A New Approach for Exploring Ice Sheets and Sub-Ice Geology

Active seismic measurements were an important part of geophysical traverses on the Antarctic ice sheet as far back as the 1920s. These methods lost their leading role for ice thickness measurements to much faster ground-based and airborne radar surveys because of the considerable logistical effort necessary for seismic data acquisition. However, new achievements with a vibrator source in active seismics (vibroseis for short) could open new prospects and foster future geological and glaciological surveys in Antarctica and Greenland and on ice caps and glaciers.

Active seismic methods have the unique ability to image sub-ice geology and remotely obtain its physical properties. Friction at the basal interface of an ice sheet plays a pivotal role in controlling ice dynamics and is largely determined by the presence of water and/or sediments underneath the ice. High-quality seismic reflection measurements came in demand as scientific interest in the dynamics of ice streams (e.g., West Antarctic ice streams) increased and site surveys were needed for optimum sampling of sub-ice sediments for paleoclimate studies (e.g., Cape Roberts Project, Antarctic Geological Drilling (ANDRILL)). Nevertheless, the available literature demonstrates that seismic studies on ice sheets are not widespread and are only carried out on small, local scales over a few tens of kilometers. Prominent examples of such seismic studies are the observation of transient processes in bed geology driven by ice flow [*Smith et al.,* 2007] and the long record of seismic exploration of subglacial lake environments, for example, around Lake Vostok and more recently around subglacial Lake Ellsworth. Seismic properties of the ice sheets remain only an occasional topic [*Horgan et al.,* 2008], often complementary to radar.

The Firn-Layer Problem

The upper tens of meters of an ice sheet consist of a highly porous layer of firn (snow that is more than 1 year old), which acts as an acoustic waveguide, or trap, making the excitation of seismic waves from a surface source difficult. Soft firn causes large inelastic energy losses for impulsive sources. During most seismic surveys in Antarctica, researchers have used explosives in 10- to 20-meter-deep boreholes to overcome signal attenuation caused by the high-velocity gradient in the surface layer. The boreholes are drilled by different techniques, requiring considerable time and energy for each hole. With the seismic source below the surface, surface ghost reflections are commonly present in the data. Despite these difficulties, explosives sources in shallow boreholes are still the simplest way to obtain acceptable data quality. Even with this approach, involving minimal efforts, the necessary logistical requirements have discouraged the acquisition of longer seismic profiles, for example, as part of overland traverses.

The Vibroseis Surface Source

During the 2009–2010 Antarctic field season the Linking Micro-Physical Properties to Macro Features in Ice Sheets With Geophysical Techniques (LIMPICS) project aimed to make seismic vibrator measurements for the first time in Antarctica [*Kristoffersen et al.,* 2010]. In contrast to an impulsive surface source of millisecond duration, a controlled vibrator source emits energy as a finite amplitude pressure pulse over many seconds. Energy losses by inelastic behavior are thus much less because of reduced ground pressure.

The project used a truck-mounted Failing Y-1100 vibrator (peak actuator force equivalent to 12 tons) on skis towed by a PistenBully snowcat on the floating Ekström Ice Shelf near the German research station Neumayer III. Sweeps of 10-second duration with a linear increase in frequency over the range of 10–100 hertz were compared to shots of 300-gram explosive charge fired in 10-meter-deep boreholes (Figure 1). Both types of data were recorded with a snow streamer (i.e., geophones towed on a cable across the snow surface), and the data show the primary reflection from the ice-water interface, its multiples, and the reflections from and within the seafloor. The explosive source is clearly rich in higher frequencies (up to 300 hertz), while the energy in the vibroseis record is limited to the sweep frequencies. The vibrator excites slightly more surface waves than the explosive charge, but the total energy level is higher relative to an explosive charge at 10-meter depth. Identifiable reflections are present over a more than 2-second two-way travel time.

With the current vibroseis–snow streamer setup, seismic data production is about 10 kilometers per day for single-fold coverage, with peak production rates up to 3 kilometers per hour. Optimization should enable a doubling of the production rate to 20 kilometers per day even for multifold coverage, comparable to onshore vibroseis surveys. Surface properties do not impose a problem, as the vibrator pad (2.5 square meters) generally sank no more than a total of 10–20 centimeters in dry snow after three consecutive sweeps.

Future Prospects

A vibrator has the advantage of being a known and repeatable source signal and

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also of having reduced logistics costs, higher production rates, and less impact on the environment than explosives. Further investigations should address appropriate selection of vibrator size (commercially available vibrators range from 50 kilograms to more than 10 tons) for a trade-off between resolution and penetration depth depending on target objectives and the applicability of vibrator types (inducing shear or pressure waves) for sophisticated analyses methods such as amplitude variation with offset. Logistical limitations require improved implementations such as mounting a vibrator directly on a sled (instead of on a truck on skis) and modular systems for deployment with smaller airplanes.

The vibroseis–snow streamer configuration used presents a tool suitable for traverses of several hundred kilometers and thus for target-oriented surveys for specific objectives such as (1) exploring the sub-ice sediment structure suitable for sampling by scientific drilling and analysis for climate information; (2) investigating the physical properties of the ice-bedrock interface; (3) exploring grounding line processes like internal basal ice structures and water-routing systems; (4) conducting surveys of subglacial lake settings, especially water depth and sediment information; (5) complementing radar in exploring the physical properties of the lower part of the ice sheet; and (6) tying together offshore and onshore seismic data for geological interpretations.

Photos of the vibrator truck and the measurement setup are available in the online supplement to this *Eos* issue (http://www.agu.org/eos_elec/).

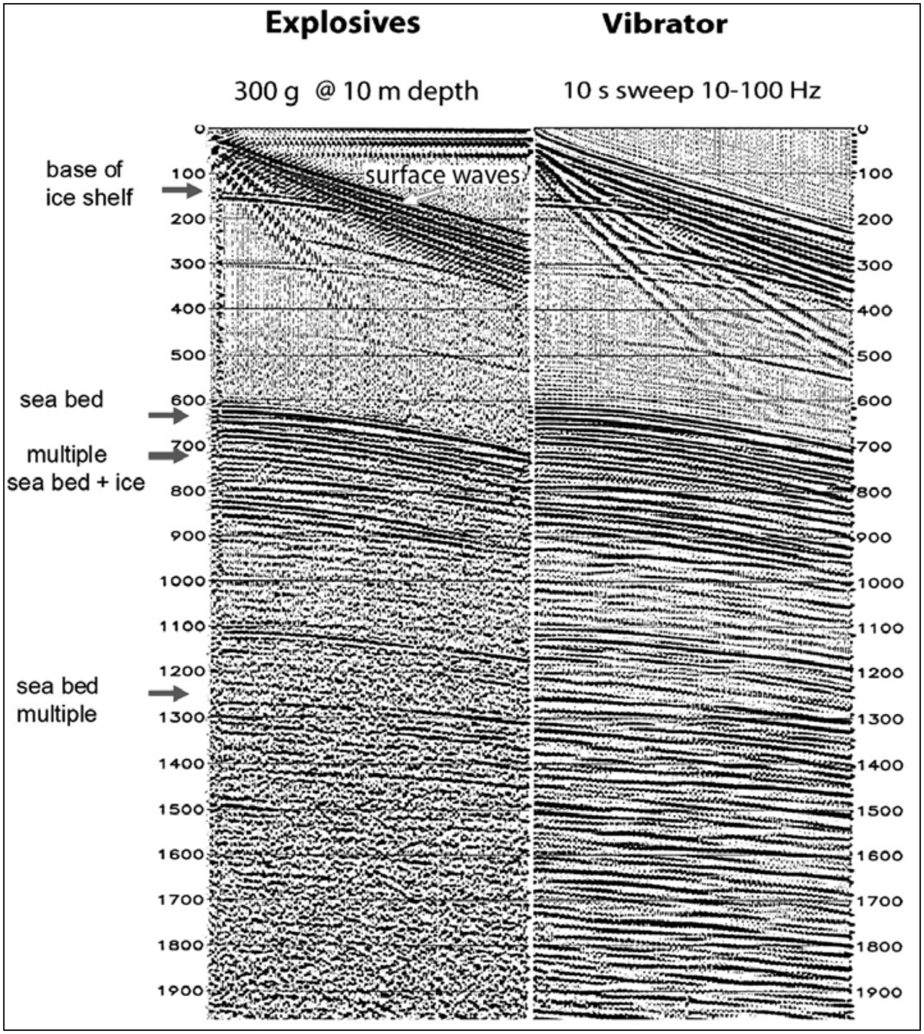

Fig. 1. Comparison of shot files sampled at 1-millisecond intervals.

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