sarah Harman No. 1 (Figure 11). If the initial energy is defined as both the first arrival and the secondary events moving with it, the initial energy duration was more than 0.2 sec at the Sarah Harman. Except for loss of high frequencies, all wave forms recorded from 1,576 to 5,892 ft were essentially the same. Some of the secondary events were large; at 5,892 ft, the event marked $a_1$ is 0.47 times

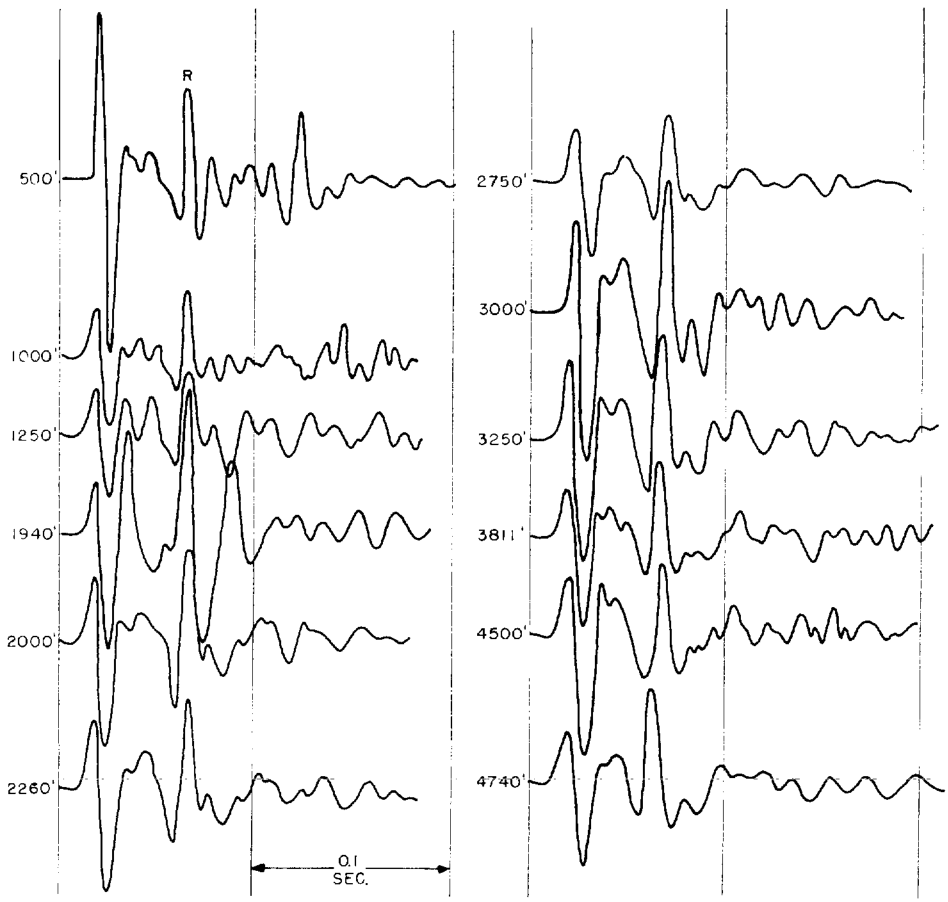


FIG. 8. Initial seismic pulses—Navajo Tribe No. 1.

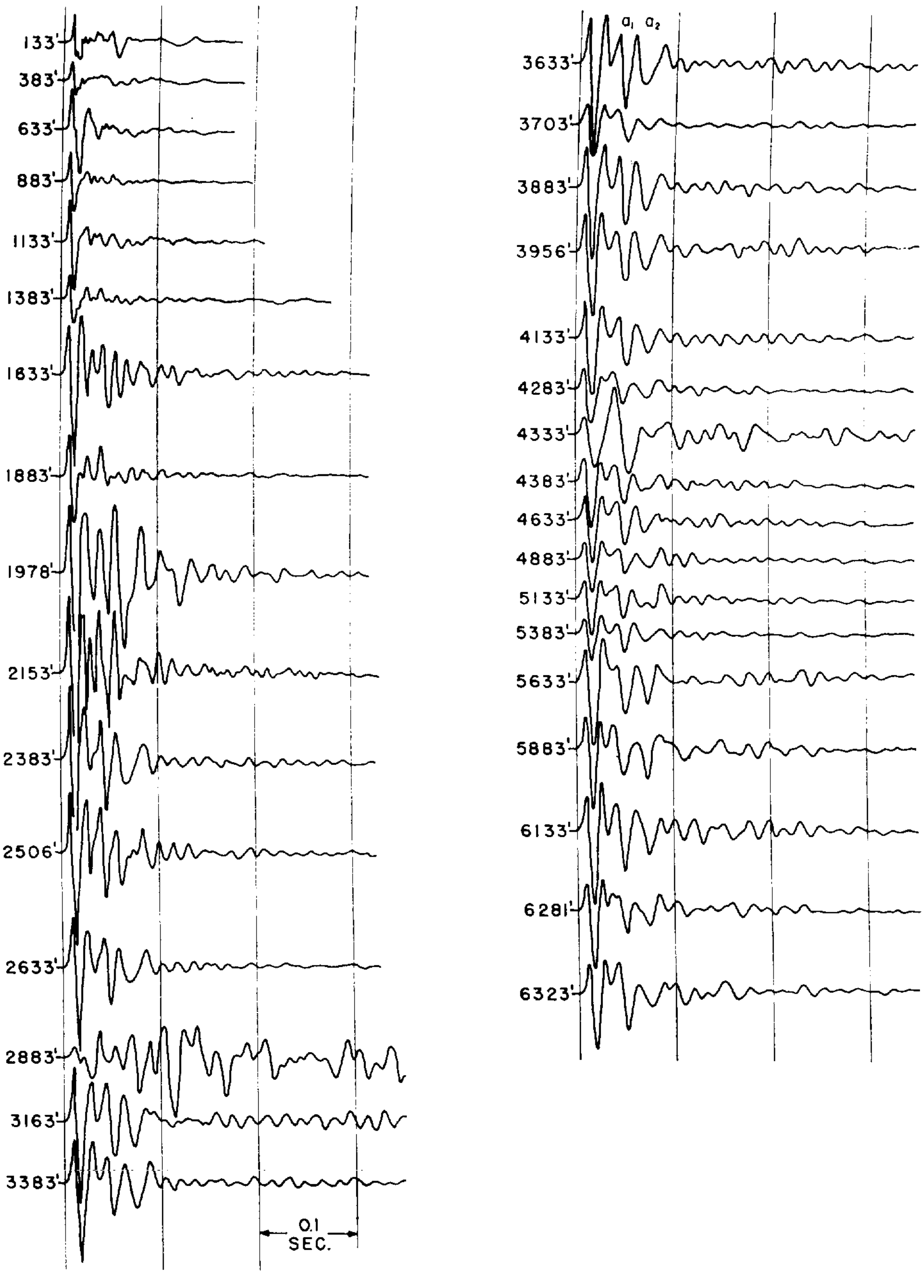


FIG. 9. Initial seismic pulses—Navajo Gothic Nose No. 1.

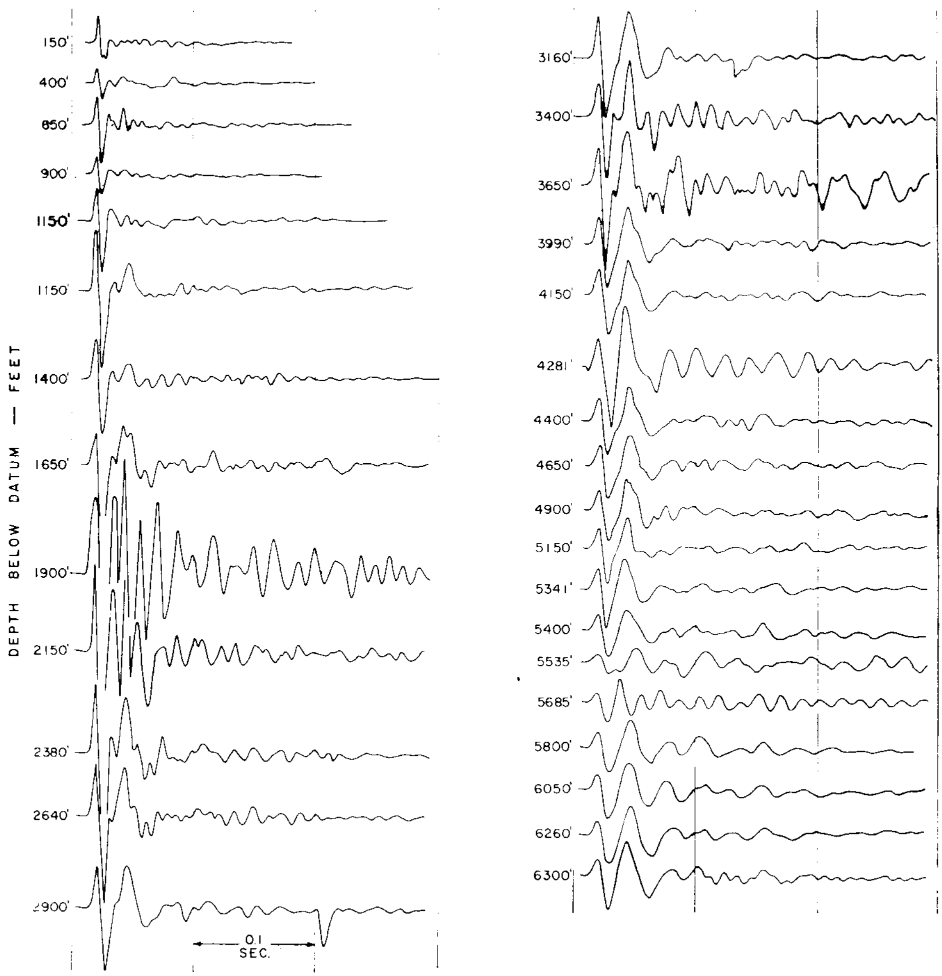


FIG. 10. Initial seismic pulses—Navajo White Mesa No. 2.

as large as the initial pulse. Other secondaries were smaller but persisted at all depths. Apparently the major generators of secondary events were three anhydrite and gypsum layers, each 30 to 40 ft thick, in the depth range of 900 to 1,600 ft. These layers, embedded in a thick shale section, had been cased off and did not appear on the electric or continuous velocity logs, but they showed as major features on the neutron log of the Sarah Harman well.

Of the eight wells listed in Table I, only three have initial pulses uncomplicated by ghost reflections or multiple reflection energy. It is the complete complex—initial pulse, ghost reflection, and multiples—that impinges upon an

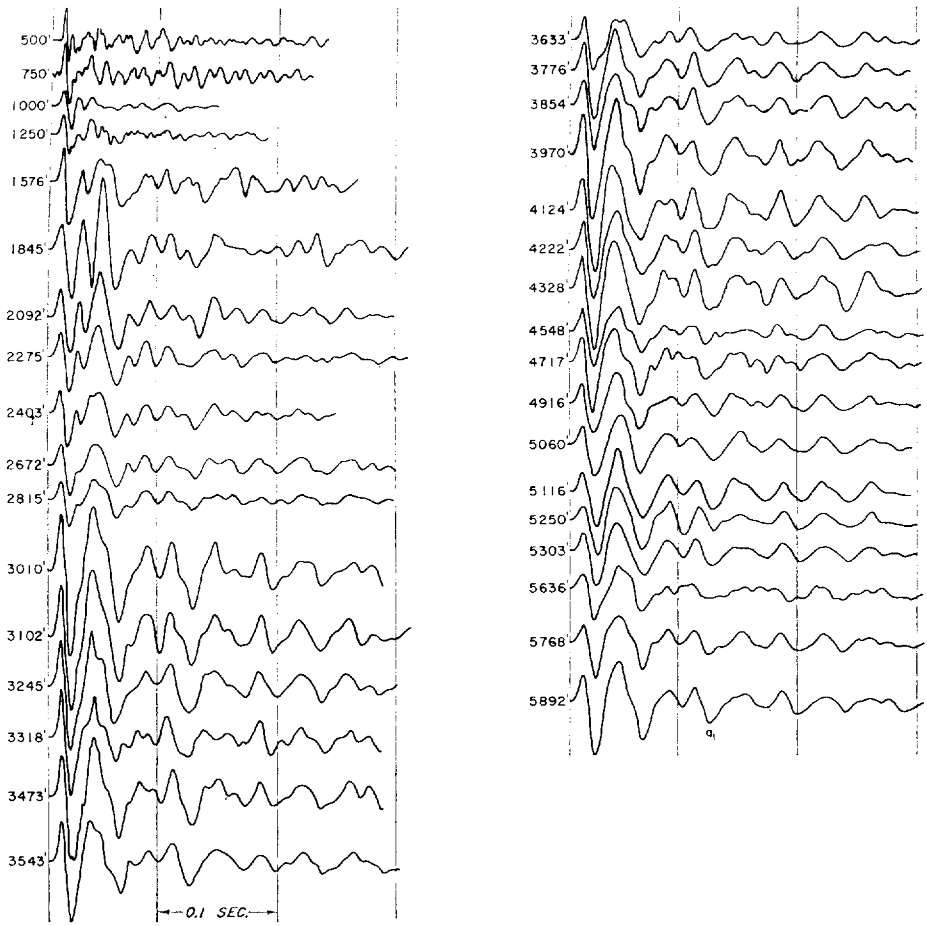


FIG. 11. Initial seismic pulses—Sarah Harman No. 1.

TABLE I
WELLS SURVEYED WITH DEEP HOLE GEOPHONES

| Name | Location | County | State | Depth (ft) | Casing (ft) | Date Surveyed |
|---|---|---|---|---|---|---|
| Coleman Stephens No. 2 | 35-T2N-R2W | Garvin | Oklahoma | 5,503 | 520 | 9-28-50 |
| Walter Morris No. 1 | 36-T18N-R8W | Webster | Louisiana | 9,636 | 3,001 | 10-30-52 |
| Mayme Morrissey No. 1 | 6-T161N-R92W | Burke | North Dakota | 7,321 | 618 | 4-16-55 |
| Hurley No. 1 | 7-5N-11ECM | Texas | Oklahoma | 5,100 | 1,496 | 5-16-55 |
| Navajo Tribe No. 1 | 4-41N-28E | Apache | Arizona | 6,382 | 911 | 9-20-55 |
| Navajo Gothic Nose No. 1 | 33-T41S-R22E | San Juan | Utah | 5,573 | 1,360 | 11-25-55 |
| Navajo White Mesa No. 2 | 22-T42S-R24E | San Juan | Utah | 5,606 | 1,386 | 12-19-55 |
| Sarah Harman No. 1 | 20-T4N-11ECM | Texas | Oklahoma | 5,916 | 1,592 | 3-20-56 |

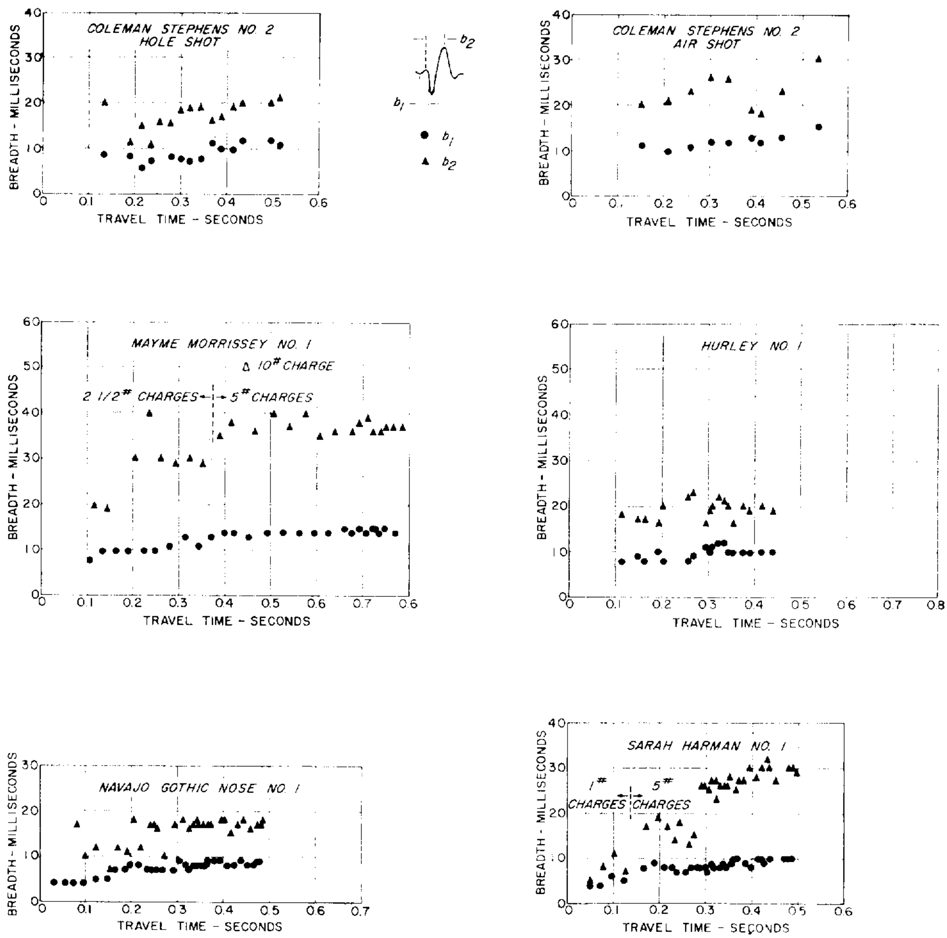


FIG. 12. Pulse breadth versus travel time—typical examples.

interface and is reflected. If the pulse complication shown here is typical, isolated "wavelet" reflections must be rare indeed.

Figures 3 to 11 illustrate qualitatively the tremendous variation in the shape of initial pulses from shots. To describe the pulses quantitatively, we give their frequency spectra and amplitudes. Plots of pulse breadth against travel time indicate in a crude manner the change in frequency content due to travel through the earth. Figure 12 shows typical breadth-time plots for some of the wells of Table I.

Pulse breadth behavior was much the same at each well: The breadths increased with increasing travel times. The magnitude of the effect varied from well to well and was more marked for $b_2$, the peak-to-peak breadth, than for $b_1$, the

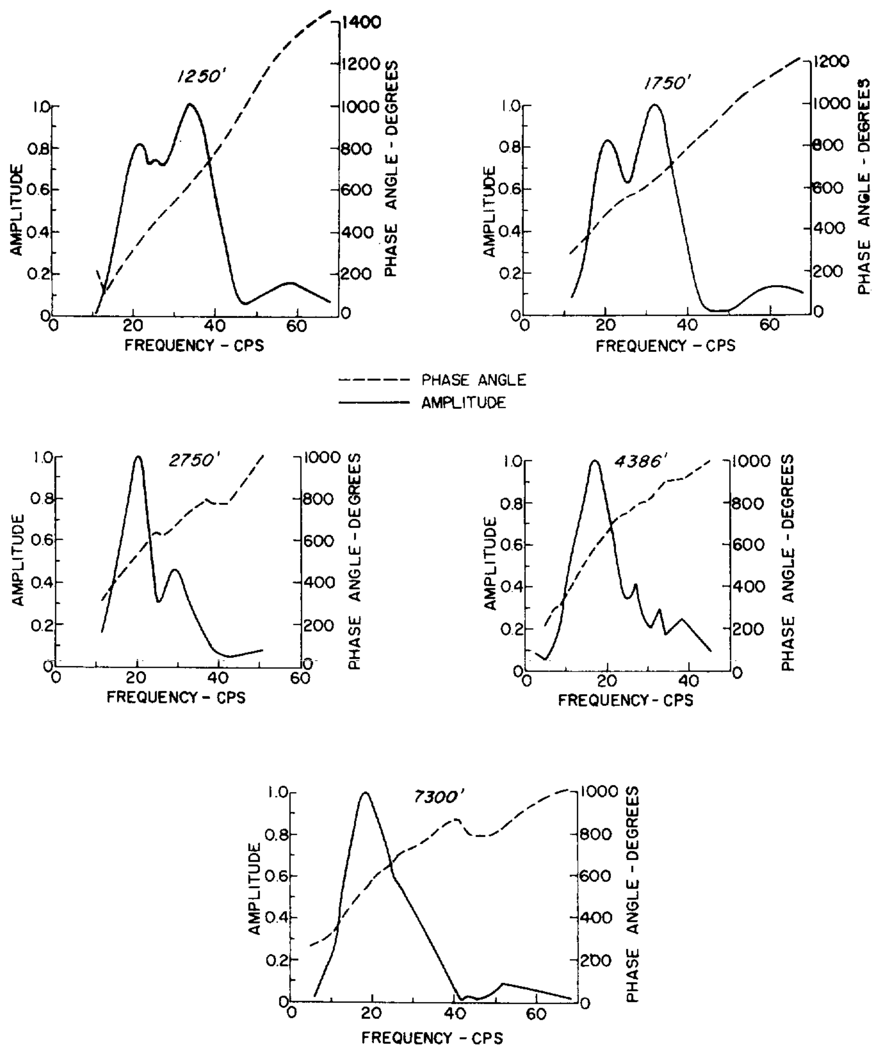


FIG. 13. Frequency spectra of initial pulses—Mayme Morrissey No. 1.

half-breadth. The $b_1$'s changed only slightly, the range in an extreme case being 4 to 10 milliseconds. On the other hand, $b_2$'s as high as 50 milliseconds and as low as 5 milliseconds were measured, and a 20-millisecond change was recorded at one well. The variation of pulse breadth with travel time was negligible at the Hurley No. 1 and Navajo Tribe No. 1, small at the other two Navajo wells and the Coleman Stephens No. 2, and considerable at the Mayme Morrissey No. 1 and Sarah Harman No. 1.

A comparison of hole and air shot breadths is interesting. At the Coleman

Stephens No. 2, air shot breadths were larger than those from hole shots (Figure 12), even though the air charges were only half the size of those fired in holes. The amplitudes of the pulses from the air shots were 1/30 of those from the hole shots.

Although charge size appears to affect pulse breadth, the data on this factor were too incomplete to permit us to correct the measured breadths to a standard charge.

Since breadth-time plots did not supply sufficiently detailed information on the frequency content of the initial pulses, we found the frequency spectra of the pulses. Figures 13 and 14 are spectra of initial pulses at several depths for the two wells of Table I showing a systematic frequency change with depth: Mayme Morrissey No. 1 and Sarah Harman No. 1. The changes at other wells were less marked.[2] Indeed, spectra from the Hurley No. 1 were single-peaked, bell-shaped, and nearly independent of depth. The corresponding initial pulses (Figure 7) were wavelet forms.

Spectra from the Mayme Morrissey No. 1 (Figure 13) and Sarah Harman No. 1 (Figure 14) showed selective attenuation of high frequencies.[3] For the Mayme Morrissey, the spectrum at 1,250 ft was two-peaked; this degenerated into a single-peaked curve at 7,300 ft, the maximum at 40 cps decreasing relative to the one at 20 cps and eventually vanishing completely. Similarly, for the Sarah Harman, a large peak near 55 cps in the 1,845-ft curve was all but gone at 5,892 ft. A peak at 40 cps, absent on the 1,845-ft spectrum, became prominent at greater depths.

It is not immediately obvious why in some areas there is marked attenuation of high frequencies; in others, relatively little selective attenuation. Logs of the Mayme Morrissey No. 1 indicated a geologic column consisting mostly of low-velocity shales. Such a section might absorb high frequencies more readily than one made up of high-speed carbonates. On the other hand, the Hurley and Sarah Harman wells were near each other and, although on opposite sides of a fault, cut similar geologic sections. The phenomena observed here are still obscure.

Another factor in a quantitative description of initial pulses was investigated, i.e., pulse amplitude. Figure 15 is a typical plot of log amplitude against log travel time. As in Jolly's Figure 4, the least square straight lines fit the data reasonably well. The values of the slopes (attenuation constants) are tabulated in Table III. The average values of $-2.38$ and $-2.26$ are lower than the $-2.5$ predicted by Ricker (1953) for a homogeneous isotropic medium and found experimentally in his Pierre shale work. Little significance can be assigned to the average slope values, since data points from the individual wells scatter, and

[2] Because of the uncertainty as to what comprises the initial pulse, the time at which the form being analyzed was cut off was chosen arbitrarily. This was unfortunate, but apparently unavoidable.

[3] The spectra were not sufficiently consistent with depth to permit us to determine the attenuation law of frequency with depth. Small differences caused by different shots for each pulse and different coupling at each depth were responsible for the observed data scatter.

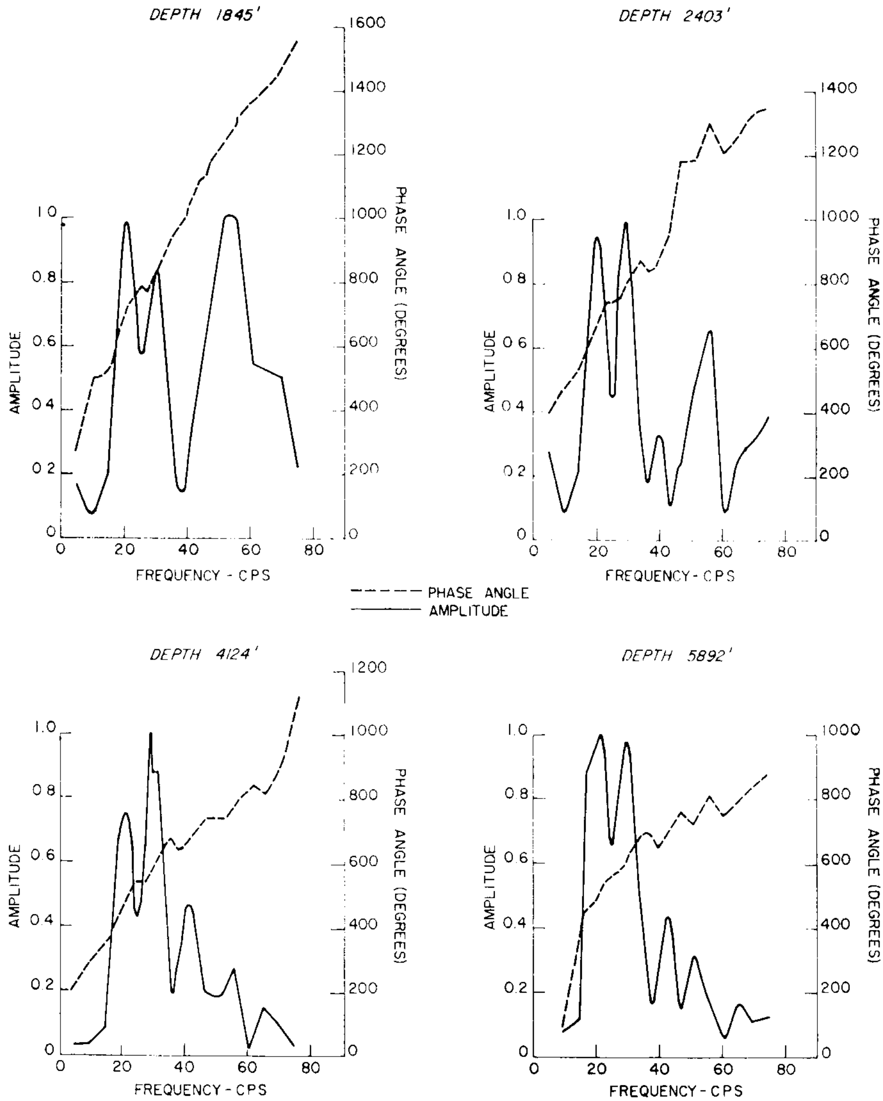


FIG. 14. Frequency spectra of initial pulses—Sarah Harman No. 1.

slopes for wells within an area do not always agree. Thus, the two Panhandle wells, Hurley No. 1 and Sarah Harman No. 1, have similar attenuation constants, but the three Navajo wells do not. In fact, both the highest and lowest slopes occur for wells only 15 miles apart—the Navajo Tribe No. 1 and the Navajo Gothic Nose No. 1. In the absence of a suitable theory, no prediction of the exact attenuation expected in complex materials can be made, nor can explanation be offered for attenuation constant variations.

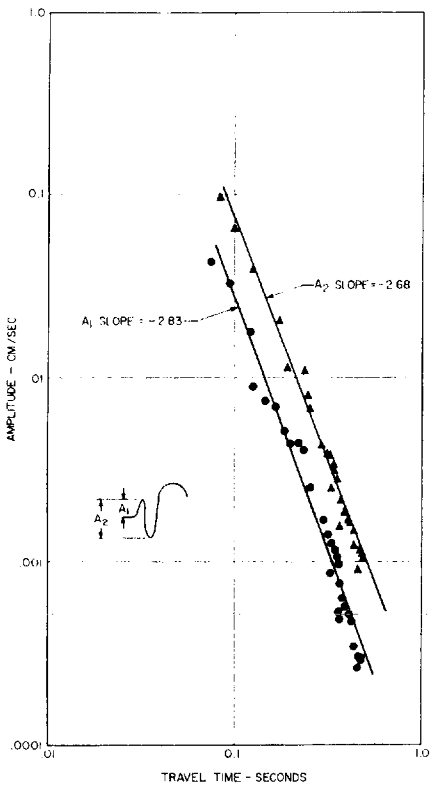


FIG. 15. Earth particle velocity of initial event versus travel time—Navajo Gothic Nose No. 1.

Although an investigation of absolute amplitude variations from well to well was not part of the deep-hole studies, the initial pulse amplitudes at 0.4 sec are listed, purely for reference, in Table II.

TABLE II
ABSOLUTE AMPLITUDE AT 0.4 SECOND

| Well | Charge (lbs) | Amplitude at 0.4 Sec cm/sec |
|---|---|---|
| Coleman-Stephens No. 2 | 5* | $2.2\times10^{-3}$† |
| Walter Morris No. 1 | 1 | $2.5\times10^{-3}$ |
| Mayme Morrissey No. 1 | 5 | $1.3\times10^{-2}$ |
| Hurley No. 1 | 5 | $2.7\times10^{-3}$ |
| Navajo Tribe No. 1 | 5 | $1.4\times10^{-4}$ |
| Navajo Gothic Nose No. 1 | 15 | $5.6\times10^{-4}$ |
| Navajo White Mesa No. 2 | 15 | $7.5\times10^{-4}$ |
| Sarah Harman No. 1 | 5 | $2.2\times10^{-3}$ |

* Hole shot; $2\frac{1}{2}$ lb air shot.
† Hole shot; $6.5\times10^{-5}$ air shot.

TABLE III

ATTENUATION CONSTANTS

| Well | $n$ from $A_1$ | $n$ from $A_2$ |
|---|---|---|
| Coleman-Stephens No. 2 | −2.6 | −2.7 |
| Walter Morris No. 1 | −2.5 | — |
| Mayme Morrissey No. 1 | −2.4 | −2.3 |
| Hurley No. 1 | −2.2 | −1.9 |
| Navajo Tribe No. 1 | −1.9 | −1.9 |
| Navajo Gothic Nose No. 1 | −2.8 | −2.7 |
| Navajo White Mesa No. 2 | −2.3 | −2.2 |
| Sarah Harman No. 1 | −2.3 | −2.1 |
| Average | −2.38 | −2.26 |

## REFLECTIONS AND MULTIPLE REFLECTIONS

The examining and tracking of reflections involve events arriving after the initial pulse. They reach the geophone after reflection from one or more interfaces. This technique used has been described in detail by Jolly (1953), and Figures 16 and 17 illustrate the method, using data from the Mayme Morrissey.[4] On plots of the deep-hole geophone traces for each depth, reflections from interfaces below the geophone follow time-depth curves which are mirror images of the initial pulse curves. The two curves form a symmetrical pair around the intersection time; the intersection occurs at the depth of the reflector.

At three wells—Coleman Stephens No. 2, Mayme Morrissey No. 1, and White Mesa No. 2—direct reflections relatively free of multiples were present. (Results from the Coleman Stephens No. 2 were presented by Jolly.) Major breaks characterized the velocity log from the Mayme Morrissey No. 1. Some of these were bounded discontinuties, 100 ft or more thick, produced by sandstone beds in shale or shale beds in a carbonate section. One break was the transition from a predominantly shale section to one containing carbonates. The important reflections correlated with the important velocity changes, the changes here being large enough to minimize intrabed interference. At the White Mesa No. 2, the strong reflections correlated with thick shale and sand beds in a carbonate section. As for the Mayme Morissey and Coleman Stephens wells, the prominent seismic events appeared to come from marked geologic changes of reasonable thickness.

There was some ambiguity in defining the reflecting interface. Both the initial pulse and the reflection consisted of several cycles; a correct depth resulted only if the corresponding cycles of the events were chosen. The choice was complicated by two factors. First, simple reflections from isolated reflectors are uncommon. Usually the observed event is a complex coming from several nearby reflectors, and the shape of the complex is not necessarily the shape of the initial pulse. Secondly, even if the reflection is an isolated event, its phase depends upon the

[4] Breaks in the traces indicate changes of 10 or 20 db in the flat amplifier gains.

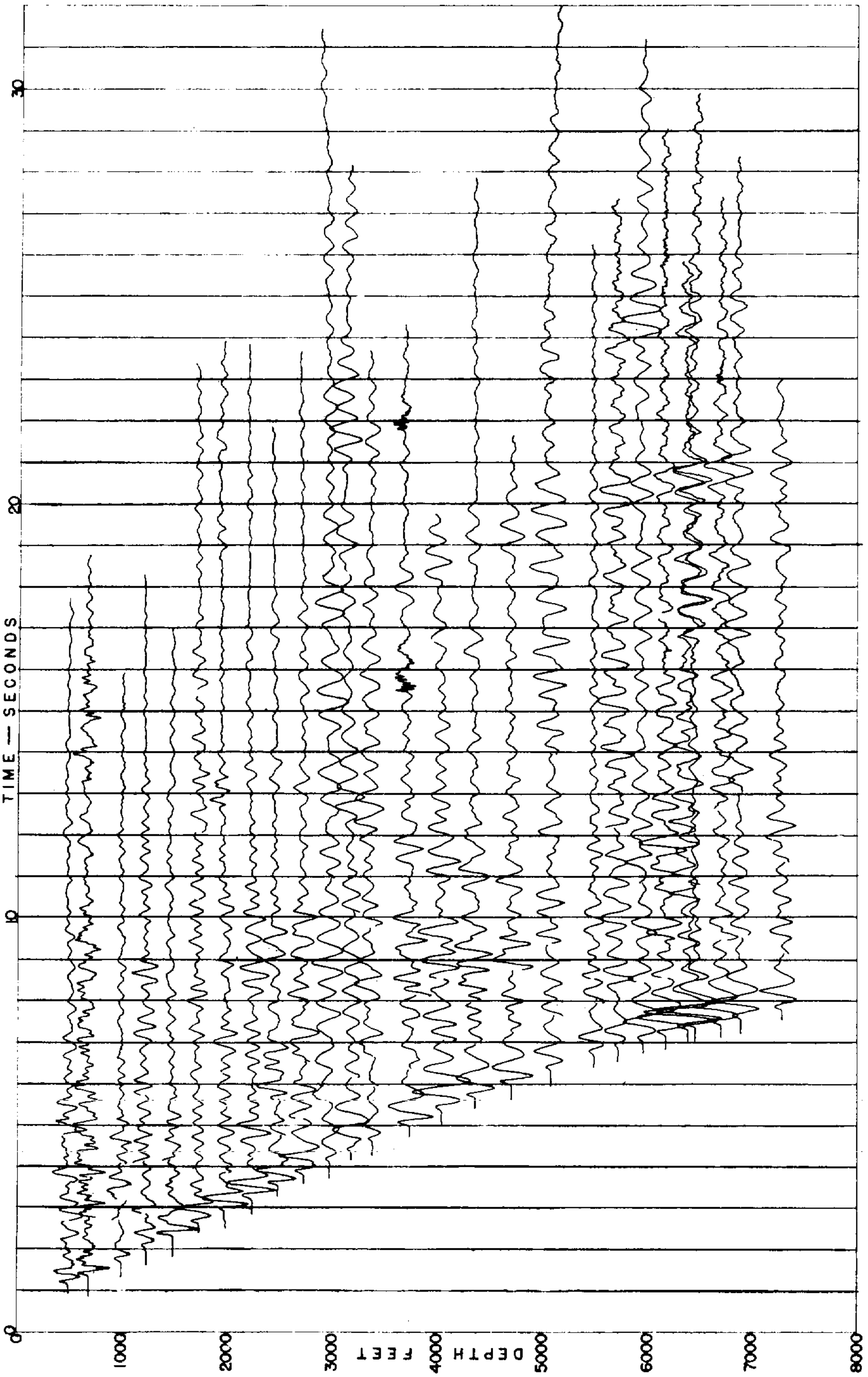


FIG. 16. Deep-hole geophone traces for all depths—Mayme Morrissey No. 1.

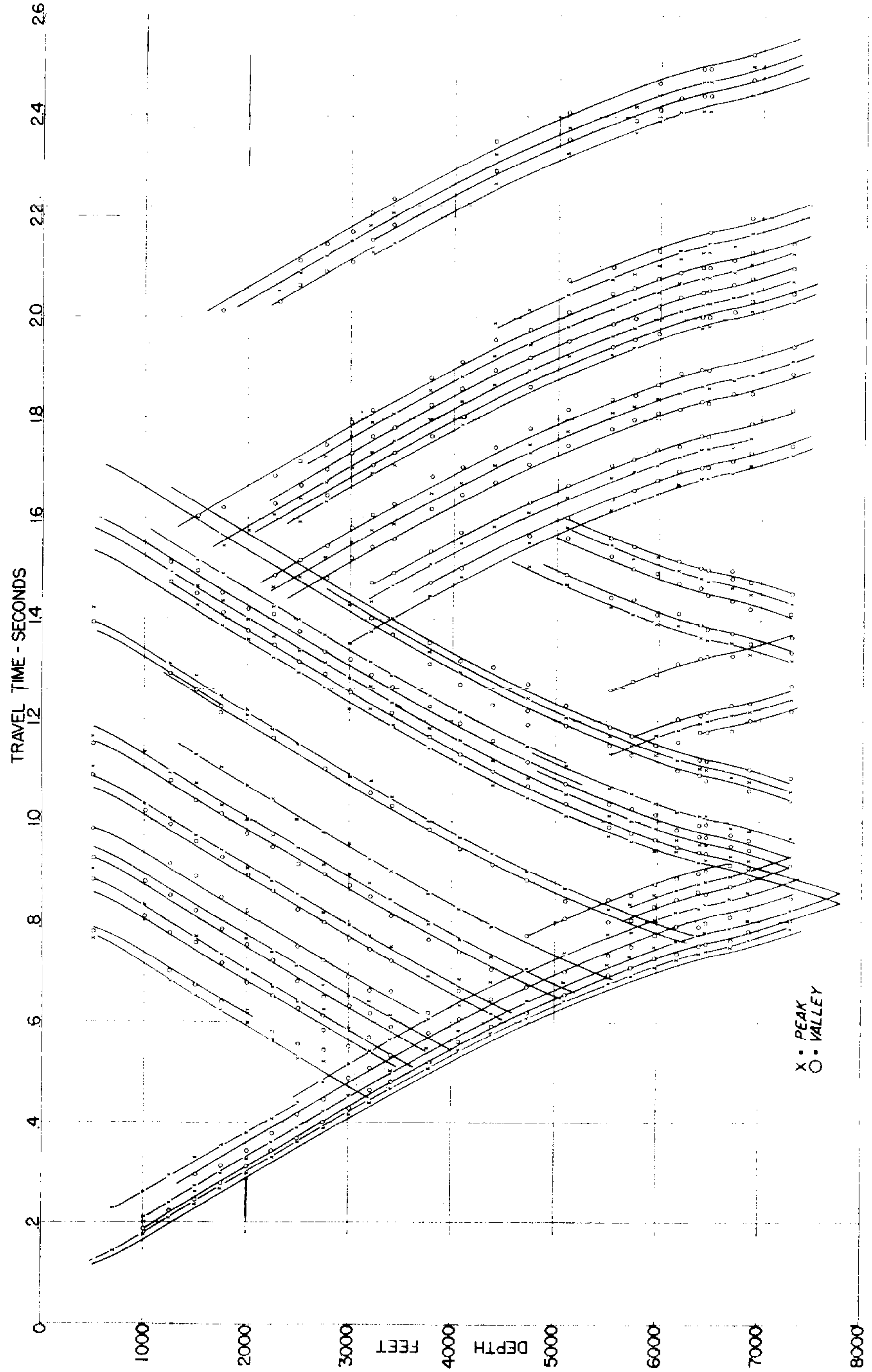


FIG. 17. Peak and valley plot for each geophone depth—Mayme Morrissey No. 1.

reflector order, i.e., upon whether the medium with higher acoustic impedance lies over the one with lower acoustic impedance, or vice versa. Our criterion for choosing the intersection was empirical: A high-amplitude reflection peak was taken to correspond to a high-amplitude initial-event peak or valley. Once the intersection was found, the velocity log sometimes tested its validity, since for prominent velocity breaks, the phase was fixed. A depth uncertainty of 100 ft in locating a reflector is possible.

On the time-depth plots of Figures 16 and 17, reflections from interfaces below the well bottom are evident. To find the corresponding reflectors, the initial pulse and reflection curves were extrapolated until they crossed, extrapolation being along mirror image curves. Although the correct curve was not known, reasonable extensions of the measured curves could be drawn for a reflector not too much deeper than the well. Figure 17 shows an extrapolation for a distinct reflection; the interface involved is about 500 ft beneath the last survey point. In this sense, the deep-hole geophone explores below the total well depth.

Using the technique described by Jolly (1953, Figure 7), effective reflection coefficients were found for 23 reflections from 5 wells. The average value was 0.36, with a range from 0.14 to 0.66. Since prominent reflections are followed most easily, reflection coefficients larger than the average for all geologic interfaces are to be expected.

When the intersection of a direct reflection and the initial pulse could be found, the depth of the reflector was known. If, further, the reflections seen on a surface seismogram made near the well could be identified with those found on well survey records, a depth of origin could be assigned to each reflection of the surface record. For the Coleman Stephens No. 2, Mayme Morrissey No. 1, and White Mesa No. 2, surface and well reflections were tied. Jolly presented the Coleman Stephens data; results from the other two wells are seen in Figures 18 and 19. Since the reflections occurred as discrete events unevenly distributed in time, there is little doubt that the identification is correct.

Besides direct reflections moving along mirror image curves, Figures 16 and 17 show events traveling parallel to, but displaced from, the initial pulses. These events are multiple reflections, arrivals that have been reflected at least once from a bed below and once from a bed above the deep-hole geophone. They hit the geophone from above. Because of their origin, they cannot appear until the geophone is below the upper reflector. In practice, except for extraordinarily good reflectors such as thick anhydrite or gypsum beds, the upper reflector is the surface or base of the weathered layer. Compared with a surface detector, the deep-hole geophone is unusually sensitive to multiple reflections. A surface detected multiple is reflected at least twice from an interface below the well geophone and consequently is smaller by the reflection coefficient of that interface than the same multiple detected in the borehole.

Depth-time plots from all the wells of Table I, except the Coleman-Stephens No. 2, showed multiples. Doubtlessly careful examination of the Coleman-

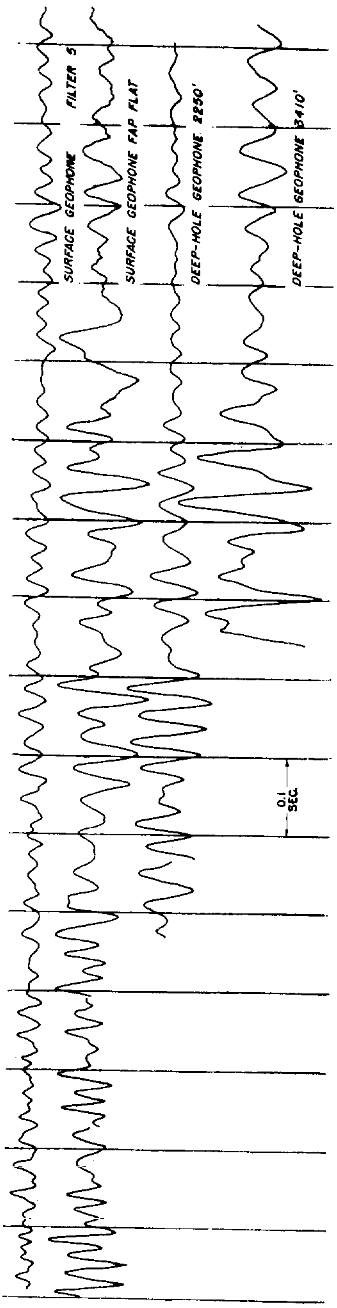


FIG. 18. Comparison of surface and deep-hole geophone signals—Mayme Morrissey No. 1.

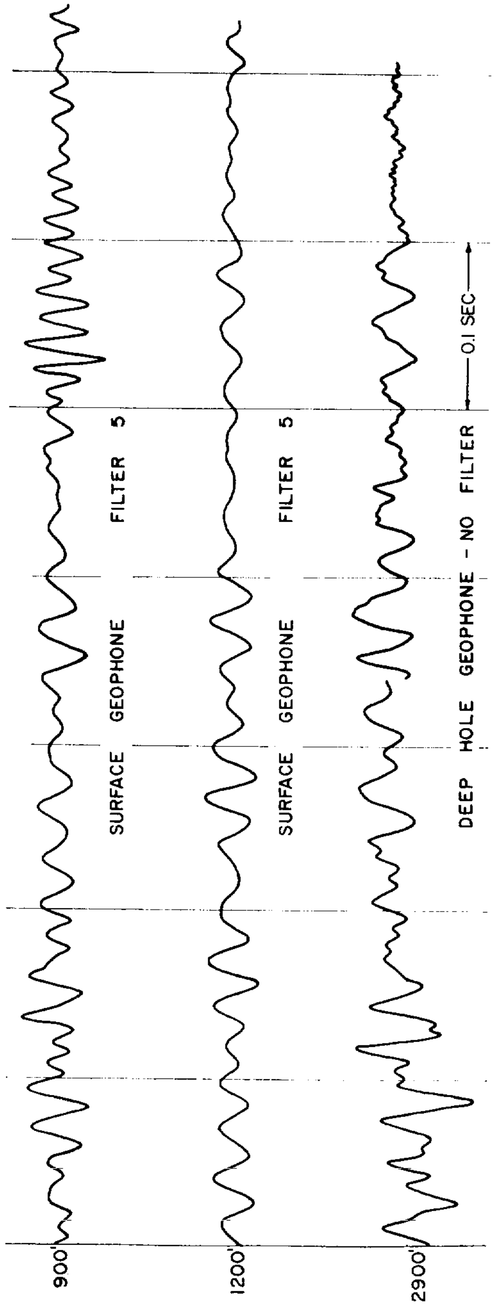


FIG. 19. Comparison of surface and deep-hole geophone signals—Navajo White Mesa No. 2.

Stephens records would also have revealed multiple reflections, but the analysis was completed before the general prevalence of multiply reflected energy was suspected. Determination of a reflector depth as the intersection of mirror image curves depends on having distinct reflection arrivals. When strong multiples are present, the reflections cannot be followed, since the overlap regions of the depth-time curves are confused. All degrees of confusion occurred. At the Mayme Morrissey No. 1 and Navajo White Mesa No. 2, multiples were present; but they appeared so late that direct reflections could be followed. At the Walter Morris No. 1, Hurley No. 1, Navajo Tribe No. 1, and Navajo Gothic Nose No. 1, there was more or less continuous interference of direct and multiple reflections. The

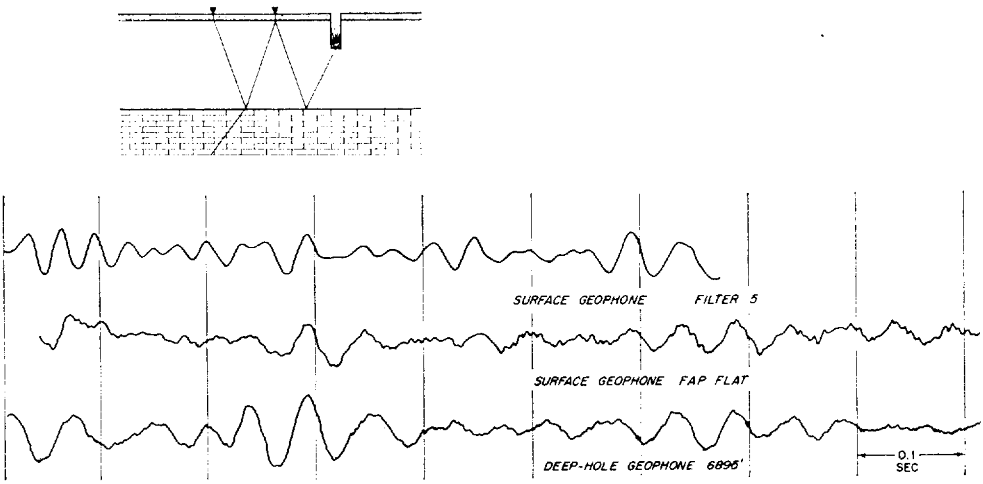


FIG. 20. Comparison of surface and deep-hole geophone signals showing multiple reflections—Mayme Morrissey No. 1.

upper reflectors at the Walter Morris were associated with a massive high-speed layer between 4,633 and 5,798 ft. At the Hurley well the upper reflectors were probably anhydrite and gypsum beds above the first geophone depth, while at the two Navajo wells probable sources of multiple reflections were the surface and massive low-speed beds which gave rise to secondary arrivals following the initial pulse. The Sarah Harman No. 1 represents a limiting case: No direct reflections were visible and all cycles moved with the initial pulse. As explained above, three anhydrite and gypsum beds were responsible for this complexity.

Where the prominent direct and multiple reflections were separated in time, the multiples as well as the direct reflections found with the well geophone could be identified on surface traces. Figure 20 is the identification of multiples for the Mayme Morrissey No. 1; the event-spacing is such that displacement of the traces by even one cycle is impossible. Thus, wall-coupled deep-hole geophones not only can tell where reflections arise in the earth, they may also tell which events seen on seismograms are multiples.

## INCIDENTAL RESULTS OF DEEP-HOLE GEOPHONE STUDIES

In the deep-hole geophone program, the emphasis was on the study of pulse propagation and reflection properties. Analysis of the experimental data gave, in addition, results not related directly to the program's purposes. Some of the by-products were of practical value, the most important being related to velocity surveying.

Wall-coupled deep-hole geophones give velocity survey data of an excellent quality. First kicks are sharper than those from a conventional well geophone. The superior kicks are due partly to the high-frequency response of the geophones, partly to noise levels 20 to 30 db below those from a hanging detector. Lower noise levels allow surveying with substantially smaller charges. Not only are powder costs reduced, but shot holes hold up under repeated shooting. For several of our surveys all depth points involved one or two shot holes only. The elimination of shot hole parameter changes promoted consistency of record data.

The consistency of time picks on deep-hole geophone records, as indicated by repeat points at the same depth, is usually $\pm 1$ millisecond, although discrepancies as great as 3.5 milliseconds have been noted. For the Walter Morris No. 1 survey, two locking-arm deep-hole geophones were used, approximately 230 ft apart. In spite of operational difficulties, travel times from fourteen depths were measured and reduced to datum by two methods. Interval velocities computed for those intervals involving a single shot recorded on the dual detectors showed a 4 percent variation; those involving two separate shots, a 17 percent variation. Though the total number of points was too small to be conclusive, the data suggest more accurate interval velocities for dual geophones. Also, the number of depths surveyed in a given time may be doubled. These advantages must be weighted against a more complex operational procedure and a greater chance of cable and instrument loss.

In addition to a lower noise level, a wall-coupled geophone has several minor advantages as compared with a free-hanging detector. The latter is sensitive to tube waves, and is therefore unsuitable for studying arrivals later than the initial pulse. On the other hand, wall-coupled geophones are insensitive to tube waves, and they do not show reversed kicks. They are excellent for making fundamental studies of elastic pulses in the earth and for obtaining additional information from routine velocity surveys.

We corrected deep-hole geophone amplitudes for shot variations, using as a correction signal the output of a surface monitor geophone placed to one side of the working area. Figure 21 shows plots of monitor amplitude as a function of ordinal shot number for some of the wells. (At the remaining wells, shot-hole conditions were not constant.) We can draw two conclusions from the figure and associated data. First, except at the White Mesa No. 2, seismic "punch" did not depend on shot number. Secondly, water tamping, i.e., the amount of water over the charge, markedly influenced the "punch." At the White Mesa No. 2, the charges were in sandstone; at the remaining wells, in shaly material. Sandstone is subject to

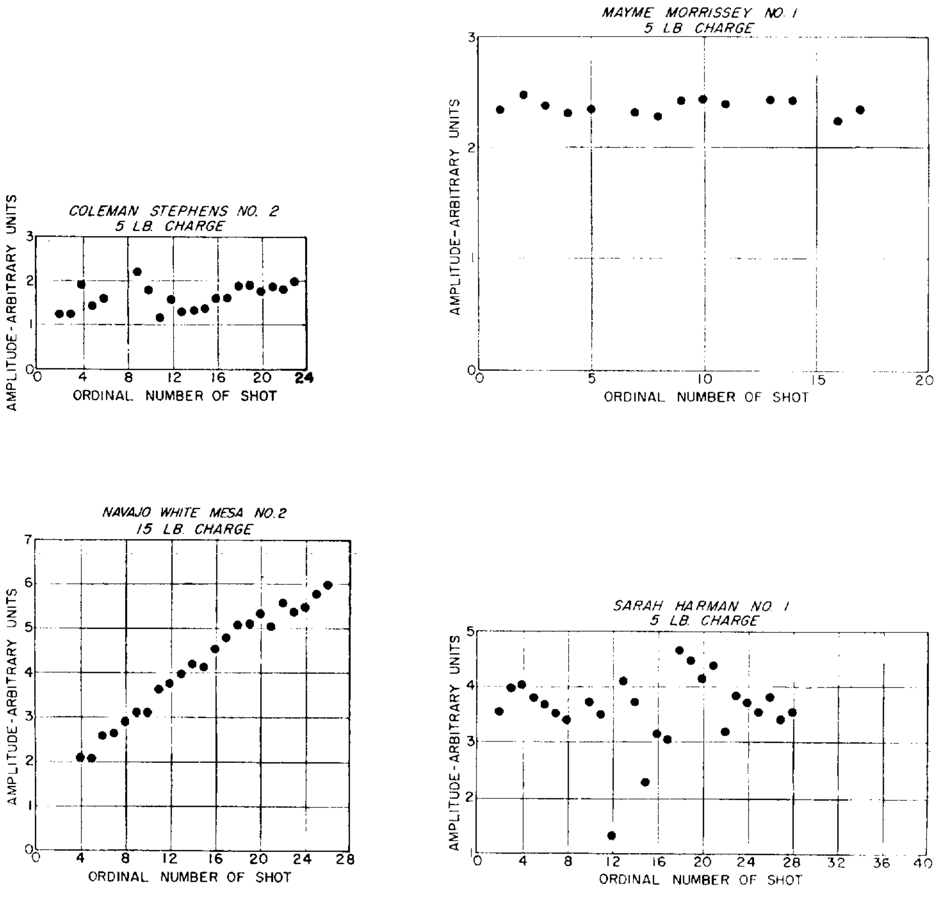


FIG. 21. Monitor geophone amplitude versus ordinal number of shot.

crushing (Ricker, 1956), whereas shale apparently is not. To a good approximation, the amplitudes at the White Mesa No. 2 were proportional to shot number from shot 4 to shot 20.

The influence of water tamping is apparent on the plot from the Sarah Harman No. 1. At the time the well was surveyed, the Oklahoma Panhandle was suffering from a severe drought and we had difficulty keeping water in the shot holes.

Whenever water was added to cover the charge, the "punch" went up only to decline on the following shots. The resulting saw-tooth pattern is evident.

ACKNOWLEDGMENT

Among the numerous members of the Geophysical Research Section involved in the deep-hole geophone studies, special mention should be made of Mr. R. N. Jolly and Miss Halcyon McNeil. Mr. Jolly directed the field work at the Coleman-Stephens No. 2 and Walter Morris No. 1 wells and completely analyzed the data from the latter. Miss McNeil did most of the calculations for the last five wells of Table I and all of the frequency analyses. A great measure of the project's success is due to the carefulness of her work.

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