Research Report 161

MOVEMENT STUDIES BY SEISMIC SOUNDINGS

GREENLAND ICE SHEET

by

Hans Roethlisberger

Charles R. Bentley

and

Hugh Bennett

APRIL, 1965

U.S. ARMY MATERIEL COMMAND

COLD REGIONS RESEARCH & ENGINEERING LABORATORY

HANOVER, NEW HAMPSHIRE

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PREFACE

This is a report on seismic investigations carried out in Greenland during the summer of 1956 under a contract with Air Force Cambridge Research Center and during the summer of 1959 as part of a project of the U. S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE), now incorporated in U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). It is one of a series of reports on subtask 5010.03134, Elastic and visco-elastic properties of snow and ice.

The field work was carried out in 1956 by Norman Goldstein of Air Force Cambridge Research Center and Charles R. Bentley, Hugh Bennett* and Ned Ostenso of Lamont Geological Laboratory, assisted by T/Sgt Charles Abe, USAF, and Sp3c Stanley Kellog, EATF, and in 1959 by a USA SIPRE team consisting of Hans Roethlisberger†, contract geophysicist, Ker C. Thomson, Colorado School of Mines, and Brenton M. Hamil, assisted by Sp4c Ronald M. Van Noy and Pfc Alan A Wickham, ER DD.

This report has been reviewed and approved by Headquarters, Army Materiel Command.

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3. Glaciers--Velocity--Greenland

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SUMMARY

A detailed seismic reflection survey was carried out at Site 2, Greenland (76°59' N, 56°05'W) in 1956 in a rectangle 3160 x 2400 ft (963 x 732 m). The survey was repeated in 1959 in the same area, which had been marked by bamboo poles. The results were essentially the same, indicating that the surface had probably not moved much in the 3-year period. However, the reflection records were not of sufficiently high quality to give an accurate estimate of the possible shift, leaving an uncertainty of the order of 50 to 100 m in the direction of the dip of subsurface (SW) and more in the direction of the strike. It is estimated that under more favorable conditions the method should give an accuracy of 30 to 50 m.

MOVEMENT STUDIES BY SEISMIC SOUNDINGS ON THE GREENLAND ICE SHEET 1956-1959, SITE 2

by

Hans Roethlisberger, Charles R. Bentley, and Hugh Bennett

Introduction

Previous seismic soundings in the vicinity of Site 2 had revealed that an area of considerable subsurface topography existed at the base of the ice sheet not far from the camp and that good reflections could be obtained (Bentley et al., 1957). It was hoped that typical features of the irregular bottom could be mapped accurately enough by detailed seismic soundings so that they could be identified again in a later survey. Repeating the survey after a few years at a marked position on the surface should then give the surface movement relative to the topographical features of the bottom.

1956 Survey

During the summer of 1956 a seismic party returning from a traverse to the center of the Greenland ice sheet conducted a detailed seismic reflection survey in an area just north of Site 2. The project began on 27 July and was completed on 30 July 1956. Weather during this period was moderately overcast with temperatures about -10 to -15 C.

The area surveyed was a rectangle 3160 x 2400 ft (963 x 732 m) with sides oriented N-S and E-W (true) of Site 2. The area was marked off at the corners by 7-ft bamboo poles with flags attached.

Equipment used in the survey consisted of a portable 12 trace shallow reflection seismograph manufactured by Midwestern Instruments.

A charge of $2\frac{1}{4}$ lb of military composition C-3 explosive (equivalent to 3 lb TNT) was used for each recording with the exception of two shots of $6\frac{3}{4}$ lb. The charge was always buried 3 to 4 ft below the snow surface. (The 1 ft uncertainty in shot depth introduces a maximum error in travel time of about $\frac{1}{2}$ millisec.) The gain settings on the amplifiers were constant for all recordings, and filter settings were 75 cps low cut and 300 cps high cut. No automatic gain control (A. G. C.) or presuppression was used.

The array consisted of two rows of 13 E-W oriented spreads (Fig. 1). Each spread contained 11 geophones spaced 128 ft apart, giving a total spread distance of 1280 ft. The distance between parallel spreads and and also between adjacent ends of spreads in line was 200 ft. Charges were placed 200 ft from each end of a spread. Thus a sub-glacial area of approximately 2960 x 2400 ft (902 x 732 m) was covered and each linear pair of spreads had one reflection path in common.

Each line was numbered and the corresponding reflection time profile plotted (Fig. 3). Then the reflection times were plotted on a grid and contoured (Fig. 2). An E-W trend in the center of the contour map, paralleling the seismic spreads, is immediately apparent. This is most likely a result of not having a N-S reflection control line. Since it was believed that a more detailed interpretation should await a seismic resurvey, no adjustment of these reflection times was made. Furthermore, these times were not converted to ice thickness, nor were shot depth corrections applied. The spread correction c_s was made, however. It was computed from the approximation $c_s = x^2/2tv^2$, with x = spread, t = travel time of the reflected signal, and v = average velocity = 12,640 ft/sec (3845 m/sec). The spread corrections are listed in Table I.

Most of the records showed good reflected energy, although the first break of the reflected pulse was sometimes not clear. The onset of 55% of the reflection signals could be picked within ± 2 millisec, 29% within ± 4 millisec, and 16% within ± 6 millisec. A slight improvement of these uncertainties was obtained by considering the alignment of first peaks.

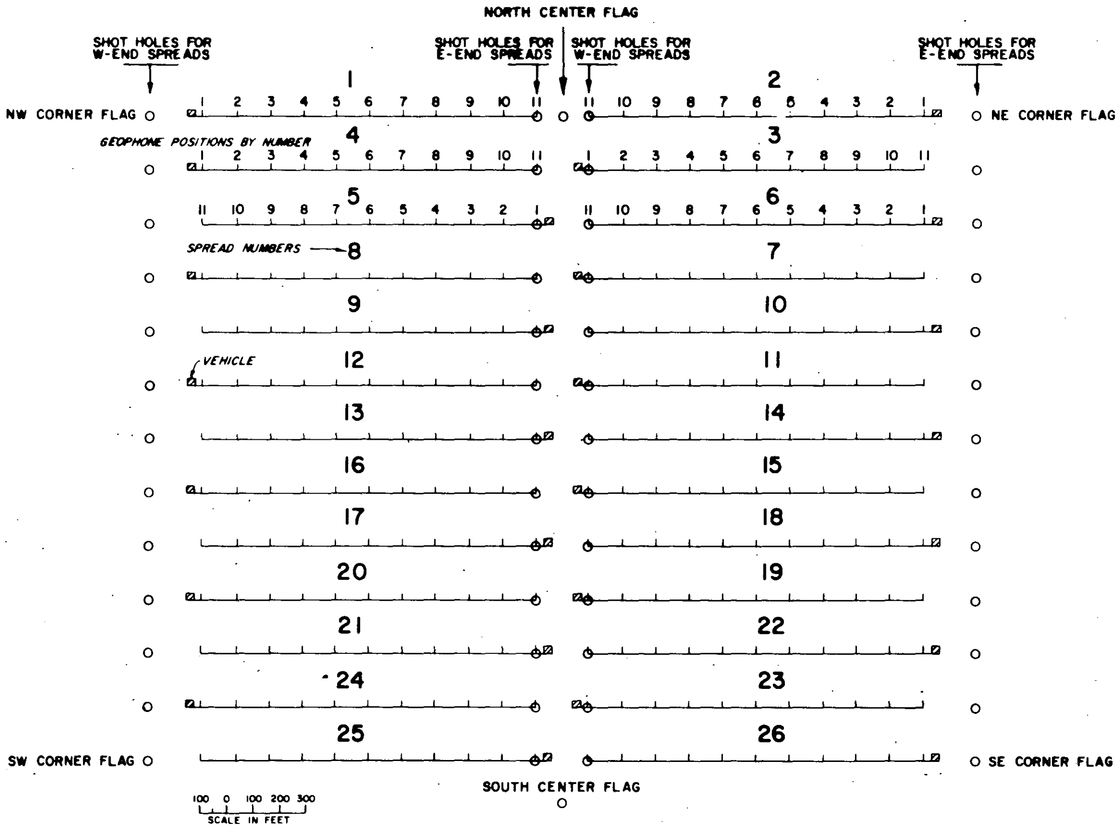

Figure 1. Spread array of the 1956 survey.

Table I. Spread correction for travel time t = 1 sec.

Spread (ft)	Spread m	Spread correction (millisec)
200	60	0
328	100	0
456	138	1
584	177	1
712	216	2
840	255	2
968	293	3
1096	332	4
1224	371	5
1352	410	6
1480	450	7
1608	487	8

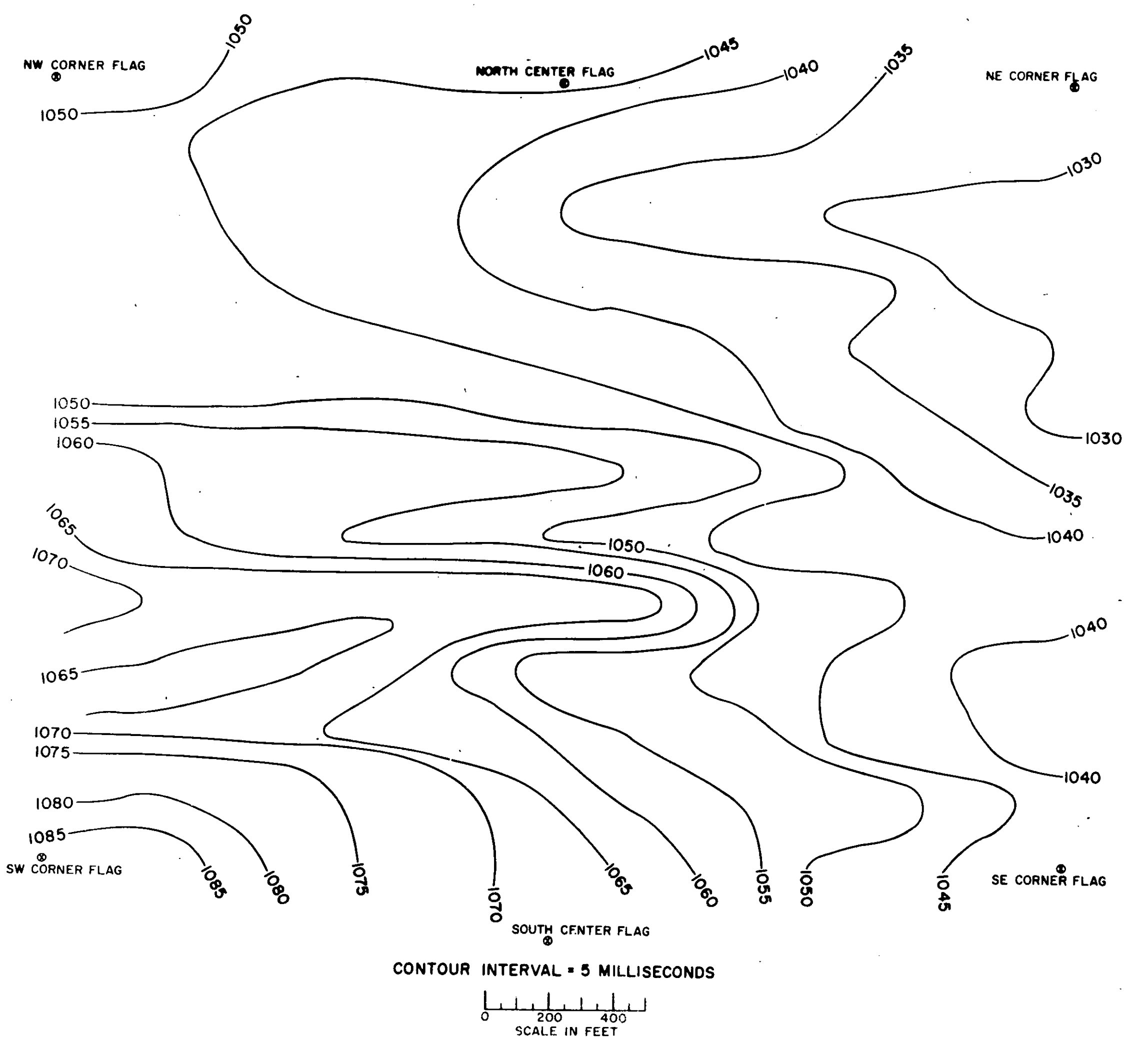

Figure 2. Reflection times and contour lines of equal reflection time (time isograms) of the 1956 survey.

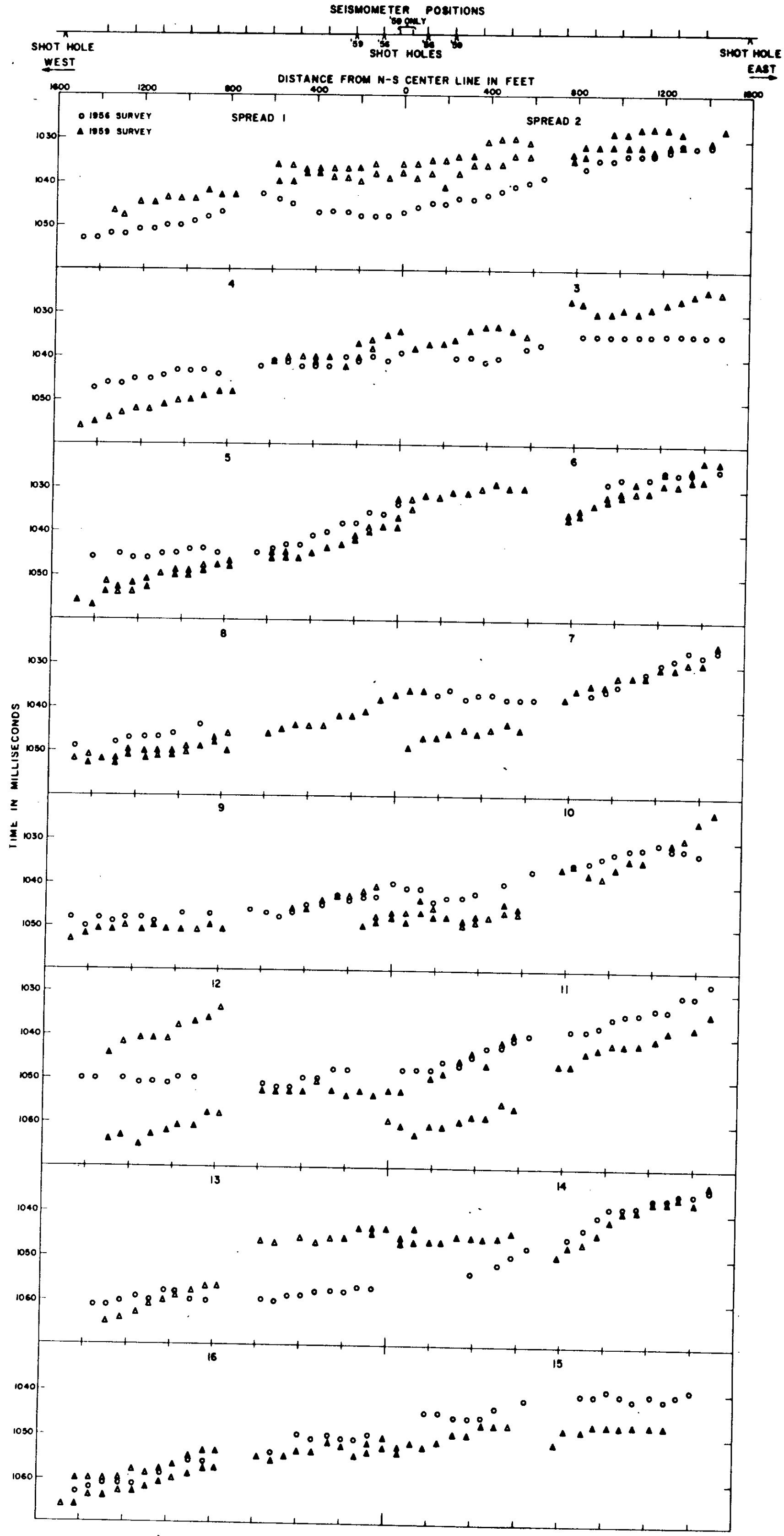

Figure 3. W-E reflection time profiles.

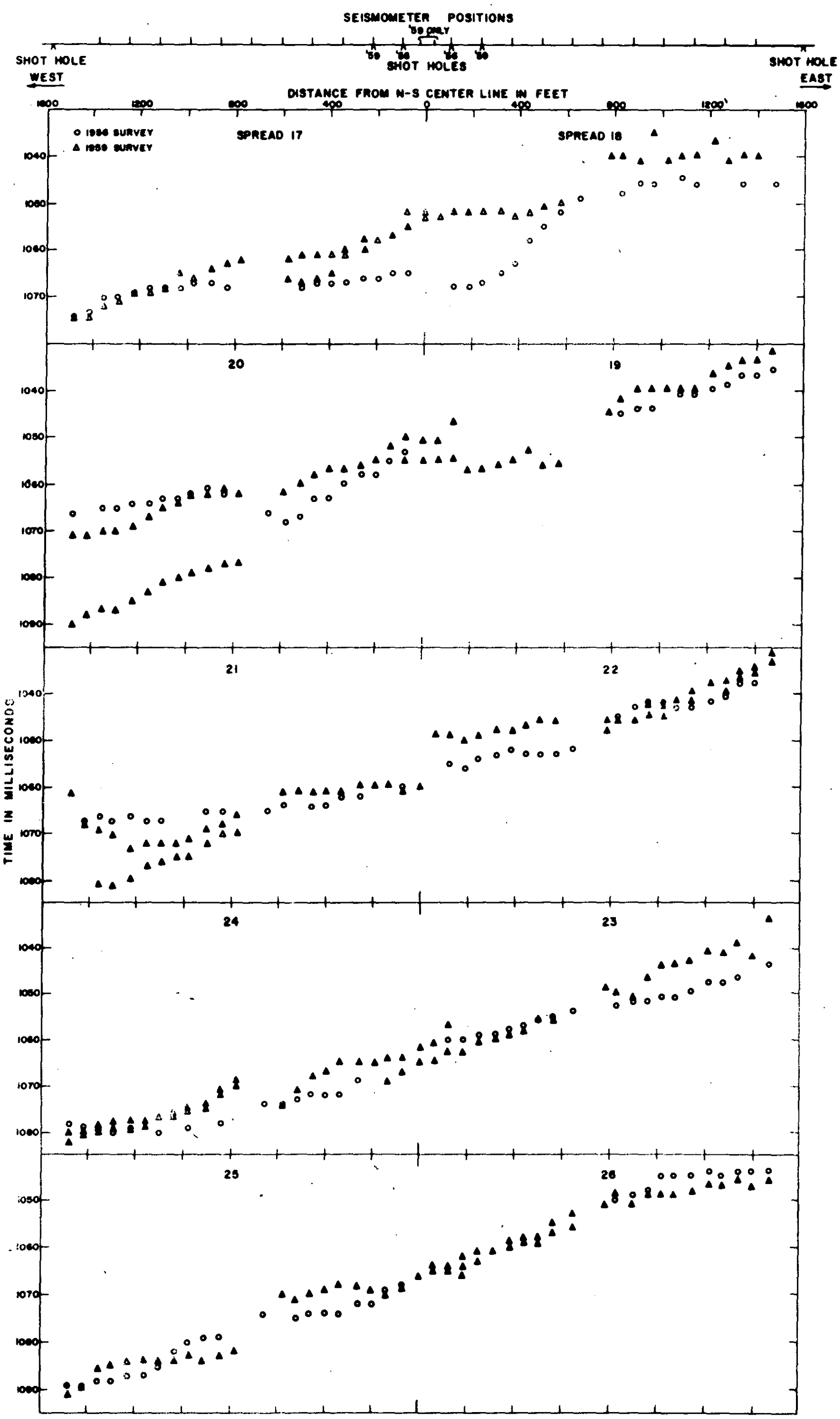

Figure 3 (Cont'd). W-E reflection time profiles.

1959 Survey

Late in the field season of 1958, one year prior to the repetition of the seismic survey, the four corner flags of the marked area were located by SIPRE personnel. The poles stood only 12 to 18 in. above the snow surface; the center markings were missing. New 12-ft bamboo poles were set in the corners.

The survey was carried out from 12 July to 18 July 1959 after two days of experimenting and briefing the party members in the neighborhood of the survey area. The weather was mostly clear and the winds were moderate. Temperatures were about -10 C. The snow was soft at the surface; the first half meter gave hardly any core with the 3-in. coring auger.

The equipment used consisted of a portable 12 channel high-frequency system model P-15 with accessories, manufactured by the Southwestern Industrial Electronics Company (SIE). Various filter settings between 70 and 425 cps were tried, but at each shot point one shot was usually fired with a fully open setting of 70 cps low and 425 cps high cut. No presuppression was used, but A. G. C. could not be switched off with this equipment. SIE type S-16 geophones with 18 cps natural frequency and 0.56 of critical damping were used. The explosions were fired with a capacitor blaster SIE type PCB-11, using Atlas "Staticmaster" caps as a rule. In the few cases when regular military caps were used, a time lag correction had to be applied, using the direct wave to calculate the time lag.

The same type of charge was used as in the first survey, $2\frac{1}{4}$ lb of C-3, but the charges were buried 2 m deep by means of a 3-in. coring auger, i. e. about 1 m deeper than in 1956 (equivalent to a time difference of about 1 millisec).

While in 1956 only 11 channels were operating, all 12 were used in 1959. The geophone lines were laid out along the same lines relative to the corner flags, the same end points were used at the outside, and the geophone spacing was the same. Since the spreads were 128 ft longer than before, some overlap occurred at the middle of the lines, and the inner shot points were 128 ft farther away from the N-S centerline than before (Fig. 4). In addition, two spreads were shot along the N-S centerline for control.

Only two spreads were accomplished in one day at the beginning of the survey as against nine towards the end. This increase was partly due to the gain of experience and partly to the establishment of a flow chart (Fig. 5) by which the successive operations along the line were coordinated.

On some days considerable trouble was caused by heavy machinery operating in or around the camp at a distance of 1 to 2 miles. This was less than the distance from the shot to the bottom of the ice sheet and back to the geophone.

The results were plotted the same way as in 1956, even using the same graph for the reflection time profiles (Fig. 3). As in Figure 2, the reflection times were plotted on a grid and contoured (Fig. 6). This time a N-S line was shot along the centerline, and therefore an adjustment could be made to eliminate the pattern parallel to the geophone lines.

Velocity versus depth

The results of the two surveys, 1956 and 1959, are stated in travel time (millisec) rather than true depths. If these travel times are to be compared directly it is important to assure that the velocity versus depth relationship was the same in both surveys. This relationship was investigated in 1955 by Bentley *et al.* (1957) in the vicinity of Site 2. In 1958 a SIPRE team under Roethlisberger measured the velocity in the surface layers at Site 2 in connection with explosion tests (USA SIPRE Project 26). The refraction technique was used with shot point and geophones placed at the surface.

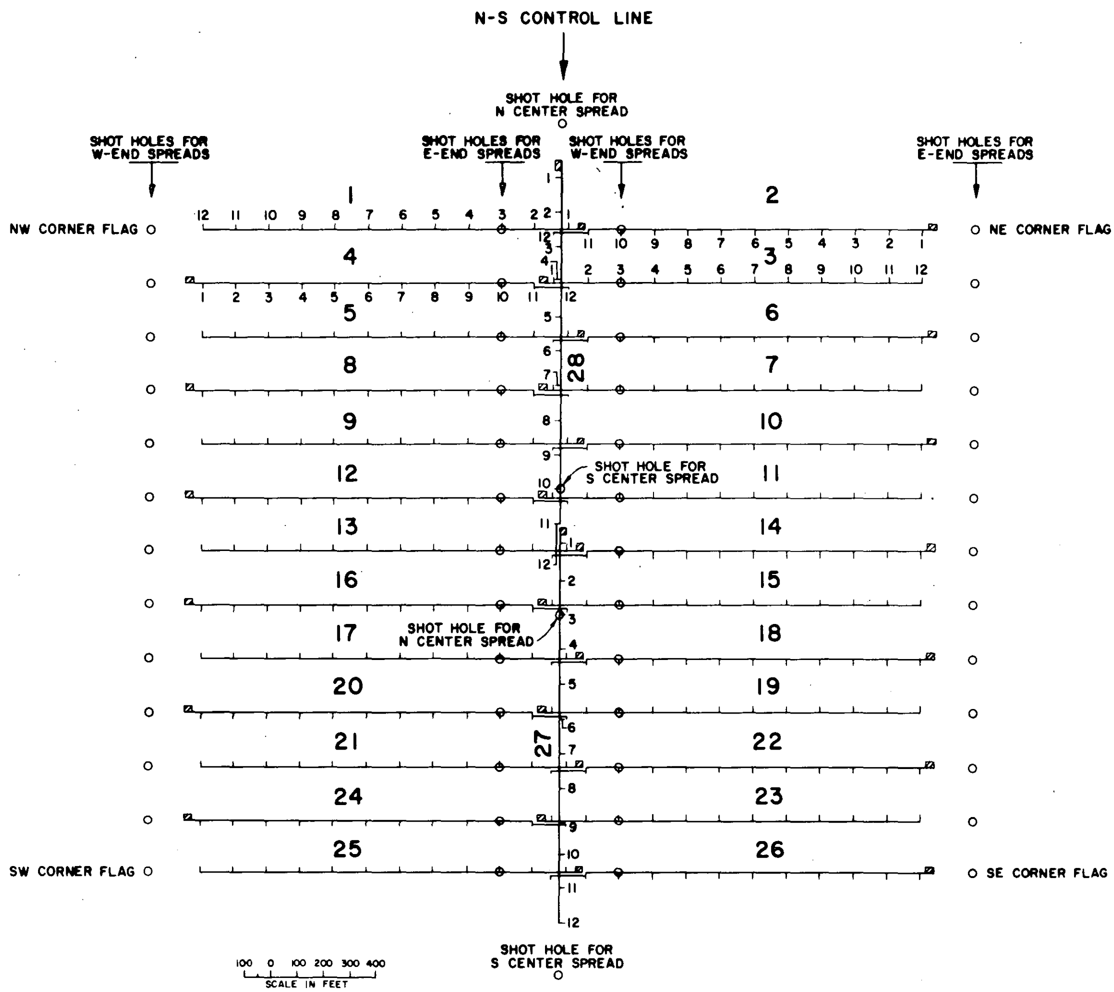

Figure 4. Spread array of the 1959 survey.

The shot point to geophone distances varied from $\frac{1}{2}$ to 110 ft at 1- to 5-ft intervals; additional recordings were taken at 130 and 160 ft distance. For the transformation of the travel time t(x) versus distance x data into velocity v(z) the Wiechert-Herglotz equation

$$z_1 = \frac{1}{\pi} \int_0^{x_1} \cos h^{-1} \left(\frac{v_1}{v(x)} \right) dx$$

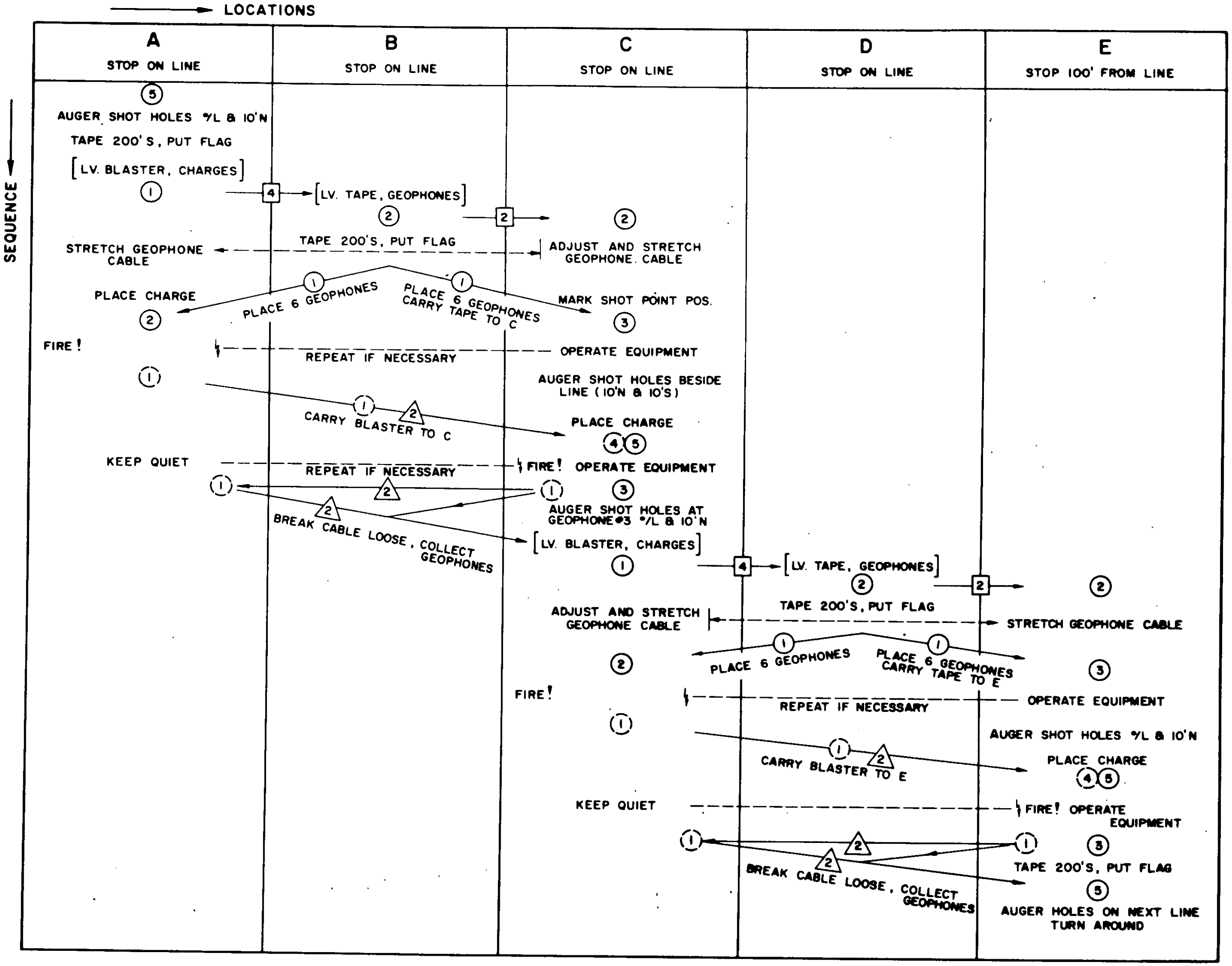

Figure 5. Flow chart for the 1959 survey. Circled numbers refer to the number of people occupied at stops A to E or along the trail, boxed ones to the number of people moving by vehicle from one stop to another. Triangles indicate that a second vehicle was used when available; broken circles indicate movement on foot or ski. Stops were marked by two flags lined up in the N-S direction.

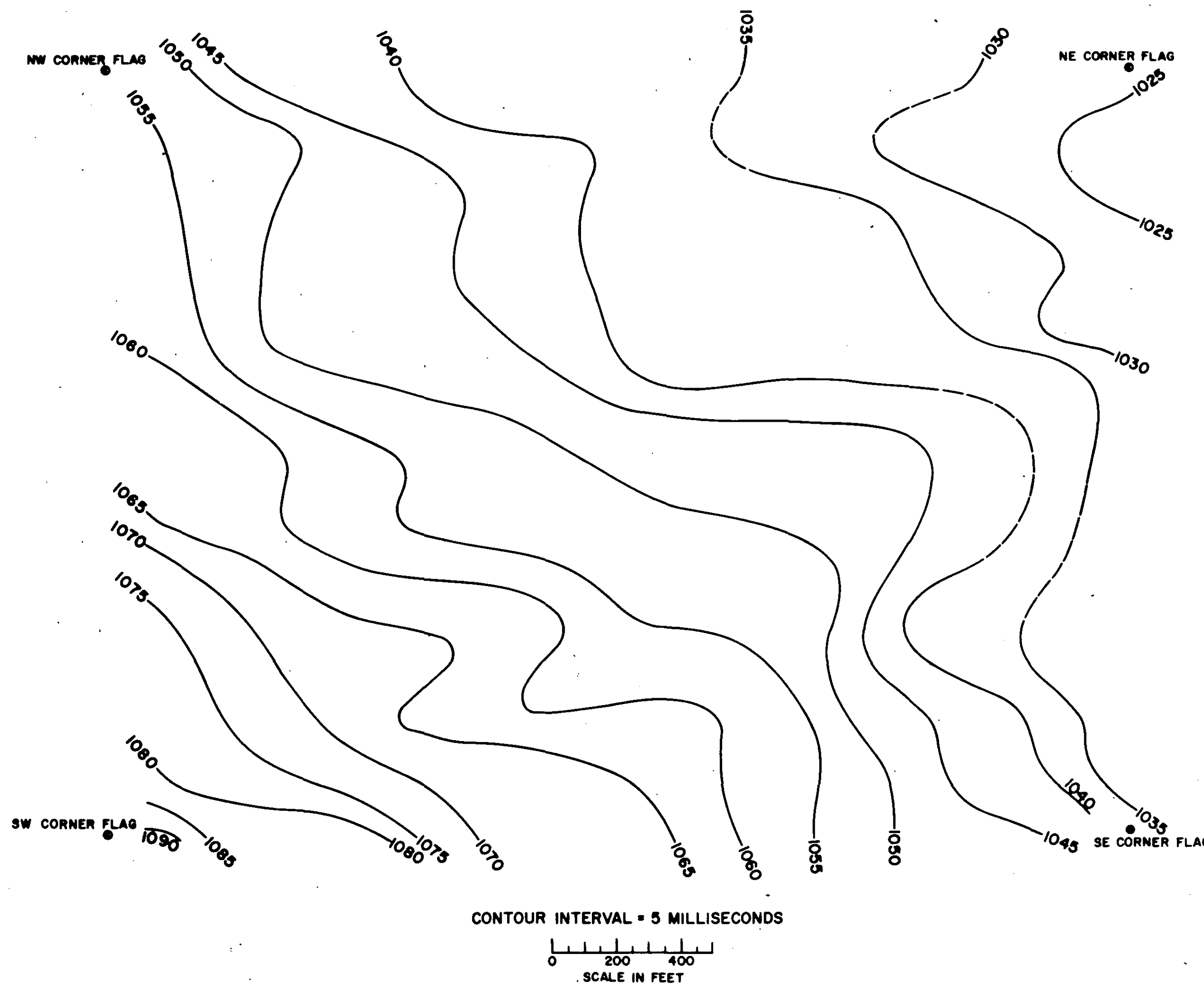

Figure 6. Reflection times and time isograms of the 1959 survey.

was used, where $1/v(x) = dt/dx$ is the slope of the travel time curve at the distance x; v_1 corresponds to the distance x_1, representing the velocity at depth z_1. A program was set up for the Bendix G15D electronic computer, making the transformation in small increments of x_1. The results are given in Figure 7 together with those of Bentley et al. (1957). The differences between the two results can be explained by experimental error, but if they were real they would produce a difference in reflection times of only 0.4 millisec. An additional maximum difference of probably the same order may be anticipated from slightly different surface conditions in 1956 and 1959, when the detailed reflection work was actually carried out.

In addition to the short-range refraction measurements, the 1958 SIPRE team determined some velocities in a vertical direction making use of the deep drill hole (Langway, 1962). Unfortunately, below a depth of about 300 m the hole was already too constricted to allow the set of hole geophones to pass. The velocity was determined between a set of two geophones 50 m apart with the shots fired at the floor of the drill pit close to the casing. The top section (about 50 m) of the hole was cased, and no velocity could be measured. From 100 to 300 m depth, a velocity of 3850 m/sec

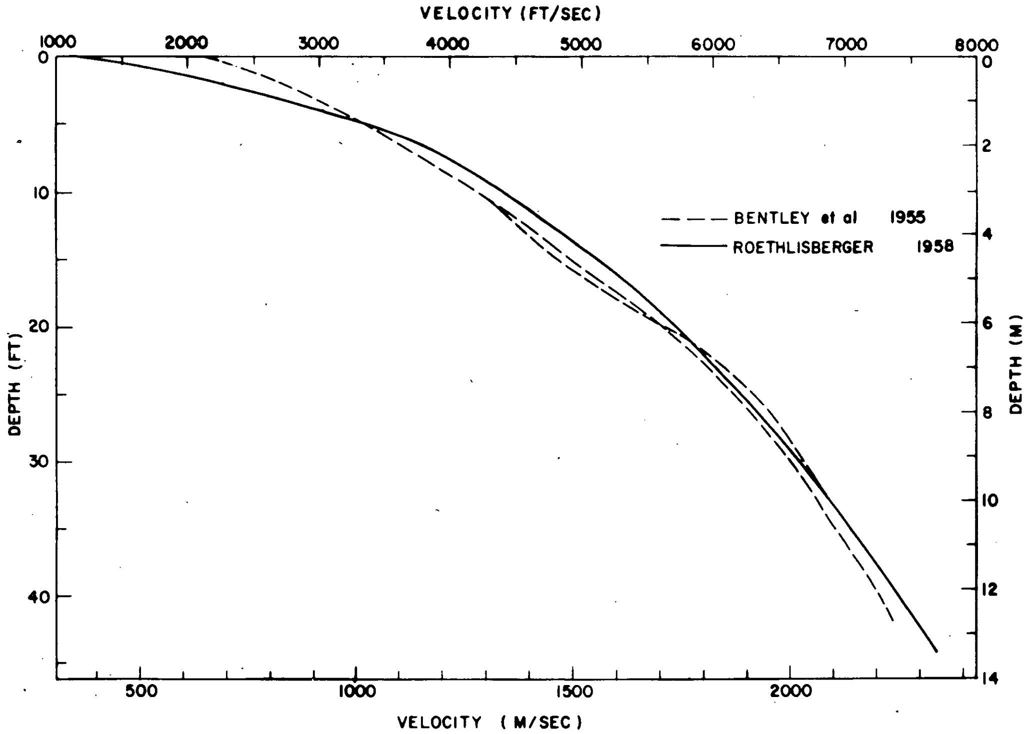

Figure 7. P-wave velocity versus depth at Site 2.

± 30 m/sec was found, which agrees satisfactorily with the value of 3865 m/sec ± 10 m/sec given by Bentley et al. (1957) for horizontally propagated waves at a depth of 350 m. The accuracy was not sufficient to decide if a small anisotropy effect exists.

Comparison of the 1956 and 1959 surveys

Travel times. The results of the 1956 and 1959 surveys, as plotted in Figures 2, 3 and 6, were obtained independently without comparing the records of the two surveys. In both cases the onset of the reflection signal was used. Since the quality of the records changed considerably from place to place, some of the travel times are much more reliable than others. While on some records the arrival of the reflection signal is clear and indisputable, on many of them it is more a matter of guessing where to pick it, and the results in those places are subjective. A misinterpretation usually affects all the traces by about the same amount so that all travel times from one shot are too short, or more likely too long. This is evident in the peculiar relief of Figure 2, which shows a trend of E-W running ridges and troughs parallel to the geophone lines. Figure 6 does not show these features as much, because a better adjustment of adjacent lines could be made owing to the larger overlap of pairs of E-W spreads in line and the N-S control spreads.

A first glance comparison of Figures 2 and 6 does not seem to indicate even that the same place was surveyed. However, the minor relief with the E-W trend having been explained as accidental, it can readily be seen that the travel times do not differ much between the two charts throughout the area. Especially it can be noted that the extreme values at the southwest and near the northeast corners match well. Figure 3 gives a comparison of the travel times along the individual E-W lines. In spite of many disagreements, there are a number of matching sections on several lines. The flatter profiles appear in the north, the steeper ones in the south part of the area in both surveys. No consistent shift of the 1959 lines in reference to the 1956 ones may be seen, but the scatter is rather large and might overshadow an effect of shifting.

Since Figures 2, 3 and 6 were obtained with both good and bad records, it was hoped to improve the comparison between the two surveys by concentrating on the good records only. When the records were reexamined, the ones from the same geophone and shot positions of both years were analyzed concurrently. First peaks were measured rather than first breaks. This introduces a small error because of different frequencies in the two records. The error is $1\frac{1}{4}$ millisec if the two frequencies are 200 and 100 cps respectively. Shot-point corrections which amounted to more than 1 or 2 millisec were applied when the direct wave deviated consistently from the average direct wave of the whole survey. There was an average difference of 1 millisec in the travel times of the direct waves between the 1956 and 1959 surveys, probably due to the difference in shot depths. No correction for this difference was applied. If the differences between the 1956 and 1959 values amounted to more than a few millisec, the records were inspected again and appropriate corrections were made whenever they could be justified.

Figure 8 shows the travel times and time isograms for the 1956 and 1959 surveys. Figure 9 gives the E-W profiles from the improved data (Figure 3 represents the preliminary results). In addition, eight N-S profiles are given in Figure 10, labeled A to H from east to west. Each point represents the average of a group of four geophones in a spread. The position of the N-S profiles is indicated by arrows in Figure 8. Using the same group averages, a SW-NE and a NW-SE profile along the diagonals of the survey field were obtained and are given in Figure 11.

In spite of the effort to obtain better results from the more reliable records, no spectacular improvement could be established in Figure 9 as compared with Figure 3. Even the most reliable records reveal discrepancies between the two surveys, and no simple shift in any one direction seems to explain them. It is therefore not possible to give a value of surface movement between 1956 and 1959. However, estimates of the maximum amount of possible shift are feasible.

The largest differences between 1956 and 1959 travel times are of the order of 10 millisec, and in most cases correspond approximately to the period of the recorded signal. These large differences may thus be explained as an error in the analysis of one of the records. However, there are cases where the difference between the two surveys develops gradually along the geophone line and the explanation as a difference of one wave period does not look appropriate. Discarding the large differences between the 1956 and 1959 results, and concentrating especially on the most reliable records, differences of up to 4 millisec between corresponding points of the two surveys remain. These differences are random, i.e. positive and negative, and cannot be explained by a shift. A difference of that order was also found between shots at the same location with different filter settings; it seems that it must be accepted as the accuracy of the survey. The time interval of 4 millisec corresponds in an E-W direction, where the travel time changes by 1 or 2 millisec per 100 ft (30 m), to a distance of 200 to 400 ft (60 to 120 m).

In order to test if such a shift could be detected without any doubt, the profiles of one year were plotted on transparent paper and were moved to the east and west relative to those of the other year. A shift of 200 ft (60 m) to either side does not generally worsen the fit of the two surveys, improves it in some places, and is therefore possible. A 400-ft (120-m) shift seems unlikely and a 600-ft (180-m) shift is incompatible with the data. The same is true when the 1959 profiles are shifted to the south. A shift to the north of 200 ft (60 m) is unlikely.

By discussing the E-W and N-S components of the shift separately, the true motion is not discussed appropriately, since it might be directed to the southwest or northwest. Figure 11 gives some information about a movement along roughly SW-NE and NW-SE lines. The SW-NE profile is quite similar to the E-W and N-S profiles and confirms a maximum possible shift without detection of less than 400 ft (120 m). The NW-SE profile running approximately parallel to the contours would imply that no statement is possible in this direction. However, both the 1956 and 1959 isograms of Figure 8 show some special features in the northeast corner which make a shift of more than some 200 m unlikely also in the SE-NW direction.

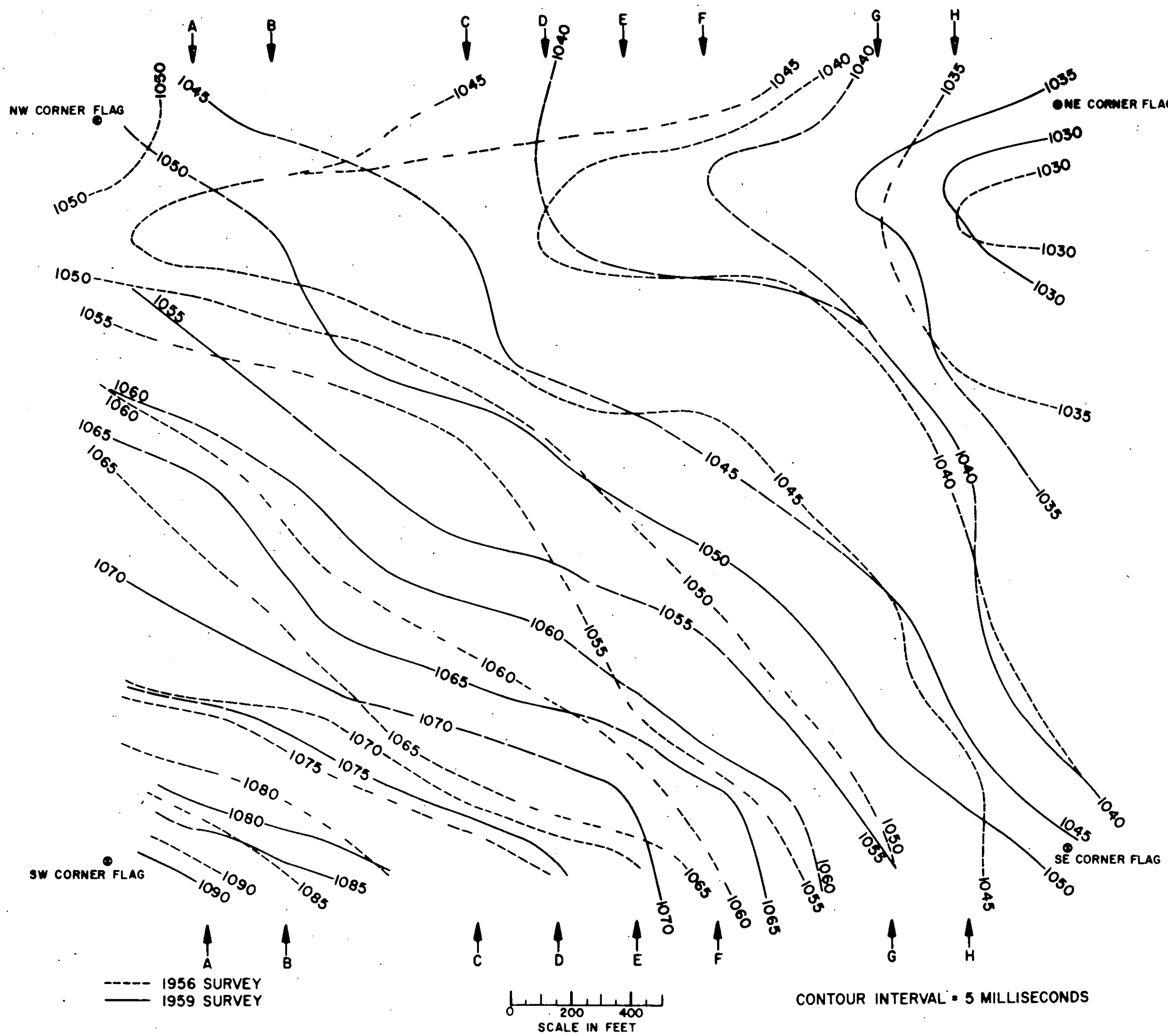

Figure 8. Re-examined travel times and time isograms for both surveys. Arrows indicate position of profiles shown in Figure 10.

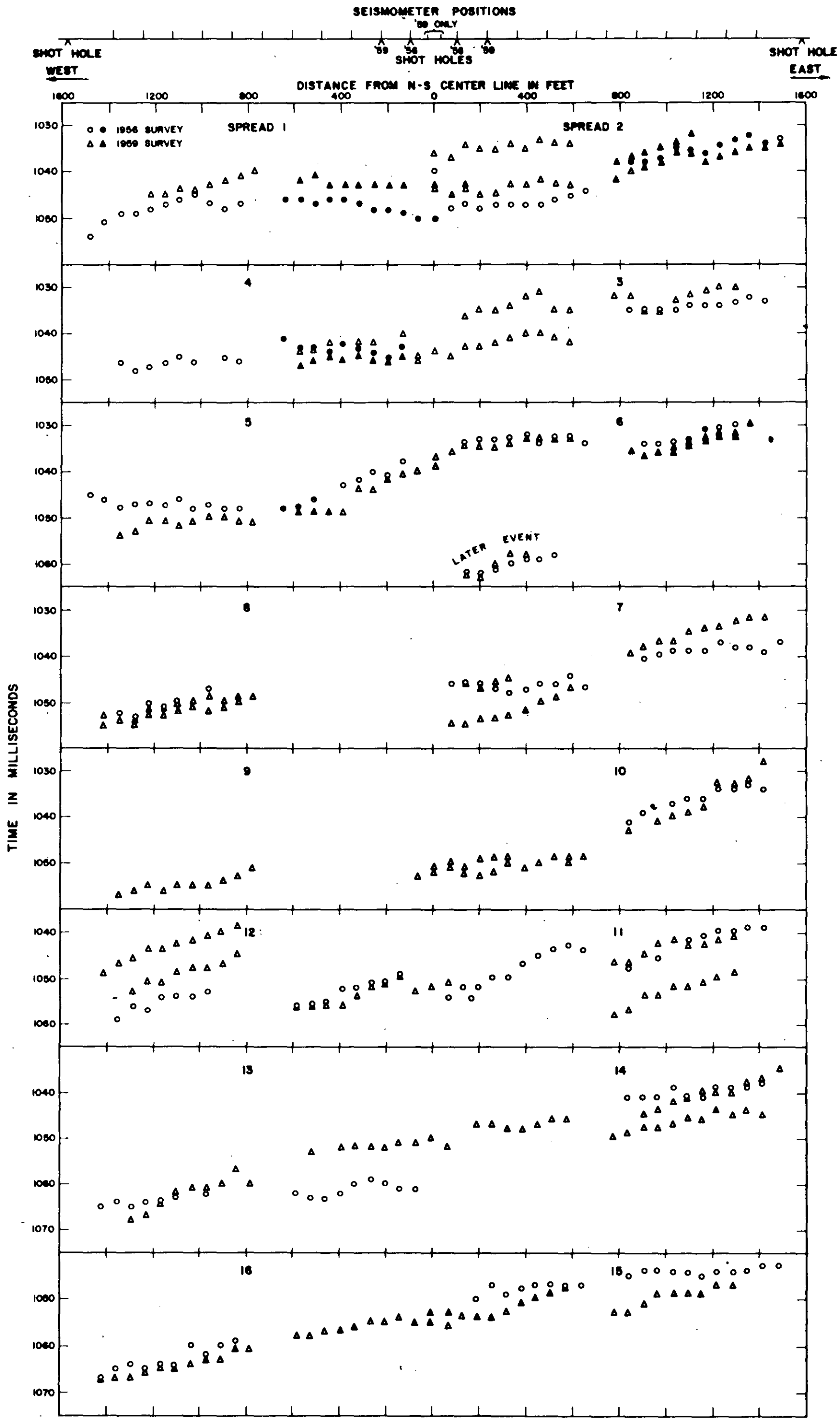

Figure 9. Re-examined W-E reflection time profiles. The most reliable results are shown by the solid symbols.

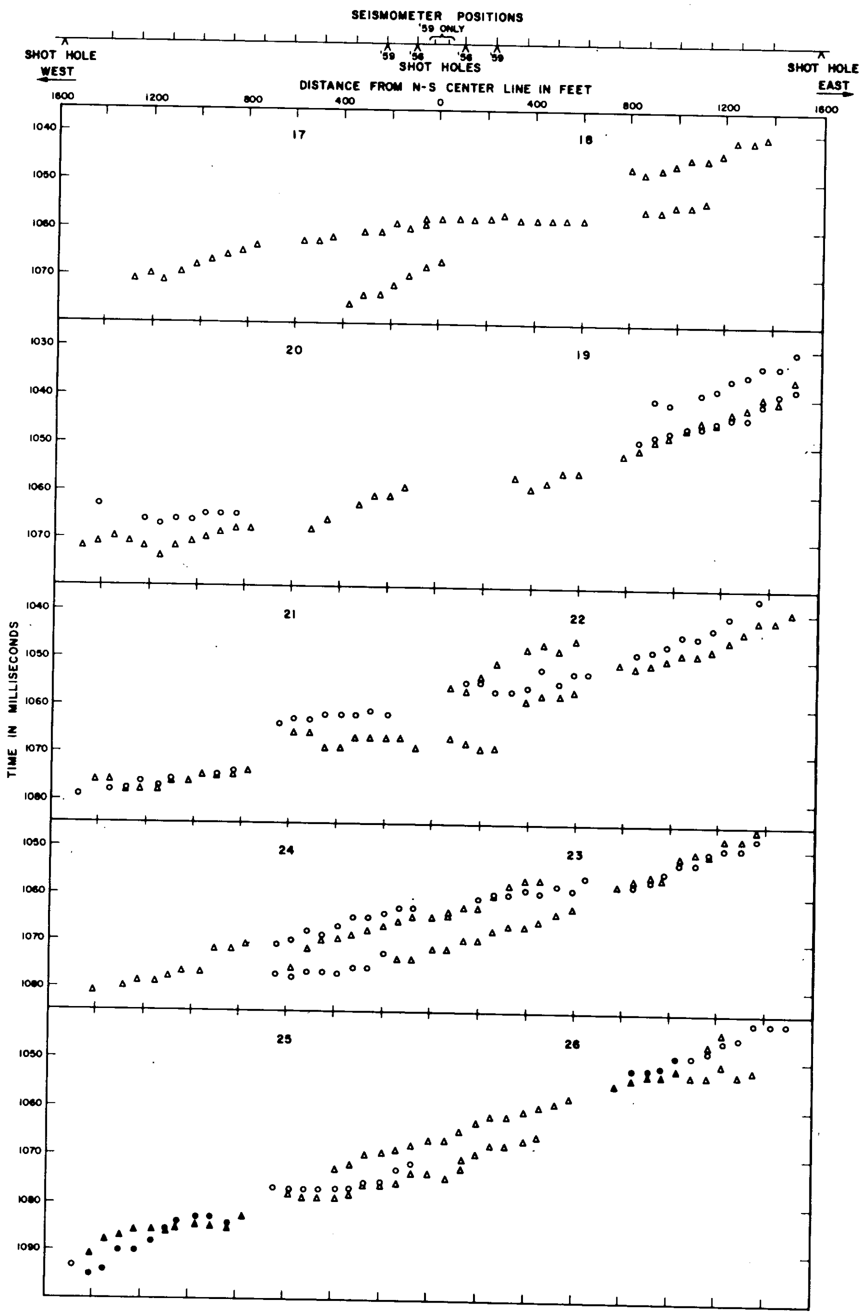

Figure 9 (Cont'd). Re-examined W-E reflection time profiles. The most reliable results are shown by the solid symbols.

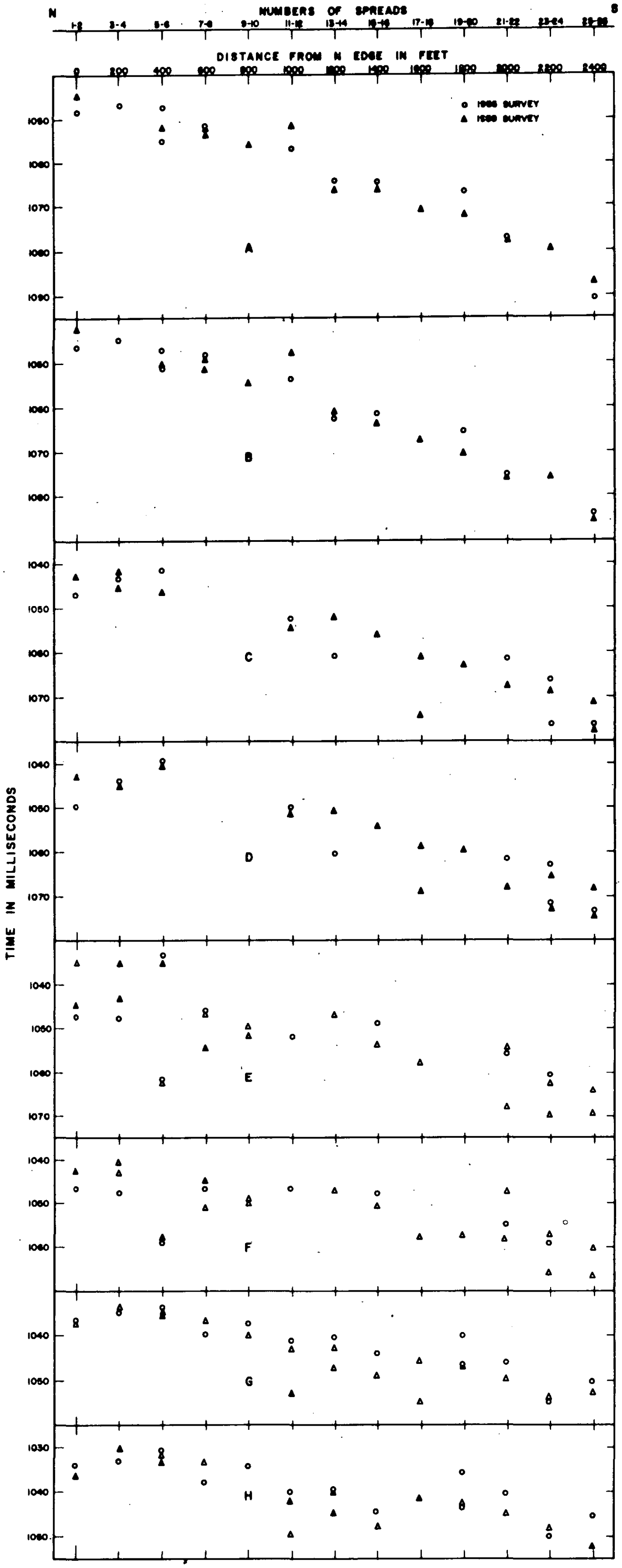

Figure 10. N-S reflection time profiles.

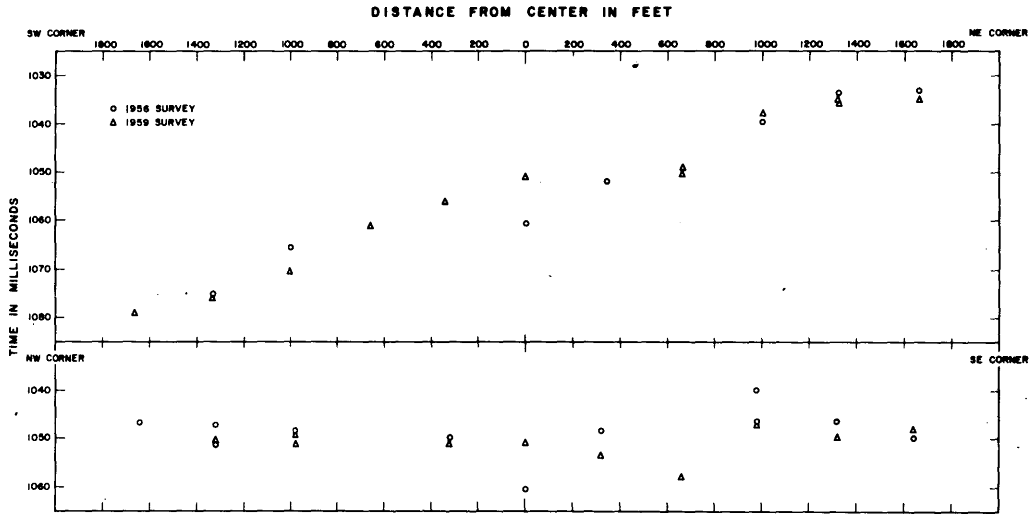

Figure 11. SW-NE and NW-SE reflection time profiles.

Comparison of records. After the comparison of travel times had shown that the surface movement between 1956 and 1959 was small, possibly less than the 200-ft (60-m) spacing of the spreads, a direct comparison of the records was tried. The objective was to see if corresponding records of the two surveys agreed well enough to imply that practically no shift had taken place.

Only a few pairs of corresponding records were available which showed about equal quality in both surveys. The reflection events were traced on top of each other with one matching time line close to the onset (Fig. 12 a-m). No attempt was made to adjust the two time bases, but in most cases the paper speed had been about equal. The polarity having been different in the two instruments, the mirror-image of one of the records (1956) had to be used. Spreads 2 E*, 11 E, some traces of 21 W, 25 W and part of 26 E (Fig. 12 a, b, c, i and k) show very closely matching onsets, while in the case of spreads 23 E (Fig. 12 e) the agreement is not so good. The records with the sharpest onsets (low noise level combined with strong reflection signal) show the best agreement (spreads 2 E and 11 E, Fig. 12 a, b), on most traces better than ± 2 millisec corresponding to a maximum shift of less than 100 ft (30 m).

To check the hypothesis of a very small shift at least in the N-S direction, records of adjacent parallel spreads were exchanged. Figure 12 g shows the reflection event of the 1959 spread 24 W plotted on the 1956 spread 25 W, implying a 200-ft shift to the south. The onset on the 1959 record clearly occurs too early. The opposite is the case in a few traces only when the 1959 spread 24 W is plotted on the 1956 spread 21 W (Fig. 12 h). A summary of the inspection of all spreads of Figure 12 is given in Table II. Although some evidence might be extracted from the table to indicate a shift of as much as 200 ft (60 m) in the N-S direction, the bulk of the information contained in the table is in favor of a smaller shift, if any, in the order of probably less than 100 ft (30 m). If the small correction of about 1 millisec for different shot depths is considered, then the 1959 traces would be delayed by 1 millisec, and Table II would be affected in favor of a slight shift of 70 to 140 ft (20 to 40 m) to the south (or, more likely to the southwest).

With the comparison of adjacent parallel spreads, only a shift in the N-S or S-N direction was checked. With the material of Figure 12, E-W/W-E shifts might also be checked, but spread corrections would have to be considered for each trace. The results would hardly be much different from the findings for N-S. For the much trickier question of a shift along the strike (about SE-NW), too few high-quality records were obtained to even attempt a comparison of reflection events along such a line.

*For the position of the spreads see Figure 1 or 4.

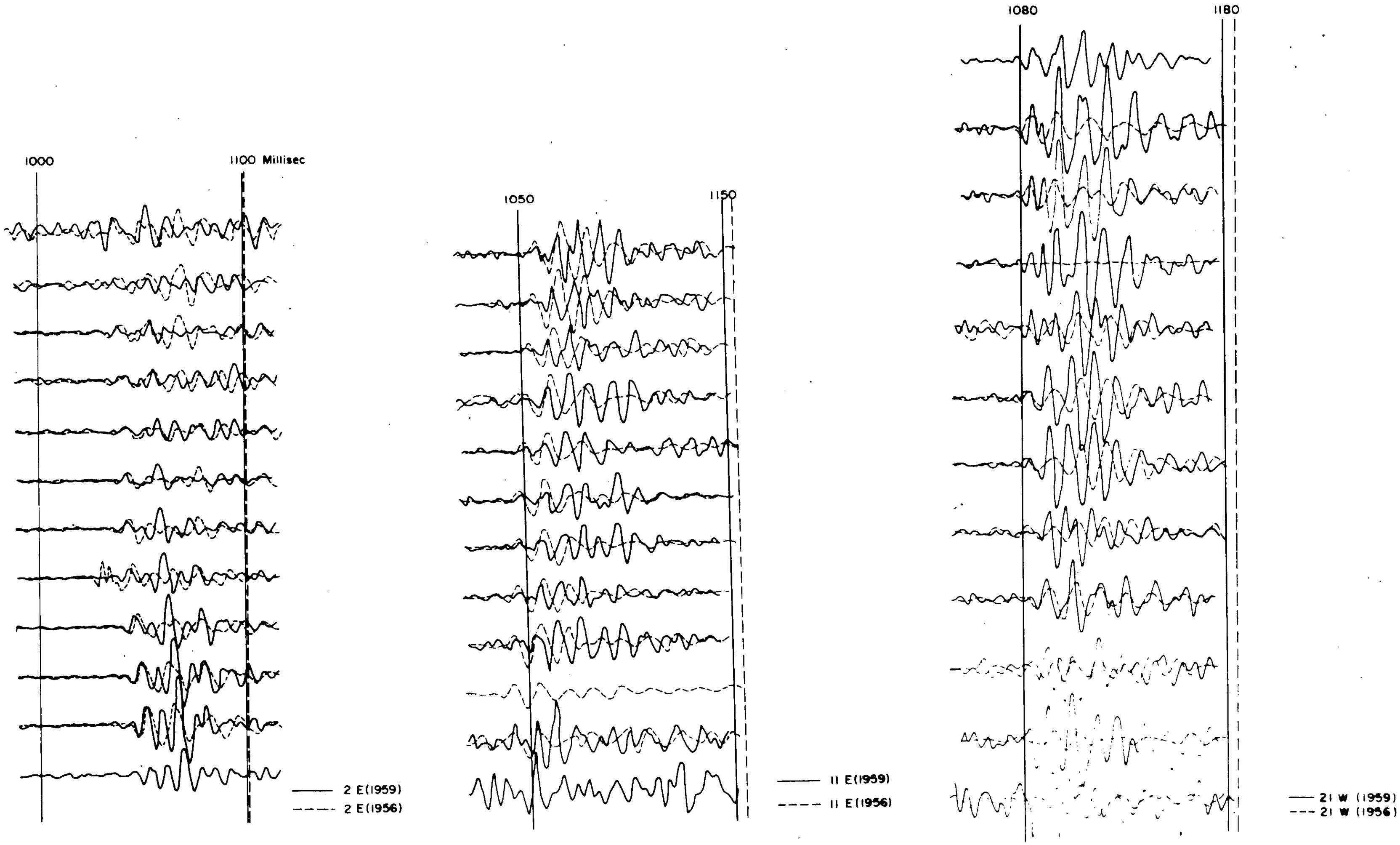

Figure 12. Superposition of the reflection events from the 1956 and 1959 records.

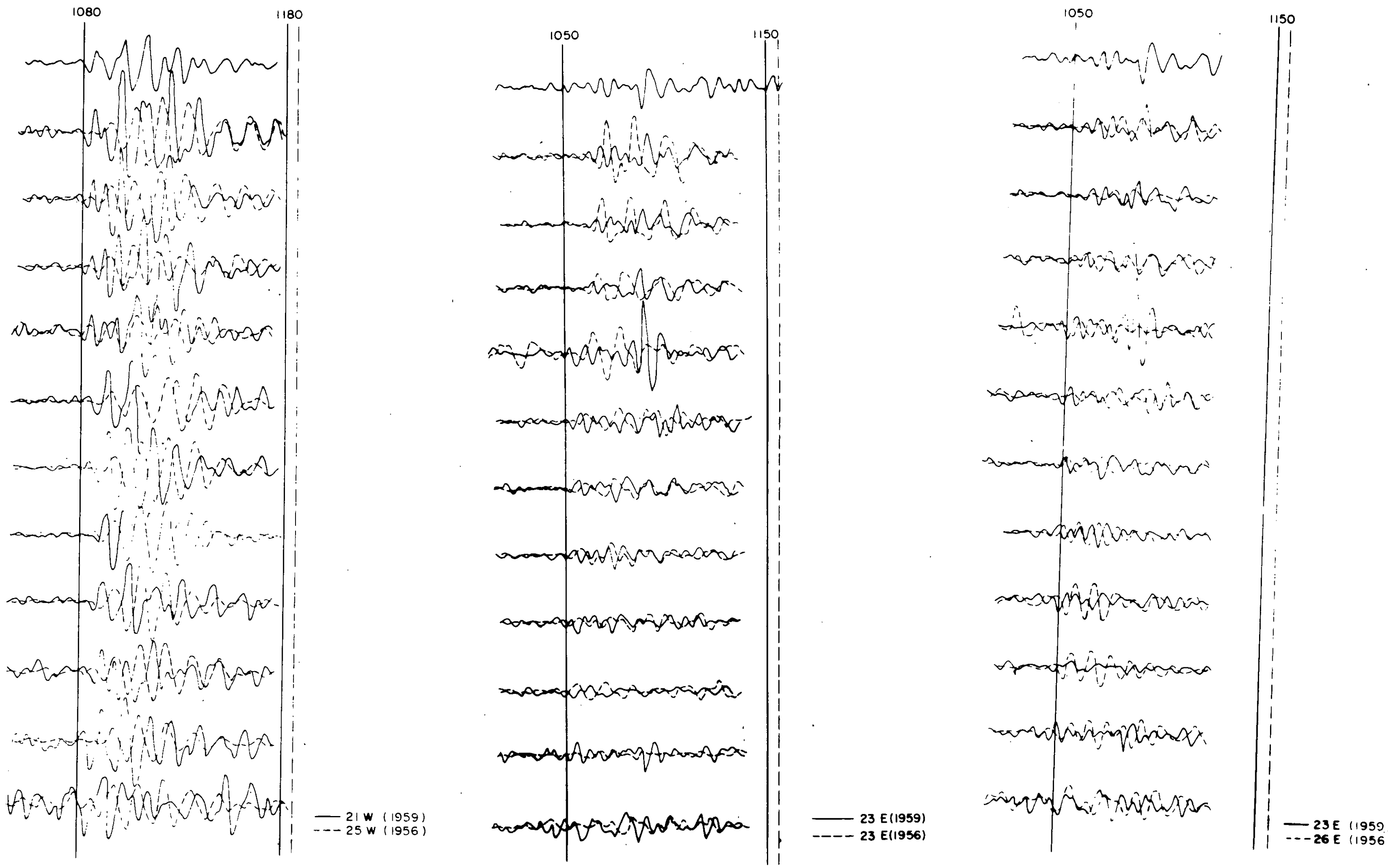

Figure 12 (Cont'd). Superposition of the reflection events from the 1956 and 1959 records.

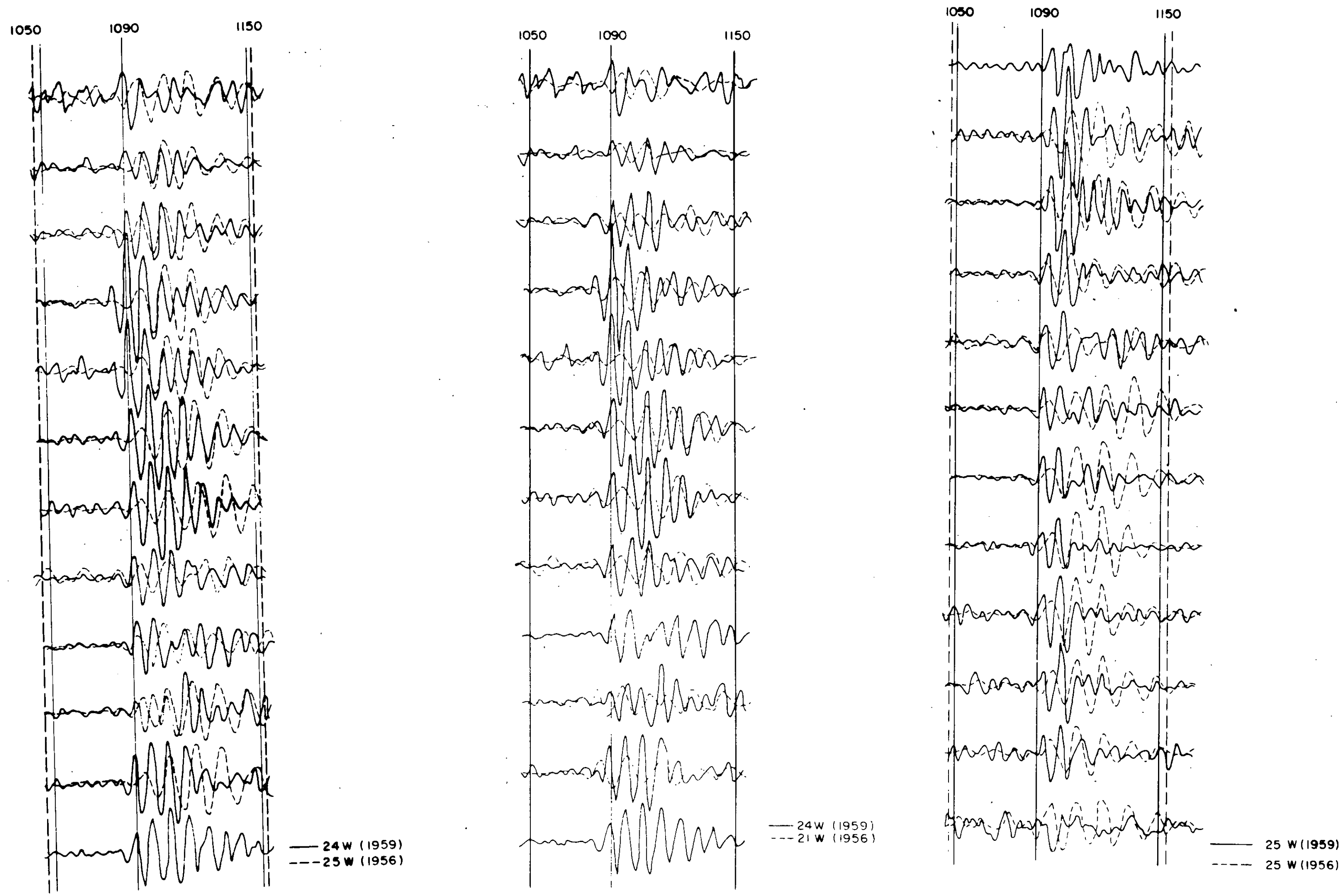

Figure 12 (Cont'd). Superposition of the reflection events from the 1956 and 1959 records.

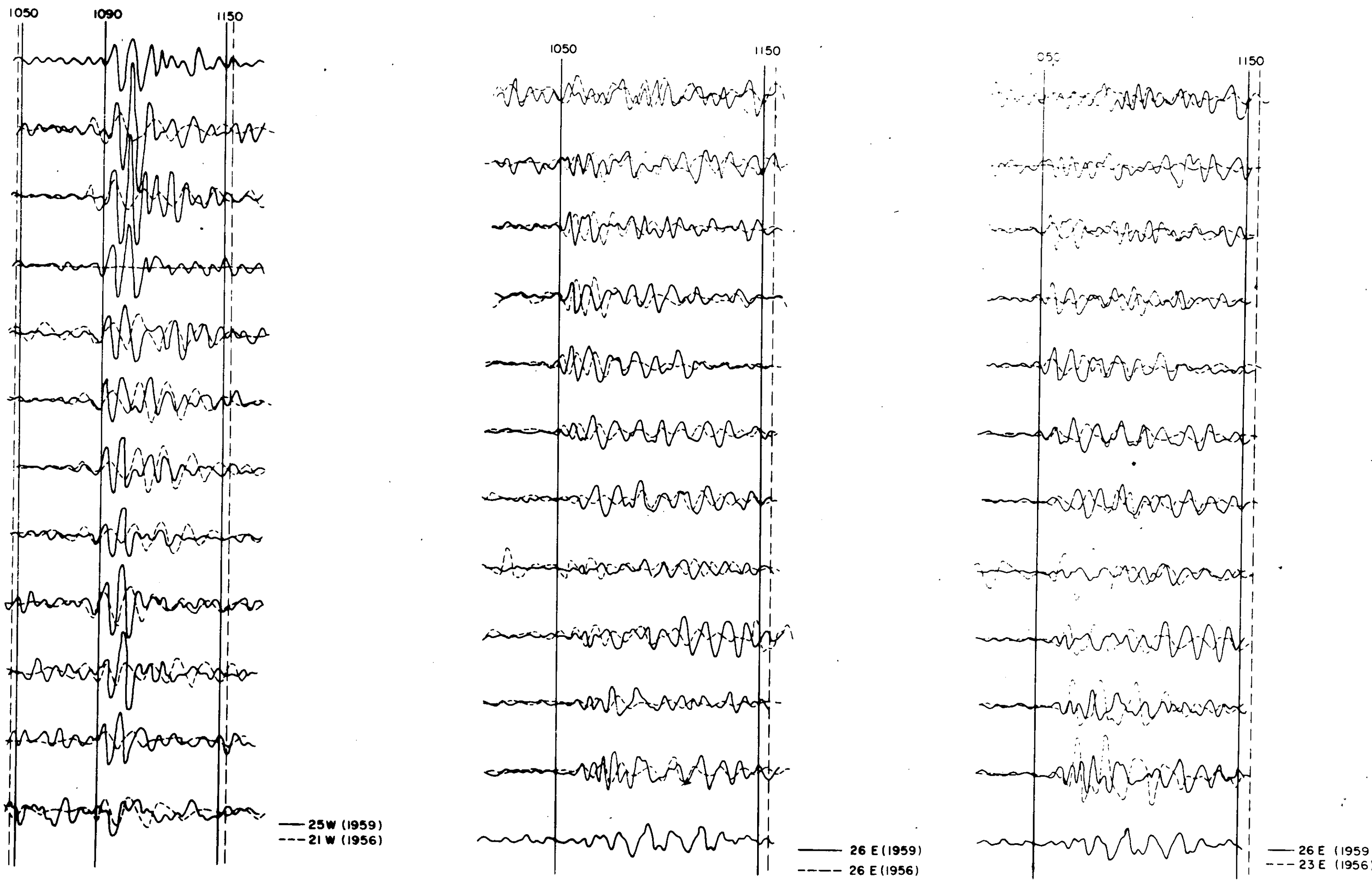

Figure 12 (Cont'd). Superposition of the reflection events from the 1956 and 1959 records.

Table II. Comparison of 1959 with 1956 records.

Figure no.	Spread no. 1959/1956	1959 compared with 1956	Deduced shift
12 a	2 E	Most traces matching	0
b	11 E	1959 ca 1 millisec delayed	40 m S
c	21 W	1959 ca 1 millisec delayed	20 m S
d	21 W/25 W	Most traces ca 7-10 millisec early	0-40 m S
e	23 E	1959 generally 2-3 millisec early	30-45 m N
f	23 E/26 E	Some traces matching or slightly early	45-60 m S
g	24 W/25 W	1959 0-6 millisec early	0-60 m S
h	24 W/21 W	Most traces matching, No. 10 and 11 6 millisec late	0-60 m N
i	25 W	3 millisec early to 3 millisec late	30 m N to 30 m S
j	25 W/21 W	Most traces 12 millisec late	± 15 m
k	26 E	Some matching, some 2 millisec early	0-30 m N
m	26 E/23 E	Some matching, rest not clear	60 m N (?)

Record characteristics. In the two surveys of 1956 and 1959 the record quality changed from place to place, and good and bad reflection areas more or less coincided*, a further indication that the shift between the 2 years was small. The possibility of determining the amount of shift from record characteristics was therefore considered.

A preliminary condition for a successful comparison of records of two surveys is that records be reproducible in any one year when shots are repeated. Although this seemed to be generally true, one striking example was found in 1959 when a second shot only 10 ft from the first one yielded a somewhat different record, using the same filter setting and only slightly changed gain (Fig. 13). The dissimilarity of two records is therefore not necessarily proof of different surface positions occupied, while very similar records would probably indicate comparable positions.

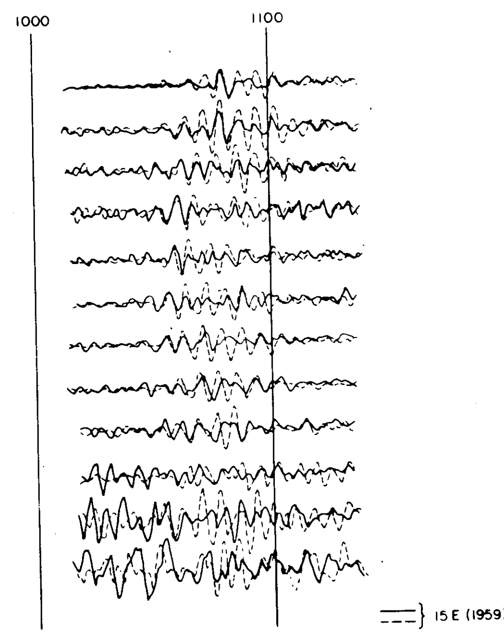

Figure 13. Reproducibility of the reflection event. Two shots fired 10 ft apart using the same filter setting and only slightly changed gain.

Having used different equipment and different shot hole depths in 1956 and 1959 it is not astonishing that the records do not show too much similarity (Fig. 12). Nevertheless, some comparable features occur, such as the two amplitude maximums in some of the traces of spread 4 E (Fig. 14), or the long duration of the reflection signal in spread 26 E (Fig. 12 k). For a quantitative determination of displacement the record features are of no use, however.

Discussion

The comparison of travel times showed considerably larger discrepancies than originally expected. A fair portion of these were undoubtedly caused by insufficient quality of one or even both records of a spread, but some of the difficulties may be inherent in the method.

*Accordingly, in Figure 9 no data are given at all for certain spreads, because the records were too poor in both years to be used.

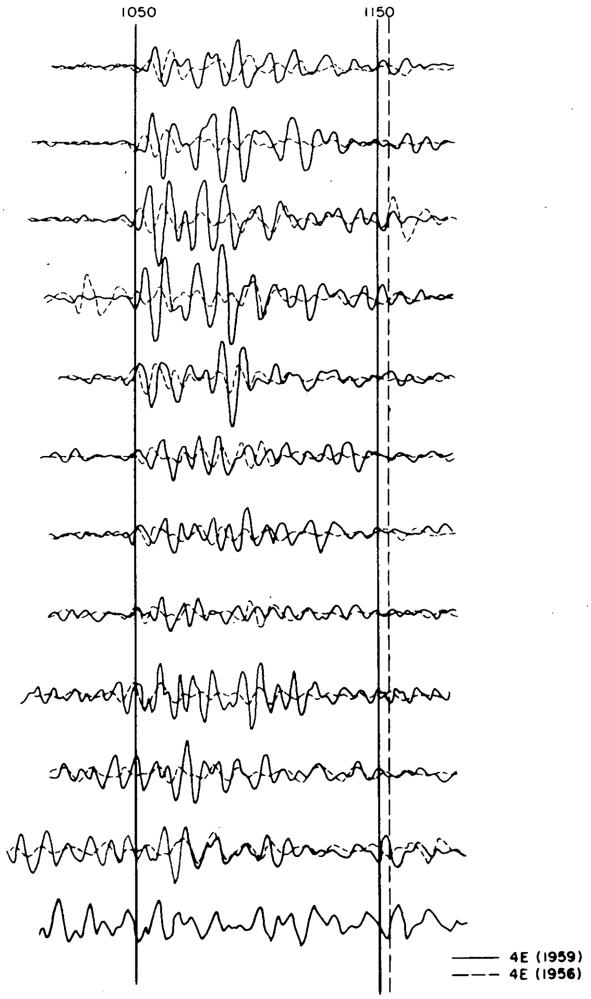

Figure 14. Comparable record characteristics: two maximums. (Different shot point position and length of spread; no position or spread correction applied.)

When evaluating the records for travel time it was often found that first breaks were hard to pick, primarily because of background noise or low signal strength, but also because they would sometimes line up across part of the record only, and then die out. Also, first peaks or troughs often could be followed across only part of the record and the first peaks of the remaining traces lined up better with second peaks of the first traces (Fig. 15). The reason for this phenomenon is probably the pronounced relief of the bottom surface. The geophone obtains reflected energy from different reflecting elements, from slightly different directions, in different amounts, and at different times. The interference of these different waves produces the observed signal. Going from one end of a spread to the other, or changing spread, the energy obtained from one reflecting element will die out and the signal from a different element will be picked up. It can also easily happen that the energy of the first arrival will be too weak to be observed at all. In the present work the first arrival was most likely observed occasionally in one year but not in the other, which accounts for the large travel time differences of the order of 10 millisec. When plotting the travel times in a diagram of the type shown in Figures 3, 9, 10 and 11, steps occur quite frequently. They are not necessarily present in the bottom topography but may represent the arrival of reflections from different directions.

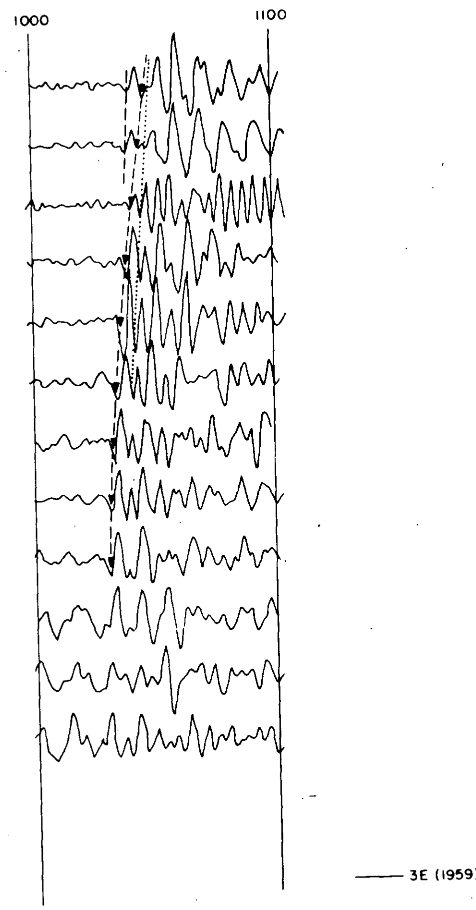

Figure 15. Signs of interference of two reflection signals.

If additional geophones were placed in the interval where the steps occurred, it could then probably be shown that in some cases the earlier break disappears gradually as one moves from one geophone to the next, and that the later break occurs after a distinct time interval. The point where the step is observed is then not only a function of the position of shot and geophone, but also of record quality, i.e. of signal to noise ratio. The result, then, is discrepancies in the travel time versus position profiles and in the travel time isograms which cannot be explained by a shift.

To illustrate the complexity of the problem, the approximate bottom relief along a N-S line in the westernmost quarter of the survey area was constructed (Fig. 16). The travel times of the N-S profile A were converted into depth by using the average velocity of 3845 m/sec given by Bentley et al. (1957). The depths were first plotted vertically under the respective spreads, shown as dots in Figure 16. A more realistic (though only two-dimensional) picture of the bottom relief was obtained by drawing the envelope of arcs through the dots. In the result it is noteworthy that the reflections occur quite frequently on hillsides at some distance from the areas immediately underneath the spreads, and that rays may cross each other. It is not astonishing that strength and shape of the reflection signals change from place to place at the surface. If the ground relief were fairly rugged with distances between ridges and troughs in the order of the wavelength of the seismic waves, i.e. 20 to 50 m, then one might even anticipate diffraction patterns at the surface. An additional complication might arise from the presence of dirt layers in the ice near the bottom.

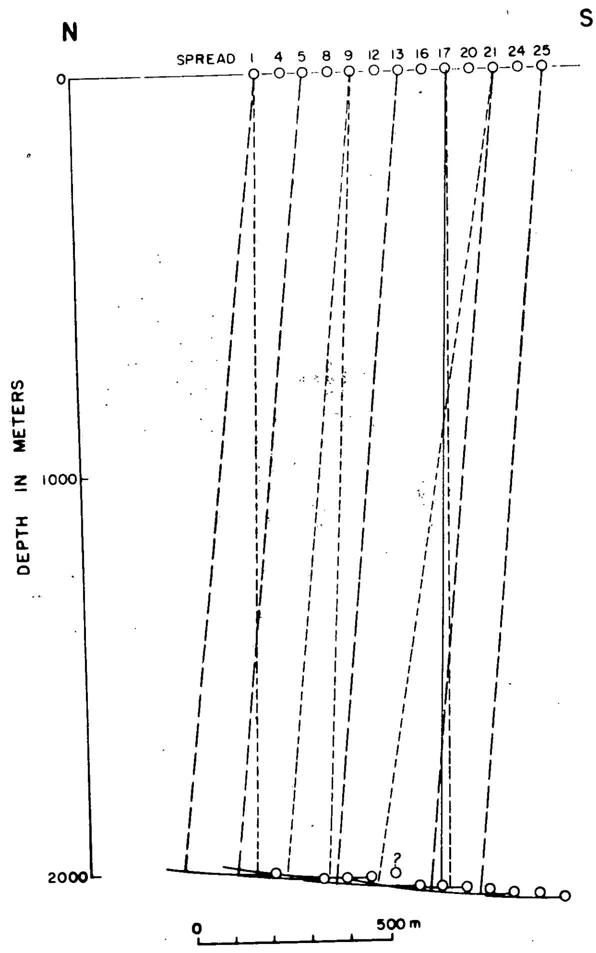

Figure 16. Two-dimensional construction of the approximately N-S bottom profile.

In the above discussions it was assumed that the surface conditions remained unchanged. In Figure 7 it was shown that this was true for the depth-velocity relationship. A different question is, whether the surface elevation remained the same, i.e., whether or not the Greenland ice sheet is in equilibrium in the Site 2 area. It may be mentioned that the average annual accumulation at Site 2 amounts to about 0.45 m of ice (Langway, 1962). If this ice did not flow off, the 3-year layer would amount to about 1.35 m of ice, which is equivalent to 0.7 millisec in the travel time of the reflected wave. Since the flow is not known it is not certain whether the surface is steady, lowering, or rising, but certainly the seismic survey would not be significantly affected by accumulation alone.

Conclusions

The attempt to determine the surface movement at Site 2 from detailed seismic soundings was not successful, because the actual movement was less than the error of the method. This error was estimated to be from 100 ft (30 m) to several times that amount, depending on the direction of the movement. It was less in the direction of bottom slope than parallel to average contour lines.

The large errors were caused by several factors, namely some poor records due to faulty equipment and lack of time in 1956, some noisy records due to heavy equipment operating nearby in 1959, the use of different equipment with different frequency characteristics, and changes in the method such as placing the shots deeper in 1959 than 1956. The bad results are therefore not conclusive for the method as such. With the use of identical equipment, the same shot depth, etc. for both surveys, and possibly with a closer spacing of lines concentrated in the areas of best records at least in one of the surveys, better results should be obtained. It seems possible that careful measurements should give an accuracy of about 2 millisec under conditions similar to the ones at Site 2, corresponding to a horizontal shift of 100 ft (30 m) in the direction of steepest slope (NE-SW) and much more in a perpendicular direction. In an area with lesser ice thickness and favorable subsurface topography better results could be expected. A good reflecting interface would for instance be built of fairly large plane elements of different dip and strike joined with sharp edges. Too rugged topography is not good because of the complicated interference pattern at the surface which is hard to match during the repetition survey. A rough estimate of the ultimate accuracy of the seismic method for surface movement studies is 65 to 165 ft (20 to 50 m). A very careful site selection and two intensive surveys would be needed to realize it.

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UNCLASSIFIED

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2. Glacier ice--Geophysical exploration (Seismic)
3. Glaciers--Velocity--Greenland

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