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SEPTEMBER, 1959

Seismic Survey 1957, Thule Area, Greenland

U. S. ARMY
SNOW ICE AND PERMAFROST RESEARCH ESTABLISHMENT
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by Hans Roethlisberger

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Wilmette, Illinois

PREFACE

This is a report on seismic investigations carried out in Greenland during the summer of 1957 in support of Corps of Engineers Projects 1.1, Approach roads, and 1.2, Core drilling in permafrost, and in connection with the planning of Camp TUTO ice-cap installations. It is one of a series of reports on USA SIPRE Project 022.01.034, Elastic and visco-elastic properties of snow and ice.

The field work was carried out by Dr. Roethlisberger, contract geophysicist, together with David F. Coolbaugh, Barodynamics, Inc., and Michael V. Anthony, USA SIPRE. Arctic Construction and Frost Effects Laboratory personnel from CE Project 1.1 surveyed the ramp road profile and the U. S. Army Engineer Arctic Task Force contributed personnel for the last few days.

Work on this project was performed for the Snow and Ice Basic Research Branch, Mr. J. A. Bender, branch chief.

This report has been reviewed and approved for publication by the Office of the Chief of Engineers.

HENRY J. MANGER
Acting Director

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SUMMARY

Seismic reflection soundings have been carried out in the vicinity of Camp TUTO, Thule, Greenland, on the edge of the ice cap. Ice thicknesses ranging from 200 to 800 ft have been determined. With a short shot point to geophone distance only sporadic results could be obtained, while with a long distance, up to 3.5 times the ice thickness, very strong reflection signals were recorded. Evidence was found that some of the reflections did not occur at a single clear interface, indicating the presence of alternate layers of moraine and ice at the bottom of the ice cap. At one location, where the result of the seismic sounding could be compared with drilling results, the error was found to be less than 10 ft, the depth at the place being about 200 ft. Later reflection signals on the seismic records are analyzed by means of a master chart (Fig. 7). The usefulness of the refraction method has been established along the ice tunnel.

SEISMIC SURVEY 1957, THULE AREA, GREENLAND

by

Hans Roethlisberger

INTRODUCTION

In recent years, occasional geophysical surveys have been carried out in the Thule, Greenland, area to determine the thickness of ice to bedrock. Large areas of the Greenland Ice Cap have been covered by soundings and some detailed studies have been made, giving a good general picture of the applicability of different methods under the conditions encountered and giving information on ice thickness in many places. Most of the field parties that used TUTO as an access route to the ice cap worked on a large scale and did not make soundings close to the edge of the cap. However, Barnes and Zavadil (1954) and Barnes and Taylor (1956) report gravimetric results from the TUTO ramp, and Rausch (1958, Fig. 27) establishes a seismic profile along the ice tunnel axis, the only information yet available from the 1956 seismic survey, CE Project 28. The seismic soundings discussed here were carried out from 23 August through 5 September 1957 in order to provide detailed ice thicknesses in the following two locations:

1. Along the ramp road, in support of CE Projects 1.1 and 1.2. Knowledge of the thickness of the ice is mandatory for the interpretation of ice movement at the surface.

2. South of the ice tunnel, in connection with the planning of Camp TUTO Ice-Cap installations.

In the ramp road profile, two drill holes of Project 1.2 had reached the bottom of the ice earlier in the season, giving the rare opportunity of checking the seismic results. Also the drill cores revealed exactly what material underlies the ice, information of basic interest for understanding the strength and character of reflections.

METHOD

Instrumentation

The equipment used for the USA SIPRE seismic work is a high frequency seismic system manufactured by the Southwestern Industrial Electronics Company (SIE), model P-15 with accessories, operated with 6 channels. The geophones, SIE type S-16, have a natural frequency of 18 cps, with damping .56 of critical. The amplifiers are equipped with automatic gain control, suppression, filters, and mixing circuits.

Although good results could generally be obtained without suppression, most records have had suppression applied. Filtering was generally set for the frequency band between 220 and 425 cps. Mixing improved the reflection signals in some cases. The paper speed in the recorder was kept at 2 ft/sec.

The explosions were fired by means of a capacitor blaster, SIE type PCB-11, using Atlas "Staticmaster" caps. The charges consisted of 1/3 to 1 1/2 lb of military explosive Composition C-4. On a few occasions, 60% dynamite was used.

Field disposition and ground survey control

The method used generally was based on the reflection technique. Only in one place could some information be obtained on the applicability of the refraction method. This result is presented separately.

For the complete investigation, the geophone spread was determined by the pick-up cable, which provided 6 pair of connections at intervals of 20 ft only. At the outset of the survey, the shot point was tentatively placed close to the geophones, offset 10 ft from the center of the geophone line so as not to damage the cable. The resulting reflections, however, were poor, even at a location where an ice thickness of 850 ft was discovered, and could seldom be identified at lesser depths. On the contrary, very strong reflections were recorded when shots were fired at a distance 1.2 to 3 times the depth, in agreement with the results reported by various authors. The charges were placed at the surface of the ice.

Along the ramp road profile, the geophones were placed in a straight-line pattern, parallel to the profile in most cases. Occasionally, however, the layout was perpendicular to the line of profile to provide a control for lateral dip. In the ice tunnel area, the geophones were placed in an L-shaped pattern; geophones 1 - 4 in a straight line and 4 - 6 in a perpendicular line, with 4 common to both branches of the L.

Since relatively little time could be spent on accurate surveying, most of the "right" angles mentioned were established by rough field methods and distances were seldom measured with a tape. Many of the shot-point and geophone locations were surveyed by ACFEL personnel with transit and stadia from reference points on the ramp road. This survey is believed to be accurate to approximately 10 ft in distance and 1 ft in elevation. In the ice tunnel area, much less was accomplished toward elevation control. A few seismic stations were related to aluminum poles installed in 1956 by Griffiths (1959) along the ice tunnel axis. A rudimentary survey was carried out by USA EATF personnel, with accuracy probably much less than that along the ramp road profile, due to lack of time, adverse weather, and the lack of reliable control reference points. It can be assumed, however, that the errors in elevation control are not larger than errors in the seismic sounding (10 ft). Thus a reasonable evaluation is possible in all cases.

For velocity investigations, the geophones were placed in a straight line inside the ice tunnel, with shots fired on the outside and inside of the tunnel at variable distances. This program was very limited, the main deterrent being lack of time and the location of the dynamite depot inside the tunnel.

Calculation procedure

When the surface and the reflecting horizon are parallel, and when the medium transmitting the elastic wave is homogeneous and isotropic, then the depth z to the reflecting horizon can be calculated from the equation

$$z = \frac{v}{2}\sqrt{t_r^2 - t_d^2}\ , \qquad (1)$$

where v = seismic velocity, t_r = travel time of the reflected wave, t_d = travel time of the direct wave (first break).

Although there is definite proof, from the ice tunnel area, of inhomogeneity and anisotrophy to a few percent in the seismic velocity, the ice has been assumed to be homogeneous and isotropic in all depth calculations. But cognizance has been given to non-parallelism of the surface and reflecting horizon along the ramp road profile.

For the case of valley glaciers, the author (Roethlisberger, 1955) has developed a three-dimensional calculation procedure which might have been applied along the ramp road. The short length of the geophone cable made it inappropriate, however, to lay the geophone in the pattern described in that paper. Further, the general trend in the area justified evaluation by simplified two-dimensional methods, assuming the strike of the reflecting horizon to be perpendicular to the profile. In some cases, this assumption has been checked by using geophone spreads perpendicular to the line of profile or by additional shots south of the E-W trending profile.

The simplified, two-dimensional calculation procedures are illustrated in Figures 1 and 2. Figure 1 presents the case where one shot S is fired in line with the geophones. Only two geophones, G_1 and G_2, are used, preferably those at the ends of the spread (the four additional reflections enhance the interpretation of the two important traces). D is chosen midway between the two geophones, G_1 and G_2. If v = velocity of the seismic wave, Δt = difference in reflection times between G_1 and G_2, and a = distance between G_1 and G_2, then

$$\cos \alpha \cong \frac{v \Delta t}{a}\ , \quad \text{if } a << r.$$

An equation for h can be given for half the distance between the shot point S and its image S' (Fig. 1).

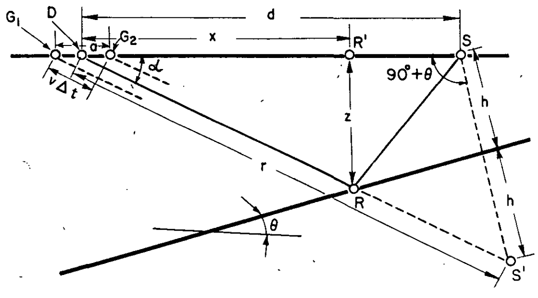

Figure 1. Illustration of equations 2 to 5.

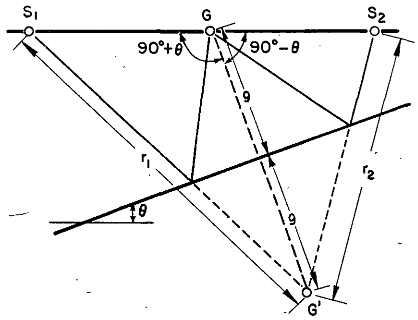

Figure 2. Illustration of equations 6 and 7.

$$h = \frac{1}{2}\sqrt{d^2 + r^2 - 2dr\cos\alpha} \qquad (2)$$

where d = distance between D and the shot point, S
$r = vt_r$
t_r = mean reflection time for G_1 and G_2.

The angle of dip θ is found from

$$\sin\theta = \frac{r\cos\alpha - d}{2h}\ . \qquad (3)$$

For small angles θ, the approximation

$$\theta \cong \cos^{-1}\frac{d}{r} - \alpha \qquad (3a)$$

may be used.* The depth z to the reflecting interface at the point where the reflection occurs is then found from

$$z = \frac{d\sin(\alpha + 2\theta)}{\sin(2\alpha + 2\theta)}\sin\alpha\ , \qquad (4)$$

z being measured perpendicular to the surface. The distance x from D to R' is

$$x = \frac{d\sin(\alpha + 2\theta)}{\sin(2\alpha + 2\theta)}\cos\alpha\ . \qquad (5)$$

The same equations can be applied when two shot points replace the two geophones at G_1 and G_2 and one geophone is placed as S.

The procedure illustrated in Figure 2 was used when two shots were fired on the profile, on opposite sides of a geophone (or a line of geophones placed perpendicular to the profile).

The distance g from G to the reflecting interface is given by

$$g = \frac{1}{2}\sqrt{\frac{d_1(r_2^2 - d_2^2) + d_2(r_1^2 - d_1^2)}{d_1 + d_2}}\ . \qquad (6)$$

Equation (6) is also true when both shot points are placed on the same side of G. Consequently, eq 6 can be used instead of eq 2 for evaluation of the former case, using one shot point at G and two geophones at S_1 and S_2.

$^*\cos(\alpha + \theta) = \frac{d}{r}\cos\theta = \frac{d}{r}\left(1 - \frac{1}{2}\sin^2\theta - \frac{1}{2.4}\sin^4\theta - \ldots\right)$

The dip θ is determined from

$$\sin\theta = \frac{d_2^2 + 4g^2 - r_2^2}{4d_2g} = \frac{r_1^2 - d_1^2 - 4g^2}{4d_1g} \qquad (7)$$

RESULTS

Ramp road

The surface location of the seismic profile line along the ramp road and the computed results of the soundings are presented in Figure 3. The smallest and the largest value obtained are 209 and 840 ft. The lowest value observed appears to be close to the limit for reflection work. No attempt has been made to measure ice thickness closer to the edge, but the records from which the 209 ft minimum ice thickness were calculated showed poor signals.

The different calculation procedures previously described were used, and the various results are plotted in Figure 3 with different symbols. For a small degree of dip, the agreement between different methods is very good. When the angle between the surface and the bottom of the ice is greater than a few degrees, equations 2 - 5 and 6 and 7 give better results than eq 1, but only then are the more complicated calculations justified. When there are no indications of sudden change in ice thickness, eq 1 is sufficient for a routine survey, and only in areas with more than a few degrees of dip should one of the more rigorous methods of calculation be applied.

In most cases the reflection signals were so sharp that there is very little doubt as to where to pick them on the records. The travel time of the reflected wave can then be determined with a high degree of accuracy, so that the error in ice thickness should not exceed a few feet. There is some doubt, however, concerning the veolcity applied in depth calculations, because of inhomogeneity and anisotropy; the results might be in error by approximately 1-3%, leading to an error of 10-20 ft. At one location, drill hole results (Project 1.2) were available for comparison with the seismic results. Only the smallest depths could be checked, since the drill holes have not reached the bottom of the thicker ice. Although reflection points have not been obtained directly at the locations of the drill holes, correlation of the two results shows a very good agreement, the error of the seismic sounding being less than 10 ft.

Two gravimetric profiles, reported by Barnes and Zavadil (1954, Fig. 2, p. 382) and Barnes and Taylor (1956, Fig. 12), have also been plotted on Figure 3. With a few exceptions, the gravimetric profiles give depths not more than 100 ft different from the seismic results, but the details of the seismic profile do not show in the gravity survey. It must be taken into consideration, however, that the gravimetric line is not exactly the same as the seismic profile. Therefore, no general conclusions should be attempted from the comparison.

Ice tunnel area

The main purpose of the investigation was to check an area 500 to 1000 ft south of the ice tunnel, to determine whether a sufficient thickness of ice is present for the planned Camp TUTO ice installations. Figure 4 shows the elevations above sea level of some seventy reflection points. In many cases where the reflection signals were not clear or where more than one signal could be identified, alternative and additional elevations are stated in parentheses. Figure 5 shows ice thicknesses along the profile X - X' of Figure 4, where most results were obtained. In Figure 6 some new determinations have been plotted on the seismic profile given by Rausch (1958, Fig. 27).

In many locations, no well defined reflection interface could be found. There were also strong indications of energy being reflected at boundaries above the bottom of the ice cap, probably representing heavy layers of dirt and boulders. These early reflections were never strongly developed but appeared strongest with large angles of incidence.

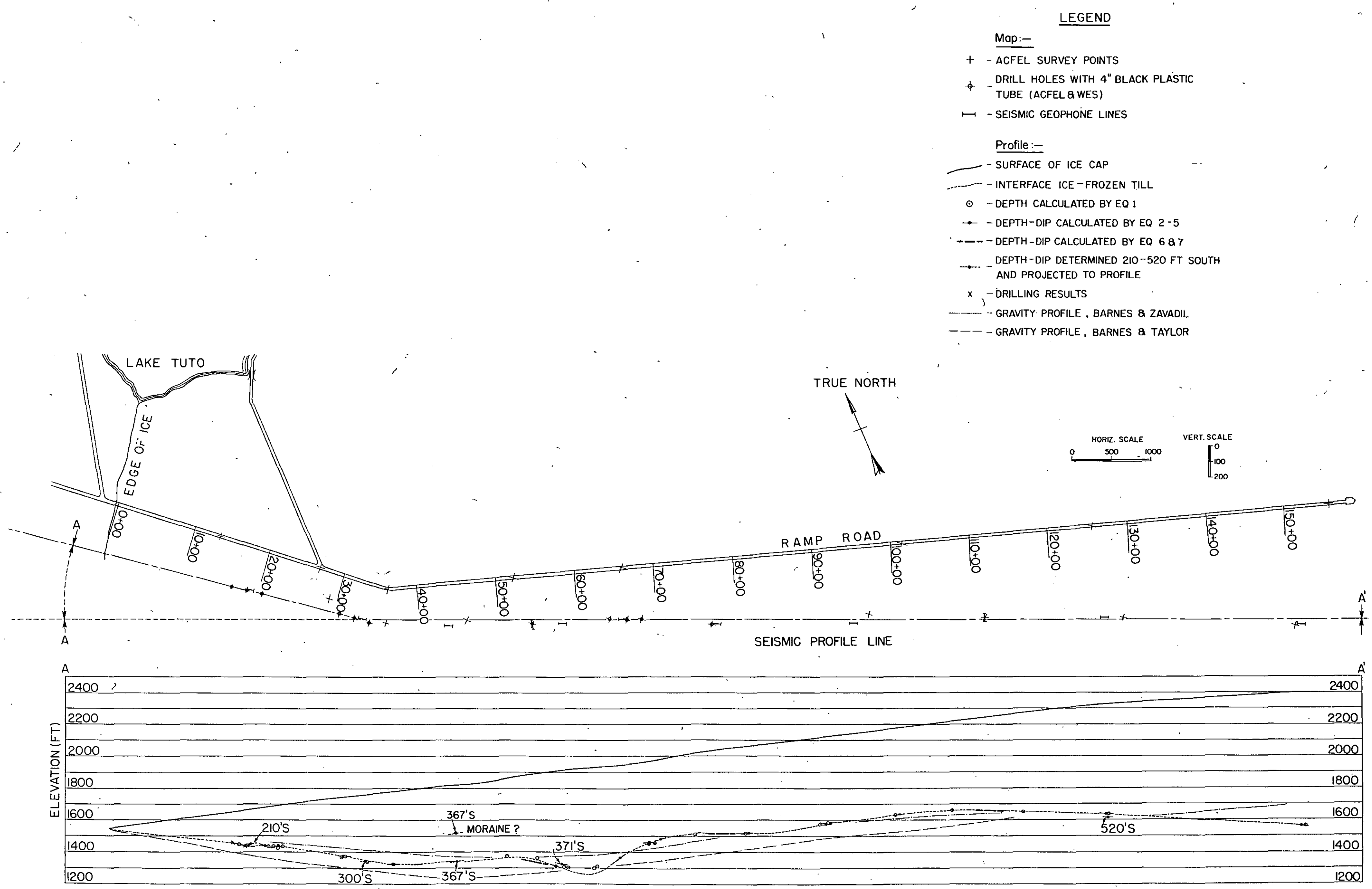

Figure 3. Seismic profile, ramp road, TUTO, Greenland.

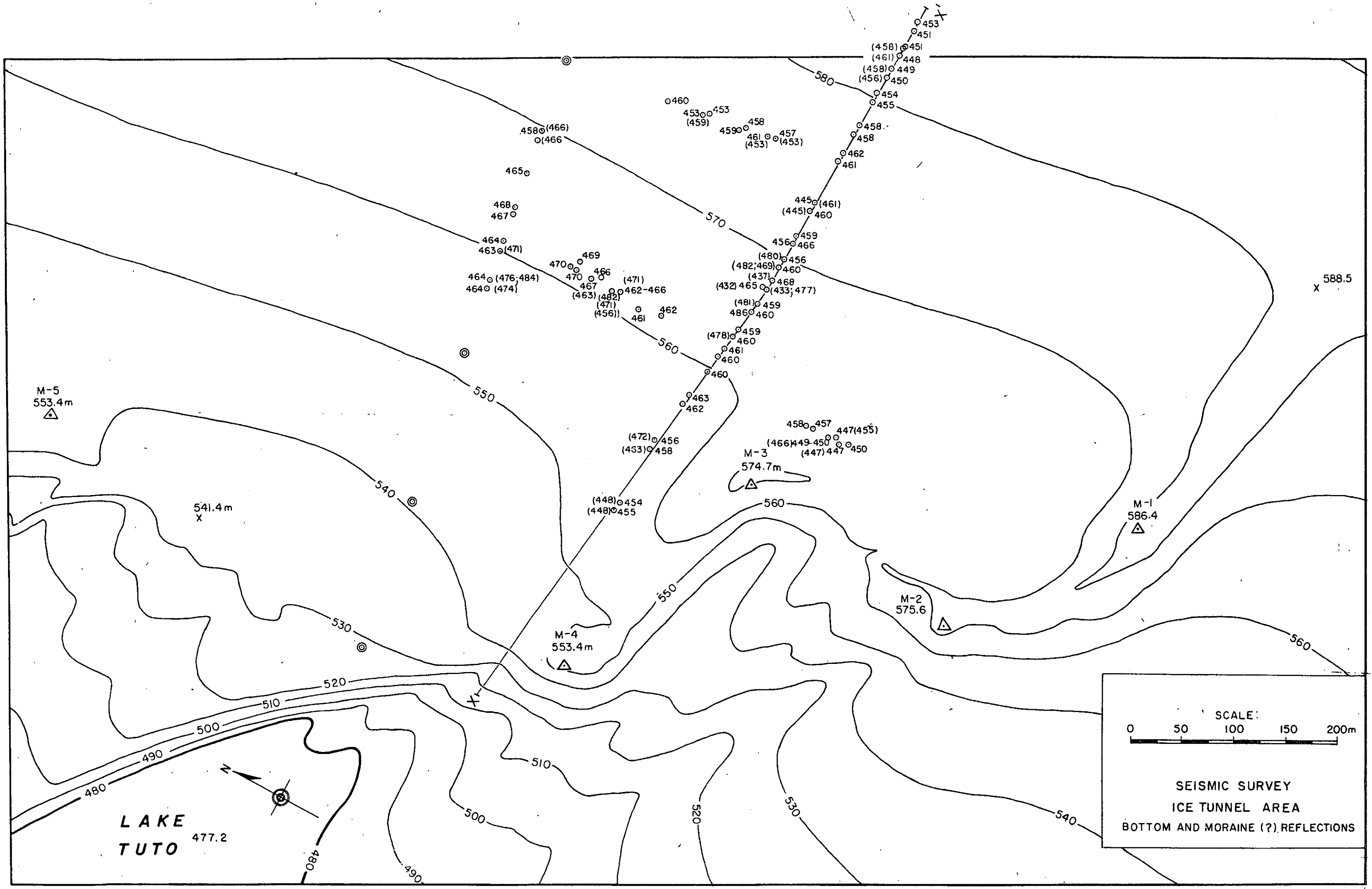

Figure 4. Seismic survey, ice tunnel area. Surface contours and elevation of reflection points (circles) in meters above sea level.

On one record (Fig. 7) the reflection marked A is strong for traces 4 to 6, less developed for 3 and 2, and about at the noise level for trace 1. It corresponds to an ice thickness of 350 ft. Traces 1 to 3 show a strong reflection B corresponding to a depth of 385 ft, which is weaker or masked by A on trace 5 and 6. The explanation might be that the upper reflection A occurs at a thinning-out dirt layer, as indicated by the letters A and B in Figure 5.

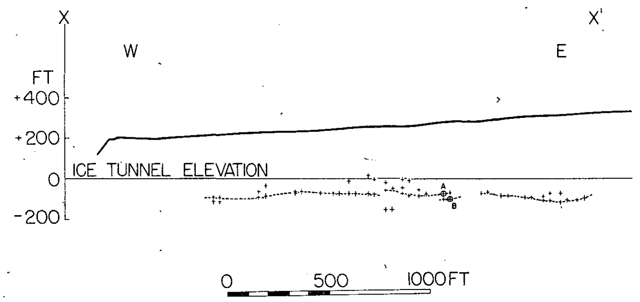

Figure 5. Seismic profile X - X', 500 to 1000 ft south of ice tunnel.

In a few cases, no reflections could be identified on the records. This could possibly be explained by the moraine at the surface causing a higher noise level of the shot, by the geometry of the interface, or by physical conditions at the boundary such as a steady increase of dirt content over some depth.

Velocity results

Since no accurate ground survey has been carried out, no accurate velocity values can be presented. In depth calculations, the compressional wave velocity, v_p, was assumed to be 3720 m/sec (12,200 ft/sec), a value frequently obtained when travel time was determined between the time break and the first break shown by the geophone trace. From time-distance curves, a value as high as 3880 m/sec (12,700 ft/sec) could be deduced, which refers to the ice at greater depths.

A definite anisotropy effect has been obtained with dynamic measurements on samples from the ice tunnel. However, since only limited investigations have been carried out as yet, no conclusions can be reached as to the degree that the seismic velocity is dependent upon the direction of travel.

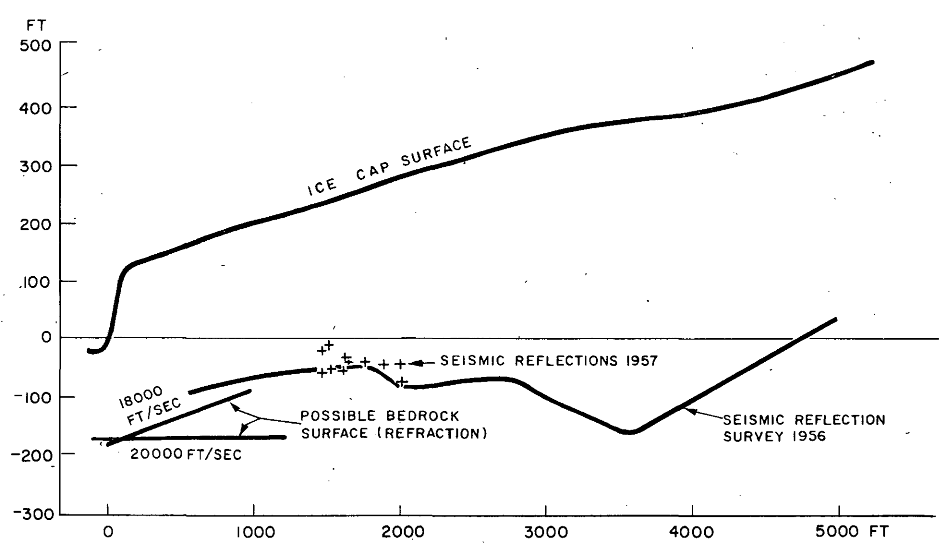

Figure 6. Seismic profile along ice tunnel axis. Line: 1956 results (Bentley); crosses: 1957 reflections.

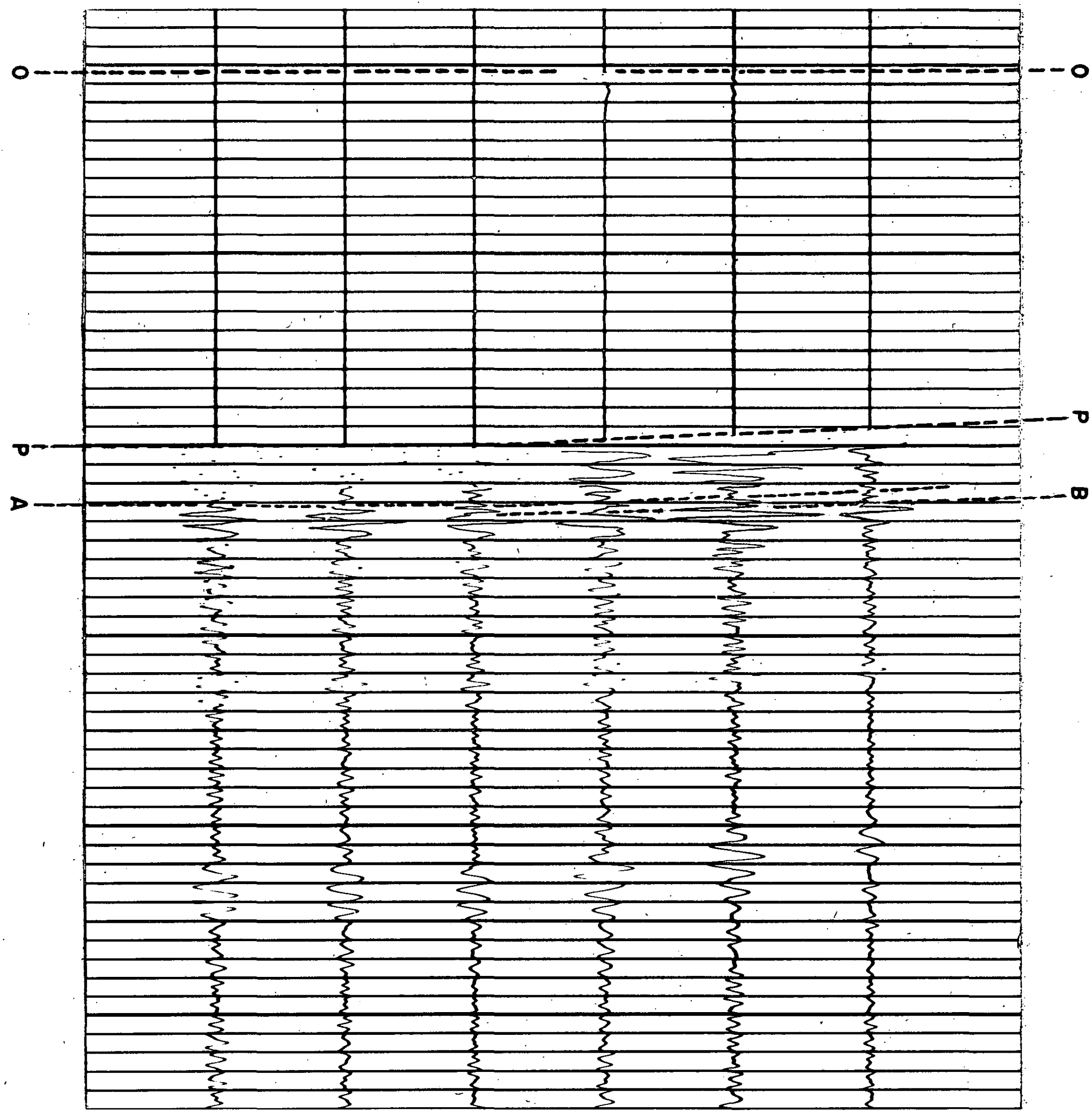

Figure 7. Record with shifting reflection from the ice tunnel area in profile X - X'. Geophones 1144, 1164, 1184 and 1204 ft from shot point in L-shaped pattern. O = shot instant; P = first break; A = reflection arrival from 350 ft depth; B = reflection arrival from 385 ft depth. Time line interval: 5 millisec.

In a few cases, shear-wave velocities could be determined. They were found to be approximately half the compressional wave velocities. Although surface waves were present in many cases, no analysis was attempted. A dependence seemed to exist, in that the surface waves were extremely weak or could not be detected where cracks in the ice trended across the profile. The cracks were 1-2 in. wide, usually water-filled and healed from the surface down to a depth of approximately 2 ft.

Shear-wave and double reflections

Later wave arrivals have been observed in many cases. To simplify interpretation, a chart has been calculated to show results independent of the variable ice thickness (Fig. 8). Values from the ramp road survey are plotted. Arrivals of the direct compressional (P) and single reflected compressional waves (PP) are not plotted, since

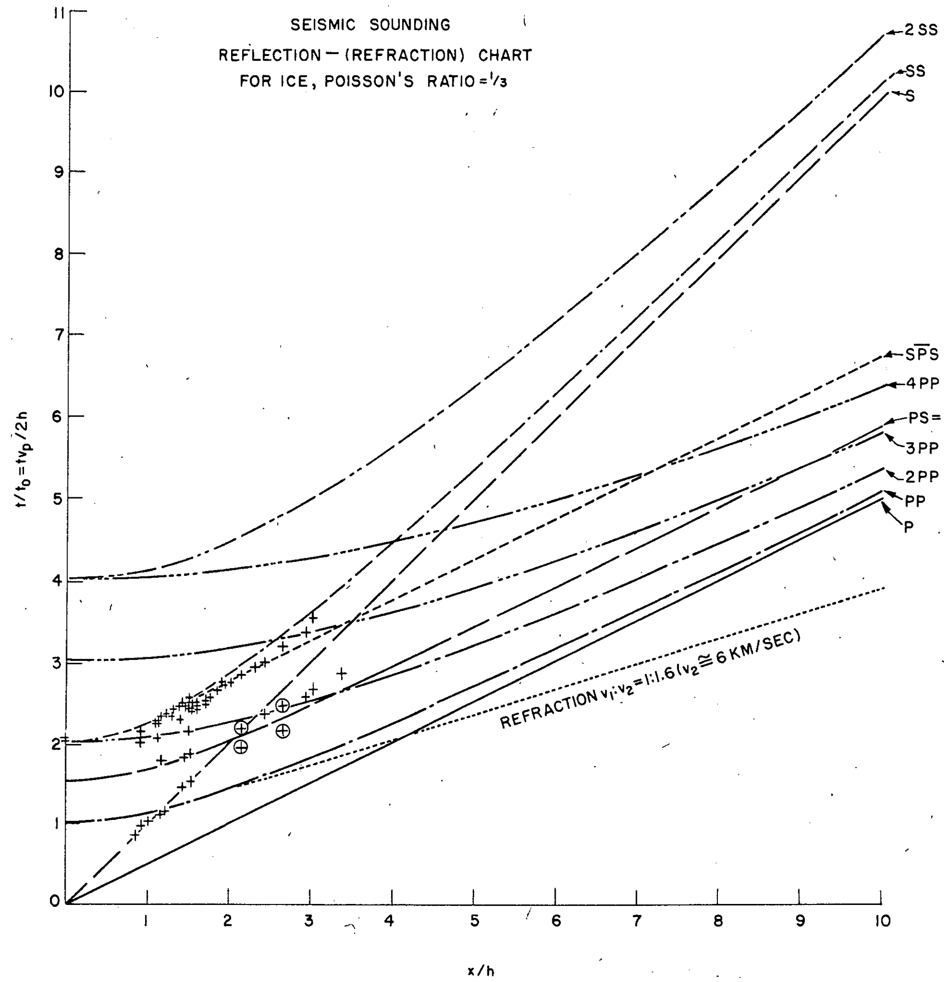

Figure 8. Reflection (refraction) chart for ice, Poisson's ratio = 1/3.

x = shot distance (spread)
h = ice thickness (depth)
v_p = velocity of p-wave
t = travel time
t_o = travel time for vertical p-wave reflection
P = p-wave
S = s-wave

PP = single p-wave reflection
2PP = double p-wave reflection
nPP = n-fold p-wave reflection
nSS = n-fold s-wave reflection
SP = s-wave reflected as p-wave
PS = p-wave reflected as s-wave
S$\overline{P}$S = SS$\overline{P}$ = $\overline{P}$SS = internally refracted wave (Berckhemer and Oliver, 1956)

those would fall exactly on the line by definition. The greatest number of later arrivals belong to the shear-wave single reflection (SS). The points generally fall below the theoretical curve, indicating that a shear wave traveling along the reflection path is slightly faster than assumed in the diagram. This means that the shear velocity is - at least for certain angles of incidence - greater than half the compressional velocity (Poisson's ratio being slightly less than 1/3).

A few times, compressional double reflections (2PP) have been observed. On the PS = SP line, three points could be plotted, with others located above and below, but on parallels to that line. The two points below the PS = SP line could be interpreted as PS-reflections, the six points above as SP-reflections, by attributing the positive and negative deviation from the theoretical line to an approximate 8° dip of the bottom of the ice relative to the surface. Berckhemer and Oliver (1956) mention the possibility of distinguishing between PS and SP waves in the case of dip, but to the author's knowledge the occurrence of the phenomena in practice has not been reported before. The record of a case with both PS and SP signals is reproduced in Figure 9. The results from geophone 1 and 6 are circled in Figure 7, the coordinates on the graph being 2.18/1.95, 2.18/2.20, 2.68/2.16 and 2.68/2.46. The SP-signals appear to be stronger than the PS ones, in agreement with the fact that only the SP signals have been recognized on the records from neighboring shots.

Refraction method

Since the reflection technique gave satisfactory results, the refraction method was not applied in the survey. Furthermore, some doubt existed whether it might be applied successfully or not. From the results of Holtzscherer (1954) and Bentley, et. al. (1957), it is evident that good refraction results can be obtained where ice overlies crystalline rock. In the TUTO ramp area, it is not known whether the bedrock is formed of sediments or the crystalline basement rock. In addition, a layer of frozen till of unknown thickness occurs between the bottom of the ice and the bedrock surface. The seismic velocity in the till is not known, but various authors have reported a wide range of observed velocities in frozen ground, the lower values being much smaller than velocities in ice and the highest ones being 10-15% higher. Therefore, the possibility of finding higher velocities in the frozen till than in the ice, and thus determining the ice thickness by refraction methods, has been considered.

Two attempts have been made to ascertain whether the refraction method would yield results in the TUTO ramp area. First, a laboratory test was carried out on samples of a drill core of the frozen till from the ramp road area, obtained from Project 1.2. The values for $v_\ell = \sqrt{\frac{E}{\rho}}$ (= velocity of longitudinal elastic wave in a cylinder), the density, and two different seismic velocities are given in Table I for a number of specimens. The two different values of seismic velocity are based on the assumption of different values of Poisson's ratio, 0.33 and 0.25. Further investigations would be necessary to determine the accurate Poisson's ratio of each specimen, in order to calculate a reliable seismic velocity. The results give ample indications, however, that refraction work can lead to sounding results when the ice thickness is sufficiently small, compared with the length of profile and the total thickness of the frozen till.

The second attempt to determine the applicability of the refraction method consisted of a single shot at the entrance of the ice tunnel, with geophones placed at the opposite end of the tunnel. The distance from the shot point to the nearest geophone was 1000 ft, with 1100 ft to the furthest geophone. At all geophones, the first break occurred considerably earlier (> 10 millisec) than the calculated arrival of the pressure wave in ice, with the apparent velocity along the line of geophones calculated to be 6100 m/sec (20,000 ft/sec). The travel time curve (Fig. 10) cannot be easily explained in relation to the occurrence of the two uppermost layers, ice and frozen till, unless the unlikely high velocity of 5000 to 5500 m/sec (16,000 to 18,000 ft/sec) is assumed for the frozen till. The apparent velocity of 6100 m/sec suggests, rather, that bedrock is not far below the bottom of the ice, which means that the thickness of the frozen till is of the order of 100 ft. Further refraction work could undoubtedly reveal more details concerning the subsurface conditions below the ice tunnel.

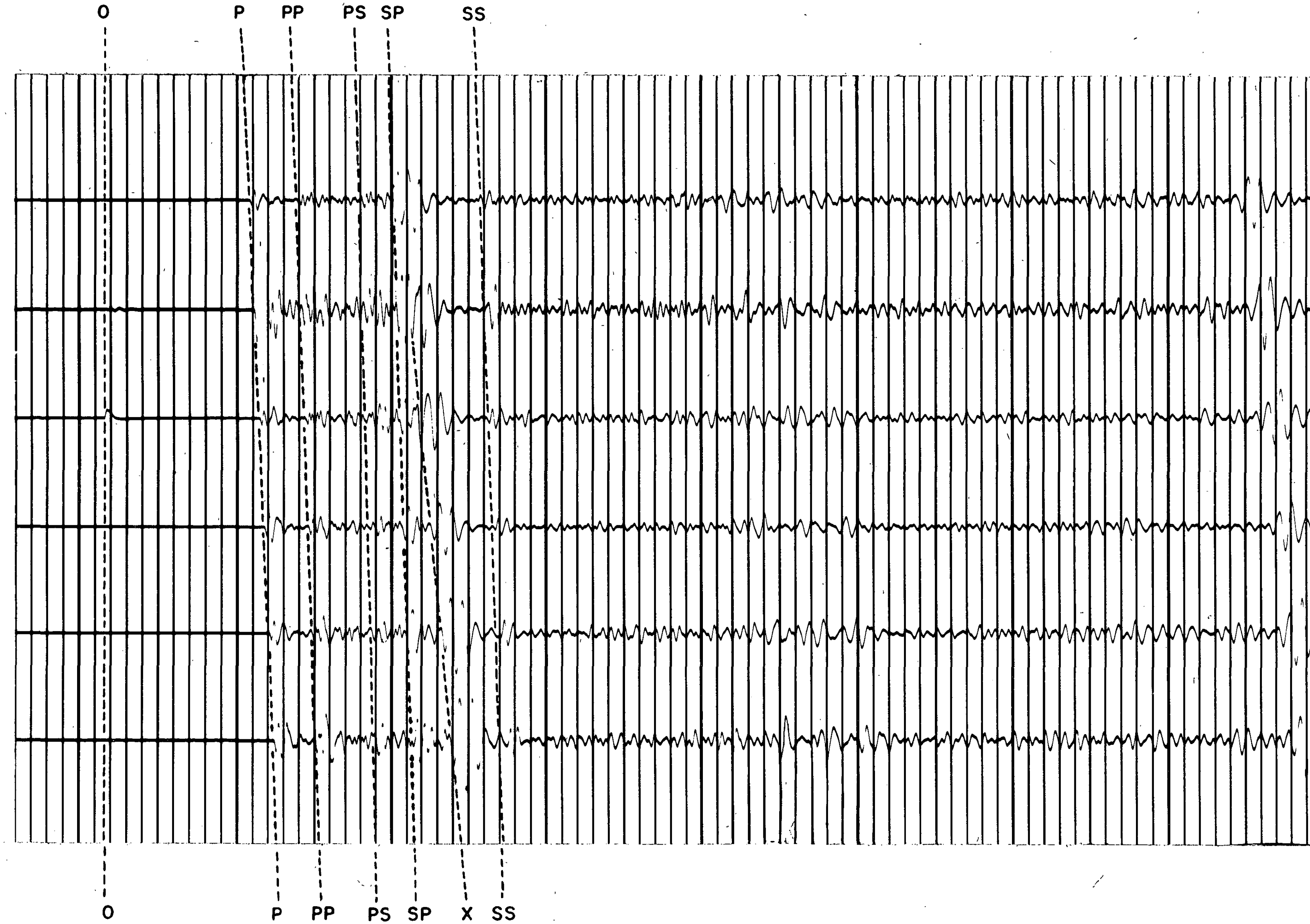

Figure 9. Reflection record from the ramp road profile with PS and SP signal. Relative dip of 8° between surface and reflecting interface. O = shot instance; P = first break; PP = P-reflection; SS = S-reflection; X = vibration from unknown source. Time line interval: 5 millisec.

Table I. Seismic velocities, v_p, of samples of frozen till from the ramp road area. (Values of ν are assumed.)

	$v_\ell = \sqrt{E/\rho}$		$v_p = \sqrt{\frac{E}{\rho} \cdot \frac{1-\nu}{(1+\nu)(1-2\nu)}}$				ρ
			$\nu = 0.333$		$\nu = 0.25$		
	(m/sec)	(ft/sec)	(m/sec)	(ft/sec)	(m/sec)	(ft/sec)	(g/cm^3)
1	3780.0	12401.575	4629.536	15188.767	4140.782	13585.24	2.05
2	3564.78	11695.4725	4365.95	14323.97	3905.02	12811.75	2.0
3	3140.28	10302.76	3846.042	12618.25	3440.004	11286.107	1.8
4	3474.0	11397.6375	4254.764	13959.1995	3805.58	12485.485	2.1
5	3171.06	10403.74	3883.74	12741.93	3473.72	11396.725	1.5
6	3686.15	12093.668	4514.59	14811.659	4037.97	13247.948	2.05
7	3358.2	11017.7167	4112.94	13493.89	3678.72	12069.303	1.95
8	3545.77	11633.103	4342.664	14247.58	3884.196	12743.42	2.0
9	3500.175	11483.51375	4286.82	14064.376	3834.25	12579.56	2.05
10	3964.39	13006.529	4855.37	15929.68	4342.77	14247.937	2.2

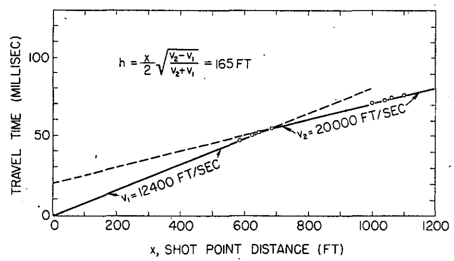

Figure 10. Travel-time curve (refraction), ice tunnel.

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