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Crevasse detection in glaciers of southern Chile and Antarctica by means of ground penetrating radar

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Abstract Detection of crevasses is critical for safe travelling on glaciers. Here we present the use of a Ground Penetrating Radar (GPR) for crevasse detection. Experiments were made in temperate ice on Glaciar Mocho, Volcán Mocho-Choshuenco, southern Chile (39°25′S) and in cold ice in East Antarctica (87°30′S). In southern Chile the radar was hand-carried 1.2 m in front of the operator who was walking over the glacier at a speed of ~0.5 m s^{-1}, while in Antarctica it was mounted on a 7 m-long rod in front of a tractor convoy travelling at a speed of ~2 m s^{-1}. In both geographical sites profiles were made perpendicularly to crevasses ranging in width from 0.1 m to 1.0 m. Buried crevasses clearly show as apexes of diffraction hyperbolae, which could be detected down to a depth of 15 m. Show as discontinuities in the firn stratigraphy which have a width equal to the crevasse width, and associated diffraction hyperbolae to each side of the crevasse. The GPR proved to be a valuable tool for detecting crevasses, allowing for a reaction time of ~9 s (equivalent to ~4.5 m on the ground) in the case of the hand-carried system and ~5 s (or ~10 m on the ground) for the tractor system.

Key words: Crevasses, GPR, temperate ice, southern Chile, Antarctica.

INTRODUCTION

Ground penetrating radar (GPR) has many subsurface applications, for example in mining, soil exploration, archaeology, groundwater exploration, detection of buried objects such as pipelines and mines, and forensic research (Daniels, 2004). Dry snow and ice are especially transparent to electromagnetic wave propagation at a wide range of frequencies from 1 MHz to 10 GHz, which allows studying in great detail the snow and glacier thickness, its internal stratigraphy and structure, and basal properties (Bogorodsky *et al*., 1985). Radar soundings at frequencies > ~100 MHz ($\lambda \approx 1.6$ m in ice) allow detection at sub-meter resolution and are especially adequate for studying the internal stratigraphy of seasonal snow cover and glaciers. The goal of this paper is to present results of GPR as a means to detect crevasses within glaciers.

The traditional view is that crevasses are formed perpendicular to the principal extending strain rate, in areas where the strain rate exceeds a critical threshold and the ice fractures as a brittle material (e.g. Vaughan, 1993; Pralong *et al*., 2003). This may happen at the margins of a glacier at shear zones in ice streams, at the front of a calving glacier, in steep areas of a glacier, or where the glacier flows over obstacles. At depth (> ~20 m) the lithostatic (compressive) pressure of ice tends to close the crevasse, although much deeper crevasses have been found in Antarctica and also in temperate glaciers with abundant meltwater. In the accumulation area of a glacier or during the autumn–winter–spring periods crevasses may be covered by snow, with shallow/weak snow bridges, which can increase the risk of glacier travel. In large parts of Antarctica, crevasses might be snow covered any time of the season. Numerous crevasse accidents have been reported in the literature, both in mountain glaciers and over ice sheets, including travel by foot (e.g. AAC, 2005) and by means of snow vehicles (http://news.bbc.co.uk/1/hi/world/americas/4297550.stm).

The GPR is a method of exploration based on the emission and propagation of electromagnetic waves in a dielectric media, with delayed receptions of reflections that are produced in discontinuities within the substrate, as a result of sudden changes of the electromagnetic parameters, such as conductivity, dielectric permittivity and the magnetic permeability. In the last few decades GPRs have been used as the main method for studying ice depth, internal stratigraphy and also physical characteristics of the glacier bed, both in temperate and cold ice (Bogorodsky *et al*., 1985; Paterson, 1994).

The GPR method has also been applied successfully on glaciers for crevasse detection in support of selection of tractor traverse routes, both from the ground (e.g. Kovacs & Abele, 1974; Delaney *et al*., 2004) and from the air (e.g. Delaney & Arcone, 1995), as well as for the detection of buried objects and installations (e.g. Arcone *et al*., 1995). The ability of GPRs for crevasse detection has allowed well detailed studies of glacier dynamics (e.g. Retzlaff & Bentley, 1993; Clarke & Bentley, 1994) where the burial depth of crevasses has been linked to the glacier flow history.

This paper discusses the results of data collected using a GPR dragged on foot on Glacier Mocho-Choshuenco, Chilean lake district (39°25′S), and transported by means of a tractor in east Antarctica (87°30′S).

STUDY SITES

The data were collected at two locations, one in the Chilean Lake District and the other in east Antarctica. During May 2004 a radar survey was performed by two operators on foot on the eastern glacier of ice capped Volcán Mocho-Choshuenco (39º25′S, 71º57′W), Chilean lake district (Fig. 1), where mass balance measurements are routinely carried out by Centro de Estudios Científicos (CECS), Chile. Measurements over the glacier are normally performed using a Pisten Bully 200 snow tractor, but sporadically with a snowmobile or on foot when snow vehicles are not available. The Volcán Mocho-Choshuenco is active, although it has been dormant since the last eruption in 1864 (Gonzalez-Ferrán, 1995). This temperate glacier has been receding during the last few decades in response to regional warming and also partly to precipitation decrease (Rivera *et al*., 2005). It had an area of 5.1 km^2 in 2004, extending from an elevation of 1603 m a.s.l. to 2422 m a.s.l. with an equilibrium line altitude located at 1956 m in 2003/2004, when the mean net accumulation yielded 2.6 m of $w.e.a^{-1}$, the mean net ablation was –3.5 m $w.e.a^{-1}$ and the net mass balance resulted in –0.88 m ± 0.09 m $w.e.a^{-1}$ (Rivera *et al*., 2005). Crevasses occur in several sectors of the glacier, both in the accumulation and in the ablation areas, being largely covered by the winter

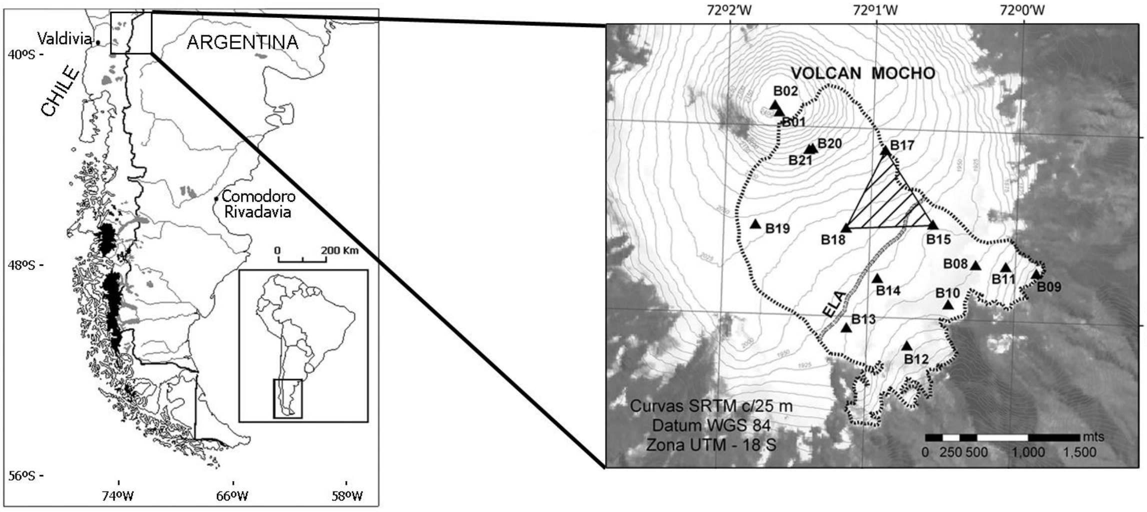

Fig. 1 Location map of the Chilean lake district with an inset corresponding to the 2003 Aster image of Volcán Mocho–Choshuenco (39º25′S, 71º57′W) showing the glacier basin. The black triangles correspond to the network of stakes used for measuring mass balance. The hachured area on the right corresponds to the crevasse area studied by GPR in the field. The dotted line indicates the equilibrium line altitude (ELA) of year 2003–2004, with net accumulation above the ELA and net ablation below the ELA.

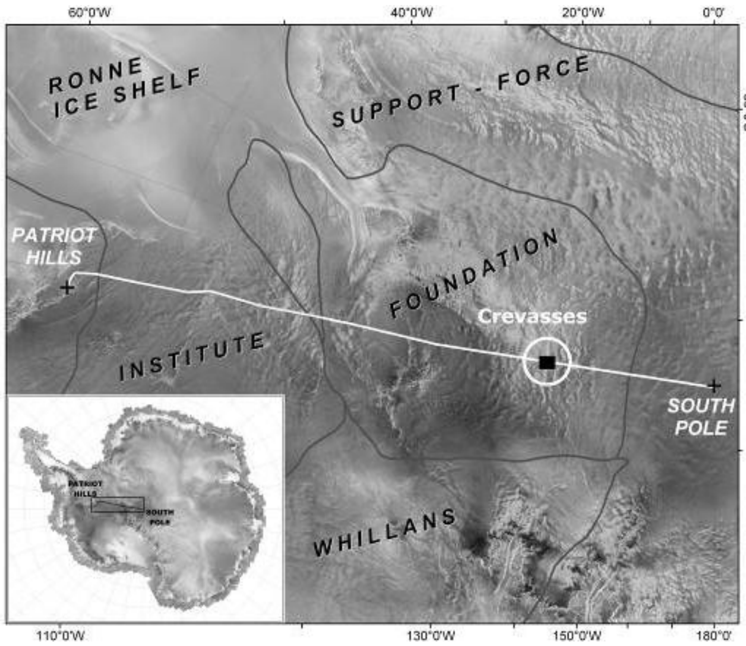

Fig. 2 RADARSAT image of Antarctica corresponding to the box indicated in the inset showing the convoy route as a white line. The crevasse location is indicated with a white circle and a box inside (87º30’ S 82º25’ W). The major glacier basins, corresponding to Ice Streams, have been added, obtained from Rignot and Thomas (2002) (Topographishe Karte vom Filchner – Ronne – Schelfeis, 1993).

snow accumulation, with a maximum surface exposure at the end of the dry season (March–April). During the field observations (May 2004) crevasses were partly covered by a thin layer of about 20 cm of newly deposited snow.

In November and December 2004 a tractor traverse was carried out in east Antarctica (Fig. 2), during the Chilean South Pole Scientific Expedition. The traverse started at Patriot Hills, followed a route south between meridians 80–83°S, reaching the South Pole on November 30 and returning to Patriot Hills on December 31. The route was chosen based on previous skiing traverses to the South Pole, and on a RADARSAT image at 25 m resolution (Jezek, 2002) where large crevasse fields were detected following a similar procedure used by the US Antarctic Program (Bindschadler & Vornberger, 2005). The radar was switched on at a few selected sites along the route. A large east–west trending crevasse was detected visually on November 25 across the route at 87º30′S, 82º25′W, within an area located over an east–west trending escarpment in the upper Foundation Glacier basin. The RADARSAT image showed a distinct crevasse field about ~ 5 km east of the chosen route (Fig. 3), which was considered safe for the tractor traverse. The crevasse in the field was about 3 m wide at the point where it intersected the planned route, with an associated topographic depression of ~1 m in elevation, which was not detected in the RADARSAT image mainly due to its limited resolution and partly also to the high brightness of this part of the satellite image. At the point where the crevasse was finally crossed by the tractor convoy (Fig. 3) its width was 70 cm, being located over a homogeneously sloping surface with no significant topographic depression.

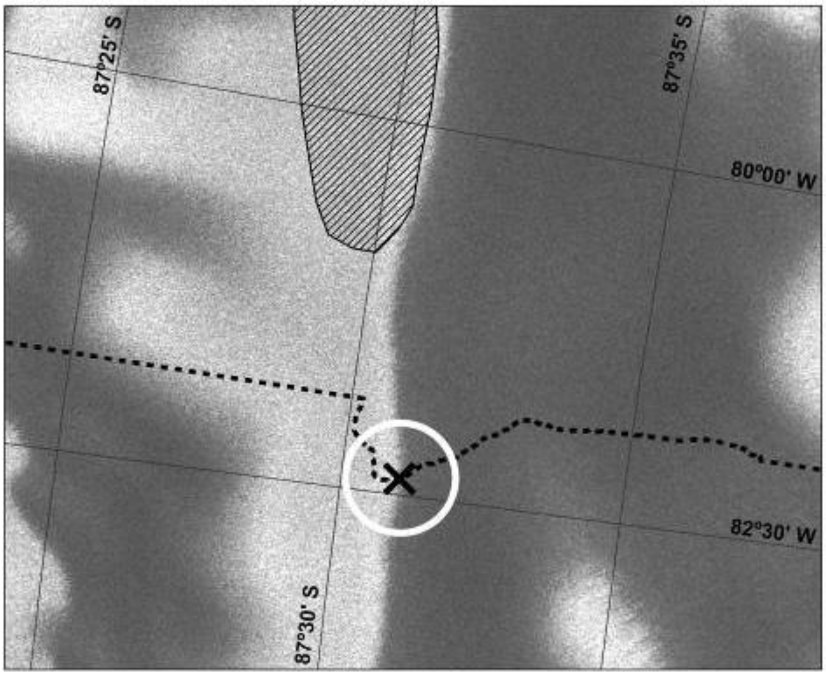

Fig. 3 1997 high resolution RADARSAT Antarctic Mapping Mission (AMM) image (Jezek, 2002) of the area of crevasses along the route to the South Pole at 87º30′S, 82º25′W, corresponding to the Foundation Ice Stream. This image is shown as a black box in Fig. 2. The hachured area corresponds to crevasses interpreted from the RADARSAT image. The black segmented line is the route followed by the tractor convoy. "X" is the crevasse crossed with the tractor convoy on 25 November 2004. The crevasse was oriented perpendicular to the route, following an E–W trend and running along the topographic escarpment which is seen on the image as the transition between the bright (steep) area on the left of the crevasse and the dark (more level) area to the right.

INSTRUMENTS AND METHODS

The GPR system is manufactured by Geophysical Survey Systems Inc. (GSSI), North Salem, USA, and is composed of a digital control unit (GSSI model SIR 3000) and a high frequency radar transducer (GSSI model 5103, 400 MHz). The transducer includes shielded dipole pairs, transmitter and receiver. The digital control unit of the radar triggers pulses at 100 kHz repetition rate. Data were recorded in 16 bit format, using 512 and 4096 samples per scan. The range was set between 100 and 240 ns to record subsurface reflection.

All data were processed using RADAN for Windows v5.0, a specific software from GSSI, and REFLEXW developed by K. J. Sandmeier (www.sandmeier-geo.de). Both software allow to display, edit and print the GPR data, in addition to performing mathematical operations (averaging, subtractions, products); Infinite Impulse Response (IIR) and Finite Impulse Response (FIR) filters, and signal processing such as migration, deconvolution and static correction, among others.

An electromagnetic signal transmitted into the glacier can be reflected at any discontinuity or interface in the medium, which exhibits contrasting dielectric characteristics within the glacier, such as a horizontal snow/firn layer or a near-vertical crevasse wall. Energy losses will be produced in the transmission/reception stages, within the medium, and at the interfaces.

In the radar echogram the horizontal axis represents the distance covered on the ground, and the vertical axis represents the two-way travel time of the propagated wave. Based on the real part of the dielectric constant of the media and the two-way propagation time, the thickness can be obtained for a monostatic radar system as follows (Delaney & Arcone, 1995):

$$h = \frac{ct}{2\sqrt{\varepsilon}} = \frac{vt}{2} \qquad (1)$$

where h is depth of the reflector in m; c is speed of electromagnetic waves in vacuum (0.3 m ns^{-1}); t is two-way travel time in ns; ε is dielectric permittivity of the medium; and v is speed of the electromagnetic wave in the medium (m ns^{-1}).

A crevasse can be detected in a radar image based on hyperbolae diffractions produced at any sharp discontinuities associated with the crevasse (Delaney *et al*., 2004), such as the roughness on the bottom of a snow bridge, and the interface between a near-vertical crevasse wall and near-horizontal snow/ice layers, which act as natural diffractors. A crevasse cavity is also a discontinuity within the glacier stratigraphy, affecting the pattern of internal reflections of the glacier. In the case of an air-filled crevasse it is seen in the radar image as an area without reflections.

At the Chilean location, the radar measurements were performed on foot by two operators, one person carrying the transducer ahead and the other person behind the digital control unit (Fig. 4). The transducer was mounted on a 1.4 m long fibreglass rod provided by GSSI.

In Antarctica the Berco TL6 tractor was equipped with a 7-m long rod composed of a metal frame with a wooden beam inside. The transducer was mounted at the end of the rod in the interior of a tire inner tube, which was pushed along the glacier surface in front of the tractor (Fig. 5). The tractor radar assembly followed the model used by S. Arcone (Delaney *et al.*, 2004). The operator carried the digital control unit inside the tractor cabin. In both sites (Volcán Mocho-Choshuenco and Antarctica) the radar records could be interpreted in real time by the operator.

Fig. 4 Ground Penetrating Radar used on Volcán Mocho-Choshuenco, Chilean Lake District. The operator on the left has the digital control unit, while the person on the right carries the transducer.

Fig. 5 Ground penetrating radar mounted on a 7-m long metal rod in front of the BERCO TL6 tractor, East Antarctica. The radar transducer is installed inside the rubber inner tube at the right end of the rod, which is connected with a cable to the digital control unit installed in the tractor cabin.

RESULTS

The part of tests of the radar system for crevasse detection were made in May 2004 at the eastern part of the glacier of Volcán Mocho-Choshuenco, in the area between stations 15, 17 and 18 (Fig. 1), at a mean elevation of 2000 m a.s.l. Crevasses here are only obvious in steep places and close to stake 17, particularly at the end of spring and summer (Fig. 1). The radar records show that for the case of temperate firn in Volcán Mocho-Choshuenco the penetration depth of the 400 MHz radar is at least 15 m and can reach 35 m or more. The radar was able to detect internal layering and the location of surface and buried crevasses.

The speed of the electromagnetic wave in firn can be calculated based on the slope of the hyperbolic diffraction asymptotes, according to equation 2 (Daniels, 2004):

$$v = \sqrt{\frac{x_n^2 - x_{n-1}^2}{t_n^2 - t_{n-1}^2}} \tag{2}$$

where Δx is the horizontal distance on the ground corresponding to a segment of a diffraction hyperbola (abscissa on Figs 6, 7 and 8), *n* represent each one of the points of the hyperbola usually expressed in *m*, and Δt is the one-way time interval of the same hyperbola segment (left ordinate of Fig. 8 divided by a factor of 2).

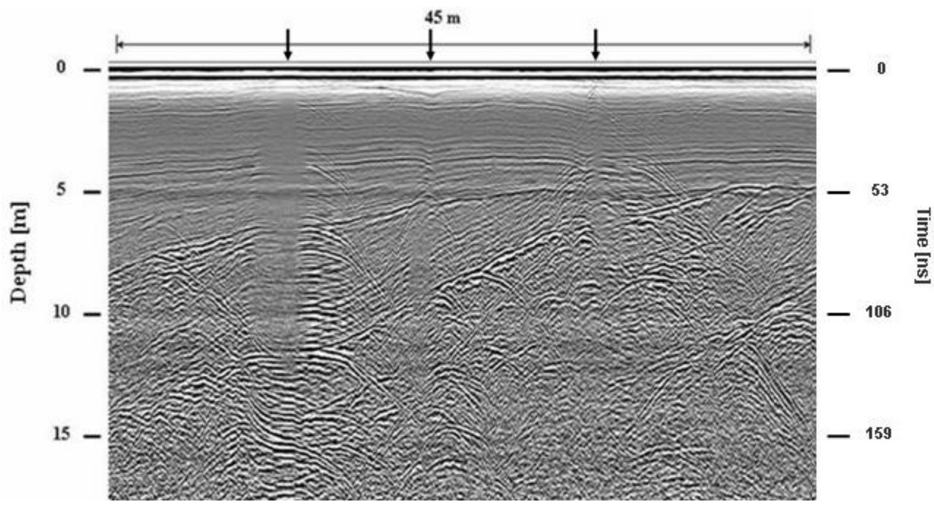

Fig. 6 Radar echogram from Volcán Mocho–Choshuenco corresponding to the crevassed area between stakes 15, 17 and 18 in Fig. 1. The vertical axis is depth (m) and the horizontal axis is a non calibrated measure of horizontal distance across the crevassed area, with a total length of approximately 45 m. The main crevasses interpreted from the image are shown by vertical arrows. The crevasse in the middle is buried while the other two reach the surface. Notice the distortions in the firn layers associated with the crevasses, particularly on the two crevasses on the right of the image. The left crevasse has a width of 0.5 m.

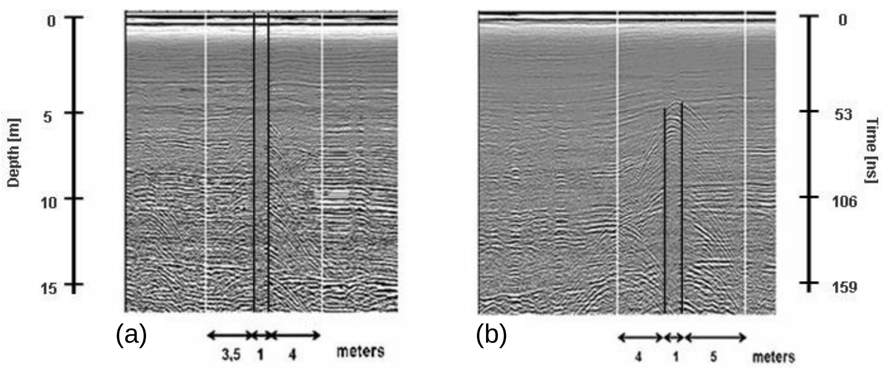

Fig. 7 Crevasses seen on radargrams from Volcán Mocho-Choshuenco. (a) is an open crevasse, while (b) corresponds to a crevasse buried under a 5 m snow bridge. The vertical scale indicates depth in m. The vertical white lines show the area on the radar records where diffraction hyperbolae associated with prominent crevasses are clearly seen, detected to within a distance of 3.5 to 5 m away from the crevasse wall. The black vertical lines show the crevasse walls. The crevasses were 1 m wide in both cases.

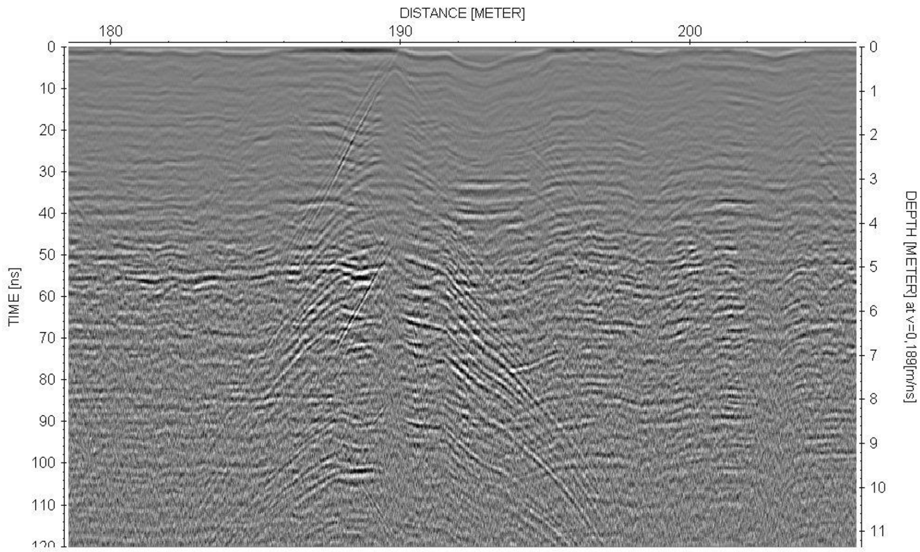

Fig. 8 Crevasse area detected during the traverse from Patriot Hills to the South Pole, East Antarctica (87º30′S, 82º25′W), corresponding to the area marked with an “X” in Figs 2 and 3. The horizontal axis is the horizontal distance scale across the crevassed area. The vertical axis on the left is two-way travel time in ns, while on the right a depth scale in m is indicated considering an airwave velocity in firn of 0.19 m ns^{-1}, obtained from a slope analysis of hyperbola segments as explain in the text. The sets of diffraction hyperbolae centered at approx. 190 m corresponds to the prominent crevasse detected on the surface. Crevasse width is 0.7 m.

Based on equation (2) the mean electromagnetic wave speed in firn at Volcán Mocho-Choshuenco was 0.19 m ns^{-1} ± 0.03 (ε = 2.49 ± 0.16) for the upper 10 m of the glacier, derived from a set of 5 hyperbolae from one crevasse.

Three crevasses can be shown in Fig. 6 on Volcán Mocho-Choshuenco. It is possible to see how the crevasses interrupt the internal layers. For example the prominent crevasse on the left of Fig. 6 has a width of 0.5 m, presenting strong diffractions and a distinct area without reflections corresponding to the air-filled cavity. A similar case of an open crevasse can be seen in Fig. 7(a). In Fig. 7(b) a crevasse covered by a 5 m snow bridge is clearly seen, with good preservation of the snow stratigraphy above the crevasse.

Based on the experience gained at Volcán Mocho-Choshuenco and considering the satisfying results obtained by polar researchers who have used GPRs during tractor traverses as a means for detecting crevasses (e.g. Kovacs & Abele, 1974; Delaney *et al.*, 2004), it was decided to mount the radar system for crevasse detection on the Berco TL6 tractor along the route during the 2004 Chilean expedition to the South Pole.

In the radar profile of Fig. 8 recorded in East Antarctica crevasses are clearly detected as apexes of diffraction hyperbolae. Similar to the case of Volcán Mocho-Choshuenco, the speed of the electromagnetic wave in the medium (firn) was calculated for a set of six hyperbolae of one crevasse from equation (2), yielding a mean value of 0.19 m ns^{-1} ± 0.03 (ε = 2.47 ± 0.16) for the upper 8 m of the glacier. This speed value is essentially equal to the speed in temperate firn measured at Volcán Mocho-Choshuenco, and is a representative value for glacier firn (Bogorodsky *et al.*, 1985). In principle a faster speed in firn in Antarctica would have been expected, since temperatures are cold and firn density is in principle smaller than on temperate firn. The 10 m depth firn temperature at the site of the crevasse (2430 m a.s.l., 87°30′S) can be estimated approximately as –43°C based on 10 m firn temperatures of 45 ± 0.5°C and 36 ± 0.5°C (Simões, personal communication, 2005) measured along the tractor traverse with a thermistor in boreholes at 2621 m a.s.l., 88°01″S and 1621 m a.s.l., 86°00′S, respectively.

CONCLUSIONS

The GPR system used at Volcán Mocho-Choshuenco and Antarctica is capable of identifying surface and buried crevasses, which are characterized by distortions and diffractions in the upper firn layers of the glaciers. Crevasse widths and burial depths could be detected in the radar images.

The first diffraction hyperbolae are detected 3.5 m from the apex of the crevasse, which is a mean representative value for the crevasses found in Volcán Mocho Choshuenco and Antarctica. Considering an average ground speed of ~0.5 m s^{-1} (1.8 km h^{-1}) in the case of the hand-carried system, and a transducer distance of 1.2 m ahead of the operator (1.4 m rod with an inclination of 30°) plus the 3.5 m hyperbolae detection distance from above, a reaction time of ~9 s could be obtained prior to detecting a crevasse. For the tractor system, with an average ground speed of ~2 m s^{-1} (7.2 km h^{-1}) in the crevassed area, a transducer distance of 7 m ahead of the tractor plus the 3.5 m, the reaction time was ~5 s.

In Antarctica, within the 1084 km track, only one crevasse area of a total distance of about 100 m was detected with data been analysed mainly in post processing. In the Chilean Andes the radar records were analysed in post processing. Therefore, in both geographic areas GPR signals were examined in detail only after post processing, with only an initial identification of the presence of crevasses. In the future this method should be applied as part of a real time decision-making process.

Although GPR proved to be an efficient tool in detecting crevasses, it should be used as a field component of an integral crevasse detection system, which should include detailed prior inspection of other information regarding the area such as satellite images (visible, near infrared and radar), digital terrain models and ice flow information at the highest available resolution. In the field appropriate safety measures should be considered when crossing glacier areas where the presence of crevasses is probable.

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