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USE OF ACTIVE SOURCE SEISMIC SURFACE WAVES IN GLACIOLOGY

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Abstract

Active source seismic surface wave experiments were performed on Jakobshavn Glacier, Greenland, to evaluate the potential utility of surface wave methods on ice. A sledge hammer source striking a wooden beam, and a receiver line with twelve 28 Hz vertical geophones were used to generate and record surface wave data. We employed the Multichannel Analysis of Surface Waves (MASW) method to obtain dispersion curves and estimate shear wave velocities of firn and shallow ice. The sledge hammer source produced signal with usable frequencies in the 12 to 100 Hz range. Maximum depth of imaging was estimated to approximately 50 m. Firn shear wave velocities progressively increased from 1000 m/s near the surface to the ice velocity of 1950 m/s at around 47 m below the surface. This indicated that the firn-ice transition was at approximately 47 m below surface. We show that surface wave methods can be a viable alternative to traditional refraction surveys in determining firn velocity structure. Surface wave methods can provide continuous shear wave velocity maps of the subsurface which can aid in developing a better understanding of firn mechanical properties and mechanisms of crevasse formation.

Introduction

Active source seismic reflection and refraction methods have been providing critical information to the study of ice sheets and glaciers for decades. Seismic methods can probe from the very near-surface to the base of the ice a few kilometers in depth (Sen et al., 1998; Smith, 2007). However, conducting seismic surveys in polar environments is a labor intensive and slow process. Considering the large expanses of rapidly changing ice masses around the globe, there is a need for improving the efficiency of active source seismic methods.

Traditionally, shallow snow and ice mechanical properties have been determined using seismic refraction. The field methods employed are similar to near-surface engineering investigations. A shallow impulsive source (sledge hammer or small explosive charge) is used to generate continuously refracted diving waves that are recorded by a linear array of geophones (Thiel and Ostenso, 1961; King and Jarvis, 1991). P-wave and S-wave sources and geophones are employed for measuring P- and S-wave velocities of the firn and for determining its Poisson’s ratio (King and Jarvis, 2007). However, generating shear waves in low density, uncompacted snow is challenging and can involve time consuming practices such as imparting shear-motion on the sidewall of a shallow trench.

The objective of the study presented here was to examine if active source surface wave methods can be used to determine the shear wave velocity structure of firn and to provide an efficient alterative to refraction surveys. The main question is whether shallow snow and ice cause dispersion of seismic surface waves and can usable dispersion curves be generated from polar seismic records?

Firn is the denser, compacted snow that eventually forms glacier ice under the weight of burial. Firn density and P- and S-wave velocities increase exponentially with depth (Patterson, 1994; King and

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Jarvis, 1991). In particular, S-wave velocities can range from under 700 m/s near the snow surface to over 1900 m/s in polar ice (Thiel and Ostenso, 1961). Depth to the firn-ice transition varies with temperature and seasonal variations. In polar regions, typical depth to ice is 50 to 70 m corresponding to burial time of 100 to 300 years (Patterson, 1994). Therefore, the expected exponential increase of firn S-wave velocity occurring over the top few tens of meters of the subsurface holds promise for the use of surface wave methods in polar environments.

Field Testing and Data Analysis

Surface wave experiments were conducted on Jakobshavn Glacier, Greenland (69.35° N, 47.2° W), to assess the potential utility of surface wave methods on ice. Surface wave data were acquired along side a conventional CMP survey line used for deep reflection imaging. The seismic source employed was a 5 kg sledge hammer striking vertically a wooden beam (0.1 x 0.1 x 1.0 m) positioned 10 m from the nearest geophone. The receiver line was the same as the CMP line consisting of twelve 28-Hz vertical geophones spaced 20 m apart. Figure 1 shows a sample seismogram recorded with the sledge hammer source. Dispersive surface wave energy is evident in the shot record.

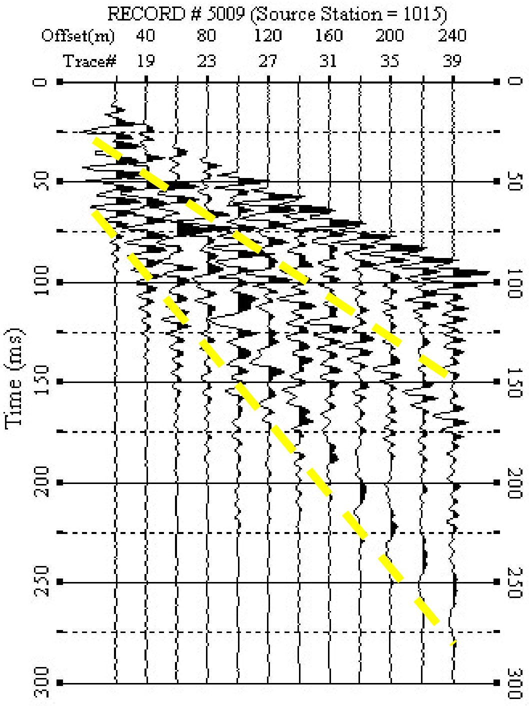

Figure 1: Shot record acquired over ice. Surface waves are outlined by yellow dotted lines.

We used the Multichannel Analysis of Surface Waves (MASW) method (Park et al., 1999; Xia et al., 1999) to obtain dispersion curves and estimate shear wave velocities of firn and shallow ice. Figure 2 displays a MASW dispersion image and the extracted dispersion curve for the sledge hammer data over ice. Rayleigh wave phase velocities are shown to vary from just under 1000 m/s at 100 Hz to 1450 m/s at 12 Hz frequency. Comparable quality dispersion curves were extracted from all shot records in this experiment.

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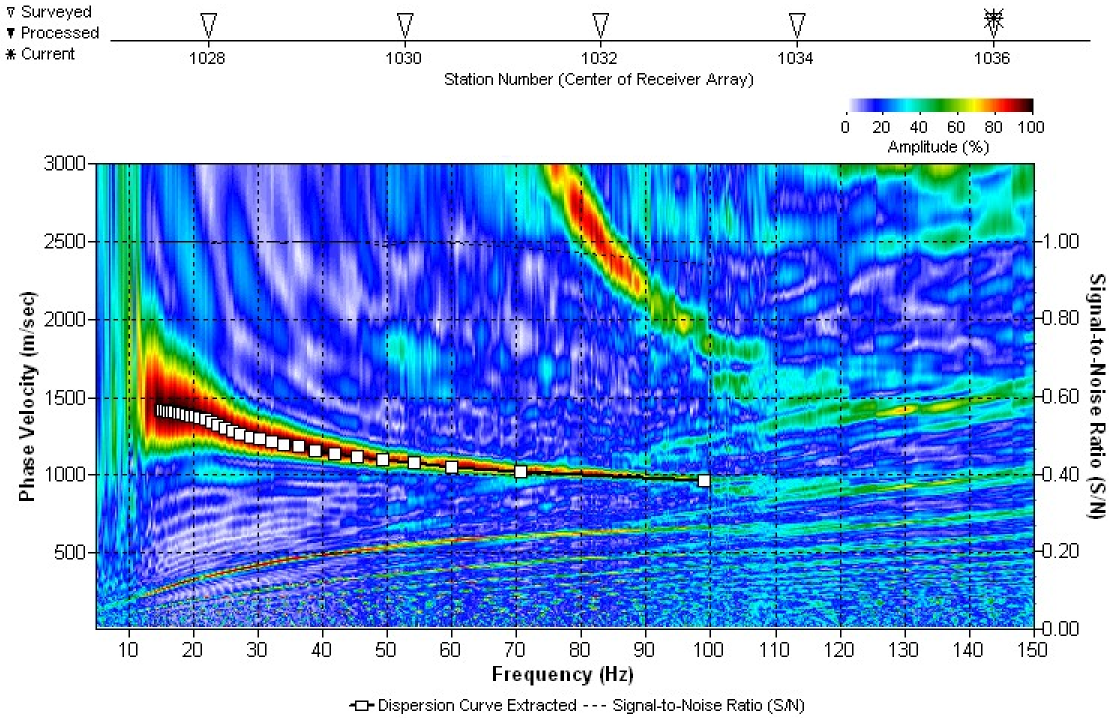

Figure 2: Dispersion image and extracted dispersion curve.

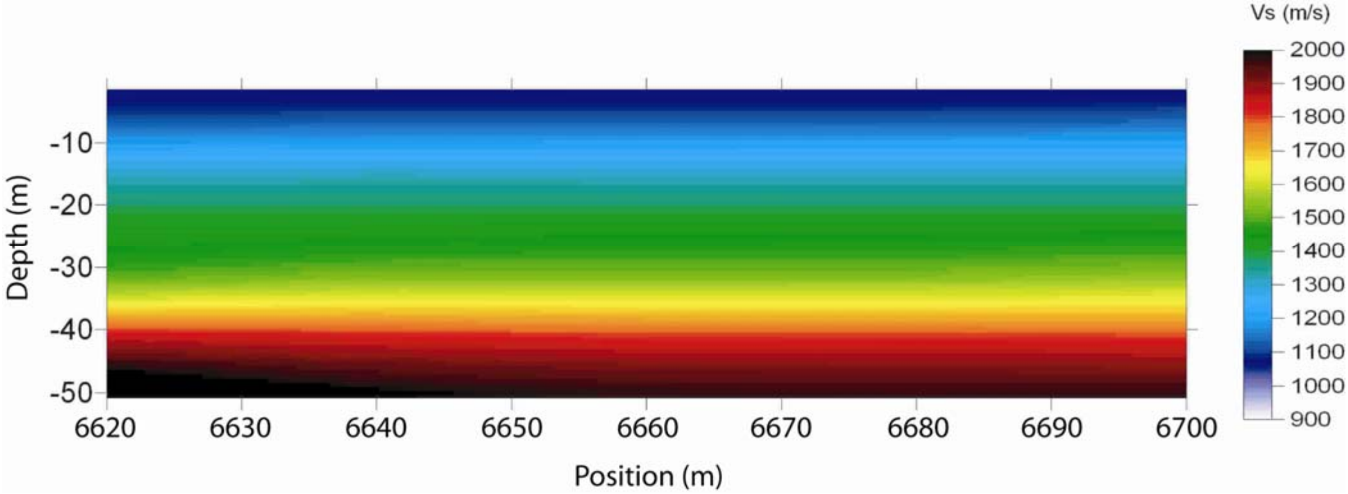

Figure 3: Approximate S-wave velocity profile.

The approximate shear wave velocity profile for this experimental data set is shown in figure 3. Maximum depth of imaging is 50 m with S-wave velocities ranging from 1000 m/s at the surface to 1950 m/s at the deepest part of the section. Surface conditions during data collection were dry, wind-packed snow with shallow hard layers, which is consistent with the relatively high near-surface snow velocity of 1000 m/s. Velocity increases rapidly with depth and shows little lateral variability, as expected in an environment where compaction and densification is the dominant mechanism transforming snow to firn and eventually to ice. The highest velocity observed of 1950 m/s is at the upper limit of S-wave velocity in ice and suggests that the firn-ice transition occurs at a depth of approximately 47 m.

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Conclusions

Active source surface wave methods tested on Jakobshavn Glacier, Greenland, yielded usable dispersion curves and a shear-wave velocity profile of firn that is consistent with the expected velocity structure in polar regions. The firn-ice transition is estimated to occur at a depth of 47 m where maximum S-wave velocity of 1950 m/s is observed. The firn proved a suitable environment for use of the MASW method due to its exponential increase of velocity and density with depth, and laterally continuous velocity structure. This study suggests that surface wave methods can be an efficient alternative to refraction surveys for firn characterization.

References

King, E. C., and Jarvis, E. P., 1991, Effectiveness of different shooting techniques in Antarctic firn, First Break, 9, 281-288.

King, E. C., and Jarvis, E. P., 2007, Use of shear waves to measure Poisson’s ratio in polar firn, Jour. Env. Eng. Geop., 12, 15-21.

Park, C. B., Miller, R. D., and Xia, J., 1999, Multichannel analysis of surface waves: Geophysics, 64, 800-808.

Patterson, W. S. B., 1994, The physics of glaciers, 3rd edition, Elsevier, New York.

Sen, V., Stoffa, P. L., Dalziel, I. W. D., Blankenship, D. D., Smith, A. M., and Anandakrishnan, S., 1998, Seismic surveys in central west Antarctica: Data and processing examples from Antalith field tests (1994-1995), Terra Antarctica, 5, 761-772.

Smith, A. M., 2007, Subglacial bed properties from normal-incidence seismic reflection data, Jour. Env. Eng. Geop., 12, 3-13.

Thiel, E., and Ostenso, N. A., 1961, Seismic studies of Antarctic ice shelves, Geophysics, 26, 706-715.

Xia, J., Miller, R. D., and Park, C. B., 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave: Geophysics, 64, 691-700.

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