Institute of Polar Studies

Report No. 70

Seismic Surface Wave Observations in West Antarctica

by

Gilbert Dewart

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The Ohio State University
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ABSTRACT

Explosion-produced seismic surface waves recorded along the Byrd Station Strain Network in West Antarctica were investigated. Amplitudes were much greater for Rayleigh waves than for Love waves. Higher modes of both wave types were registered. Group velocity dispersion analysis revealed significant lateral inhomogeneity in near-surface structure of the ice sheet throughout the study area. Velocity anisotropy was indicated at one site.

ACKNOWLEDGMENTS

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INTRODUCTION

The potential usefulness of seismic surface waves as a tool for the investigation of glaciers and ice sheets has been recognized for some time (Anderson, 1963). Recent developments in geophysical exploration of the Antarctic ice sheet involving surface waves have been summarized by Bentley (1975). Most interest so far has centered on studies of anisotropic propagation of seismic waves in relation to the internal structure of the ice, especially in regard to crystal orientation (Robinson, 1968), but the possibilities of surface wave analysis in glaciological research appear to be varied and extensive.

The dispersion of seismic surface waves - the variation of velocity with frequency - is governed by the variation in density and elastic constants with depth below the surface of the transmitting medium. The dominant factor in this wave-guide phenomenon is the increase of rigidity with depth, or, in terms of wave motion, the shear wave velocity gradient, a parameter that is often difficult to establish independently. Compressional wave velocity gradients have been correlated with metamorphic zones near the surface of the West Antarctic ice sheet by several investigators (Kohnen and Bentley, 1973; Robertson and Bentley, 1975). Their data suggest that in the vicinity of Byrd Station the critical depth for close grain packing of snow occurs at about 14 meters below the surface, and the firn-ice boundary at about 56 meters. There is also an intermediate seismic horizon that appears to have metamorphic significance. The velocity values level off to a nearly constant magnitude at between 200 and 300 meters depth. It is these near-surface strata of snow and firn densification that control the dispersion characteristics of the surface waves that are produced by small, shallow explosions in the ice sheet. The application of seismic methods of analysis to this zone is especially important because it has thus far proved intractable to electromagnetic exploration.

This report presents selected observational data on explosion-produced seismic surface waves in the Marie Byrd Land region of the West Antarctic ice sheet. Since the standard model of a polar ice sheet assumes lateral homogeneity and vertical heterogeneity, particular attention is paid here to seismic anomalies, i.e, evidence of lateral heterogeneity.

Observations were made on the Byrd Station Strain Network (BSSN) from the vicinity of Byrd Station (80°00'34" S., 119°28'50" W.) approximately along the ice stream flow-line (Hughes, 1977) for 140 km to Post 93 (79°14'34" S., 113°25'03" W.), which is near the Ross ice-flow divide. Basic information about the overall program and instrumental data for the standard 24-channel exploration seismograph

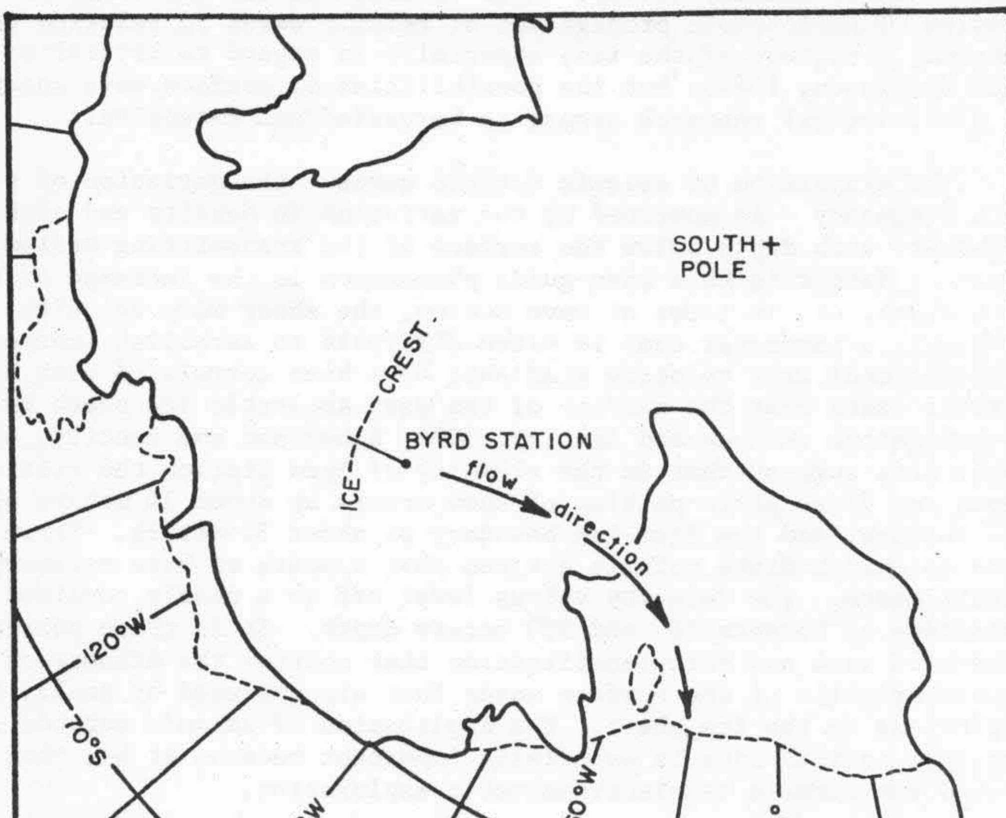

Fig. 1. Map of West Antarctica showing the location of the Byrd Station Strain Network, from the ice crest to Byrd Station.

system that was used in this investigation have been presented in a previous report of this series (Dewart, Whillans and Brecher, 1974). The position, elevation, estimated ice thickness from seismic and gravity data, surface mass balance and geophone array configuration for the seismic recording sites occupied in this investigation are given in Table I.

BSSN Post No.	Distance from Byrd Sta. (km)	Elev. (m)	Ice thickness	Surface mass balance ($gcm^{-2}a^{-1}$)	Type of array
1	1	1550	2280	11.8	L
25	37	1619	2480	14.5	L and in-line
27	40	1631	2450	13.9	in-line
33	48	1651	2480	14.8	L and in-line
34	48	1652	2360	14.8	L
35	51	1654	2580	15.5	L
45	67	1676	2820	15.7	in-line
55	82	1717	2820	15.2	L
65	97	1744	2750	14.7	in-line
73	108	1762	2670	16.0	in-line
87	130	1799	3000	17.0	L
93	139	1812	3280	19.1	in-line

Table I. Byrd Station Strain network recording site data. (from Dewart, Whillans and Brecher, 1974)

FIELD PROCEDURES

Two geophone arrays were established to register, among other things, seismic surface waves from relatively distant sources. The geophone spacing on these, as on the ordinary reflection spreads, was 30.48 meters (100 feet). With BSSN Post 25 as mid-point, the two halves of the 24-take-out spread were arranged in-line with the BSSN profile. Starting at the southwest end (toward Byrd Station) take-outs 1, 2 and 3 were connected to a single-position, 20 Hz, 3-component geophone combination: horizontal longitudinal, vertical, horizontal transverse; 4 and 5 were connected to 7 Hz horizontal transverse geophones; 6 and 7 to 7 Hz horizontal longitudinal; take-outs 8 to 12 to 4 Hz vertical; 13 through 18 to 20 Hz vertical; and 19 to 24 to 30 Hz vertical. Shots of 5-25 kg of seismogel and nitramon were made at borehole depths of 3-5 meters at various distances in-line with this array out to about 4 km to the northeast. Distances were measured by steel tape.

With Post 33 as center, the second array was arranged as follows, southwest to northeast: 1 and 2, 20 Hz vertical; 3 to 6, 7 Hz horizontal transverse; 7 to 12, 7 Hz horizontal longitudinal; 13 to 18, 4 Hz vertical; 19 to 24, 20 Hz vertical. Shots of size and depth similar to those at Post 25 were taken at intervals of approximately 500 meters out to 3 km to the northeast. Distances were measured by Geodimeter electronic distance measuring equipment.

Amplifiers were set at wide-band response, with a nearly flat amplitude from 5-500 Hz (periods of 2-200 milliseconds). The effective response of the whole system was divided into two bands: a band with a plateau response up to about 50 millisecond period for the 20 and 30 Hz geophones, and another band with a similar response over the 50-200 millisecond period range for the 4 and 7 Hz geophones. The two-band system facilitated analysis of the records of mixed fundamental- and higher-mode surface waves.

Ordinary reflection seismograms were also examined for surface wave phenomena where the noise level was sufficiently low for identification. The maximum shot-detector distance for these measurements was 365.76 meters. Both "L" (half-spreads parallel and perpendicular to the BSSN profile) and "in-line" spreads of 20 Hz geophones were used for the reflection shots. Angles were measured by theodolite.

RAYLEIGH WAVES

The "ground roll" of long trains of nearly sinusoidal high-amplitude waves that commonly appear on seismic records from explosions in regions with a strong positive downward velocity gradient, normally consists largely of Rayleigh waves (Dobrin, Simon and Lawrence, 1951). Since this kind of velocity structure is characteristic of the snow-firn-ice progression near the surface of a polar ice sheet, it was expected that Rayleigh-type ground motion would be prominent on the BSSN records. Analysis of the orbital motion in the snow recorded on the seismograms was carried out by means of the three-component detectors at Post 25 and one-component detectors aligned orthogonally at relatively small spacings in comparison with wavelength at Post 33. Elliptical retrograde motion in the vertical radial plane identified the high-amplitude ground roll as Rayleigh wave trains in most of the cases examined. However, some of the waves were not of the pure Rayleigh type: trajectory distortions and transverse components of motion were frequently observed. Significant rotation of the trajectory ellipse axes was also common.

Fundamental Mode

A representative seismogram from the array at Post 33 is shown in Figure 2. The vertical timing lines represent intervals of 20 milliseconds. The shot was fired at a depth of 4 meters at Point 1001, which was 2525.6 m from the mid-point of the spread. On this record fundamental-mode Rayleigh waves are well developed on the traces in the middle of the record registering the long-period vertical and longitudinal motion. Higher-mode Rayleigh waves are strongly marked on trace 2 and less well on traces 19 to 24. Love waves appear weakly on trace 5 (the long-period transverse geophone).

A dispersion curve of the group velocities of fundamental mode Rayleigh waves on this seismogram is presented in Figure 3. This plot is based upon the arrival times of sequential wave peaks at shot-detector distance of 2708.46 m versus the corresponding wave periods. The span of measured Rayleigh wave periods is about 48 to 117 milliseconds. At the calculated velocities this corresponds to a wavelength range of 40-164 m. The wavelengths are about 1 to 5 times the geophone interval, and the forms of individual waves can be followed across a spread length that is 5 to 20 times the wavelengths. The longest wavelengths that could be measured here approach the thickness of the wave-guide.

Figure 4 is a composite group velocity dispersion curve that extends the range to shorter periods. It is derived from a shot at the Post 25 array at a distance of 1548.6 m and a shot on a standard

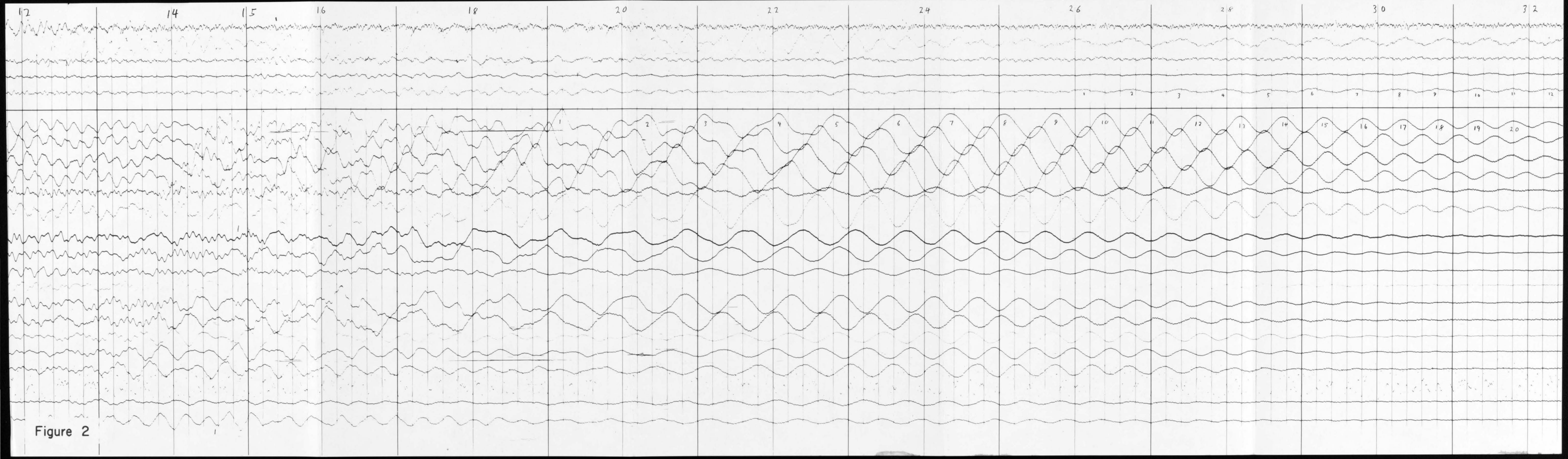

Figure 2

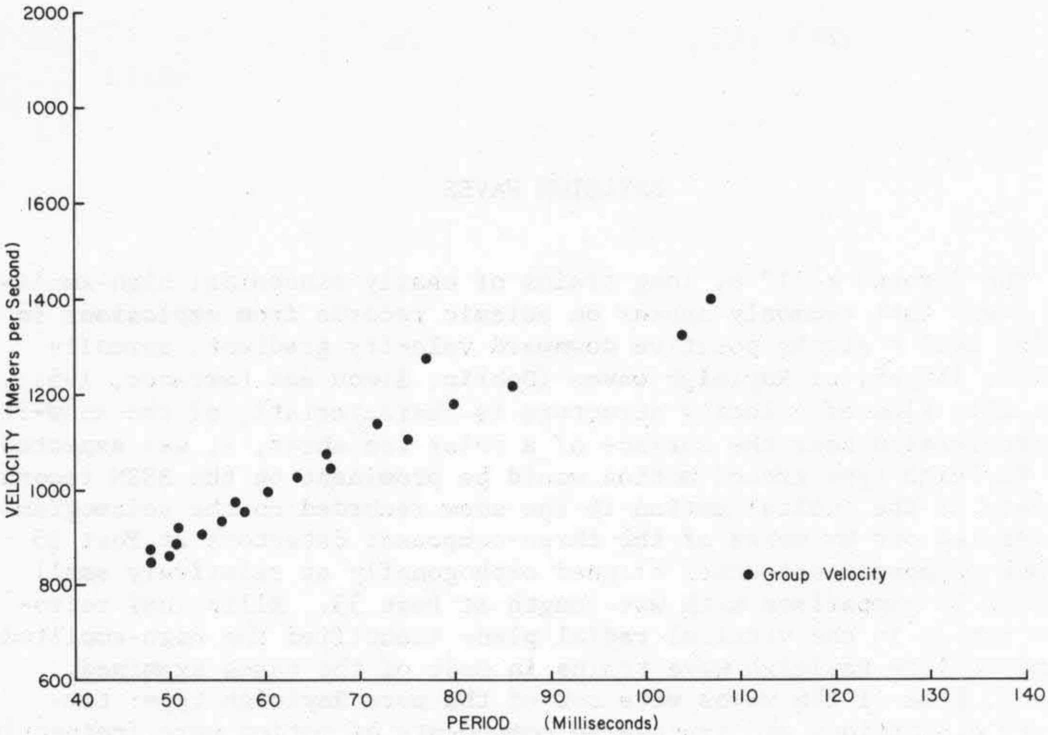

Fig. 3. Rayleigh wave group velocity dispersion data, Post 22, Shot-point 1001.

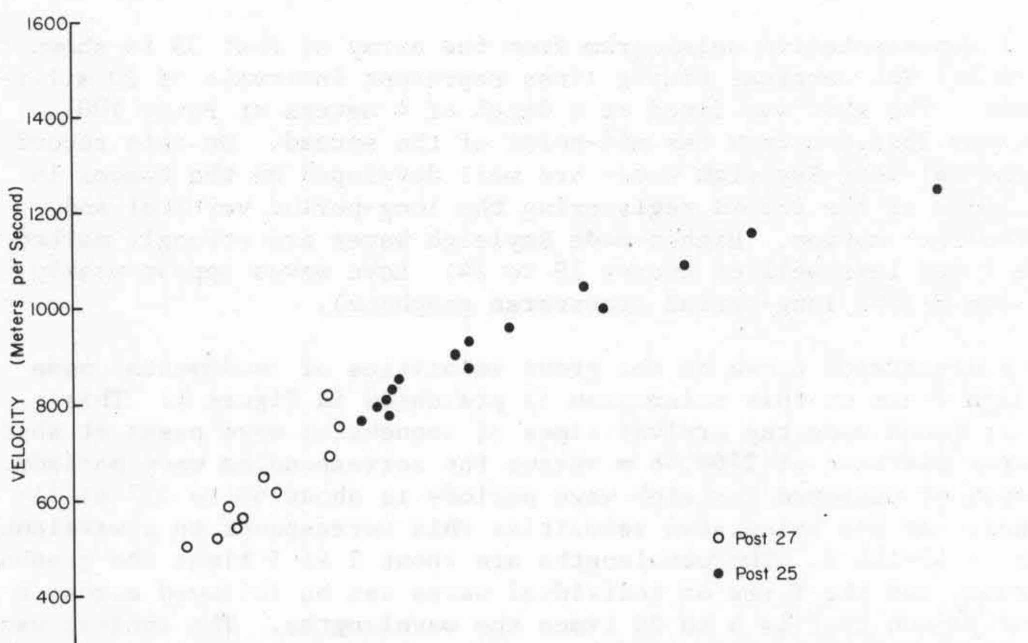

Fig. 4. Group velocity dispersion data, Posts 25 and 27

spread (365.76 m) at Post 27 (about 6 km away). The long-period half of the curve of Figure 4 is almost identical to that of Figure 3, except that the velocities at the upper end of Figure 3 are somewhat higher. Both curves display considerable scatter, and both show a marked break in slope in the period range 40-60 milliseconds.

In Figure 5 curves from the two sites for nearly equal shot-detector distances are presented (Post 25: 1548.6 m; Post 33: 1553.91 m). The basic similarity of the dispersion characteristics of the two locations is again evident.

Rayleigh wave phase velocities were determined by computing the phase shift for each period between waves recorded at two points on the array. The phase angle was converted to a time interval and divided by the distance between the points to obtain the velocity. The phase velocity and corresponding group velocity dispersion curves for the Post 33 site are plotted in Figure 6 for a source at Point 801 (distance 3215.21 m). Theoretically, the two curves will converge at the ends of the spectrum.

The phase velocity C_R of Rayleigh waves in the substratum of a layered or graded medium is related to the shear wave velocity β in the substratum by the expression:

$$C_R = 0.9194\ \beta$$

From this relationship and the phase velocity curve of Figure 6 an estimate of the shear velocity in the ice column beneath the wave-guide can be obtained. The phase velocity curve is trending toward a value of at least 1800 ms^{-1} at the long-period end (where $\lambda \cong 250$ m); hence, shear velocity in the ice sheet will reach a value of at least

$$\beta = 1958\ ms^{-1}$$

Kohnen and Bentley (1973) found a shear velocity maximum of approximately 1950 ms^{-1} beneath a seismic profile 10 km southeast of Byrd Station.

A comparison of fundamental mode Rayleigh wave group velocity dispersion data at various distances along the BSSN (Figure 7) reveals obvious differences, but the pattern is not clear. At periods below 30 milliseconds there is a gap of nearly 100 ms^{-1} between the curves for Post 25 and Post 93. Snow accumulation at the latter point is 37 percent greater than at the former (Table I), but the relationship suggested by these data is not strongly supported by the curves for the intermediate sites.

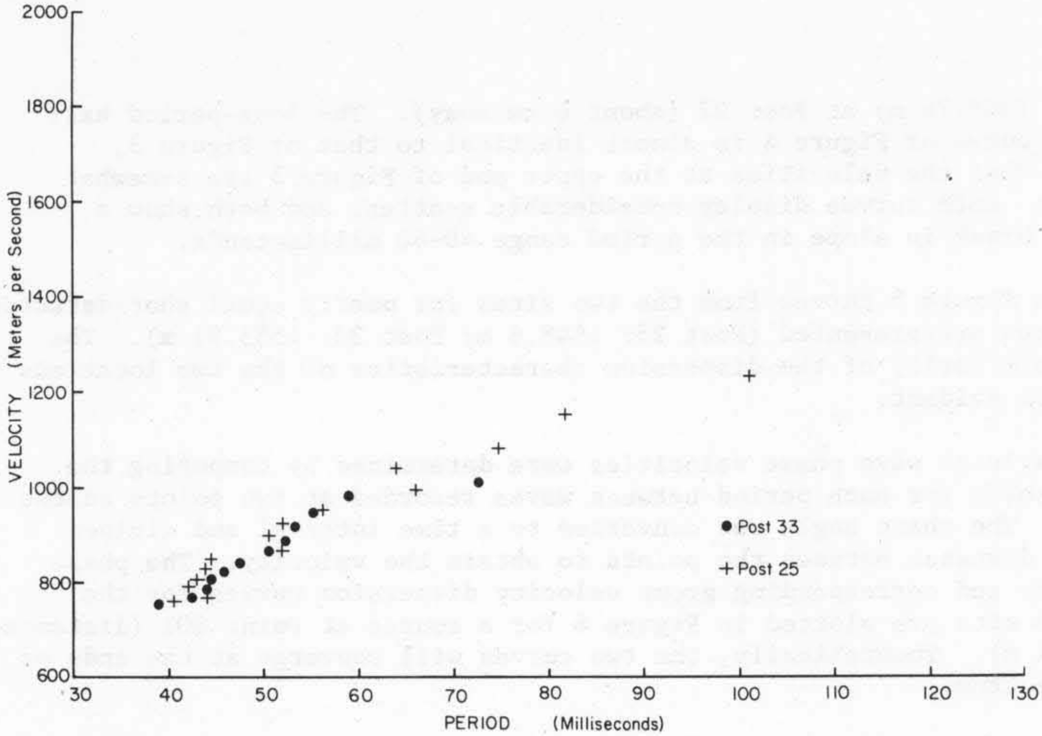

Fig. 5. Group velocity dispersion data, Posts 25 and 33.

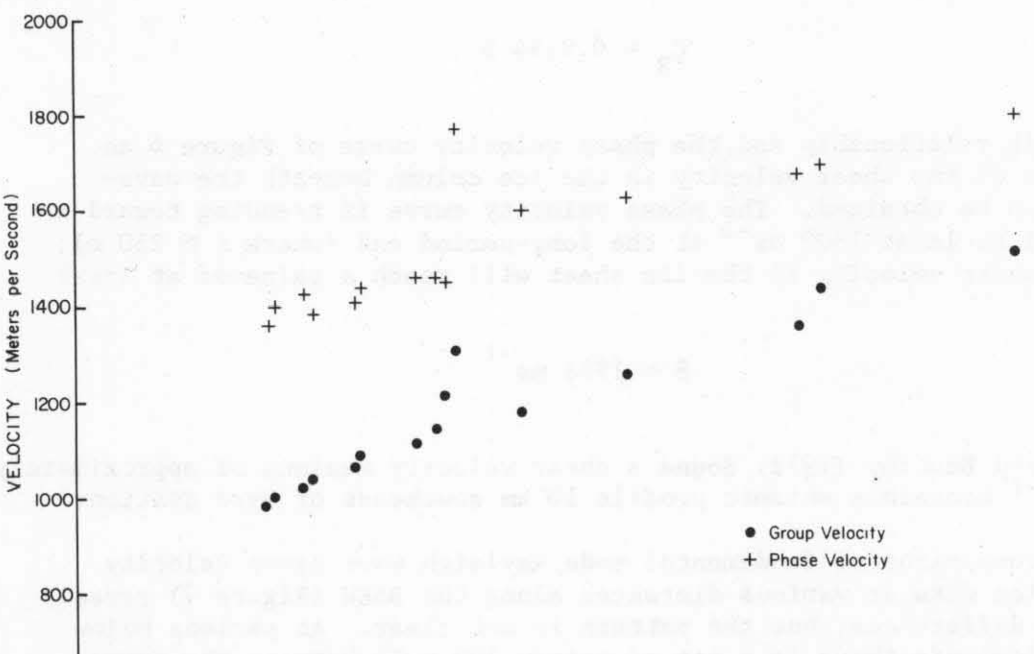

Fig. 6. Group and phase velocity dispersion data, Post 33.

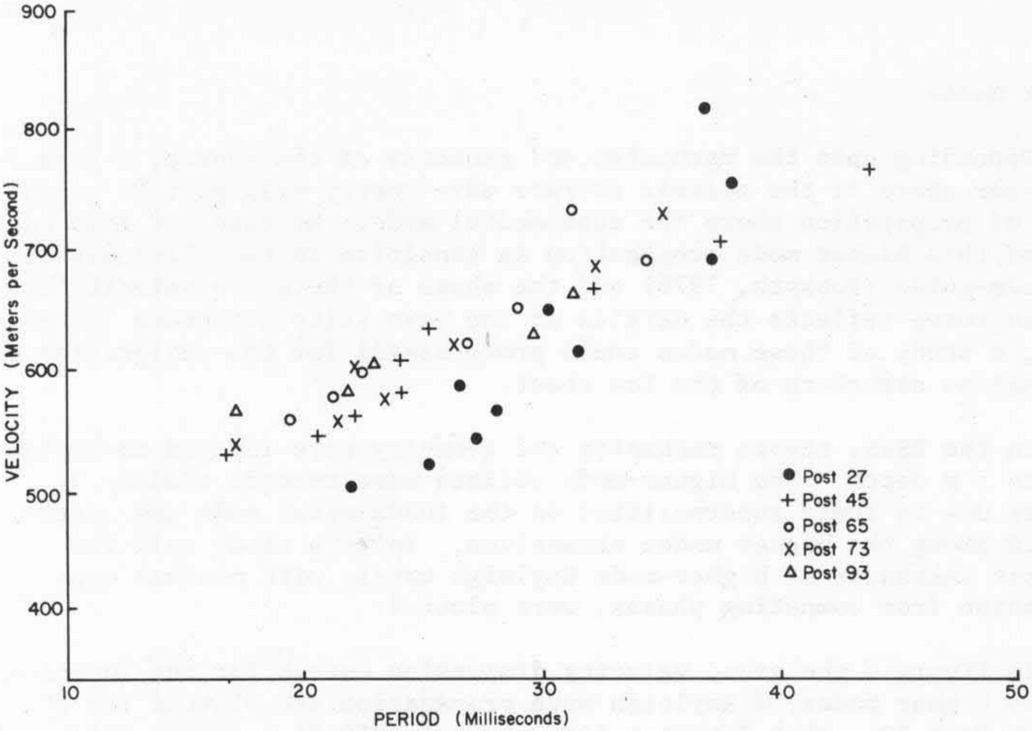

Fig. 7. Group velocity dispersion data, intervals along the BSSN.

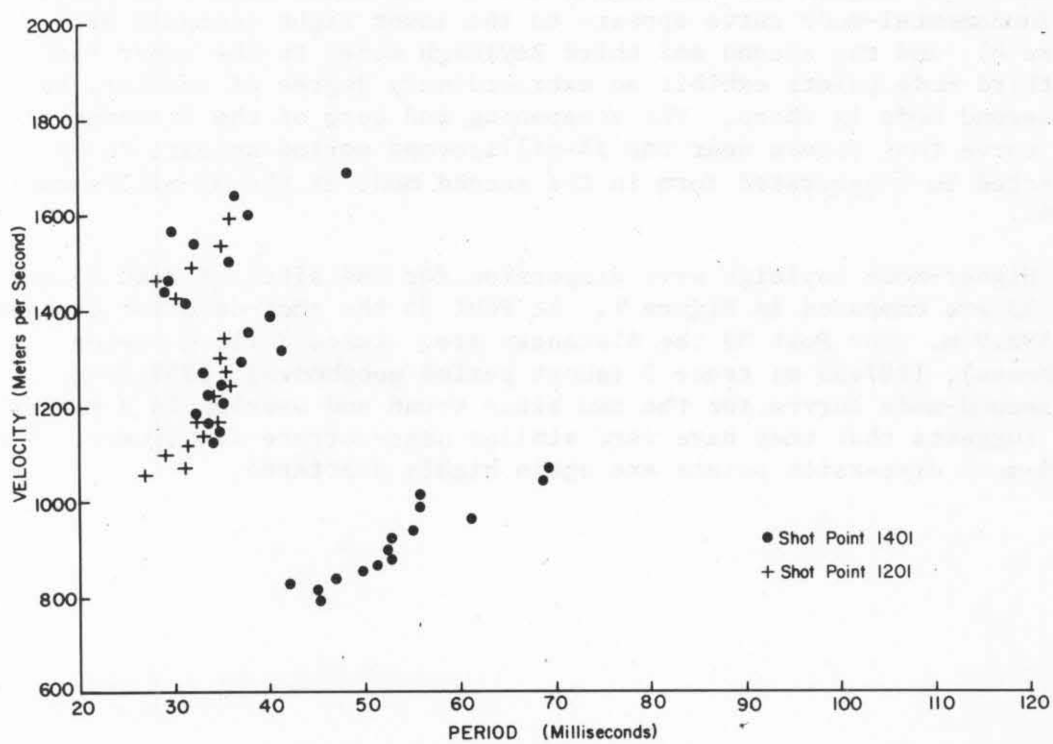

Fig. 8. Fundamental- and higher-mode group velocity dispersion data, Post 33.

Higher Modes

Depending upon the mechanism and geometry of the source, a greater or lesser share of the seismic surface wave energy will go into normal modes of propagation above the fundamental mode. Because the frequency band of this higher mode propagation is sensitive to the thickness of the wave-guide (Forsyth, 1976) and the shape of the group velocity dispersion curve reflects the details of the wave-guide structure (Alterman, 1969), a study of these modes could prove useful for the exploration of the shallow structure of the ice sheet.

On the BSSN, source mechanism and geometry were limited to explosions at 3 to 5 m depth. The higher-mode surface wave records tend to be complex due to their superposition on the fundamental mode and interference among the higher modes themselves. In this study only the clearest instances of higher-mode Rayleigh waves, with minimal contamination from competing phases, were plotted.

In Figure 8 the group velocity dispersion curves for the fundamental and two higher modes of Rayleigh wave propagation are plotted for the site at Post 33. Shot-detector distances of 1858.71 m (Point 1401) and 2268.99 m (Point 1201) were used; the waves were recorded on trace 2 (short-period vertical geophones). The characteristic feature of these curves - that for a given period the corresponding velocities are progressively higher for the higher modes - is clear from this plot. The fundamental-mode curve appears to the lower right (compare with Figure 4), and the second and third Rayleigh modes to the upper left. The third mode points exhibit an extraordinary degree of scatter, but the second mode is sharp. The steepening and cusp of the fundamental-mode curve that occurs near the 55-millisecond period appears to be reflected in exaggerated form in the second mode at the 35-millisecond period.

Higher-mode Rayleigh wave dispersion for the sites at Post 25 and Post 33 are compared in Figure 9. At Post 25 the shot-detector distance is 1192.9 m. For Post 33 the distances are: trace 7 (long-period geophones), 1207.59 m; trace 2 (short period geophones), 1359.99 m. The second-mode curves for the two sites trend and overlap in a manner that suggests that they have very similar near-surface structures. The third-mode dispersion points are again highly scattered.

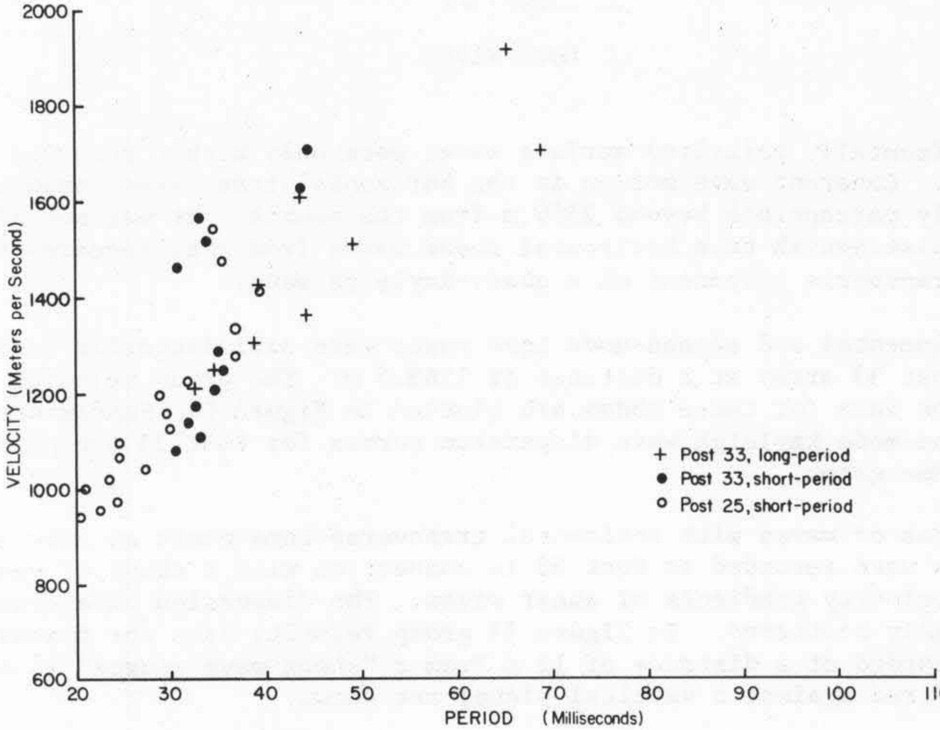

Fig. 9. Higher-mode group velocity dispersion data, Posts 25 and 33.

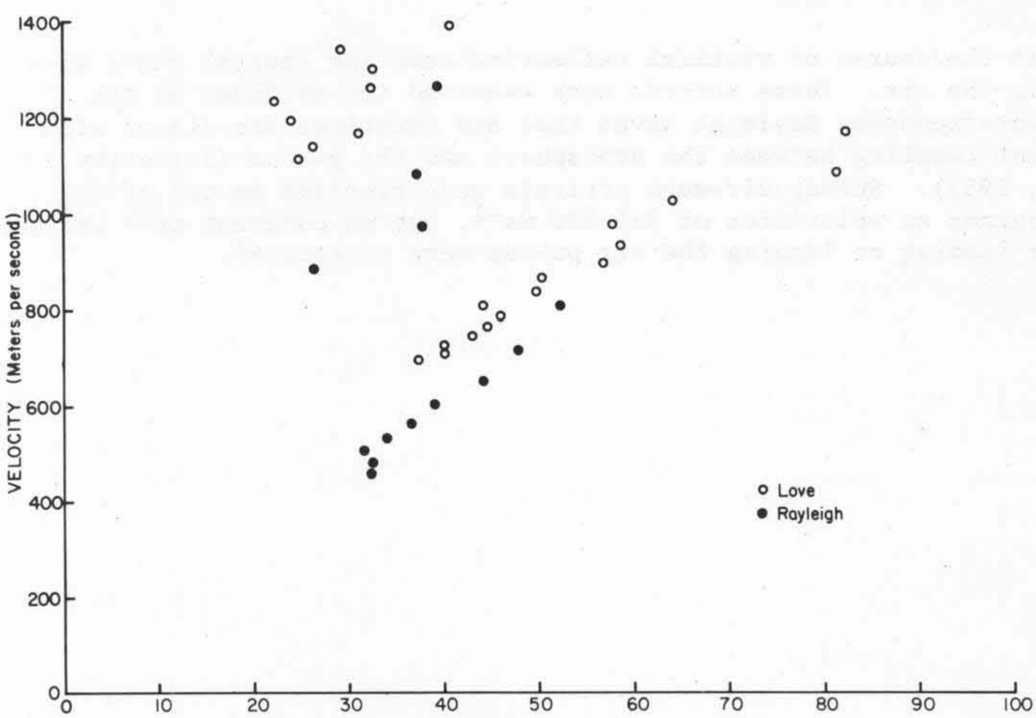

Fig. 10. Love waves: fundamental- and higher-mode group velocity dispersion data, Post 33.

LOVE WAVES

Horizontally polarized surface waves were only weakly recorded on the BSSN. Coherent wave motion in the horizontal transverse component was barely perceptible beyond 2500 m from the source. It was not always easy to distinguish true horizontal shear waves from what appeared to be the transverse component of a quasi-Rayleigh wave.

Fundamental and second-mode Love waves were satisfactorily recorded on the Post 33 array at a distance of 1268.5 m. The group velocity dispersion data for these modes are plotted in Figure 10. Fundamental and second-mode Rayleigh wave dispersion curves for Post 33 are plotted on the same graph.

Trains of waves with horizontal transverse components at very short distances were recorded at Post 55 in connection with a study of near-surface velocity gradients of shear waves. The dispersion data proved to be highly scattered. In Figure 11 group velocity data for transverse waves recorded at a distance of 12 m from a "shear wave source" (a detonator fired against a vertical plate) are shown.

AIR-COUPLED WAVES

In the course of vertical reflection sounding several shots were made in the air. These records were examined for evidence of the constant-frequency Rayleigh waves that are sometimes associated with resonant coupling between the atmosphere and the ground (Jardetsky and Press, 1952). Strong air-wave arrivals were recorded on two of the seismograms at velocities of 315-320 ms^{-1}, but no coherent wave trains either leading or lagging the air pulses were registered.

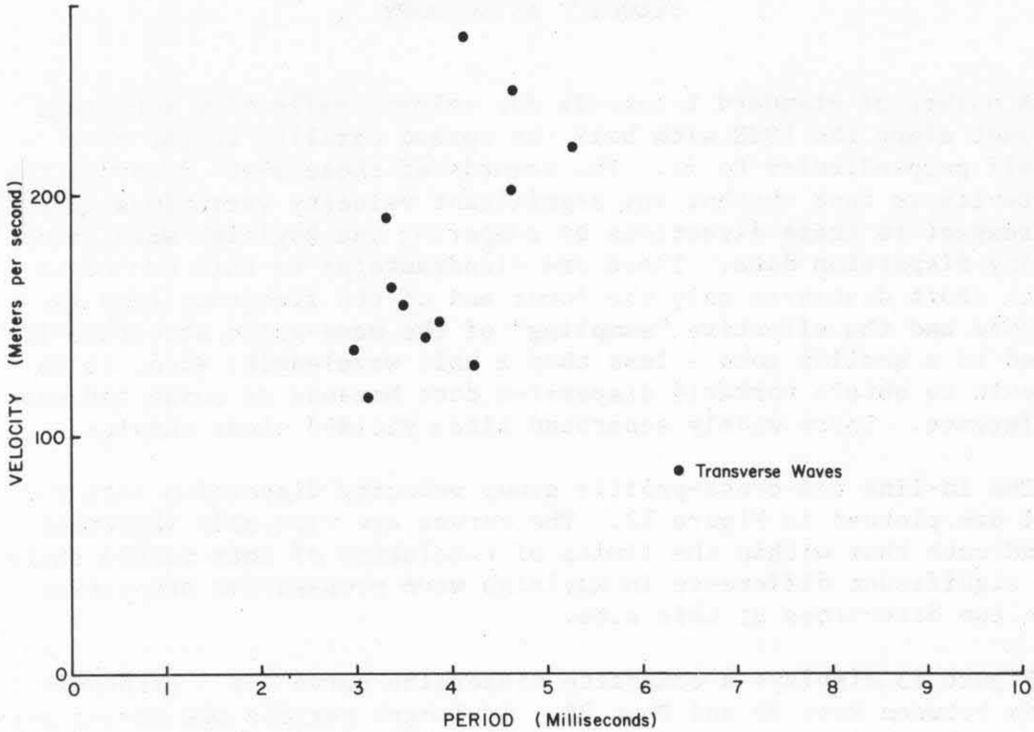

Fig. 11. Transverse waves: group velocity dispersion data, Post 55.

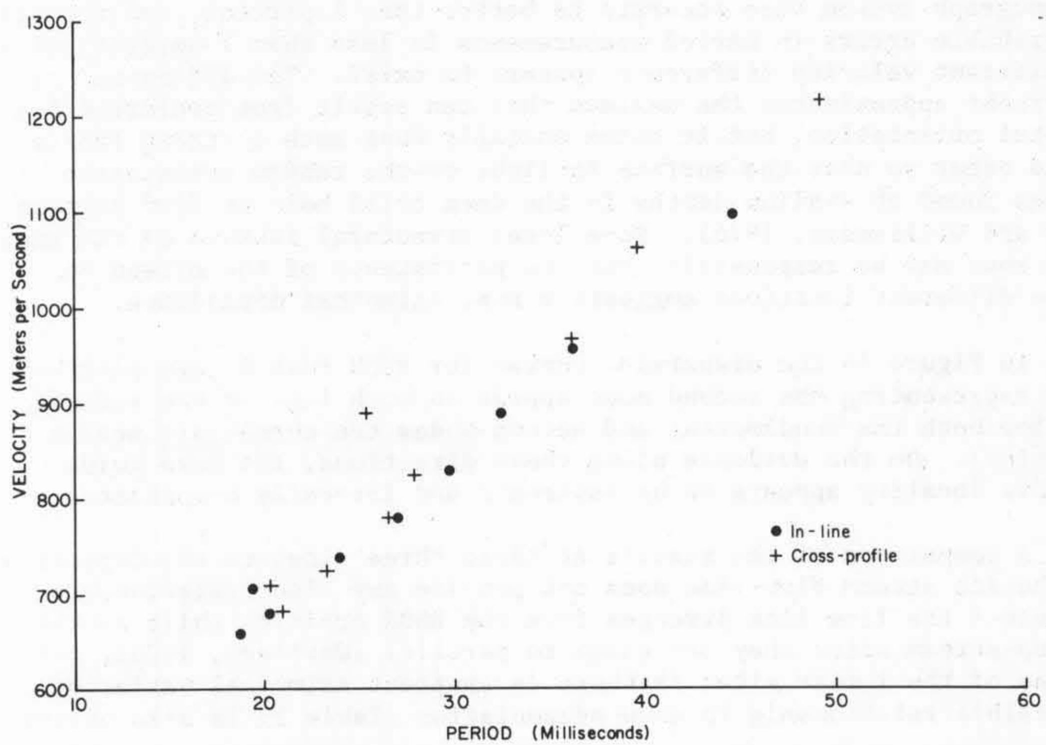

Fig. 12. Orthogonal spread: Rayleigh wave group velocity dispersion data, Post 1.

VELOCITY ANISOTROPY

A number of standard L-spreads for seismic reflection soundings were shot along the BSSN with half the spread parallel to the profile and half perpendicular to it. The records of these shots afforded the opportunity to test whether any significant velocity variations exist with respect to these directions by comparing the Rayleigh wave group velocity dispersion data. There are disadvantages to this procedure: at such short distances only the lower end of the frequency band is available and the effective "sampling" of the wave-guide structure is limited to a shallow zone - less than a half wavelength; also, it is difficult to obtain workable dispersion data because of noise and mode interference. Three widely separated sites yielded clear results.

The in-line and cross-profile group velocity dispersion data for Post 1 are plotted in Figure 12. The curves are virtually identical and indicate that within the limits of resolution of this method there is no significant difference in Rayleigh wave propagation properties in the two directions at this site.

Figure 13 displays a composite dispersion curve for 3 perpendicular spreads between Post 33 and Post 35. At longer periods the curves appear to merge, but below a period of about 30 milliseconds the cross-profile velocities are about 40 ms^{-1}, or 7 percent greater than the in-line velocities for the same period. Velocity measurements with this seismograph system were accurate to better than 1 percent, and the effect of probable errors in period measurements is less than 1 percent, so a significant velocity difference appears to exist. The difference of 7 percent approximates the maximum that can result from preferred ice crystal orientation, but it seems unlikely that such a strong fabric would occur so near the surface in light of the random orientation of c-axes found at shallow depths in the deep drill hole at Byrd Station (Gow and Williamson, 1976). Some local structural feature of the snow-firn zone may be responsible, but the persistence of the effect at three different locations suggests a real azimuthal dependence.

In Figure 14 the dispersion curves for BSSN Post 87 are plotted. Data representing the second mode appear on both legs of the spread, and for both the fundamental and second modes the curves are nearly identical. On the evidence along these directions, the wave guide at this locality appears to be isotropic and laterally homogeneous.

A comparison of the results at these three sites to the direction of the ice stream flow-line does not provide any clear relationship. At Post 1 the flow line diverges from the BSSN profile, while at the two up-stream sites they are close to parallel (Whillans, 1976); only at one of the latter sites is there an apparent azimuthal variation. A possible relationship to snow accumulation (Table I) is also obscure.

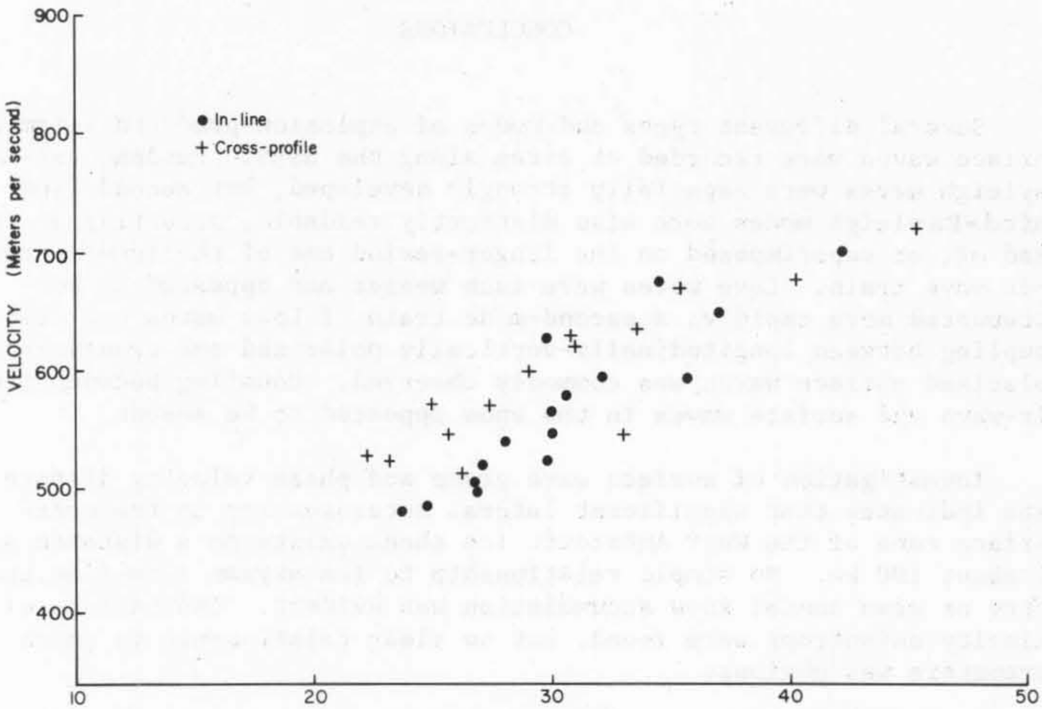

Fig. 13. Orthogonal spread: Rayleigh wave group velocity dispersion data, Posts 33-35.

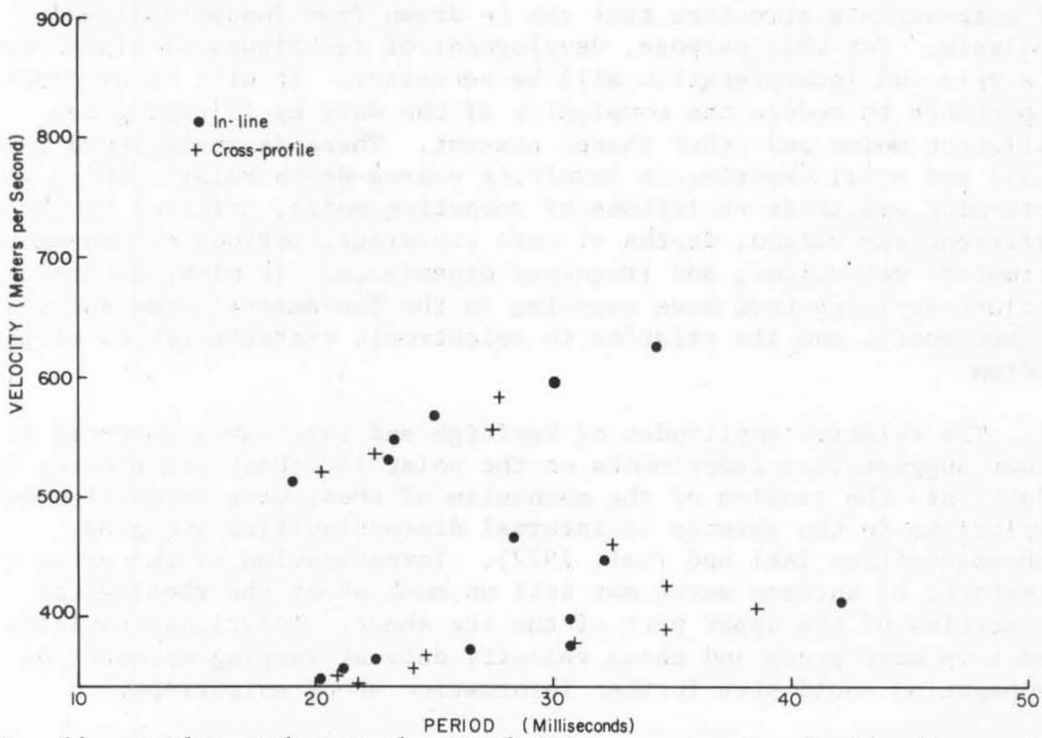

Fig. 14. Orthogonal spread: Rayleigh wave group velocity dispersion data, Post 87

CONCLUSIONS

Several different types and modes of explosion-produced seismic surface waves were recorded at sites along the BSSN. Fundamental-mode Rayleigh waves were especially strongly developed, but second- and third-Rayleigh modes were also distinctly readable, occurring at the head of, or superimposed on the longer-period end of the fundamental-mode wave train. Love waves were much weaker and appeared to be attenuated more rapidly; a second-mode train of Love waves was identified. Coupling between longitudinally-vertically polarized and transversely polarized surface waves was commonly observed. Coupling between the air-wave and surface waves in the snow appeared to be absent.

Investigation of surface wave group and phase velocity dispersion data indicates that significant lateral heterogeneity in the near-surface zone of the West Antarctic ice sheet exists on a distance scale of about 100 km. No simple relationship to ice stream flow-line geometry or mean annual snow accumulation was evident. Indications of velocity anisotropy were found, but no clear relationship to known parameters was obvious.

Analysis of higher-mode surface waves appears to offer possibilities of detailed exploration of the firn zone of a polar ice sheet. Since the higher modes penetrate more deeply for a given period than the fundamental mode, they may be useful in augmenting and refining the picture of near-surface structure that can be drawn from fundamental-mode analysis. For this purpose, development of techniques of higher-mode analysis and interpretation will be necessary. It will be of particular importance to reduce the complexity of the data by filtering the different modes and other phases present. There is ample scope for field and model experiments involving source-depth relationships to determine amplitude variations of competing modes, critical depths of efficient excitation, depths of zero crossings, periods of non-excitation, azimuthal variations, and frequency dependence. It might be fruitful to explore Rayleigh-Love wave coupling in the fundamental mode and the higher modes, and its relation to anisotropic characteristics of the medium.

The relative amplitudes of Rayleigh and Love waves observed in this study suggest that experiments on the polar ice sheet can provide insight into the problem of the mechanism of shear wave production by explosions in the absence of internal discontinuities and gross inhomogeneities (Aki and Tsai, 1972). Investigation of the attenuation constants of surface waves may tell us much about the rheological properties of the upper part of the ice sheet. Additional Rayleigh and Love wave group and phase velocity data at varying azimuths of propagation could give further information about anisotropy.

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APPENDIX A

A distinct envelope of Rayleigh waves is evident on this standard vertical L-spread shot at BSSN Post 1, December 1, 1970. Shot data: 2.25 kg nitramon in 3 m sprung hole, linear gain, filters 0-90 Hz.

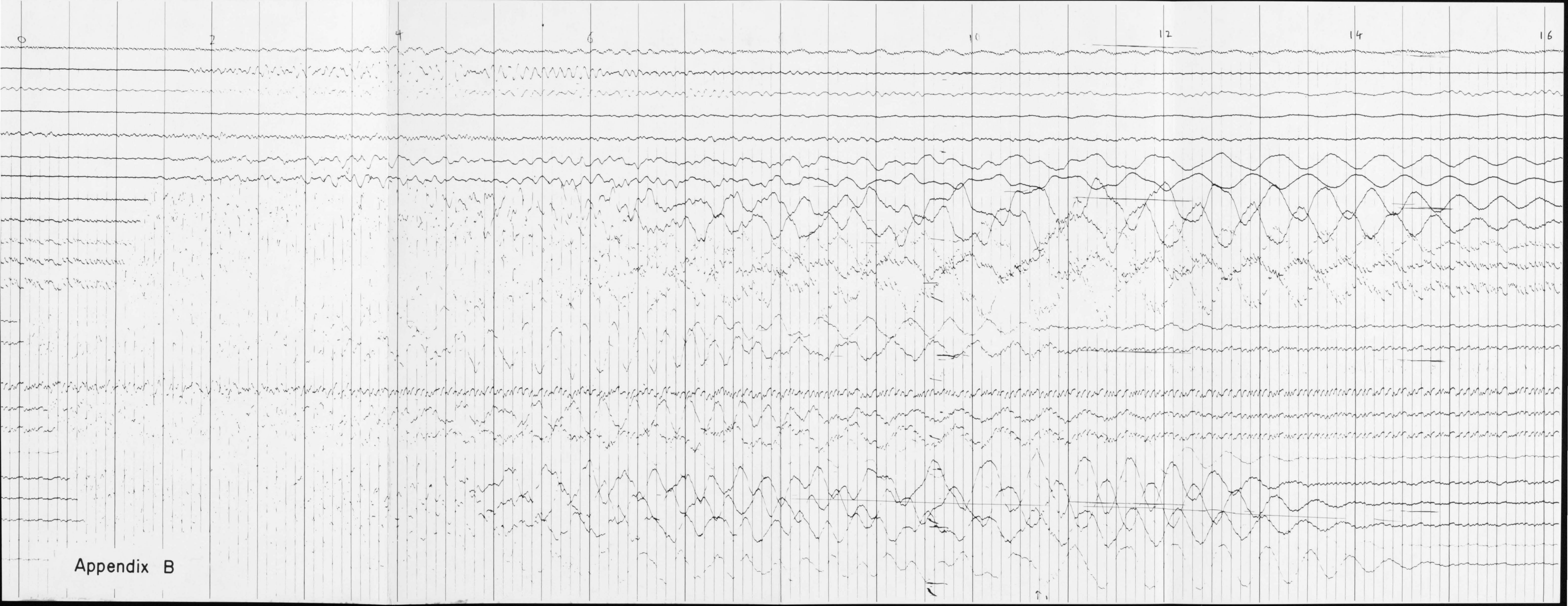
(Figure in rear cover pocket)

Appendix A

APPENDIX B

Higher-mode Rayleigh waves are well developed on this record from Post 25, January 7, 1968. Shot data: shot to spread mid-point distance 1 km, 6.8 kg nitramon at 5.5 m depth, linear gain, filters out, cables reversed.

(Figure in rear cover pocket)



Appendix B

APPENDIX C

Surface wave development on the array at Post 33, February 2, 1970. Rayleigh-Love coupling is indicated on traces 2 (vertical) and 5 (horizontal-transverse). Shot data: shot to spread mid-point distance 524.77 m, 4.5 kg nitramon at 4 m depth, linear gain, filters out.

(Figure in rear cover pocket)

Appendix C