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Application of radar and seismic methods for the investigation of temperate glaciers

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Abstract

The capabilities of seismic and radar methods for the study of ice sheets have been analysed by other authors in the past. The joint use of both techniques has allowed the comparison of information, such as ice thickness, retrieved from both sources. Though these methods, specially the radar sounding, have also been widely used for the study of polythermal and temperate glaciers, the literature lacks joint analysis of their use for the study of temperate glaciers, where physical processes absent in the cold ice masses come into play. We have used seismic and radar methods collected at Johnsons Glacier, a temperate ice mass located in Livingston Island (Antarctica), to show the glaciological information that can be retrieved from such data. The aspects considered include the determination of ice thickness, the retrieval of information concerning the internal structure of the glacier (distinction between accumulation and ablation zones, determination of the depth of the firn–ice transition, detection of buried crevasses), the estimation of physical parameters such as seismic and radio wave velocities, water content in temperate ice and firn density, and the use of radar and seismic data to infer the presence of water channels at the ice–bed interface and to determine the nature of subglacial sediments.

Keywords: Seismic reflection; Seismic refraction; Ground penetrating radar; Glacier; Temperate

1. Introduction

The propagation of elastic and electromagnetic waves through a given medium depends on very different properties of the material, and thus seismic and radar methods can be jointly exploited to retrieve complementary structural information. The seismic methods have a widespread use for geophysical exploration. The use of radar techniques is also becoming generalised for particular geophysical applications, the main constraint being the limited penetration of the electromagnetic waves through

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most subsurface materials. The shorter wavelengths employed in the radar techniques, however, imply a higher resolution. For this reason, the radar methods are becoming increasingly popular as surface based geophysical methods to study shallow subsurface geology, say down to 40 m below the surface, where the accuracy of the present seismic methods is not always adequate (Daniels, 2004). When dealing with glaciers and ice sheets the penetration is no longer a constraint of the radar methods, as the low conductivity of glacier ice, and hence its low dielectric losses, make it an ideal geological material for the propagation of electromagnetic waves. Penetrations up to several hundred, even a few thousand, metres have been achieved in glaciers and ice sheets (Plewes and Hubbard, 2001). The interest, however, is not restricted to glaciology, as, in many cases, analogues can be found in other branches of geophysics, as will be discussed later.

Focusing in glaciological applications, the radar and seismic methods are the most widely used methods for determining the ice thickness of glaciers and ice sheets. Seismic methods have been shown to be an effective tool to determine the basal topography and ice thickness in cold and temperate glaciers (Crary, 1963; Levato et al., 1999; Benjumea and Teixidó, 2001). Seismic surveys allow the investigation of the conditions at the ice–bedrock interface (Nolan and Echelmeyer, 1999), the nature of bedrock material and whether or not bed deformation is occurring (Smith, 1997); they also provide a means for obtaining density–depth profiles in polar ice sheets (Robin, 1958; Bentley, 1975). Radar airborne and ground-based sounding methods have also been used extensively for the retrieval of information concerning ice-thickness, bed conditions, internal layering and physical parameters of the ice in cold, temperate and polythermal glaciers (see, e.g., the reviews by Gogineni et al., 1998; Plewes and Hubbard, 2001). Low-frequency (say, below 15 MHz) monopulse ground-penetrating radars (GPR) have been found to be the most appropriate radar tool for the study of temperate glaciers, since they overcome the strong scattering caused by water inclusions at higher frequencies (Watts and England, 1976). The joint use of both techniques has usually been addressed for comparison of ice thickness in cold glaciers and polar ice sheets (e.g. Weber and Andrieux, 1970; Drewry, 1975), as well as for calculating the depth-averaged densities of ice shelves (Doake, 1984). Another application has been the use of the density–depth curves in the firn zone, obtained from seismic measurements, to calculate the radio wave velocities needed to convert reflection times to depth and to detect buried crevasses and their direction (Retzlaff and Bentley, 1993; Clarke and Bentley, 1994).

In this paper, seismic and radar data collected along coincident profiles are used to analyse the suitability of both methods for the study of ice thickness and physical parameters, bedrock topography, internal structure and subglacial conditions of a temperate glacier in Antarctica (Johnsons glacier). The aim is to show the capabilities of both techniques for the study of temperate glaciers and to illustrate how they complement to each other in accomplishing this task. The study, however, does not intend to be exhaustive, in the sense of discussing the capabilities of both methods in general, but is limited to a case study for a particular glacier and constrained by the instruments used for the field work and the available field data sets. Neither a full glaciological discussion of Johnsons glacier is undertaken in this paper; rather, we have used an approach of discussion of methods and presentation of corresponding examples. The selection of Johnsons glacier was dictated by both logistic reasons (due to its proximity to the Spanish Antarctic station Juan Carlos I) and scientific aspects, as there is a quite large amount of glaciological data available and the glacier dynamics is reasonably well understood.

Most of the methodologies discussed in this paper can be extrapolated to other fields of applied geophysics. Just to give a few examples, the technique of using back-scattered seismic surface waves to detect buried crevasses could be used for the detection of fractures in salt mines; a snow-filled crevasse could be considered as an analogue of a dike; the study of water content from radar and seismic velocities is just an application of two-component mixture formulae to the analysis of physical properties of porous media; the use of GPR for water content estimate can be applied to groundwater studies of sandy sedimentary environments of high electrical resistivity; and so on.