Journal of Glaciology, Vol. 46, No. 155, 2000

Instruments and Methods

Acoustic televiewer logging in glacier boreholes

Roger H. Morin,[1] Guillaume E. Descamps,[2] L. DeWayne Cecil[3]

[1]*United States Geological Survey, Denver, Colorado 80225, U.S.A.*

[2]*Université Laval, Québec, Québec G1K 7P4, Canada*

[3]*United States Geological Survey, Idaho Falls, Idaho 83402, U.S.A.*

ABSTRACT. The acoustic televiewer is a geophysical logging instrument that is deployed in a water-filled borehole and operated while trolling. It generates a digital, magnetically oriented image of the borehole wall that is developed from the amplitudes and transit times of acoustic waves emitted from the tool and reflected at the water–wall interface. The transit-time data are also converted to radial distances, from which cross-sectional views of the borehole shape can be constructed. Because the televiewer is equipped with both a three-component magnetometer and a two-component inclinometer, the borehole's trajectory in space is continuously recorded as well. This instrument is routinely used in mining and hydrogeologic applications, but in this investigation it was deployed in two boreholes drilled into Upper Fremont Glacier, Wyoming, U.S.A. The acoustic images recorded in this glacial setting are not as clear as those typically obtained in rocks, due to a lower reflection coefficient for water and ice than for water and rock. Results indicate that the depth and orientation of features intersecting the boreholes can be determined, but that interpreting their physical nature is problematic and requires corroborating information from inspection of cores. Nevertheless, these data can provide some insight into englacial structural characteristics. Additional information derived from the cross-sectional geometry of the borehole, as well as from its trajectory, may also be useful in studies concerned with stress patterns and deformation processes.

INTRODUCTION

For several decades, geophysical techniques have been successfully applied to the characterization of ice properties in situ, and this work has contributed significantly toward our fundamental understanding of glacier structure, composition and dynamics. For example, borehole-inclination logs (e.g. Hooke and others, 1992) and echo-sounding techniques (e.g. Jacobel and Raymond, 1984) have provided information regarding mass balance and englacial deformation. Ground-penetrating radar (Murray and others, 1997) has identified thrust faults, and cross-hole electrical resistivity experiments (Hubbard and others, 1998) have imaged drainage features.

In this paper, we present data generated from an acoustic televiewer and recorded in two boreholes located in a temperate glacier. This instrument produces a magnetically oriented image of the borehole wall and is routinely used in petroleum, mining and ground-water investigations to locate fractures, identify lithologic sequences and assess well-bore stability conditions. In this particular application, the televiewer was deployed in water-filled boreholes drilled into ice, and the resulting data recorded in situ enable us to evaluate the capabilities and limitations of this tool when applied in a glacial environment.

SETTING

Continuous ice cores were recovered from two boreholes penetrating Upper Fremont Glacier in the Wind River Range of west-central Wyoming, U.S.A. The study area is situated within the accumulation zone of this mid-latitude temperate glacier at about 4000 m a.s.l. The holes were located near the presumed flow center line (Fig. 1), and cores

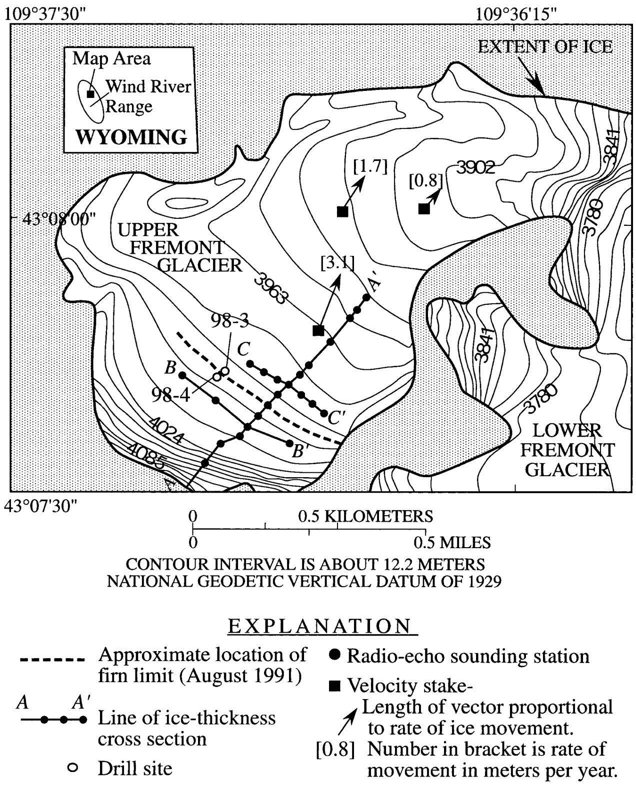

Fig. 1. Locations of study site and boreholes (adapted from Naftz and Smith, 1993).

https://doi.org/10.3189/172756500781832684 Published online by Cambridge University Press

were collected, processed and analyzed for paleoenvironmental studies (e.g. Cecil and others, 1998; Schuster and others, 2000). Ice thickness ranges from about 60 to 172 m in the upper half of the glacier, and the ice flow is toward the northeast (Naftz and Smith, 1993).

The two boreholes were produced by a thermal drill (Holdsworth and others, 1984), with a penetration rate of approximately 6 m h^{-1}. This device consists of a non-rotating core barrel that is heated at the bottom. An annulus of ice is melted away by contact with this warm cylinder, and an ice core is collected within the hollow barrel. Water level in each hole was about 3 m below the snow surface, and ice was encountered at roughly 2 m depth. Hole DH98-3 was the first borehole to be cored. After reaching 49 m depth and returning to the surface to retrieve the ice core, the drillbit was deflected to one side on its subsequent lowering and would not follow the existing hole. Repeated efforts to return to the bottom were unsuccessful, and this hole finally had to be abandoned. A second hole, DH98-4, was initiated and advanced to the base of the glacier, extending to a total depth of 162 m. The two holes were approximately 10 cm in diameter and about 35 m apart. Ice cores were described, cut, and stored in 1 m sections for future laboratory-based analyses.

ACOUSTIC TELEVIEWER LOGGING

Equipment and principle of operation

Although the main scientific objective of this project was to extract a detailed isotopic record from the ice, the boreholes also afforded an opportunity to deploy an acoustic televiewer (Zemanek and others, 1970) in a glacial environment and evaluate its performance. This logging tool is 5 cm in diameter by 193 cm long and is connected by means of a standard four-conductor cable to an electric winch (Fig. 2). During logging operations, it is lowered or raised in the borehole at a trolling speed of about 1.5 m min^{-1}, and data are transmitted through the logging cable to a computer at the surface. This instrument is equipped with a 500 kHz transducer that rotates at 12 revolutions per second and emits 256 pulses per revolution. The signals are transmitted through the borehole fluid, reflect off of the fluid–ice interface, and return to the tool where acoustic amplitude and transit time are recorded digitally. It should be noted that these high-frequency signals do not penetrate into the ice, and consequently do not provide any view of conditions beyond the borehole; they reflect off of the fluid–ice interface with the intent of developing an acoustic image of the borehole wall. Top and bottom centralizer springs attached to the instrument help to guide it in the borehole and minimize any systematic offsets in transit times produced by a decentralized tool.

The televiewer's principle of operation relies on a sharp reflection of acoustic energy at the fluid–wall interface. It is commonly used in boreholes drilled through rocks, where the acoustic impedance contrast between the borehole fluid and surrounding material produces a reflection coefficient on the order of 0.60. In a glacier, the acoustic impedance contrast between ice and water is less dramatic, and the resulting reflection coefficient is reduced by about half.

Field data

Acoustic amplitudes are converted into brightness (gray scale) or color, and the resulting image appears as a planar, "unwrapped" representation of a cylindrical surface (see left panels in Fig. 3). Acoustic transit times are also converted into a brightness scale for visual display (see right panels in Fig. 3), though these latter data contain spatial information that can be further processed to obtain radial distances and delineate cross-sectional borehole shapes. Non-horizontal planes that intersect these boreholes appear as sinusoids in the unwrapped images (Fig. 3). The particular orientations of these planes can be computed by a simple geometric exercise, where dip angle is proportional to the sinusoid amplitude and strike corresponds to the azimuth of its lowest point (Fig. 4).

Fig. 2. Photograph of acoustic televiewer system deployed at study site, showing tool, cable, electric winch and thermal drill.

Because of the deterioration in acoustic reflection coefficient associated with glacier applications, the processed images are not as crisp and clear as those typically generated in rock environments. This is illustrated in Figure 3, where televiewer images recorded in sedimentary rocks (Fig. 3a) can be compared to those obtained in hole DH98-3 (Fig. 3b). Steeply dipping features are observed in both media, though the view obtained in rocks is of better quality and exhibits more detail. Regardless of this inherent deficiency, the televiewer logs obtained at this site do detect englacial features. However, their exact physical interpretation may be problematic, likely requiring supplemental information from inspection of cores.

The planar feature intersecting hole DH98-3 at a depth of about 16 m dips to the east-northeast at 63° and has a strike of N25° W (Fig. 3b). Lower-hemisphere stereographic plots of all features identified in the two boreholes are presented in Figure 5. These data contain information that may be related to englacial structure or stress conditions at this study site

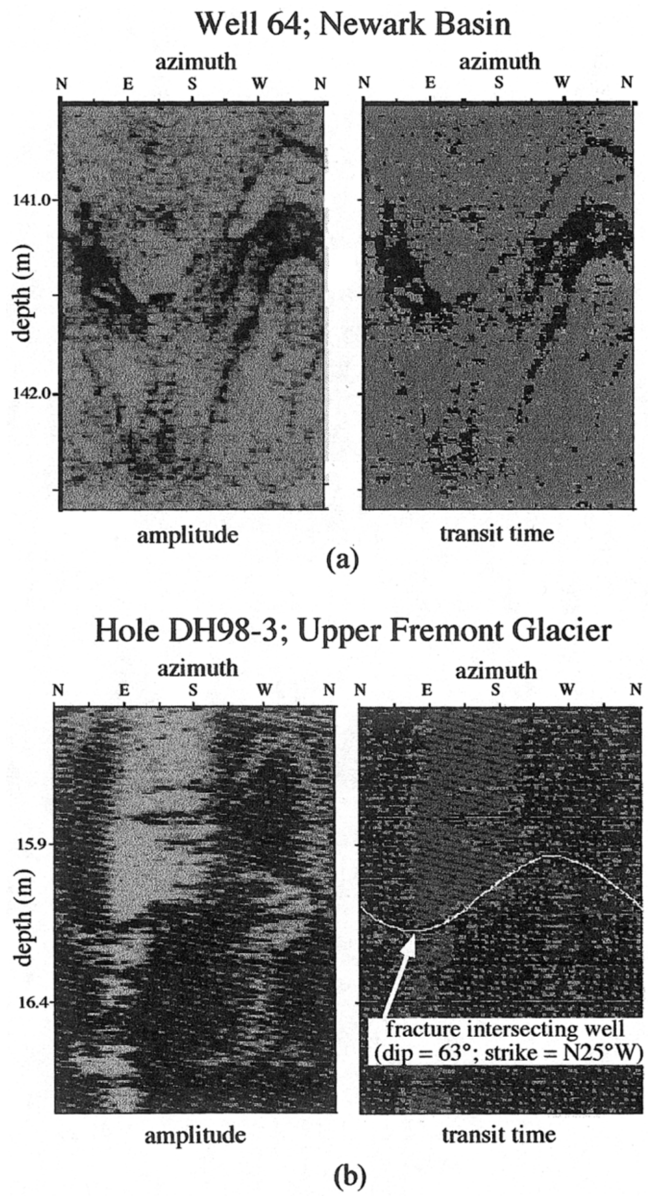

Fig. 3. Depiction of magnetically oriented, acoustic televiewer data obtained from (a) well in sedimentary rocks of the Newark Basin, Pennsylvania, U.S.A. (from Morin and others, 2000), and (b) hole DH98-3 in this glacier study. Unwrapped, planar images of borehole wall generated from acoustic amplitude data (left panels) and acoustic transit-time data (right panels) are shown. Outlined sinusoid locates a steeply dipping (63°) fracture in ice striking at N25° W.

(e.g. Sharp and others, 1988). The diagrams identify the presence of conjugate, high-angle features (> 45°) with orientations that are consistent for both boreholes and shallow dipping features (< 30°) that diverge significantly.

Because the televiewer emits 256 acoustic pulses per revolution of its internal transducer, the travel-time data, such as those depicted in the right panels of Figure 3, can be converted to 256 measurements of radial distances as a function of azimuth; cross-sectional views of the borehole can subsequently be constructed. In Figure 6a, a circular, intact borehole is delineated at 39.8 m depth in hole DH98-4, whereas a damaged and enlarged borehole geometry is identified 6 m deeper (Fig. 6b). Gaps in the cross-section indicate no return of acoustic signal. This type of information may be useful in inferring stress conditions by identifying localized zones of brittle failure such as borehole breakouts (e.g. Zoback and others, 1985) or by monitoring creep processes through bore-

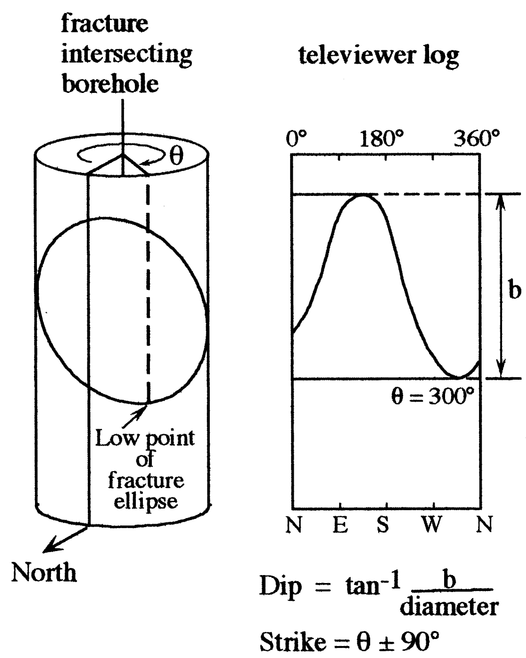

Fig. 4. Diagram illustrating method for determining strike and dip of intersecting feature observed in televiewer image from depth scale and magnetic orientation.

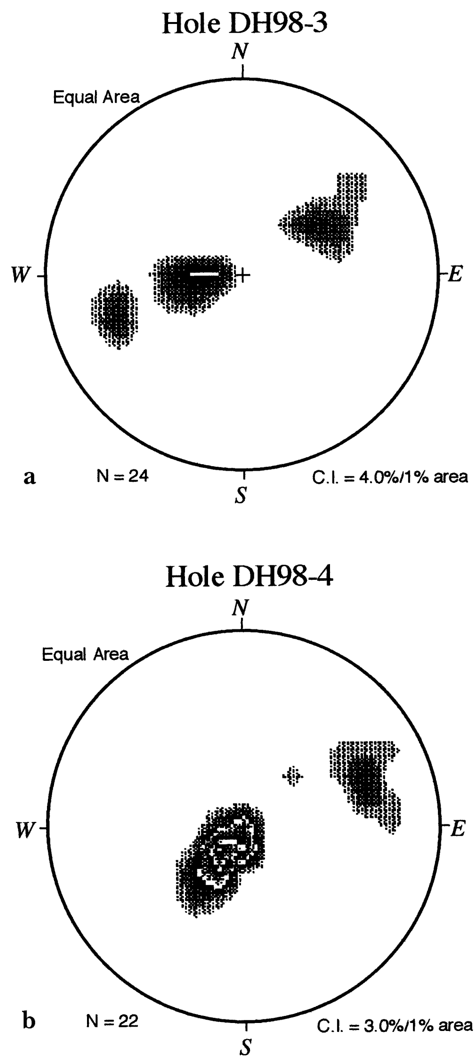

Fig. 5. Lower-hemisphere stereographic plots of features intersecting (a) hole DH98-3 and (b) hole DH98-4. C.I. is the contour interval (%), and N is the total number of features.

https://doi.org/10.3189/172756500781832684 Published online by Cambridge University Press

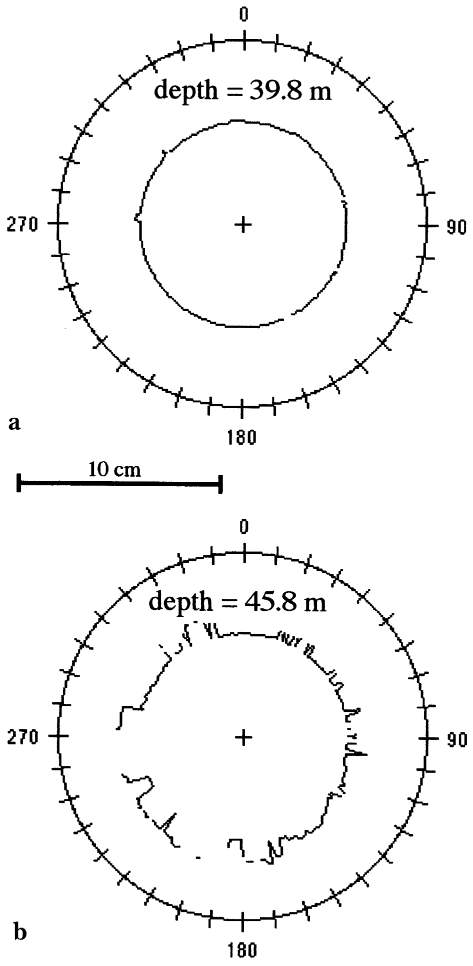

Fig. 6. Magnetically oriented cross-sections of borehole shapes recorded in hole DH98-4. Images depict (a) a circular, intact borehole at 39.8 m depth, and (b) an enlarged borehole at 45.8 m. Gaps indicate no return of acoustic signal.

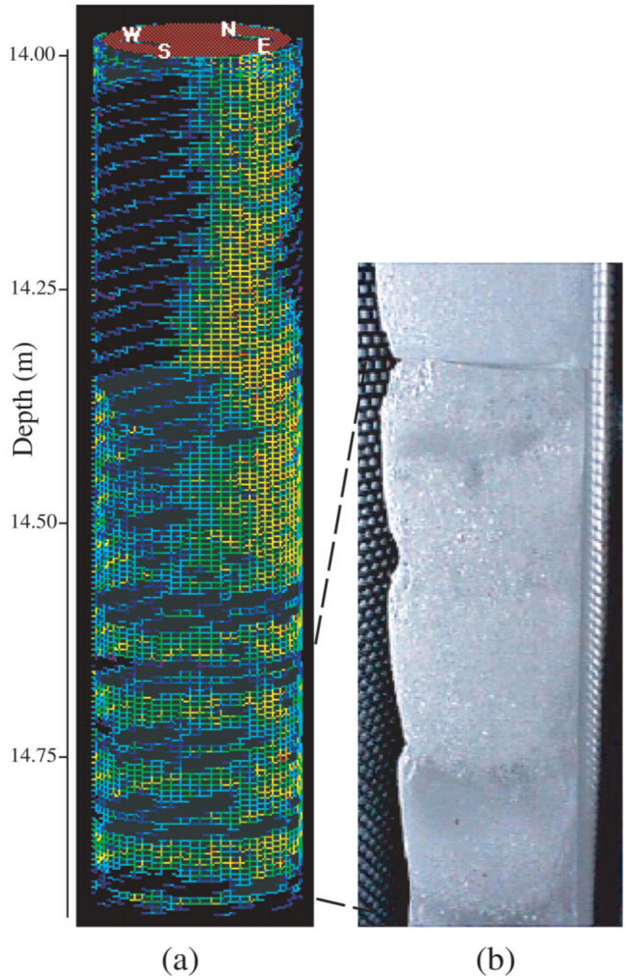

Fig. 7. (a) Cylindrical projection of borehole (hole DH98-3) developed from combination of amplitude and transit-time data showing alternating bands of clear and bubbly ice. (b) Photograph of corresponding core section.

hole deformation (Paterson, 1977). These polar views of the borehole can also be stacked to produce three-dimensional cylindrical projections. For example, the layers depicted in the televiewer image from Figure 7a are alternating bands of bubbly ice and clear ice, as confirmed by a photograph of the corresponding core section (Fig. 7b).

In order for the acoustic images to be magnetically oriented, the televiewer is equipped with a three-component magnetometer. It also contains a two-component inclinometer, and the combination of these two instruments permits a continuous borehole-inclination log to be recorded during logging operations. This capability is incorporated into the tool in order to enable the computed dip angles of intersecting features to be corrected for the vertical deviation of the borehole. Inclination and azimuthal bearing are continuously measured at 1 cm depth intervals, and a cumulative plot of the hole trajectory is constructed from these data. Deviation angles ranged from 2° to 5° in hole DH98-4, and its spatial coordinates are represented by the polar plot of Figure 8 with depth markers at 8 m increments. This diagram indicates that this hole drifts to the south-southwest and is displaced horizontally by about 4.2 m at 78 m depth.

CONCLUDING REMARKS

To our knowledge, this work marks the first attempt to log boreholes in ice with an acoustic televiewer. Numerous planar features intersecting the boreholes were identified by inspection of the digital images. Their depths and orientations were determined, and this information can yield insight into englacial structure with respect to depth. However, images generated in ice were not as visually crisp as those typically recorded in rocks, because of the lower reflection

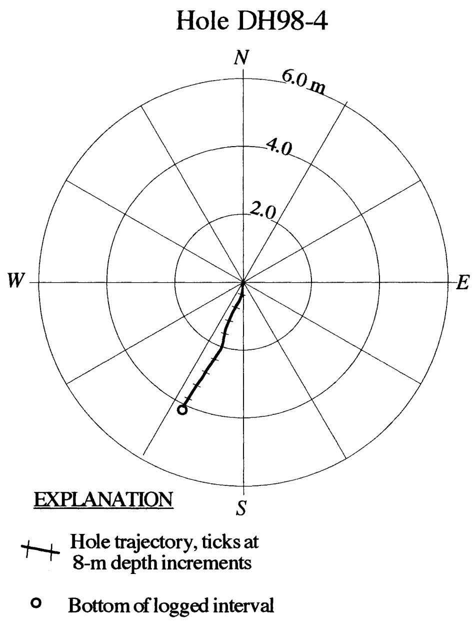

Fig. 8. Polar diagram of inclination log for hole DH98-4.

https://doi.org/10.3189/172756500781832684 Published online by Cambridge University Press

coefficient between water and ice. Therefore, although the features identified in the logs were found to be fractures, contacts between clear and bubbly ice, and/or localized zones of borehole enlargement, they could not be distinguished solely from the acoustic images. It was necessary to supplement these data with core descriptions in order to confidently interpret their physical significance.

This tool can only be deployed in fluid-filled boreholes; it will not function in air-filled ones. Obviously, video logs (e.g. Pohjola, 1994) or optical televiewer logs are better suited for this latter condition. The acoustic tool offers the advantage over optical methods of recording radial dimensions as a function of azimuth from which cross-sectional views of borehole geometry can be constructed. This capability, as well as the concurrent inclination log, may be useful in studies designed to investigate ice-deformation processes.

Regrettably, the particular tool employed in this study was not adequately insulated to withstand the cold temperatures encountered in the boreholes and it failed to function properly after about 1 h of sustained immersion. This timeframe was sufficient to log the shallow hole, but was not long enough to completely log the deeper hole. Consequently, only about half of the deeper hole (from the surface to 78 m depth) was investigated. Thus, unless boreholes are shallow enough to be logged in about 1 h, improvements in insulation will be required to use this tool in glaciers.

ACKNOWLEDGEMENTS

Funding for this project was provided through an interagency agreement between the U.S. Department of Energy and the U.S. Geological Survey, No. DE-A107-98ID13598. Drilling services were provided by the Polar Ice Coring Office, Lincoln, Nebraska.

REFERENCES

Cecil, L. DeW., J. R. Green, S. Vogt, R. Michel and G. Cottrell. 1998. Isotopic composition of ice cores and meltwater from Upper Fremont Glacier and Galena Creek rock glacier, Wyoming. *Geogr. Ann.*, **80A**(3–4), 287–292.

Holdsworth, G., K. C. Kuivinen and J. H. Rand, *eds*. 1984. Ice drilling technology. *CRREL Spec. Rep.* 84-34.

Hooke, R. LeB., V. A. Pohjola, P. Jansson and J. Kohler. 1992. Intra-seasonal changes in deformation profiles revealed by borehole studies, Storglaciären, Sweden. *J. Glaciol.*, **38**(130), 348–358.

Hubbard, B., A. Binley, L. Slater, R. Middleton and B. Kulessa. 1998. Inter-borehole electrical resistivity imaging of englacial drainage. *J. Glaciol.*, **44**(147), 429–434.

Jacobel, R. and C. Raymond. 1984. Radio echo-sounding studies of englacial water movement in Variegated Glacier, Alaska. *J. Glaciol.*, **30**(104), 22–29.

Morin, R. H., L. A. Senior and E. R. Decker. 2000. Fractured-aquifer hydrogeology from geophysical logs: Brunswick Group and Lockatong Formation, Pennsylvania. *Ground Water*, **38**(2), 182–192.

Murray, T., D. L. Gooch and G. W. Stuart. 1997. Structures within the surge front at Bakaninbreen, Svalbard, using ground-penetrating radar. *Ann. Glaciol.*, **24**, 122–129.

Naftz, D. L. and M. E. Smith. 1993. Ice thickness, ablation, and other glaciological measurements on Upper Fremont Glacier, Wyoming. *Phys. Geogr.*, **14**(4), 404–414.

Paterson, W. S. B. 1977. Secondary and tertiary creep of glacier ice as measured by borehole closure rates. *Rev. Geophys. Space Phys.*, **15**(1), 47–55.

Pohjola, V. A. 1994. TV-video observations of englacial voids in Storglaciären, Sweden. *J. Glaciol.*, **40**(135), 231–240.

Schuster, P. F., D. E. White, D. L. Naftz and L. DeW. Cecil. 2000. Chronological refinement of an ice core record at Upper Fremont Glacier in south central North America. *J. Geophys. Res.*, **105**(D4), 4657–4666.

Sharp, M., W. Lawson and R. S. Anderson. 1988. Tectonic processes in a surge-type glacier. *J. Struct. Geol.*, **10**(5), 499–515.

Zemanek, J., E. E. Glenn, L. J. Norton and R.L. Caldwell. 1970. Formation evaluation by inspection with the borehole televiewer. *Geophysics*, **35**, 254–269.

Zoback, M. D., D. Moos, L. Mastin and R. N. Anderson. 1985. Well bore breakouts and in situ stress. *J. Geophys. Res.*, **90**(B7), 5523–5530.

MS received 24 June 1999 and accepted in revised form 17 July 2000