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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A VERTICAL SEISMIC PROFILING EXPERIMENT TO DETERMINE DEPTH AND DIP
OF THE PALEOZOIC SURFACE AT DRILL HOLE U10bd,
NEVADA TEST SITE, NEVADA

By

Alfred H. Balch, Myung W. Lee, and D. C. Muller

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ABSTRACT

The U.S. Geological Survey conducted a vertical seismic profile experiment in drill
hole UE10bd during September 1978 at the Nevada Test Site, Nevada. The purposes of the
experiment were to obtain seismic reflections from the Paleozoic surface beneath the
Quaternary and Tertiary deposits of Yucca Flat, and to compare different sources used to
generate seismic energy for vertical seismic profiles. Five profiles were made, two using
different surface sources and three using different downhole sources. The seismic signal
was detected with a downhole clamping geophone. The reflection from the Paleozoic surface
was evident on all five profiles, with no source showing a comparative advantage over the
others. Velocity filtering was shown to be an extremely valuable tool for enhancing the
reflection from the Paleozoic surface. The vertical seismic profiles suggest that seismic
energy trapped in the near-surface zone is probably the reason for the limited success of
previous attempts to map the Paleozoic surface with surface seismic-reflection surveys.
Vertical seismic profiling was shown to be a viable method for obtaining reflections from
the Paleozoic surface beneath Yucca Flat.

INTRODUCTION

The depth to Paleozoic surface[1] and its local structural configuration are two essential
parameters used to select and evaluate proposed sites for the underground detonation of
nuclear weapons at the Nevada Test Site (NTS), Nev.

Surface gravimetry is presently being used to estimate these parameters. Depths
estimated by surface gravimetry are only within ±256 ft (G. E. Brethauer, D. L. Healey, and
D. R. Miller, written commun., 1979), thus small diameter exploratory holes are often drilled
to obtain more accurate depths.

Earlier efforts to map the Paleozoic surface seismic-reflection surveys have met with
limited success probably due to near-surface effects. Some recent experiments suggest that
the Paleozoic may be mappable by the reflection seismic method using very expensive "maximum
effort" common depth-point procedures.

The drilling of test holes to the bedrock is not an appealing prospect, because of the
depths involved (fig. 1). Refraction seismic surveys have been used with limited success
to locate the Paleozoic surface in areas where the depth is 1,640 ft or less, but no
systematic program has ever been attempted to map the Paleozoic surface by refraction.

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[1] In the report the Paleozoic surface is defined as the boundary between Paleozoic rocks
and the overlying or adjacent Tertiary rocks. This boundary may represent either the eroded
top of the Paleozoic rocks or the fault scarp offsetting it.
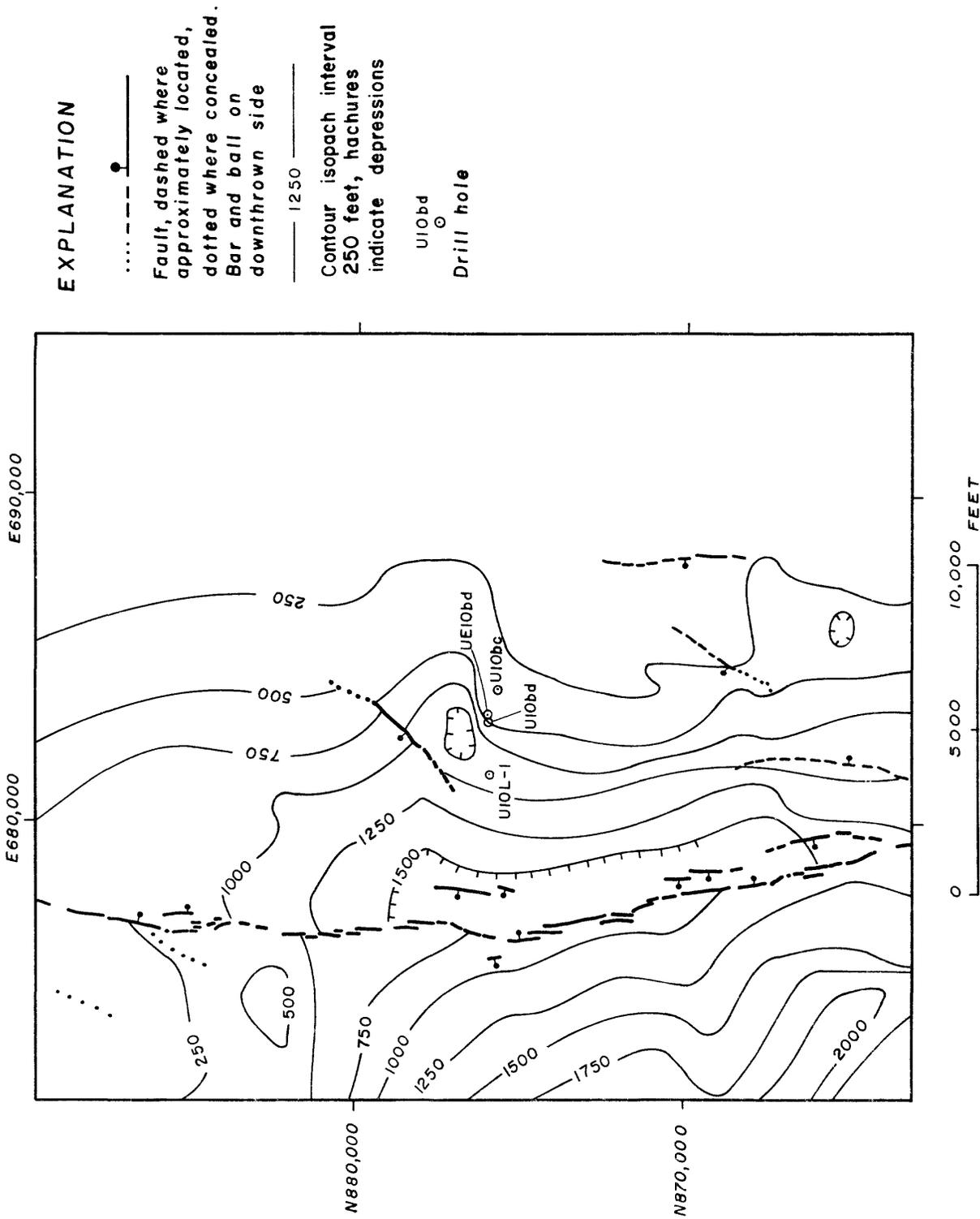
Figure 1.--Isopach map of surficial deposits in the vicinity of drill site U10bd
(from A. T. Fernald, written commun., USGS).

In May 1978, the U.S. Geological Survey (USGS) proposed a vertical seismic profile (VSP) in a large diameter (64-96 in.) hole to determine whether or not an accurate depth to the Paleozoic surface could be determined using this method. VSP is a combined well-logging and reflection seismic technique, whereby the entire seismic wave field associated with a given borehole is measured with a downhole wall-locking seismic detector. The seismic source may be located either on the surface near the borehole, or in a neighboring borehole.

There are many advantages to this technique. A principal one in this case is that it may enable one to detect and identify a reflection at or near its point of origin (the reflecting interface) and to track this reflection, level by level, to the surface.

The objectives proposed for the VSP experiment were:

1. To obtain primary seismic reflections from the Paleozoic surface using surface air guns, vibrators, and downhole air guns.

2. To determine the advantages and disadvantages of each of the above sources.

3. To determine the feasibility of using a bottom-hole air gun for time-of-arrival borehole velocity surveys.

4. To use the bottom-hole air gun as a source for recording with surface geophone arrays.

This proposal was accepted and incorporated into a larger experiment which included several surface seismic investigations. The entire experiment was conducted in September 1978 at the U10bd drill site (fig. 1).

The U10bd site was chosen for this experiment because there is an exploratory drill hole, UE10bd, 100 ft east of it where the exact depth to the Paleozoic is known. A cross section showing the rock-layer sequence and the gross structure of the Paleozoic surface is shown in figure 2.

Figure 3 is an isopach map of the rocks above the Paleozoic surface based on gravity data in the vicinity of the U10bd drill site. The gravity data are consistent with the geologic cross section, and indicate the possibility of a minor fault located between U10bd and the major fault beneath U10bc to the east (fig. 4).

In June 1977, a Vibroseis geophone survey had been made in UE10bd to determine uphole and interval velocities. A reflection originating at the Paleozoic surface was noted (fig. 5). Since this reflection had been obtained from a somewhat crude geophone survey without the benefit of extensive computer processing, the UE10bd drill hole was considered the best location on NTS to demonstrate the advantages of refined VSP methods.

Acknowledgments
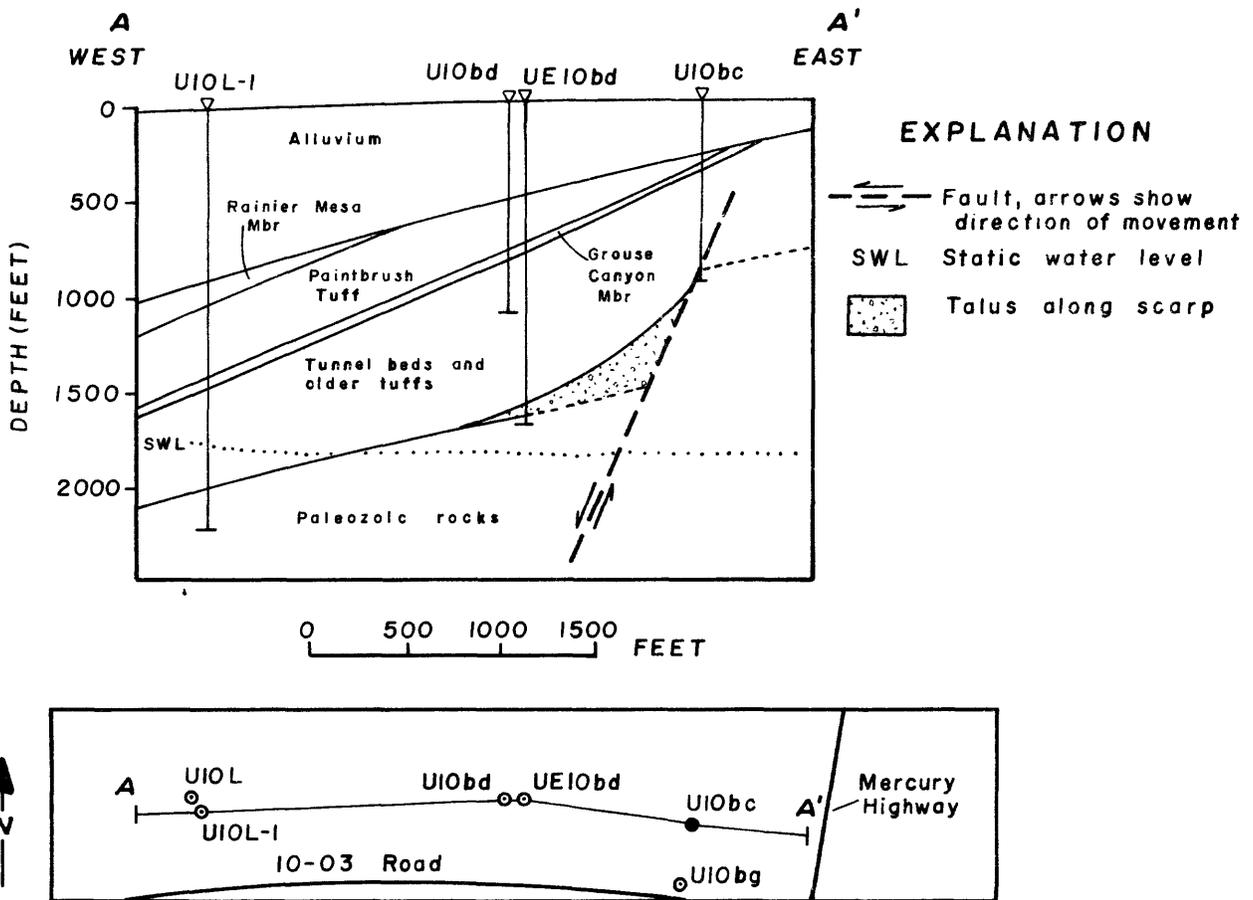
Figure 2.--Geologic cross section and plan view through drill site U10bd
(from F. M. Byers, Jr., and W. D. Quinlivan, USGS, unpub. data).
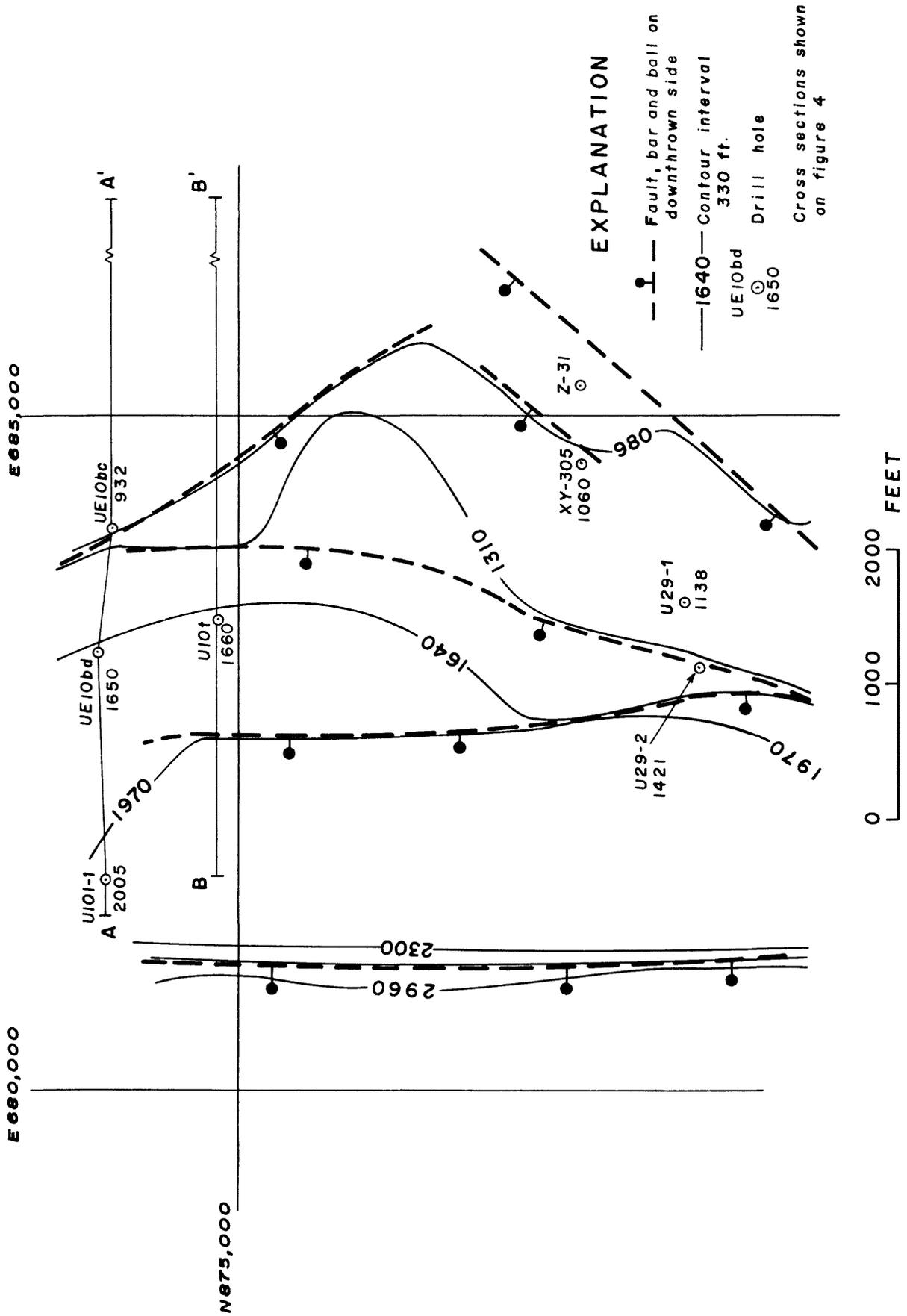
Figure 3.--Isopach map of rocks above Paleozoic surface in the vicinity of UE10bd and U10t based on 3-D analysis of gravity data (from D. L. Healey, USGS, unpub. data).
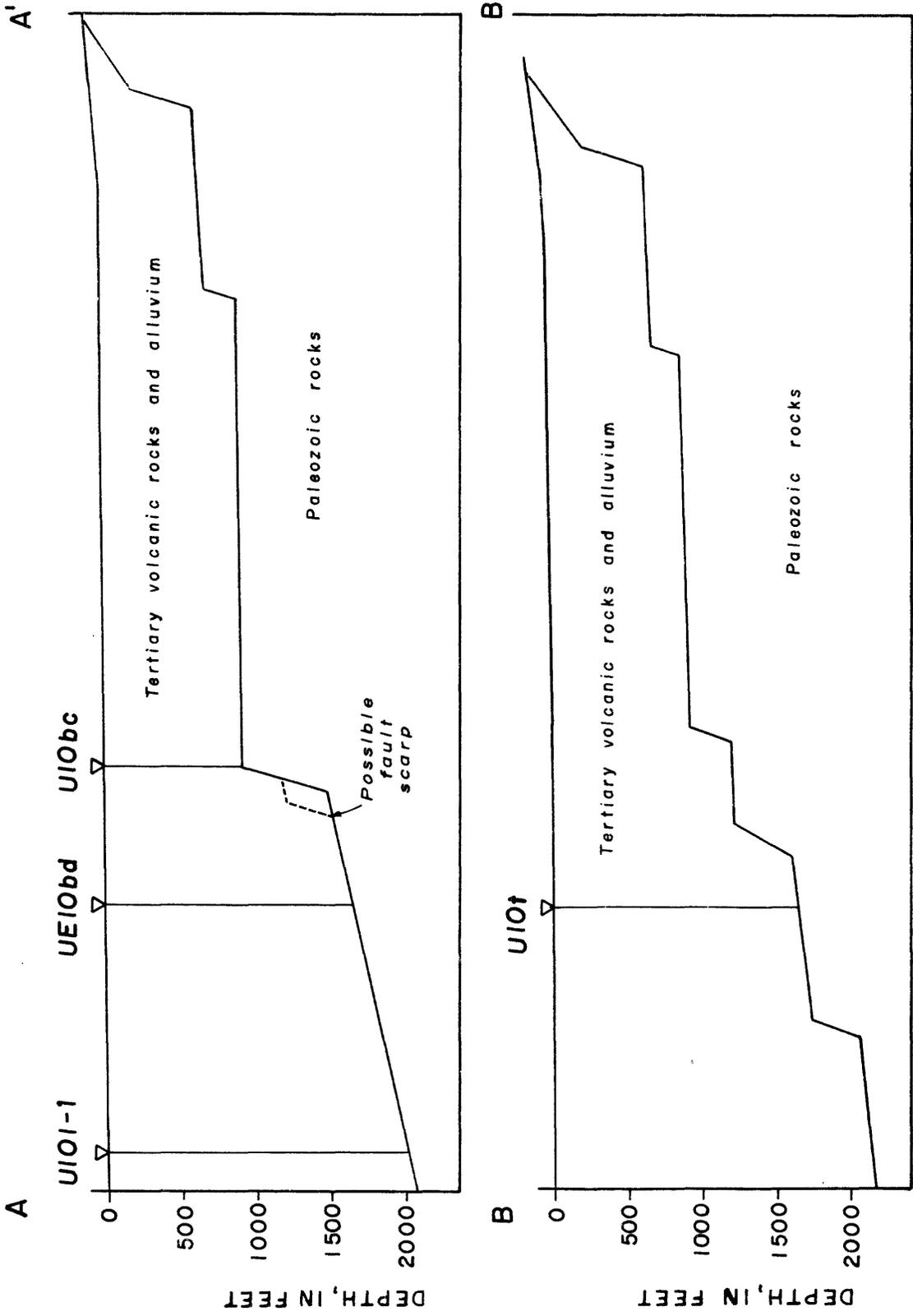
Figure 4.--Diagram showing Tertiary-Paleozoic interface, U10bd and U10t area, based on 3-D analysis of gravity data (from D. L. Healey, USGS, unpub. data). See figure 3 for line of section.

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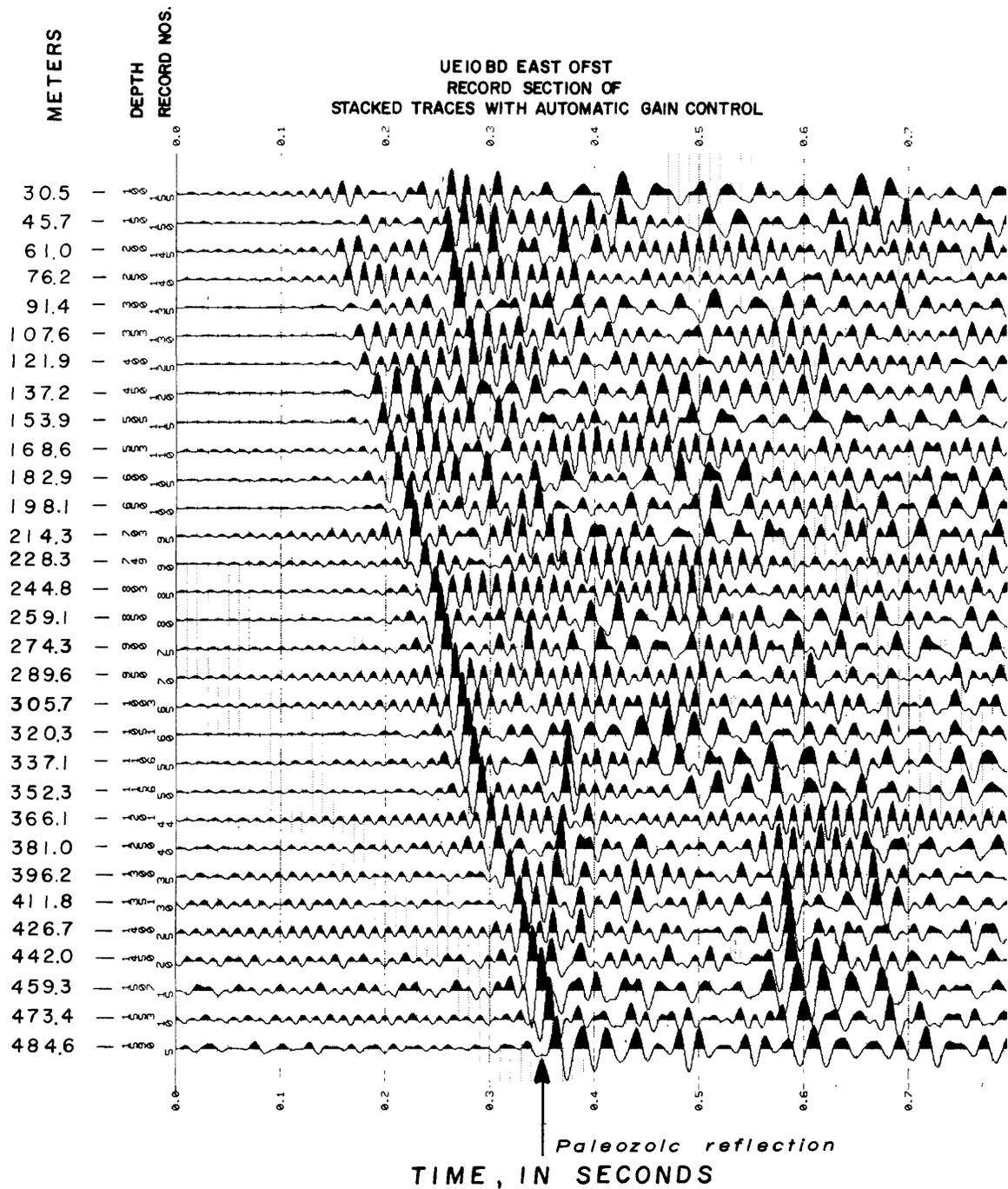
Figure 5.--Vibroseis downhole geophone survey in drill hole UE10bd
(log provided by Birdwell, Inc.).

FIELD PROCEDURE

In conducting the investigation, five different source-receiver combinations were used. That is, the UE10bd drill hole was actually profiled five times. Two profiles involved surface sources. One surface source was comprised of three Y600 SSC Vibroseis[2] units with a peak force of 15,000 lbs located at S_1, S_2, and S_3 (fig. 6). The other surface source consisted of four Bolt LSS-3 land air guns, with 60-in.^{3} chambers, located at S_1, S_2, S_3, and S_4. Three different types of sources were located at the bottom of the adjacent U10bd drill hole (S_5 in figs. 6 and 7). The first was a Bolt LSS-3 land source, detached from the parent truck, and lowered into the dry hole. The bottom of the U10bd hole was then flooded to a depth of about 50 ft and the profile was repeated with the LSS-3 submerged. Finally, a Bolt PAR marine air gun with a 120-in.^{3} chamber was lowered into the hole and the profile was repeated again. In all cases, a Birdwell-type LOK A-6/2 wall-locking, vertical-component, seismic detector was locked at a multiplicity of levels in the UE10bd hole.

The geophone was placed in UE10bd and the bottom-hole air guns in U10bd to avoid the problem of having more than one cable in the same drill hole.

Additional seismic recordings were made with a source-monitor geophone located in a hole at M (fig. 7), near the surface sources, and with an "uphole" geophone placed at the surface close to the UE10bd hole. The monitor geophone was originally scheduled to be in a hole 200 ft beneath the surface in order to obtain an approximate source signature. Due to circumstances beyond the investigators' control the first hole provided was only 4 ft deep. Later a 16-ft hole, and finally a 60-ft hole was provided. None of these proved to be adequate for a proper source signature measurement; however, the monitor phone was useful to document the consistency of the surface seismic source during the land air-gun experiment. During most of the downhole source work, excessive crossfeed between the monitor channel and the downhole seismometer channel rendered the monitor recording virtually useless. A summary of the five profiling operations is presented in table 1.

DISCUSSION OF THE RAW DATA AND INITIALLY PROCESSED DATA

The digital field recordings were first read, demultiplexed, and plotted by the USGS Phoenix I Seismic Data Processing System. The data plots were inspected and poor-quality recordings were eliminated from further processing. Several timing errors on the remaining data were corrected. Then, all the recordings for a given source on the same level were summed, or stacked, to improve the signal-to-noise ratio. These stacked traces were passed through a band-pass digital filter to further improve signal-to-noise ratio. These filtered, stacked seismograms or seismic traces were plotted, and displayed as "raw data." A number of observations and conclusions can be made from these raw data.

Figures 8, 9, 10, 11, and 12 (in pocket) show computer plots of the raw data. Those plots designated A represent unfiltered versions, and those designated B have been band-pass

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[2]Use of brand names and company names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

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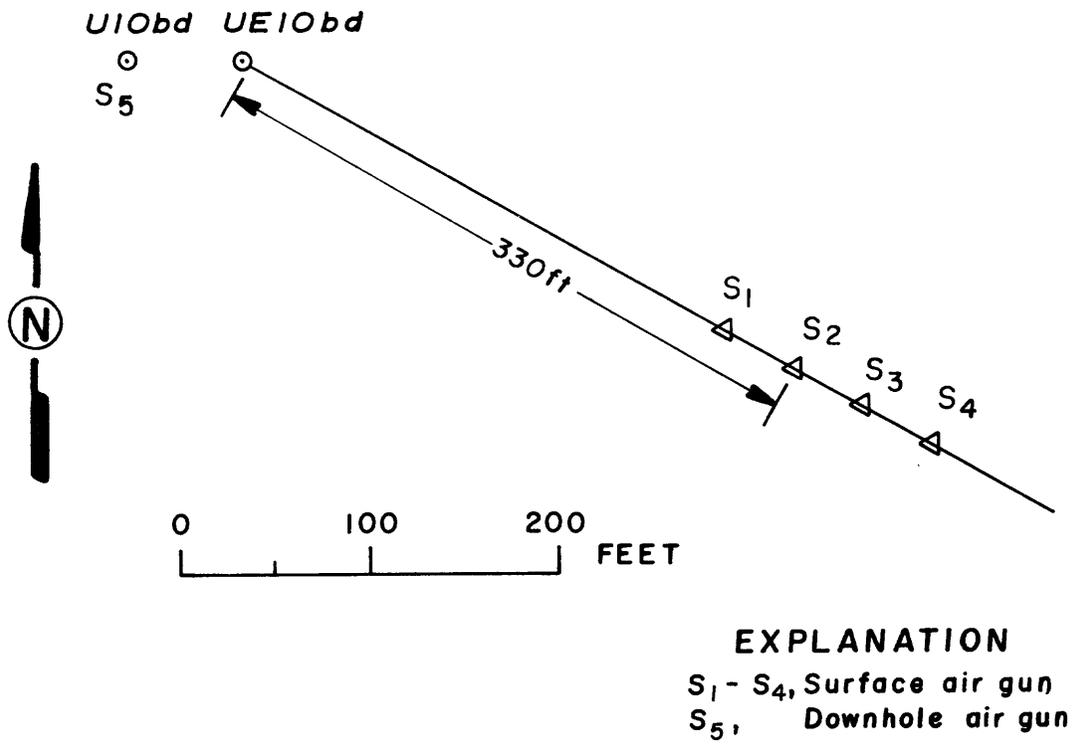
Figure 6.--Plan view showing seismic source locations.
(S_1-S_4--location of vibrators and surface air
guns. S_5--location of drill hole containing
downhole sources.)
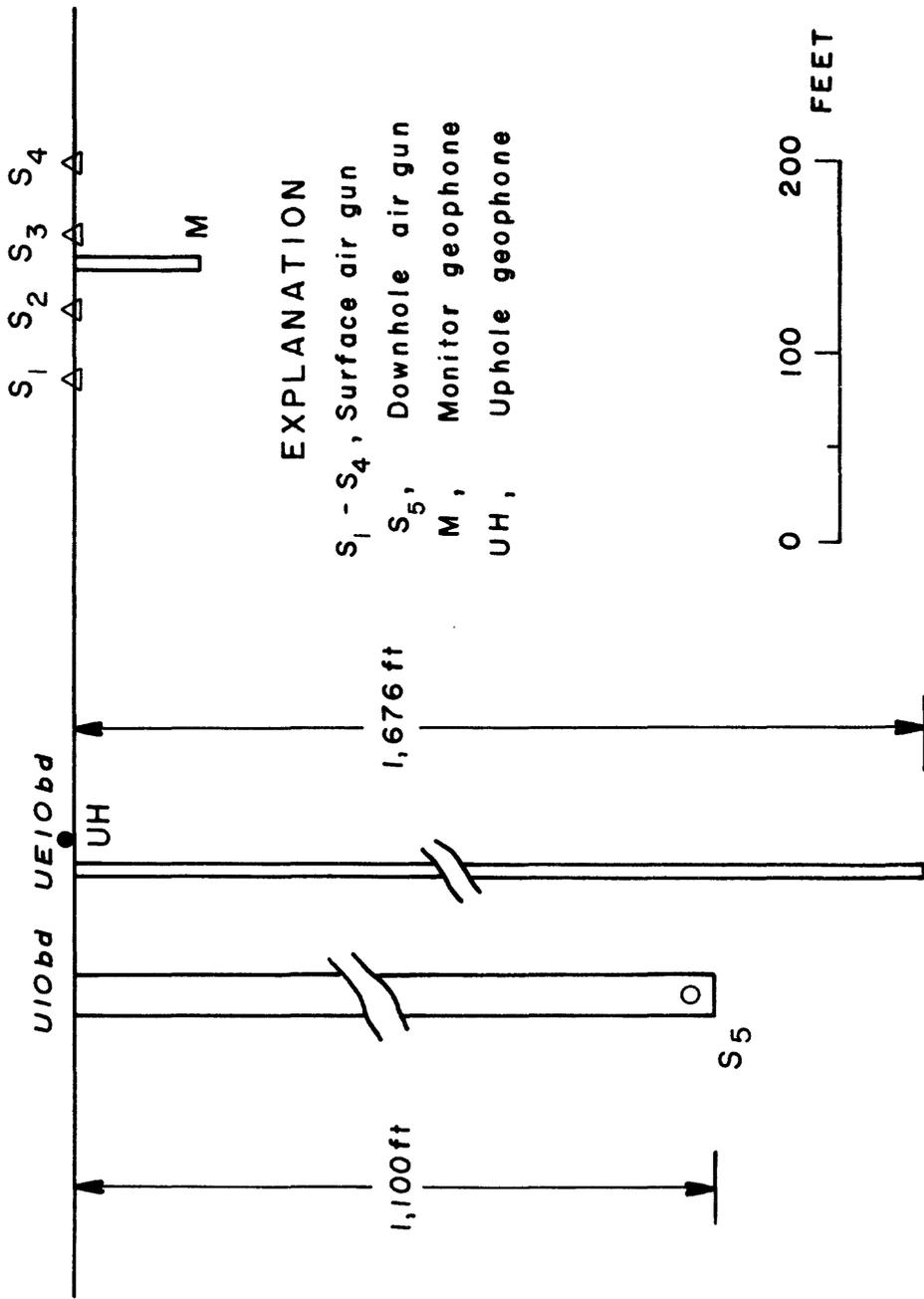
Figure 7.--Elevation sketch of VSP locations. (S_1-S_4--location of surface air gun. S_5--location of downhole source. UH=uphole geophone). M=monitor geophone.

Table 1.--Summary of vertical seismic profiling field work done at the Nevada Test Site, September 1978

Seismic source	Location	Detector location	Dates	Shots/level	Remarks
4 Bolt LSS-3 land air guns (truck mounted)	S_1, S_2, S_3, S_4	UE10bd from 1,560-160 ft at 20-ft intervals	9/19/78 to 9/23/78	20	Surface source
1 Bolt LSS-3 land air gun	S_5, at 1,071 ft with 3 ft of slack	UE10bd from 1,560-700 ft at 20-ft intervals and 700-180 ft at 40-ft intervals	9/21/78	20, from 1,560-1,140 ft; 15, from 1,120-180 ft	Dry hole
1 Bolt LSS-3 land air gun (60 in.^{3} at 2,000 lb/in.^{2}	S_5, under approx. 16 ft of water at 1,071 ft beneath ground level	UE10bd from 1,560-180 ft at 20-ft intervals	9/22/78 and 9/23/78	20	Wet hole; source buried itself several feet into the well bottom during the course of the shooting
1 Bolt marine air gun 120 in.^{3} 500-2,000 lb/in.^{2}	S_5, under approx. 20 ft of water at approx. 1,050 ft beneath ground level	UE10bd from 1,575-250 ft at approx. 25-ft intervals	9/26/78	20, 1,560±-1,050 ft 10, 1,025±-250 ft	Gun pressure varied to test effect of pressure on signal strength; considerable hole caving took place, gun was buried at end of survey
3 Vibroseis units Y600 SSC	S_1, S_2, S_3	UE10bd from 1,560-1,380 ft at 20-ft intervals and 1,375-100 ft at 25-ft intervals	---	10	Sweep frequency 112-28 Hz 10 s duration; recording unit different from that used in recording data from impulsive sources

filtered as indicated. In all cases the individual traces represent the composite recording at a given level (depth) in the UE10bd drill hole. The depth is indicated in the margin, next to the trace. The horizontal scale is time. The first displacement of the traces corresponds to the first arrival of seismic energy at that level, via either a direct or refracted path from the source. Note that in figure 10, the first arrival appears earliest on the recording taken at a depth of about 1,120 ft. This is because the source was located at the bottom of the U10bd hole for the data in figure 10, and the detector was nearest to the source when it was at the 1,120-ft level in the UE10bd hole.

In all cases, the most predominant feature of the unfiltered data is the "ringing," at a frequency of about 100 Hz, accompanying the first arrival. This ringing phenomenon appears to be independent of the sources as it appears on all plots irrespective of which source was used. We are strongly of the opinion that this "ringing" or oscillatory phenomenon is pure artifact and is the result of very poor coupling between the seismic detector and the drill-hole wall in the UE10bd hole. We have seen this ringing phenomenon during other investigations, but rarely, if ever, has it been as severe as that observed with the NTS data. This poor coupling can probably be traced to the rather primitive locking arm on the downhole detector used by Birdwell, Inc. Although Birdwell has developed a more advanced locking arm, it regrettably was not available for use during this investigation. This coupling problem was further aggravated by the fact that the wall of the UE10bd hole is very irregular. There are many zones in the hole where caving or washout has taken place that would tend to make the drill hole a difficult one in which to lock a tool even under the best of circumstances. This contention is strengthened by the autocorrelation and spectral analysis results, shown in figure 13 (in pocket), and the source waveform monitor plots, for the same levels, shown in figure 14 (in pocket).

The autocorrelations are shown on the left and the associated power spectra are on the right. Note that for level after level the source pulse for a given monitor phase depth remains essentially unchanged (fig. 13). Yet the autocorrelations and power spectra show drastic changes from level to level. We are forced to conclude again that these drastic changes from level to level are not source dependent, but rather downhole geophone dependent. In the absence of any correlation between this ringing and geologic changes, the only logical remaining explanation for this phenomenon is poor coupling between the seismic detector and the borehole.

In figure 14, note that the seismic waveforms measured by the monitor phone at the surface fall into three main categories. These three categories or families correspond exactly to changes in depth of the monitor phone. The waveforms recorded by the monitor phone are useless for the purpose of measuring the shock-wave form directed downward into the earth. Close to the source, as in categories I-III, the radiation patterns of the individual air guns cause a great deal of constructive and destructive interference and so we have no clear picture of the composite waveform. The consistency of the recorded wave-form from shot-to-shot suggests very strongly that the air-gun array produced identical waveforms on every shot.

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Returning to figures 8, 10, 11, and 12, our next step was to filter the data heavily in order to eliminate the ringing caused by poor coupling. Examination of the filtered results shows that in all cases we achieved considerable success in eliminating this noise. The success of the filtering is shown especially well on figures 8(B) and 10(B). It must be kept in mind that by heavy filtering we have thrown away all information above about 75 Hz. And in fact, very little information remains above 65 Hz. We had no choice but to do this in order to improve signal-to-noise ratio. The consequent loss of resolution is a heavy but necessary price to pay for this improvement. The loss of resolution, however, put a rather severe limit on our ability to process and interpret the data.

No additional filtering was applied to the Vibroseis data shown on figure 9. This is because the Vibroseis data is automatically filtered in the correlation process, and much of the high-frequency ringing appears to have been eliminated in this way. Even so, a good deal of extraneous ringing remains on the Vibroseis data. For example, note the excessive ringing on the 1,300-ft level recording.

Inspection of figures 8(B) and 9 shows that even at this initial unprocessed stage a distinct coherent reflection appears to be coming from the Paleozoic level. This is most encouraging because if the Paleozoic surface reflection appears at all at this stage it tells us that we have a very good chance of enhancing it and interpreting it later in the processing sequence.

On the plot of the surface air-gun data (fig. 8), note that on the levels from 1,480 to 1,575 ft the first arrival times appear to be inverted. That is, the first arrival appears at 1,575 ft before it does at 1,480 ft. We strongly suspect that this is a refracted event. In other words, the Paleozoic geometry is such that the shortest time travel path is by refraction through the Paleozoic layer to the bottom of the hole. At about 1,460 ft this small refracted event merges with the very large direct arrival and can no longer be seen. Nevertheless, any interpretation of the final processed data should take this apparent refraction arrival with negative velocity into account.

Before proceeding to the next initial processing step we invite the reader's attention to figures 15 and 16 (in pocket). Figure 15 shows a typical set of recordings for the uphole phone located on the surface near the UE10bd hole. Although the data are rather badly corrupted by cultural "noise" near the phone (generators, people, vehicles, etc.), a strong first arrival from the surface air guns can be seen in all cases. The high degree of consistency of the waveform on this set of data gains, supports our contention that the pulse emitted from the air-gun array, from shot to shot, and from level to level, varies very slowly.

Figure 16 is a plot of the time breaks internally generated by the seismic recording instruments. This is, of course, an essential piece of data because it gives us our zero time for all downhole recordings. There is a rather drastic shift in the internally generated time break, or zero time, between the recordings made on the 1,300-ft and the 1,320-ft levels. This indicates an inconsistency in recording instrument performance which must be accounted for in data processing and interpretation.

Figures 17, 18, 19, 20, and 21 (in pocket) show the same "raw data" as figures 8, 9, 10, 11, and 12. They have been plotted here to a larger scale for easier viewing and, more importantly, they have been plotted with a time varying amplitude scale or automatic gain control (AGC).

During the 2 seconds of recording time, the amplitude of the seismic signal may drop off by a factor of 100,000 or so. It is, therefore, highly desirable to gradually increase the gain or amplitude, with time, in order that the latter events may show up. On the filtered version of figure 17 (surface air-gun data) a reflection from the Paleozoic shows up distinctly. This is, of course, the event of principal interest and has been further enhanced, displayed, and interpreted in subsequent sections of this report.

The data shown on figure 18 are similar to figure 17 and represent an AGC version of the surface Vibroseis data. Although the Paleozoic reflection shows up on figure 18, it is our opinion that the "ringy" nature of the Paleozoic reflection makes it somewhat lower in quality than the surface air-gun data. Figures 19, 20, and 21 all involve sources at the bottom of the U10bd hole. When we inspect the downward traveling first arrival, from about 1,060 to 1,560 ft, we see in all cases what amounts to two first arrivals. The first event appears to be traveling at a velocity close to the medium velocity. The second, immediately following, event appears to be traveling at a somewhat lower velocity and is interpreted as a shear-wave arrival. Thus, the downhole source in this experiment always seems to generate a substantial amount of shear-wave energy. From an interpretation point of view, this is a disadvantage because we must deal with two energy modes instead of one. Because we used a single-component seismic detector (i.e., vertical component) and because the apparent velocities observed are dip dependent, it is often difficult to distinguish between the compressional and shear modes.

An important feature of the data shown in figure 19 is the large amount of seismic energy trapped in the near surface. Because of high contrast of velocities near the surface, this trapped mode or wave-guide effect is certainly to be expected. This phenomenon will undoubtedly also occur when the area is "shot" or explored using any surface seismic technique. We suspect one reason for the great difficulty that has been encountered in using surface methods in this area to record Paleozoic reflections, is because of interference from these near-surface trapped modes or reverberations.

On the other hand, both sets of surface data (figs. 17 and 18) clearly indicate that substantial quantities of seismic energy can be put deep into the ground and reasonably strong Paleozoic reflection can be obtained. We therefore believe that with proper choice of surface recording parameters the Paleozoic surface could be successfully mapped from the surface of the ground.

Returning to figure 19, we note that coherent energy returning from the bottom of the UE10bd hole, which represents the Paleozoic reflection, is rather weak. We believe this is primarily due to a mechanical problem that we encountered in using the LSS-3 bell in a dry-source hole. Every time this assembly is fired it flies up a foot or two and then falls back to the bottom of the hole. The secondary impact or bounce, and possibly a second bounce as well, produced a succession of seismic pulses from the bottom of the source hole

instead of one single, clean pulse. We attempted to compensate for this by shooting on each level at a variety of different air-gun pressures. This caused the gun to bounce a different height on each shot, and hence, the bounce period changed on each shot at a given level. It was hoped that when all shots from a given level were composited, as on figure 19, the individual bounces would be at least partially suppressed. Whereas this is true, it is also true that even the suppressed individual bounces are higher in amplitude than the Paleozoic reflection; hence, they tend to obscure the Paleozoic reflection. However, the bouncing is a correctable mechanical problem and does not disqualify the LSS-3 bell for use in a dry hole as a future seismic source. By making the bell much heavier, perhaps by as much as several thousand pounds, this bouncing effect could be greatly suppressed or even eliminated.

Taken as a group, figures 19, 20, and 21, involving the downhole sources, do not appear to give a substantially stronger reflection from the Paleozoic when compared with figures 17 and 18 involving surface sources. Because the downhole sources are much more difficult to operate and offer no clear cut advantage over surface sources, from the point of view of getting good Paleozoic reflections, there seems to be no reason to use downhole VSPs if a surface VSP is possible. This does not rule out further work with downhole sources if, for some reason, a surface source cannot be used. For example, the structure of interest might be a broadside scarp.

There is one further observation we can make on the unprocessed data. Figure 22 (in pocket) shows the output of the monitor geophone when the dry-hole VSP was run. Although the source and monitor geophone detector were in the same relative position throughout the entire profiling operation, we notice a variation in first-arrival time which corresponds exactly to the arrival time recorded on the downhole geophone. We conclude from this that there was severe cross coupling between the monitor-phone recording channel and the downhole-phone recording channel. This renders the monitor-phone recording virtually useless for any waveform monitoring purpose. It also underscores the need for much more vigorous quality control in future work.

ADVANCED DATA PROCESSING

The purpose of the advanced data processing techniques is to enhance the Paleozoic reflection and to provide information relevant to the interpretation of the configuration of the Paleozoic surface. There are a number of imperfections in the field data. The ultimate effect of these is to limit the quality of the processed output, and the reliability of the final interpretation. The most important data-processing step is velocity filtering. For velocity filtering to be fully effective we require a consistent shot waveform, broad-band signal, and dense, uniform, spatial sampling. Fortunately, although none of these requirements was fully met, the field-data quality was still good enough to make the velocity filtering partially effective. As a result the Paleozoic reflection was isolated and interpreted.

Data Processing Steps

Figure 23 shows a flow chart of the processing. After the field tapes were demultiplexed, we plotted every seismic recording to check the quality of data. We then removed poor records and irrelevant test records. After the original recordings were edited, the data at every level were summed to enhance the signal to random noise ratio. Each recording consists of a superposition of many events plus random noise traveling upward or downward in the earth at different velocities. In order to help sort these events, we applied velocity filters to the data set. These filters tend to suppress events or arrivals traveling at certain specified velocities, and tend to enhance events traveling at other specified velocities.

As a first step, we applied a series of velocity filters to enhance seismic events with a step out over 12 levels of 0, -1, -2, -3, -4, -5, and -6 ms/level. The negative sign implies upward-traveling events. Figure 24 (in pocket) shows some of the results of this processing applied to the surface air-gun data. Note that many events change amplitude with changing level, on a given velocity-filtered plot. This is because the apparent velocity of these events change with changing level. This phenomenon is always observed when the coherent event is a reflection from a steeply dipping reflector. The reflection wave front is curved (approximately spherical) and, therefore, it intersects the hole at an angle which depends on the depth. The apparent velocity along the axis of the hole depends upon this angle.

As an aid to interpretation, we next made a composite plot which shows the highest-amplitude upward-traveling event for each level at each time. We call this a maximum coherence plot, because it shows only those events with maximum coherence at a given point in space and time. Figure 25 (in pocket) is the maximum coherence plot corresponding to the data shown on figure 24. No event of interest appears to have velocities in the -4, -5, and -6 ms/level range, so these velocities were not considered in making figure 25.

We also filtered the data to enhance downward-traveling events. Figure 26 (in pocket) is a maximum coherence plot showing some of these results, applied to the surface air-gun recordings. Figure 26 indicates that the initial arrival from the source changes markedly with increasing depth.

It is also apparent from figure 26 that the downward-traveling (source) pulse is not a pulse at all, but a downward-traveling wave train, and these trains are superimposed on each other and on the upward-traveling train. Because it is easier to interpret data consisting of short pulses, a predictive deconvolution operator was applied. This had the effect of yielding a set of data similar to what we would have had if the source had been a single unchanging pulse. Finally, an additional band-pass filter of 10-50 Hz was applied to further improve signal-to-noise ratio.

COMPARISON OF THE SOURCES

Surface Air-Gun Data

Figures 26 and 27 (in pocket) are the completely processed surface air-gun recordings. Even after deconvolution, the downward-traveling wave field (fig. 26) is complex. Clearly, the subsurface structure in this area is also complex. A number of events in the near surface are apparently multiples which tend to obscure weak reflected events.

```
PRELIMINARY
PROCESSING

DEMULTIPLEXING--------------------------Field tape

          ↓

EDIT, SUM

          ↓

SHAPING FILTER--------------------------Design shaping filters from
                                        the monitor phone records and
                                        apply to the well phone

          ↓

FREQUENCY ANALYSIS----------------------Determine signal frequency band

          ↓

BAND-PASS FILTERING
AGC

          ↓

ADVANCED
PROCESSING

MULTI-CHANNEL VELOCITY------------------Separate upward- and downward-
FILTERING                               traveling waves for all probable
                                        velocities

          ↓

MAXIMUM COHERENCY----------------------Pick maximum amplitude for a
                                        specified range of velocities

          ↓

DECONVOLUTION--------------------------Downward-traveling wave train
                                        deconvolution or predictive
                                        deconvolution

          ↓

FINAL BAND-PASS FILTER
```
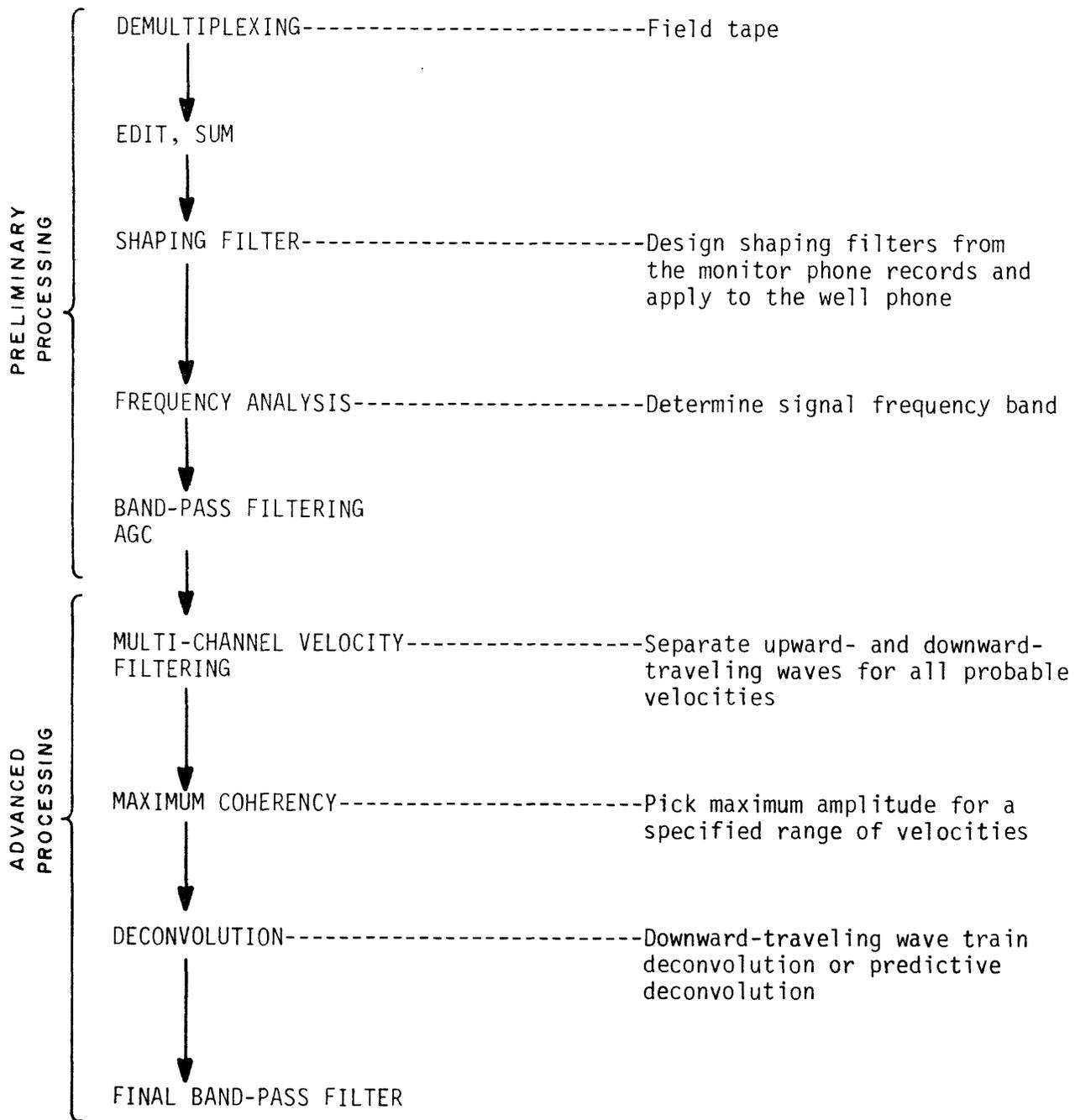
Figure 23.--Flow chart showing sequence of VSP processing.

After deconvolution and band-pass filtering, the high-amplitude event appearing at about 380 ms at 1,470 ft on figure 27 is almost certainly the Paleozoic basement reflection. At 990 ft, it merges into another event with a substantially different apparent velocity. The waveform frequency content and amplitude of this other event are also different, which is why we doubt that it is a continuation of the Paleozoic reflection. If it is not a continuation of the Paleozoic reflection, then the Paleozoic reflection is absent above 990 ft, either because of faulting or post-Paleozoic/pre-Tertiary erosion. This theory will be elaborated upon in the following section.

Another coherent event appears in figure 27, with a much higher apparent velocity, at about 800 ms in the depth range from 1,070 to 1,430 ft. We cannot make any definite interpretation of this event except to suggest that it may be a side reflection from an adjacent Paleozoic surface. Finally, we note several Paleozoic multiple reflections.

Vibroseis Data

The complete processed Vibroseis data set is shown on figure 28 (in pocket). For evaluation purposes, it should be compared to figure 27. The sought-after Paleozoic basement reflection shows up well, although this reflection is of considerably longer duration. It appears to "ring" or oscillate. Poor well-detector clamping could be responsible for this. Based on the frequency content of the reflection we conclude that the Vibroseis sweep frequency of 28-112 Hz was too high, and that considerable Vibroseis energy at the higher frequencies was wasted.

Wet-Hole Data

In figures 29 and 30 (in pocket), we present the completely processed recordings when the source was an LSS-3 air-gun bell immersed in 20 ft of water at the bottom of the U10bd hole.

On figure 31 (in pocket), two "first arrivals" appear at every level. The slower event is interpreted as a shear wave, generated by the downhole source. Although we were not surprised to see the shear wave, its vertical component amplitude was much greater than anticipated. The presence of large amounts of shear-wave energy can create several ambiguities in the interpretation, because they are difficult to identify when only vertical component records are made.

Ordinarily, we could distinguish between shear and compressional modes on the basis of velocity. However, in this case the dipping reflectors have a profound effect on observed, or apparent, velocity, and we doubt if reflected shear events can be reliably identified.

If three component detectors had been used, it might have been possible to make two interpretations: one based on shear and one on compressional events. We note the Paleozoic reflection from the wet-hole source is missing (fig. 31). We are at a loss to explain this. It may be that the dipping Paleozoic reflector is in a "shadow zone" for the LSS-3 radiation pattern. We do see a Paleozoic reflection on figure 30 starting at about 0.750 s, at the 1,450-ft level. This is a "surface multiple" that is the energy travel path upward from

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the source to the surface downward to the Paleozoic horizon, and thence upward again. Figure 31 shows a superposition of the traces shown in figures 29 and 30.

Dry-Hole Data

The processed "dry-hole" air-gun data are shown in figure 32 (in pocket). The source was an LSS-3 air-gun bell at the bottom of the U10bd hole with the hole dry.

These data are similar to the "wet-hole" air-gun data (fig. 31). They are poorer in quality because of the gun bounce effect described earlier. This is a viable downhole source, but redesign of the bell will be required.

Marine Air-Gun Data

In figure 33 (in pocket), we show a maximum coherence plot (velocities 6 to -6 ms/level) for the marine air-gun source. A Bolt PAR air gun with a 120-in.^{3} chamber immersed in 30 ft of water was fired 20 ft from the bottom of the U10bd hole.

Due to time limitations in the field, the spatial sampling interval was coarse and unequal. Optimally effective velocity filtering was therefore impossible. A variety of gun-chamber pressures was used to ascertain the effect of pressure on signal quality. The resultant change of source waveform prevented effective deconvolution. The final result is poorer in quality than the surface air-gun data for these reasons. We did demonstrate that the marine air gun is also a viable downhole source, but certainly are unable to claim any superiority for this source.

GEOMETRICAL DETERMINATION OF THE DEPTH AND DIP OF THE PALEOZOIC SURFACE

If a horizontal reflecting plane surface intersects the well bore, or passes beneath the well bore, its depth and dip can be determined by inspection. In this case, the apparent velocity of the reflected event, measured in the well, will equal the medium velocity. And the medium velocity can be easily determined by observing the first arrivals from the source. The depth is simply that depth at which the reflected event first appears. If the layer lies beneath the well bore, the depth still can be rather easily determined (if the velocity is known) by extrapolating the reflection times and first-arrival times until the two times coincide.

If the reflecting surface has substantial dip, then the reflected wavefront enters the well bore at an oblique angle, and appears to have a velocity greater than that of the medium surrounding the well bore. If the velocity of the medium is known, this angle can be determined rather easily and, thus, also the dip.

By a rather straightforward extension of these ideas, it is possible to determine the dip and depth of the reflecting surface under the more complicated situation wherein:

1. The source is not directly above the borehole.
2. The reflected wavefront is not plane (source-receiver distance small).
3. The reflecting surface may not intersect the hole, but passes beneath it.

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Figure 34 shows the ray-path model used in obtaining the required relationship. The medium is assumed homogeneous above the reflecting surface.
Let

l = source offset distance

S = source depth

X = geophone (well phone) depth

H = depth at which the dipping bed intersects the borehole, or boreholes extended

$\emptyset$: dip angle

$\alpha = \tan^{-1}(\frac{l}{H-S})$

Then, using an image source, we can derive the following formula for the arrival times.

$$T_r = \frac{\sqrt{a^2+b^2+2ab\ \cos(2\emptyset\pm\alpha)}}{V}$$

$$T_d = \frac{\sqrt{l^2+(S-x)^2}}{V}$$

(1)

where

T_d: direct arrival time

T_r: reflected arrival time

V: velocity of the medium

$a = \sqrt{(H-x)}$

$b = \sqrt{l^2+(H-S)^2}$

and the upper sign applies when a source is in the updip direction and conversely when a source is on the downdip side.

From equation 1, we can derive the following:

$$Q_{(x)} \triangleq T_2{}^2 - T_d^2 = \frac{2HY}{V^2} - \frac{2XY}{V^2}$$

(2)

where $Y = H-S+b\ \cos(2\emptyset\pm\alpha)$.

Equation 2 is linear with respect to X, so we can compute $\emptyset$ and H by least-squares fitting of a Q(X) versus X plot to a straight line.

Let C and D be the estimates of the slope and intercept of the least-square fitting curve. Then,

$$\tilde{H} = \frac{-D}{C}$$

$$\tilde{\emptyset} = \frac{\alpha}{2}+\frac{1}{2} \cos^{-1}\left[\frac{S+\frac{D}{C} - \frac{C}{2}}{b}\right]$$

where $\tilde{H}$ and $\check{\emptyset}$ is the best estimate of H and $\emptyset$, respectively.

Notice that H is independent of velocity V, while $\emptyset$ is very sensitive to the velocity when H is very shallow.
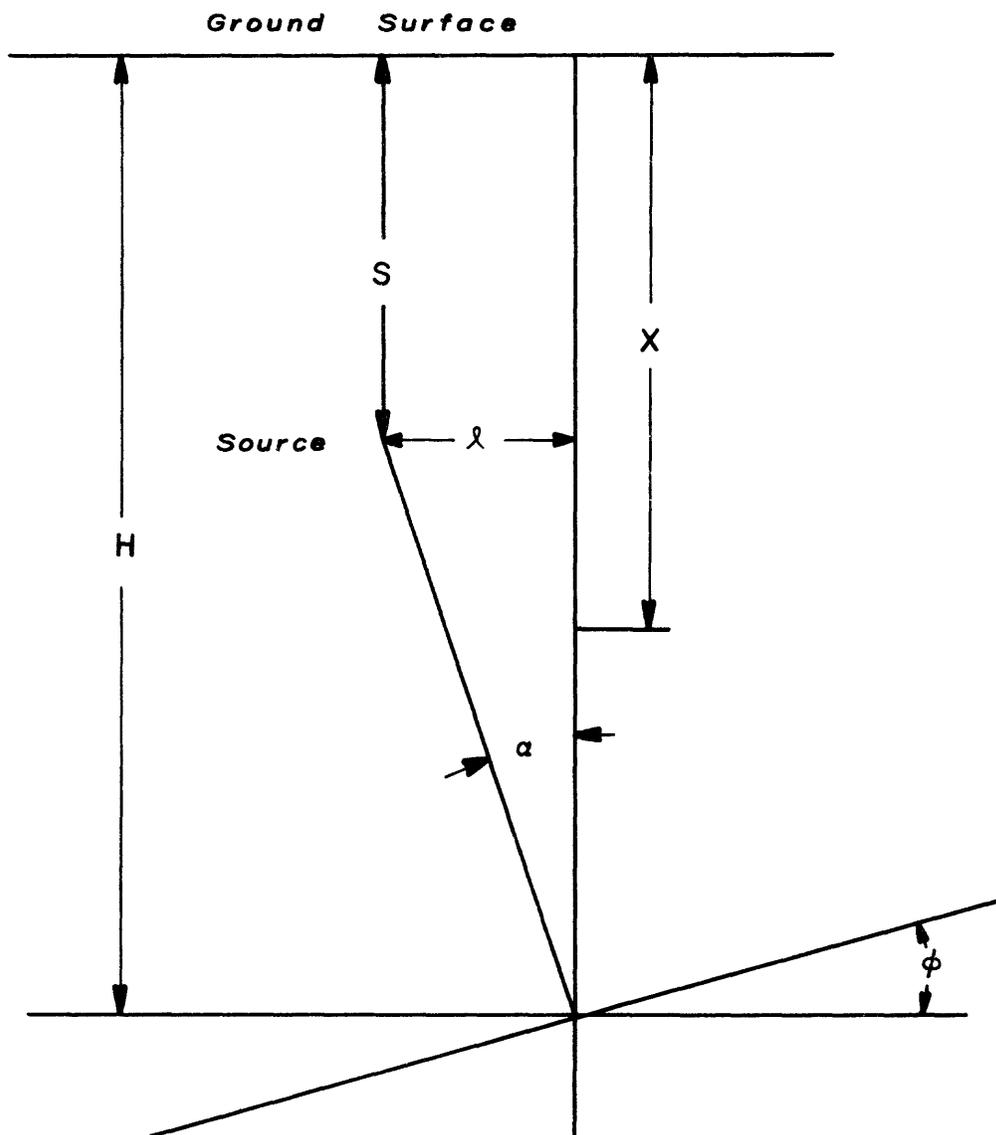
Figure 34.--Geometric ray-path model used to determine depth and dip of the Paleozoic surface.

In the derivation of this formula, we assumed that the medium is homogeneous. But in the real case this is only an approximation. There are many choices for the velocity, V, in the least-squares fitting. Three possibilities are average velocity, medium velocity, and RMS velocity. We did not test which velocity would give the best result.

In most cases, average velocity is the lowest of the three possible velocities and velocity of the medium is the highest. We will obtain the highest dip-angle estimate using the average velocity.

Figure 35 shows the plot of Q(X) versus X for the surface air-gun data. This plot clearly indicates that Q(X) is linear with X. We can see the abrupt slope change at 990 ft. This phenomenon was discussed earlier. We interpreted the linear segment from 990 to 1,470 ft. Table 2 shows the result of this interpretation. This is a "dip line" interpretation. It is fairly accurate even if the true dip direction differs from the source-receiver direction by 10°-20°. For differences greater than this, the interpretation will be in error, and a three-dimensional interpretation must be made.

SUMMARY AND CONCLUSIONS

The primary objective of the investigation was accomplished. Reflections from the Paleozoic were obtained, and a comparison of the advantage and disadvantage of five types of seismic sources was made.

The Paleozoic surface has been established as a good reflecting horizon and its depth and dip can be estimated. As a corollary to this, we have also shown that sufficient seismic energy can be generated at the ground surface to create a Paleozoic reflection.

We acquired a considerable amount of comparative data among five different types of seismic sources: two surface sources and three downhole sources. The data using downhole sources could undoubtedly be improved with improved field technique, based upon experience, but we see no advantage to pursuing the downhole-source concept at this time. The surface source methods--Vibroseis and surface air guns--seem more than adequate for the job. Whenever surface sources can be used successfully, they probably should be used. However, if in the future a situation occurs in which surface sources cannot be used, an improved downhole source appears to be a viable alternative.

It is also clear, as a result of this investigation, that velocity filtering is an extremely valuable tool for enhancing the Paleozoic reflection.

Without it the Paleozoic reflection is weak in contrast to the initial downward-traveling waveforms. With it the Paleozoic reflection can be identified and interpreted. Prior to this investigation, velocity filtering has apparently not been attempted on vertical seismic profile at the NTS.

We also believe that this study shows the advantage of using multiple surface sources. By using three vibrators, or alternatively three or four surface air guns, a vastly improved signal-to-noise ratio can be obtained. Whereas it is true that an improved signal-to-noise ratio can also be obtained by repeating a given level many times, the upper limit on signal-to-noise ratio improvement by using a stronger source is approximately proportional to the increased strength of the source. On the other hand, the signal-to-noise ratio improvement
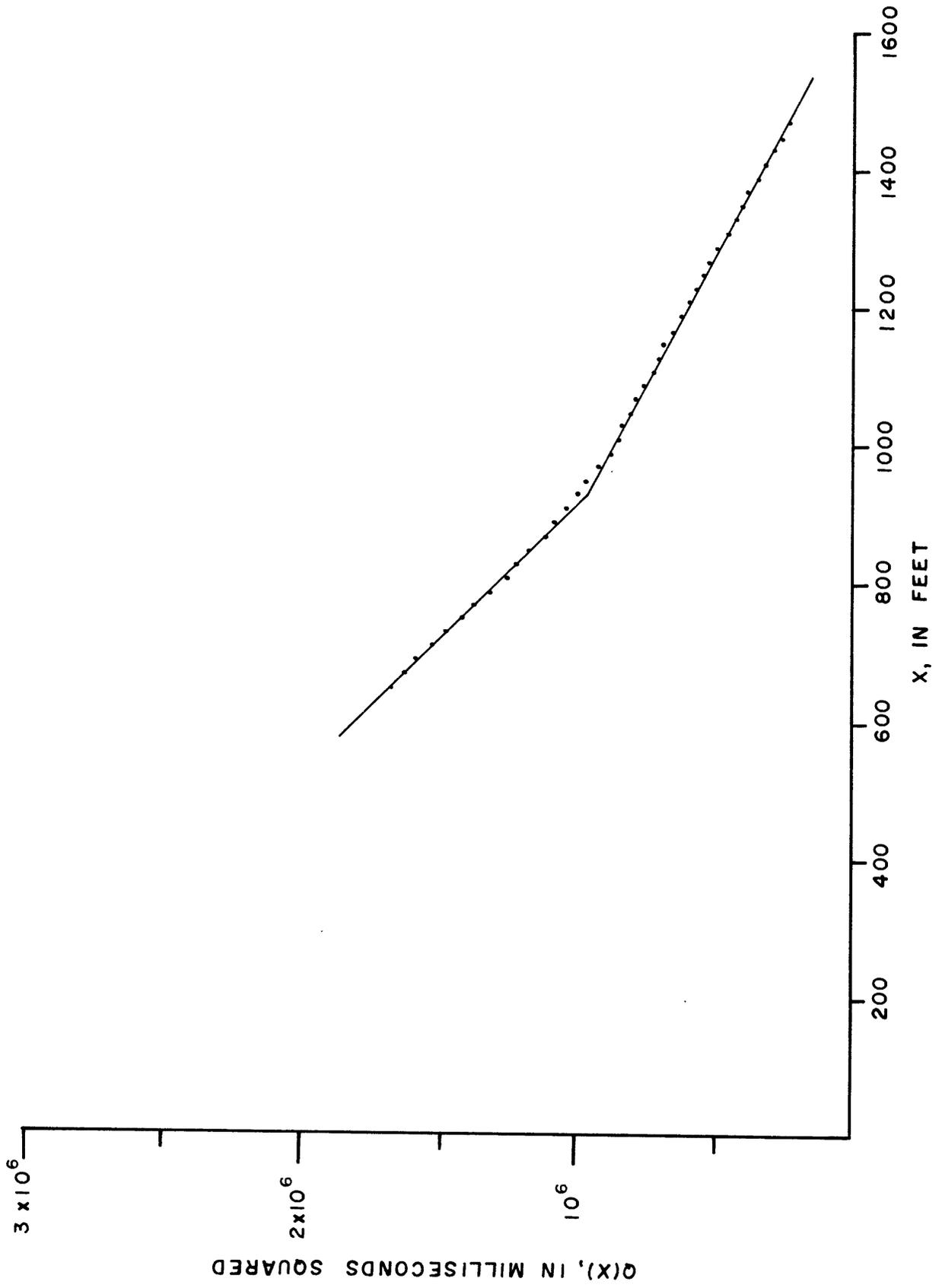
Figure 35.--Plot of Q(X) versus X.

Table 2.--Estimated dip angle, G, and depth, H, of the Paleozoic surface

Velocity	$\tilde{\emptyset}$	$\tilde{H}$	Remarks
V=4.6 ft/s	42°	1,650 ft	Using average velocity and actual arrival time
V=5.7 ft/s	30°	1,650 ft	Using medium velocity near Paleozoic and 51 ms time shift of arrival time to compensate for inhomogeneity of the medium
V=5.7 ft/s	36°	1,655 ft	Using medium velocity near Paleozoic and 51 ms time shift of arrival time to compensate for inhomogeneity of the medium

by using repeated levels is roughly proportional to a square root of the number of repetitions on a given level. So while both techniques are useful and in fact should be used, a fourfold increase in signal strength represents approximately the same signal-to-noise ratio improvement as a 16-fold increase in repetitions on a given level.

Examination of the overall frequency content of the Vibroseis VSP suggests rather strongly that the highest frequencies transmitted into the ground, and reflected by the Paleozoic, are less than 60 Hz. It seems pointless to use frequencies higher than 60 Hz in the original Vibroseis sweep, because this energy apparently is dissipated near the source and no use of this higher frequency energy is made. By using a 10-second sweep which starts at about 60 Hz, a considerably enhanced signal-to-noise ratio should be attainable from the Vibroseis data. Of course, this figure could vary from location to location within the NTS. However, as a summer and correlator are available during the field operation, the frequency of the VSP signal being returned can be estimated on location before the main experiment begins. This should be done in future work and the sweep frequency then adjusted to correspond more closely to those frequencies actually being recorded.

Another possible use of downhole sources may be to calibrate surface recorders which are to be used at the shot time of a nuclear test. During a weapons test, a large number of surface seismographs are used to monitor the explosion. Yet it is often difficult to predict in advance of the weapons test how well these surface recorders might perform at various locations at the test site. We believe a downhole air gun that fired repeatedly at the blast level might be an excellent means of predicting, in advance of the weapons test, the best location for surface seismic recorders.

Finally, we observe that the Paleozoic surface reflection generated by surface sources is so strong, at the U10bd site, that it should be detectable on the surface. That is, we believe that the Paleozoic surface could be mapped using a specialized surface seismic technique. We are aware that previous attempts to do this have met with only limited success. Several of the VSPs suggest that energy trapped in the near-surface zone is probably the reason for this.

In other words, the Paleozoic reflection exists and is of sufficient amplitude to be detectable, but it is partially or completely obscured by the near-surface reverberations. We believe this difficulty can be overcome with a carefully designed surface shooting and recording configuration.

Because it is often desirable to map the Paleozoic surface prior to drilling test holes for nuclear tests, we recommend that additional experimental VSP and surface reflection seismic data be collected to study the nature of the Paleozoic reflections in other parts of the NTS.