A borehole camera system for imaging the deep interior of ice sheets

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ABSTRACT. The design and first deployment is described for the Jet Propulsion Laboratory–California Institute of Technology ice borehole camera system for acquisition of down-looking and side-looking images in a borehole made by a hot-water drill. The objective of the system is to acquire images in support of studies of the basal dynamics and thermodynamics of West Antarctic ice streams. A few sample images, obtained during the 2000/01 Antarctic field season, are shown from the basal layers of Ice Stream C.

1. INTRODUCTION

A new approach for in situ data acquisition in the glaciological deep subsurface is of interest from a variety of perspectives. Recent results from Greenland and Antarctica have implicated basal phenomena in key processes controlling the movement of ice in the great ice sheets (e.g. Rignot, 1998; Fahnestock and others, 2001; Joughin and Tulaczyk, 2002). Their results call for further examination of basal thermal and hydrologic processes; some questions will require in situ observations. In addition, there is strong evidence of a large, old, deep, salty ocean beneath a thick ice cover on Europa, and this would be a superb site for in situ study (Greeley and others, 1998; Carsey and others, 2000; Showman and Malhotra, 2001; Stevenson, 2001), with similar technology.

Access to the deep subsurface of a glacial environment is accomplished routinely for terrestrial ice sheets and glaciers (e.g. Engelhardt and Kamb, 1997), but hot-water and coring drills may not be practical for all sites, especially those at great depth. Another terrestrial approach, the Philberth or thermal probe (Philberth, 1966; Aamot, 1967; summarized by Kelty, 1995), is a cylindrical robotic vehicle of 10–20 cm diameter and 1–3 m length. The classical thermal probe operates by heating its downward tip, melting the ice below it, and moving down by displacing the meltwater.

In our evolution of the thermal probe, in situ data acquisition is a central interest, and the ice borehole camera is part of an approach to collecting data from a new glaciological robotic access vehicle (Zimmerman and others, 2002) called a Cryobot. The Cryobot is an update of the Philberth probe through the integration of a hot-water drill in the nose as well as modernized command and control systems.

An optimal scheme for acquisition of in situ ice data is to optically interrogate the ice near the Cryobot; this ice has not been significantly affected by the proximity of the probe, and the clarity (at least in terrestrial ice sheets) is such that the use of optical tools for ranges of a few centimeters is workable. For an initial study, we have designed, built and field-tested a simple system of cameras in a pressure housing; this system is the ice borehole camera (Behar and others, 2001). In the context of a Cryobot, the pressure housing is the equivalent of the science bay of the vehicle.

2. MEASUREMENT GOALS

Photographic still images from the bed of Blue Glacier, Washington, U.S.A., were acquired and used (Engelhardt and others, 1978) to evaluate glacier–bed interaction. High-quality real-time images from the bed and the basal layers of ice sheets have been a goal for some time but have been elusive because of technological challenges. However, data describing the conditions at and near the base of the ice are essential for understanding the dynamic behavior and evolution of the ice sheet and ice streams. In situ optical examination of the ice and bed serves to provide insight into such processes as debris burden, bottom accretion and the nature of ice–rock relative movement, and to supply data on ice which, because of its high temperature, is not readily removed for laboratory analysis. Additionally, a camera and light system can interrogate 10–1000 times the simple volume of ice that is examined in a core. In order to initiate deep subsurface optical data acquisition in glaciological environments, staff of the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), collaborated with glaciologists at Caltech to design and build the ice borehole camera and use it to acquire images of scientific quality in the basal domain of Ice Stream C, West Antarctica, in the 2000/01 field season. Interest was focused on a down-looking light source and camera for observations of the ice–bed interactions, and on a side-looking light source and camera for observations of accretion horizons, till inclusions and bubbles.

3. SCIENTIFIC OBJECTIVES

The objectives of the borehole camera development were to:

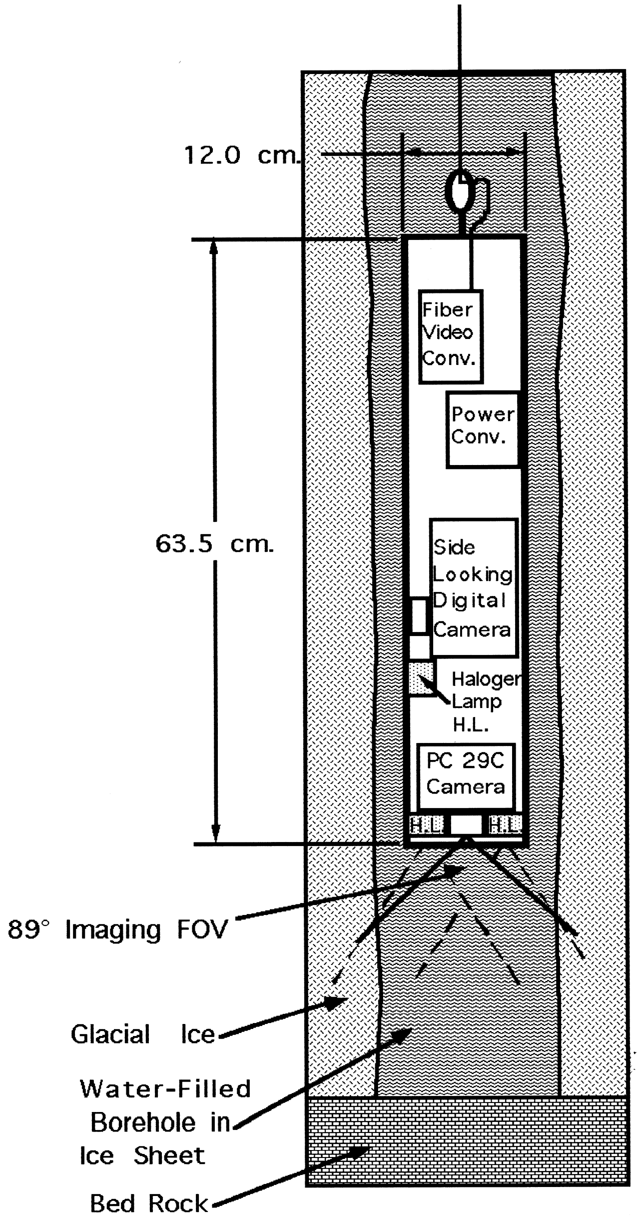

Fig. 1. Ice borehole camera probe design.

Develop an understanding of Ice Stream C subglacial accretion of ice and debris, with emphasis on differences between sticky spots and the (slowly) streaming ice.

Directly observe ice–bed interactions in Ice Stream C including, if possible, the nature of water flow and ice–rock relative motion.

Visually examine other ice-sheet properties in situ.

4. DESIGN REQUIREMENTS

4.1. Operations

The operational approach is to create a borehole with hot-water drilling and to acquire images before the hole is closed by refreezing. Camera data are transmitted to the surface as they are acquired, so that the scientists can monitor what the cameras are observing and recording. The data-storage approach is to record down-looking images at the surface station, and side-looking data in the camera as well as at the surface station; data recorded in the camera are of better quality as well as yielding a back-up copy. The spool was subdivided with a 100 m length used for profiling; the probe was lowered to the area of interest, the 100 m cable end was attached to the ground station, and data were taken. The 100 m segment was then rewound and detached, and the probe was moved to a new depth. We expected the region of interest to occupy only a few meters, at most, adjacent to the bed. (Use of a slip ring for power and a wireless link from the drum to the ground system for data transmittal would enable the entire cable to be continuously paid out during data acquisition; but a field-reliable slip ring has not yet been developed and tested.)

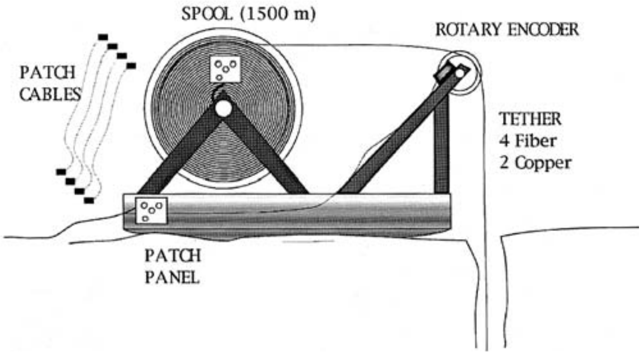

Fig. 2. Spool and tether. The tether contains a twisted pair of 18 AWG copper wires to supply power, as well as four optical fibers, and the sheave rotations are counted and digitized.

4.2. Environmental and operational constraints on the design

Duration
The 1000–1200 m deep boreholes are drilled in 12–24 hours. A 17 cm diameter borehole allows for only about 4 hours camera working time due to rapid refreezing of the borehole in –26°C ice. Reaming of the borehole can extend this time if required.

Probe size
12 cm diameter, 64 cm long. Probe dimensions are governed largely by the camera size; for a thermal probe design, there is an additional constraint from optical-fiber bending radius. It would be possible to make a borehole imaging probe about half this size with a special camera. The ice borehole camera design is shown schematically in Figure 1.

Cable
1600 m fiber-optical cable with four optical glass fibers, two 18 AWG electrical conductors, an Aramid strength member, a water barrier and an outer jacket. The cable diameter is 9.5 mm.

Reel
Two-compartment drum powered by a three-phase 208 V a.c. motor with a variable-speed mechanical gear drive (Shimpo). The cable-and-reel system is shown in Figure 2.

Bandwidth to surface
At least 1 Mbit s^{-1} for adequate real-time information.

Temperature
0°C working; –40°C transit.

Descent indicator
A rotary encoder on the winch sheave monitors the length of cable paid out and is the primary depth sensor; its data, in digital counts, are stored with the image data.

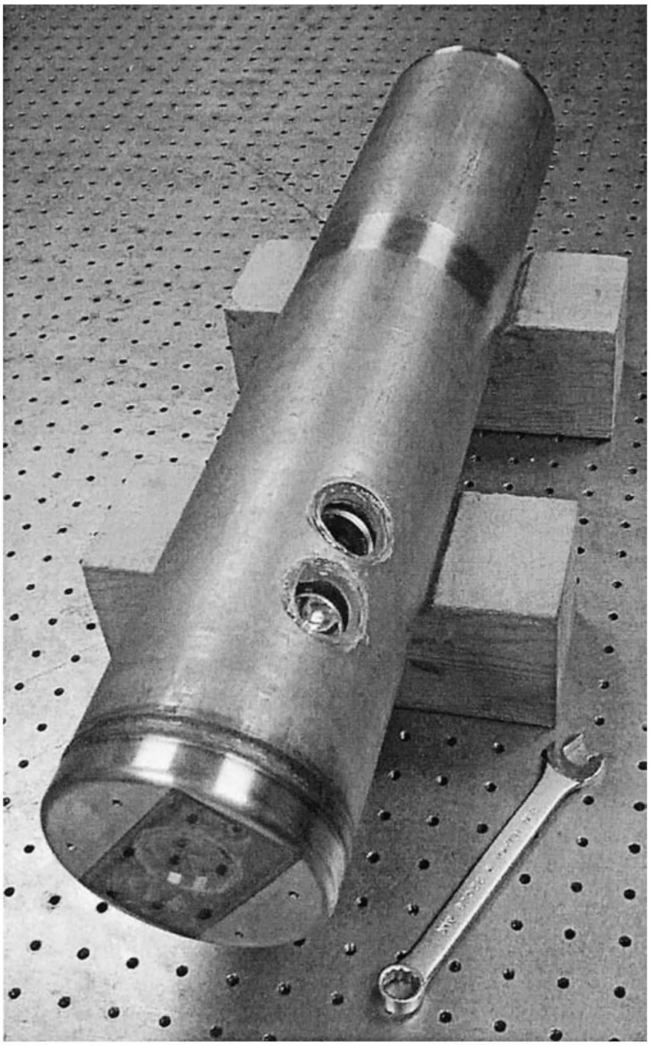

Fig. 3. The pressure housing showing the ports for cameras and light sources.

Redundancy
Two complete probe/reel systems.

Sensors
Down- and side-looking cameras, with light sources, capable of resolving 0.3 mm features. Because ice-sheet ice is quite clear, and it is not obvious how deep into the ice features will be visible, stereo images are required to resolve feature depth in the ice. With the current system, stereo information is acquired through repeated framing as the probe is slowly lowered, as discussed below.

Data storage
Digital video (DV).

Live real time
Surface-station video display for performance monitoring and for selecting regions of interest.

5. ICE BOREHOLE CAMERA SYSTEM

5.1. Probe design

The ice borehole camera hull is 3/8 in (0.95 mm) 304L stainless steel capable of withstanding pressure to about 2.0 km (depending on window material); it contains the cameras and associated electronics. Two charge-coupled device (CCD) cameras are used. A Sony DCR-PC1 high-quality digital camera is the side-looking camera, and a Super-circuits high-resolution video security camera is the down-looking camera, chosen because of its size. The down-looking camera had 768(H) × 494(V) pixels and a fixed 4 mm lens; the side-looking camera had 720(H) × 480(V) pixels and a variable zoom lens (3.3–33 mm) which was kept wide open for routine profiling. Note that cameras and camera chips with far greater numbers of pixels are available commercially. There are also smaller cameras, and the camera chosen is governed by the mix of requirements (remote image monitoring and control, on-board data storage, etc). Halogen bulbs provide illumination, with one bulb for the side-looking camera and two bulbs for the down-looking camera. Video-to-analog fiber-optic converters send images through the tether in real time to the surface station. High-voltage d.c. is sent down the tether cable, and a 300 V d.c. to 12 V d.c. converter provides "clean" power for the lights, cameras and data-transmission functions. The probe hull, with side-looking windows, and the probe electronics are shown in Figures 3 and 4. The probe hull is used to conduct and dissipate heat from the electronics and power conversion units. In this design, water was assumed in the borehole; for use in other drilling fluids, care would be required in selection of tether insulation and connectors; the current materials may not do well in *n*-butyl acetate.

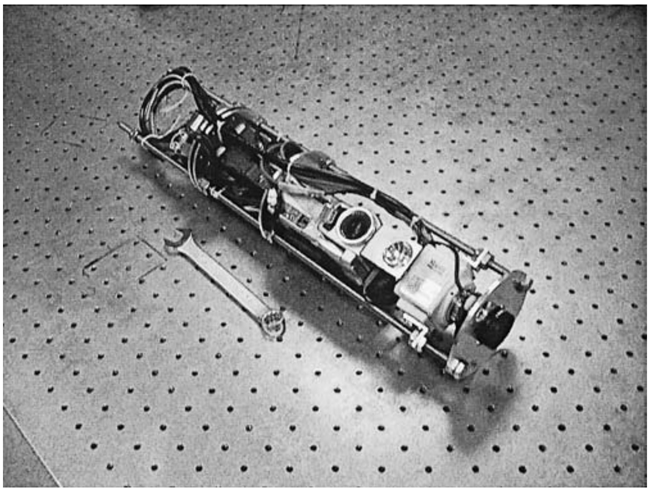

Fig. 4. Interior of the probe showing the side-looking and down-looking cameras and associated electronics.

5.2. Surface station

The surface station houses the computer and equipment that records and displays image and engineering data, issues commands to the probe and performs engineering tests. The analog image data streams from the cameras are converted and recorded onto digital format recorders to preserve data quality for numerous replays, and the control station computer decodes the probe depth information from the cable sheave rotations. All the data are time-tagged to enable detailed correlations post facto. The ice borehole camera system block diagram is shown in Figure 5. To assist the operator to locate unique features, the real-time video display has sub-windows for depth and time. The highest-quality digital images, recorded on DV tape within the side-looking camera, are removed from the probe and camera housing after the probe is returned to the surface station. Time tagging provides a direct correlation between the DV taped images and the analog real-time recorded images recorded at the surface.

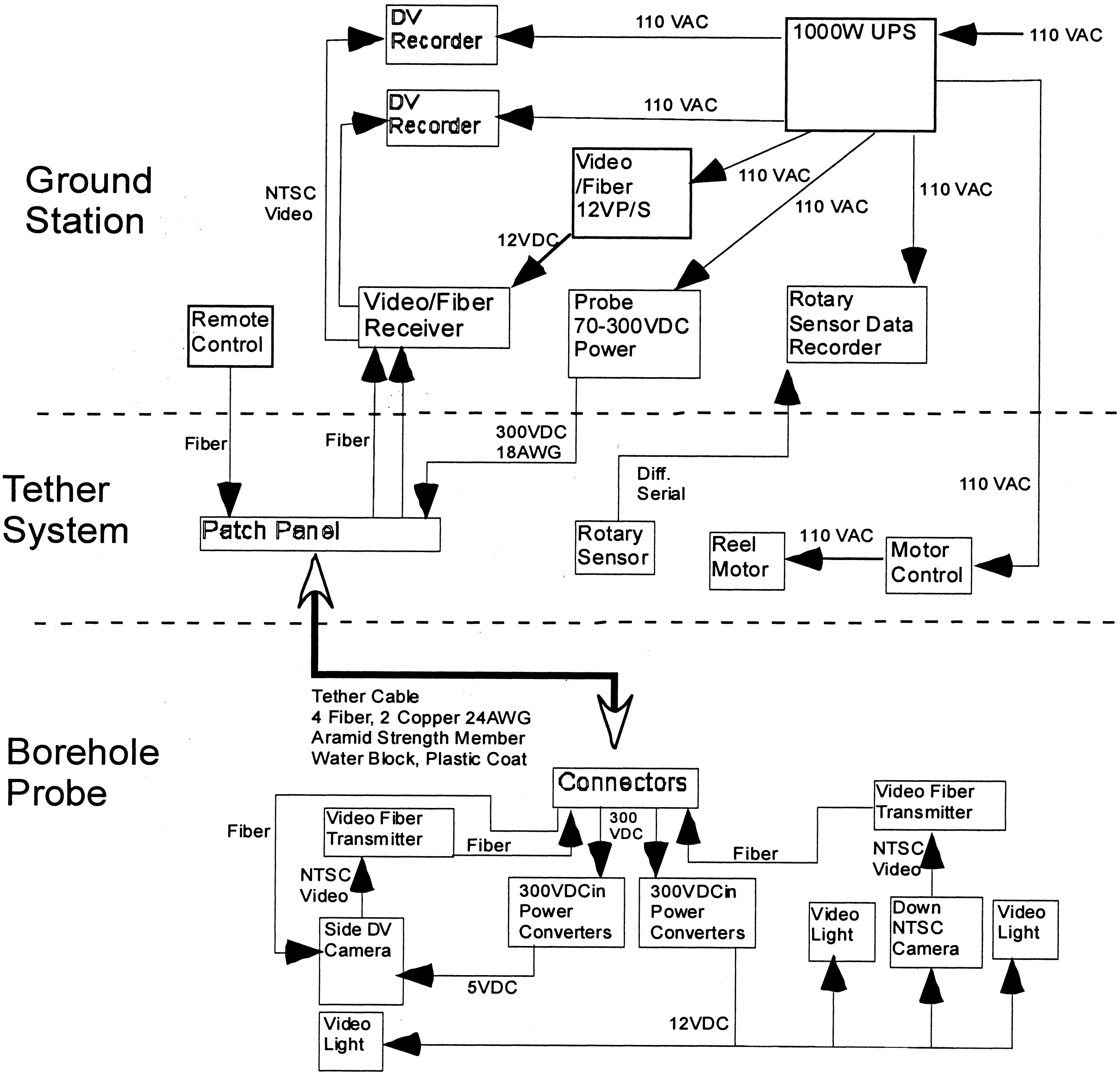

Fig. 5. Block diagram of probe system. It has three subsystems: the downhole probe, the tether and the ground station.

5.3. Sled-mounted deployment system

The sled-mounted tether-support system is shown in Figure 2, a copy of systems utilized in past years by Caltech. The entire unit, the cable, spool, motors and sled, weigh approximately 180 kg. The main spool is rotated with a three-phase a.c. motor giving a pay-out rate of about 1 m s^{-1}.

6. INITIAL FIELD DEPLOYMENT IN WEST ANTARCTICA

The ice borehole camera mission was one element of the 2000/01 Antarctic field project of the California Institute of Technology. The probe was lowered into three hot-water-drilled boreholes along a 7.2 km line near the base camp at 82°22′ S, 136°24′ W; these holes were made in a sticky spot, at the boundary between the sticky spot and the streaming ice, and in the ice stream.

7. IMAGES OF BASAL ICE AND DEBRIS IN UPPER ICE STREAM C

7.1. Ice Stream C activities

The borehole camera operated in a satisfactory manner and met its measurement requirements. A total of ~600 min of imaging data were acquired. The down-looking camera observed some aspects of water movement at the bottom of the borehole, but the relative motion of ice and rock was not observed. The observing time required to resolve ice–rock relative movement in the (slowed) Ice Stream C was so long that the risk of freezing in the probe was considered too great to continue.

7.2. Samples of Ice Stream C images

The side-looking camera noted several interesting phenomena. While complete analyses of these data are in progress, some features are shown in Figures 6–9 as examples of what can be accomplished with simple imaging.

7.3. Stereo

A logical use of the side-looking dataset is for stereo analysis. To resolve the depth of a feature, two frames showing the feature can be analyzed. The relative heights of the feature in the image planes of the two images are noted, as is the

Fig. 6. Side-looking image of roof of subglacial water-filled cavity. On the shoulder of the sticky spot an ice cavity was observed with about 1.4 m depth (with unresolvable width and length). While such cavities in glaciers are common behind obstacles, a cavity depth of this size is unexpected in Ice Stream C. (Up in the figure is down in the ice.)

Fig. 7. Debris strata. Accretion of basal ice in the presence of saturated sediments could generate ice lenses of this type. Each image covers about 4 cm in the vertical at the ice wall. These strata are a few millimeters in thickness and separation. Note the clarity of the ice in the lenses. (Up in the figure is down in the ice.)

distance the camera traveled between exposures. These are related through the tangent of the viewing angle α:

$$R = \frac{QZ}{2P\tan(\alpha/2)},$$

where R is the range to the feature in the ice, Q is the vertical pixel count of the CCD (780), Z is the probe height change between frames, P is the difference in height above the center of the CCD, in pixels, of the feature in the two frames, and α is the (whole) viewing angle of the camera, measured in the laboratory to be 43.6°. We note that rotation of the probe is small but measurable; this change in viewing geometry will not generate significant error in this calculation. Another source of error is the change in distance from the probe to the ice wall; this should be quite small for sequential images, but it has not been analyzed. The parallax produced by imaging of

Fig. 8. Isolated debris clasts. Numerous examples of isolated debris clasts were observed, surrounded by clear ice. The image covers about 4 cm in the vertical at the ice wall. (Up in the figure is down in the ice.)

Fig. 9. Down-looking image of the borehole near the bed. The down-looking system shows the inclusion strata, but not as well as the side-looking system. At lower right, a chain can be seen hanging from the probe; it serves to calibrate depth. The clast on the right is large, about 2 cm on a side. Bright spots at center left and right are from the lights; better diffusion of the sources is called for. For scale, the hole is about 17 cm in diameter.

features at different ranges from the camera will result in changes in relative positions of the features on images acquired at different depth as the probe is raised or lowered. Three such images are shown in Figure 10 where the frames were taken with 1 cm vertical separation in camera depth in the borehole. Data of this kind can be quantitatively processed for three-dimensional imaging (Zhao and others, 2000).

8. CONCLUSIONS

We are strongly encouraged by the utility of in situ optical observations of the ice-sheet basal domain. The bed–ice-sheet interactions are clearly more complex for Ice Stream C than were anticipated, and it is clear that the camera data will be useful for understanding the processes. Comparisons with other ice streams and with the basal domain both up-

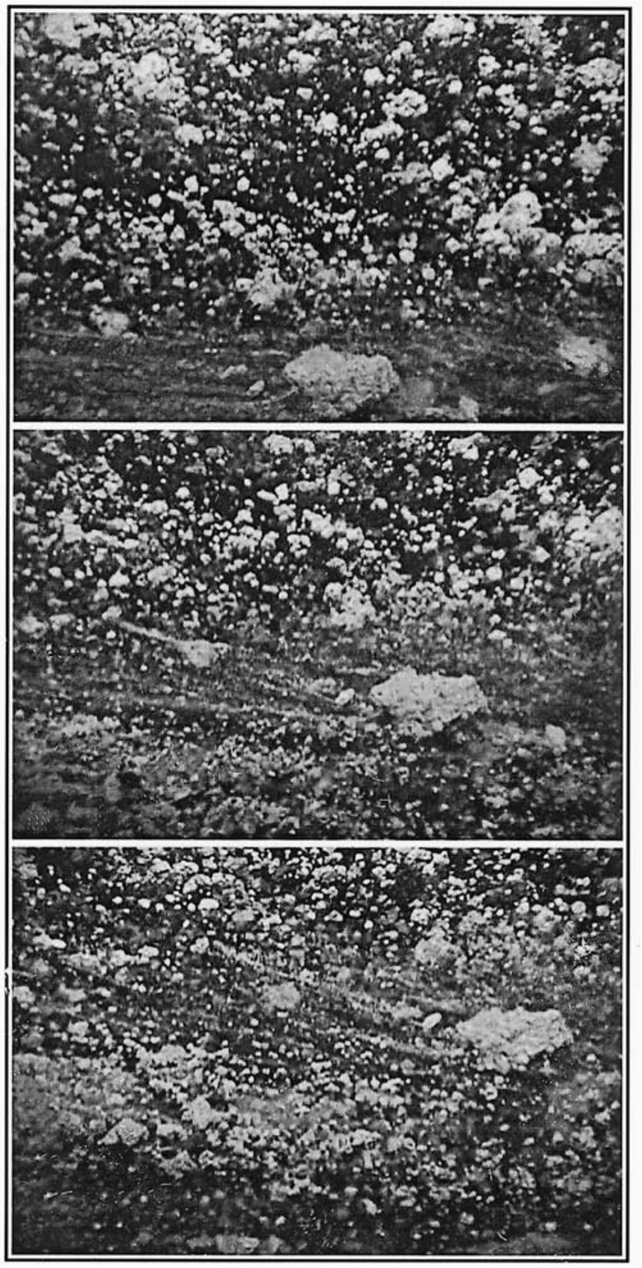

Fig. 10. Stereo images. These three images were taken near the bed with 1 cm separation. Note the changes in relative position of clasts. Actual image acquisitions are more closely spaced, but an image per centimeter describes the ice well. Each image covers about 4 cm in the vertical at the ice wall.

and down-glacier are potentially intriguing. The present version of the ice borehole camera is relatively simple, and we anticipate increased value from additional optical (as well as other) systems integrated into the probe. In general, a simple camera can describe the ice sheet to the extent of recording the size and number density of large clasts, but other quantitative analyses will require additional instrumentation. Candidate additions would include spectroscopic Raman and ultraviolet fluorescence, mass spectrometry, Mie scattering from dust, electrochemistry of meltwater or basal water, and microscopic imaging of hydrates. Some properties of interest (e.g. crystal fabric and orientation) have as yet no method of in situ measurement; this would be of great value.

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