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INSTRUMENTS AND METHODS

GLACIER BORE-HOLE PHOTOGRAPHY

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Abstract. A 51 mm diameter bore-hole camera allows observation of subglacial conditions, measurement of basal sliding rates, and study of internal structure and debris in ice at depth. The camera is simple in construction, field operation and maintenance. Water turbidity is a significant problem but it can be overcome by pumping.

Résumé. *Photographie dans un puit de forage.* Une caméra de 51 mm de diamètre pour puits de forage, permet l'observation des conditions sous-glaciaires, la mesure des vitesses de glissement à la base et l'étude de la structure interne de la glace et des débris morainiques en profondeur. La caméra est simple de construction, d'utilisation et d'entretien. La turbidité de l'eau pose un problème délicat que l'on peut néanmoins surmonter par pompage.

Zusammenfassung. *Photographie in Gletscher-Bohrlöchern.* Eine Bohrloch-Kamera von 51 mm Durchmesser erlaubt die Beobachtung subglazialer Zustände, die Messung der Gleitgeschwindigkeit am Untergrund und das Studium der inneren Struktur und des Schuttgehaltes von Eis in der Tiefe. Konstruktion, Feldgebrauch und Instandhaltung der Kamera sind einfach. Die Trübung des Wassers ist ein bedeutsames Problem, das jedoch durch Pumpen gelöst werden kann.

Introduction

Although bore-hole photography and television have been applied successfully to problems in well-drilling and mineral development, they have not been used previously in the study of glaciers. Among possible applications is the study of glacier sliding. Bore-hole photography makes it possible to measure sliding velocity on a day-to-day basis, and to observe the actual subglacial conditions simultaneously. These have been the main objectives of field work carried out on Blue Glacier (Mount Olympus, Washington, U.S.A.) during the summers of 1969 and 1970. In this paper we describe the equipment and methods developed, and discuss a selection of photographs which illustrates the observation of the sliding process and the possible application of the technique to other problems. A full account of results relevant to the sliding problem will be given separately (paper in preparation by Harrison and Kamb).

Cameras

Two virtually identical cameras have been built (Fig. 1). They are single-shot instruments using circular disks of film punched from sheet film. The tubular camera body is 51 mm in diameter, and the image on the film is 43 mm in diameter. The lenses, in compur-shutter assemblies, were obtained from old Vest Pocket Kodak cameras, and have focal lengths of 89 and 83 mm. Focusing is done by adjusting the position of the film plane, which is located by a focus ring whose position can be adjusted inside the camera body (Fig. 1). Small apertures (typically f/80) are usually used to maximize the depth of field. The shutter is actuated with a small alternating-current solenoid. Typical exposure times are several minutes with ASA 400 film.

Into the front of the camera body plugs a solid acrylic plastic ("lucite") viewing tube which is optically polished on the ends and carries lamps and reflectors. A tube for axial viewing is

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shown below the camera body in Figure 1. Four such tubes, of lengths 241, 197, 76 and 57 mm, have been constructed. The longer tubes are used to obtain close-up, detailed views of the bore-hole bottom, or portions of it, and to bring the lamps close to the object. The shorter tubes are used for wider-angle views. For lateral viewing, a tube equipped with a 45° mirror, shown in the right part of Figure 1, is used.

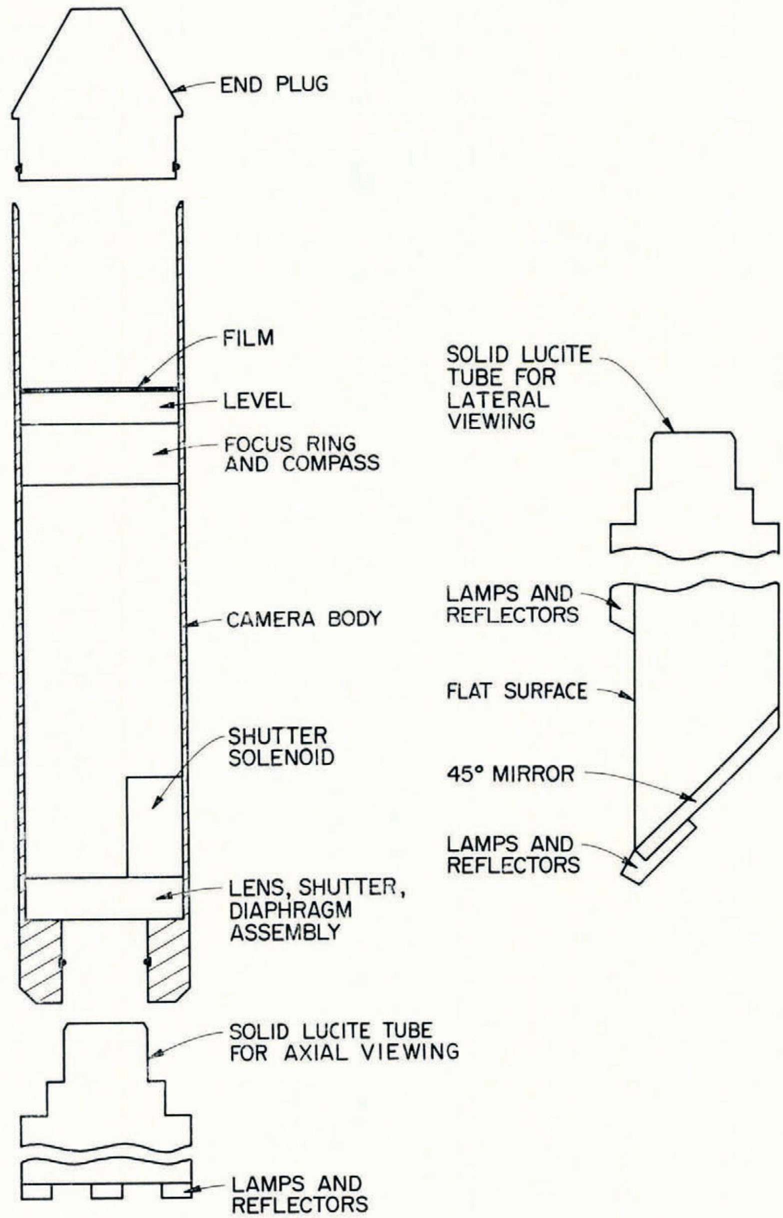

Fig. 1. Bore-hole camera including tube for axial viewing at left; tube for lateral viewing at right. The outside diameter of the camera is 51 mm.

The azimuthal orientation of the camera at the time a photograph is taken is obtained by replacing the simple focus ring with one carrying a small compass needle, which casts its shadow on the film. A level unit can also be inserted (Fig. 1), which allows the camera to function simultaneously as an inclinometer. The angle and direction of tilt of the camera body are shown by the shadow on the film of a small steel ball, which rolls on a concave glass plate.

Field methods

In clean ice, bore holes were made by thermal drills similar to those described by Shreve and Sharp (1970). They were maintained at a diameter of about 60 mm by reaming at intervals of about 1 week with a special conically shaped thermal drill. In order to reach the glacier bed, mechanical drilling through debris-laden basal ice was required. A cable tool and a sand-pump bailer were used for this (Johnson, 1966). All bore holes were uncased and most of them contained water. Usually the water near the bottom was extremely turbid after mechanical drilling or bailing, although in one hole it remained clear. Turbid water was removed with an air-lift (Johnson, 1966). Polyethylene tubing of 13 mm inside diameter was run to the bottom of the hole, which in most cases was at a depth of about 120 m. Air brought through 5 mm tubing from a small compressor was bubbled into the 13 mm tubing at a depth of about 30 m. The flow rate of 4 l/min obtained was usually not sufficient to draw down the water level in the hole. which remained roughly 5 m below the surface of the glacier. A siphon was used instead of the air-lift where the glacier was sufficiently steep. Thousands of litres of water were removed and, although the water pumped out eventually became clear, turbidity lingered for several weeks. During this period it was often necessary to pump just before running the camera in, and to minimize the amount of water in the light path by using the longer viewing tubes. Even then photography was not always successful.

The camera was suspended in the bore hole by a cable from a platform mounted on legs sunk into the ice or firn. When photographing the bottom of a bore hole, the desired camera position was obtained by first allowing the camera to touch the bottom, as determined by a decrease in cable tension, and then raising it to the desired height. A mark was placed on the cable and its distance from the top of the platform was measured. Positioning for subsequent photographs was done by adjusting this distance, allowing for a change in bore-hole length of typically 25 mm/d due to deformation of the ice. This procedure introduced some uncertainty in camera position but avoided repeated disturbance of the bore-hole bottom. After deformation caused the bore hole to tilt, the camera azimuthal orientation could be controlled by the use of an eccentric weight. Camera motion with consequent blurring of the photographs was an intermittent problem in some holes. Immediate access to results is a practical necessity, and this was achieved by changing and developing the film at the site, using a film-changing bag and fast developer.

Observations of sliding motion and subglacial conditions

If the bed of the glacier is reached by the bore hole, it can be photographed with the camera looking down along the axis of the hole. Motion of the ice with respect to the bed should be evident from the comparison of photographs taken at different times. This is illustrated by the pairs of photographs in Figures 2 and 3. Those in Figure 2 were taken with the 57 mm viewing tube. The time interval is 18.3 h and the motion of the ice with respect to the bed is about 14 mm/d. The photographs in Figure 3 were taken with the 241 mm viewing tube. The time interval is 22.0 h and the motion is about 25 mm/d. The bed seen in Figures 2 and 3 evidently consists of rock debris rather than smooth bedrock, and there is a gap between it and the base of the ice.

Scale must be known to find the sliding motion from a photograph pair. This was usually calculated from the position of the film plane and the distance of the camera from the bed. However, it can be determined directly and more accurately by introducing an object of known size into the photograph. This was the purpose of the small ball seen in Figure 3; it has a diameter of 9.5 mm. Even when no such object is present, the ratio of the scales in a photograph pair can be determined directly by comparing the distance between features on the bed visible in both photographs. It is necessary to know this ratio more accurately than the absolute magnification, because motion is determined by subtracting distances measured on two photographs, and the error introduced by small uncorrected scale differences can be appreciable.

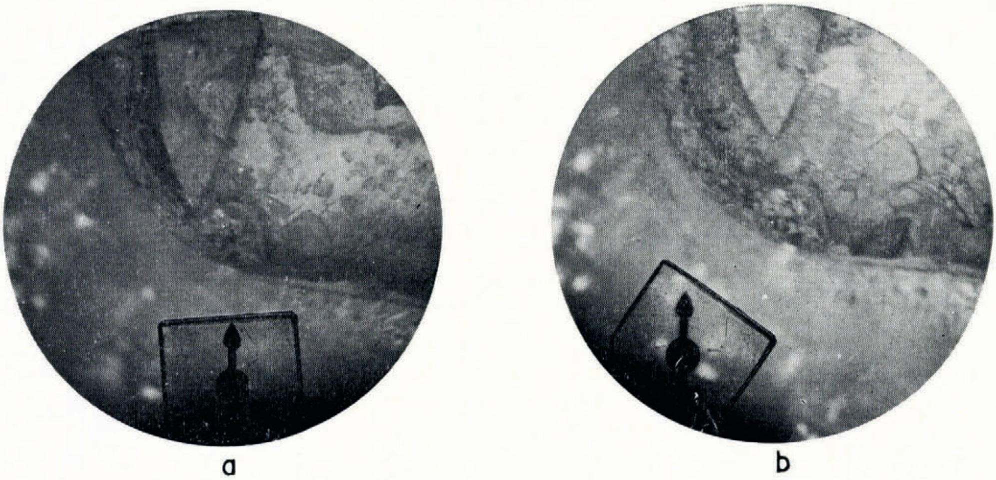

Fig. 2. Hole V1, 1969. (a) 18 August, 16.05 h. (b) 19 August, 10.25 h. The bore-hole wall fills the left and lower portions of the photographs, and a portion of the bed is seen at the upper right. Photograph diameter corresponds to a distance of about 85 mm on the bed.

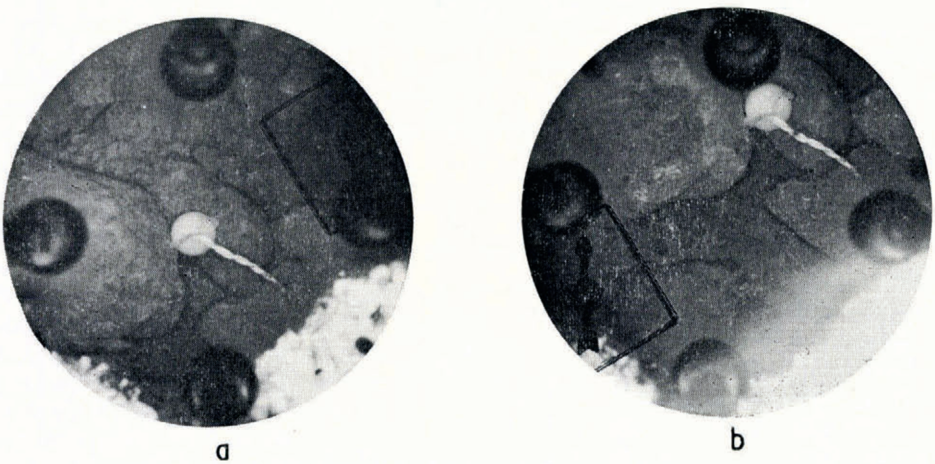

Fig. 3. Hole V1, 1969. (a) 7 September, 12.45 h. (b) 8 September, 10.50 h. The two bright areas in each photograph consist of ice attached to the bore-hole wall. Four lamp reflectors are seen, and a small nylon ball which rests on the bed. The portion of the bed seen has a diameter of about 87 mm.

The pairs of photographs in Figures 2 and 3 are stereo pairs because the camera has moved laterally with respect to the bed between exposures. Consequently, stereo views of the bed (but not the bore-hole wall) can be obtained with a stereoscopic viewer. This is an important aid to photo-interpretation, and it offers a method of studying the small-scale topography that plays a key role in theories of glacier sliding.

Stereoscopic information about both the bed and the bore-hole wall can be obtained by a different technique which consists of comparing two photographs taken at different distances from the bed. The photographs of Figures 2b and 4 are suitable for this. Both were taken with the 57 mm viewing tube, but the camera was about 300 mm from the bed for Figure 2b and 90 mm closer for Figure 4. The film plane was located for optimum focus, and was therefore also different for the two photographs. Taking all this into account and, using the laboratory-determined relationships between scale and object distance for the two film-plane settings, it was possible to estimate the width of the gap between the base of the ice and the bed. This is roughly 40 mm, although the surface of the bed is rather ill-defined.

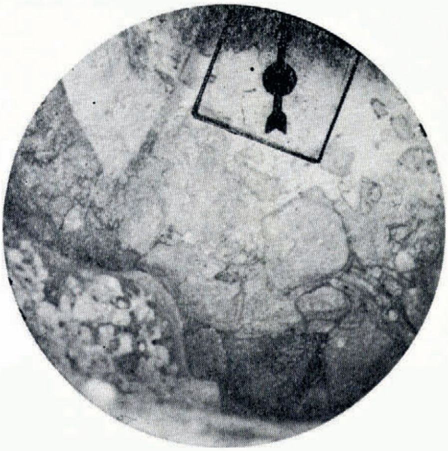

Fig. 4. Hole V1, 1969. 19 August, 11.55 h. Similar to Figure 2b, but taken closer to the bed. The portion of the bed seen has a diameter of about 52 mm.

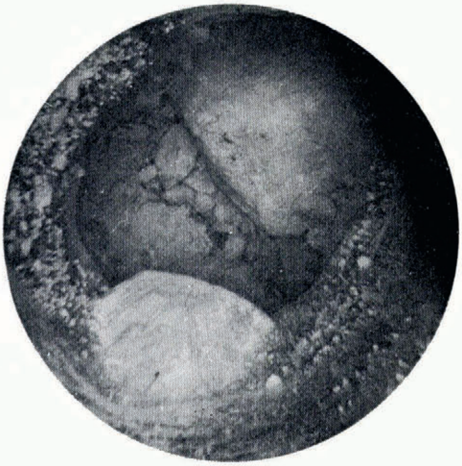

Fig. 5. Hole X, 1970, showing the entire bottom of a bore hole. A cobble and some finer material are seen embedded in the ice of the bore-hole wall. The portion of the bed seen has a diameter of about 105 mm.

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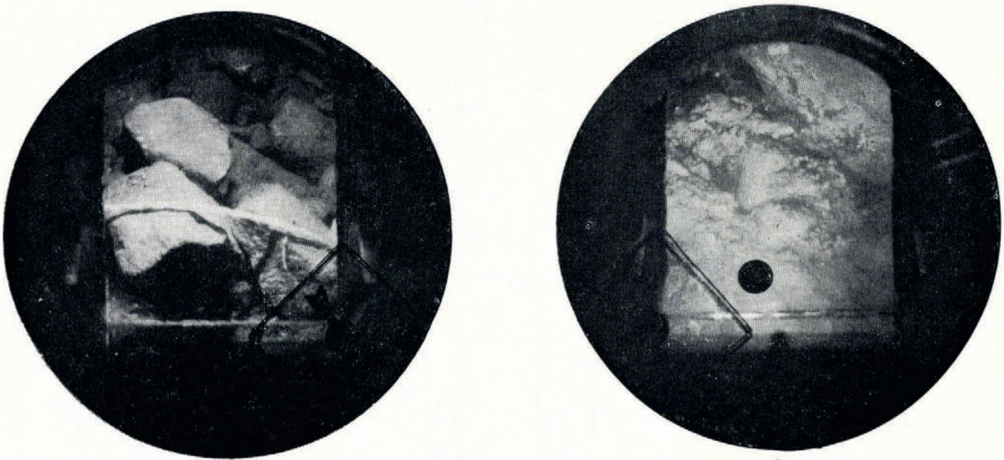
If the water is sufficiently clear, the camera can be positioned high enough to photograph the entire bore-hole bottom. This is illustrated by Figure 5, which was taken with the 57 mm viewing tube. The compass was not used here because the orientation of features in the bore-hole wall had already been determined from earlier photographs.

Figures 6 and 7 show how lateral views at the bottom of a bore hole give information about subglacial conditions. In Figure 6b the level unit was used, and the black spot is the shadow of the level ball. It indicates a camera tilt of 7° from the vertical. Figure 7 was taken with an early version of the camera in a hole that penetrated a subglacial cavern. The height of the cavern was found by using photography to locate the bottom of the ice, which crosses the center of the photograph. Water did not stand in this hole and droplets on the surface of the viewing tube can be seen in the photograph.



a b

Fig. 6. (a) Hole V1, 1969, taken with the tip of the 45° mirror touching the bed. The string seen here is attached to the ball in Figure 3. Width of the foreground is about 38 mm. (b) Hole X, 1970, taken with the tip of the mirror 10 mm above the bed. Debris is seen in the basal ice. Width of strip photographed is about 41 mm.

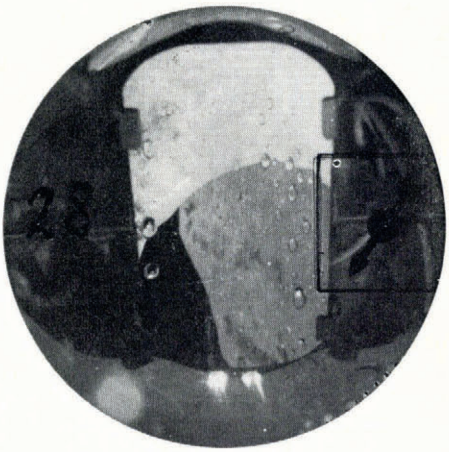


Fig. 7. Hole I3, 1967, showing where the bore hole intersected the roof of a subglacial cavern. Part of an icicle-like feature suspended below the base of the ice can be seen in the background. Width of the foreground is about 30 mm.

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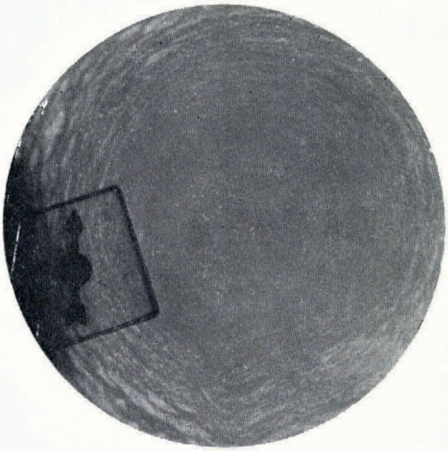
Other applications

1. *Structure*

Both axial and lateral photographs can give information about structure in the ice. Figure 8a is an axial photograph taken with the 57 mm viewing tube in bubbly ice. Figure 8b is a lateral photograph showing ice foliation near the bottom of a hole.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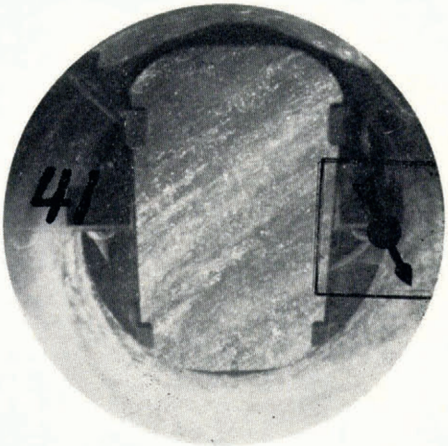

b

Fig. 8. (a) Hole V1, 1969. Bubbly ice. The notch in the hole wall at the bottom of the photograph was melted by the power cable during thermal drilling. Bore-hole diameter is about 59 mm. (b) Hole I6, 1967. Ice foliation. Width of strip photographed is about 30 mm.

2. *Bore-hole configuration*

Photography can give useful information about the shape of a bore hole, especially when its tilt is changing so rapidly with depth that measurement by conventional inclinometry is difficult. This is illustrated by Figure 9, which was taken with the 57 mm viewing tube. The

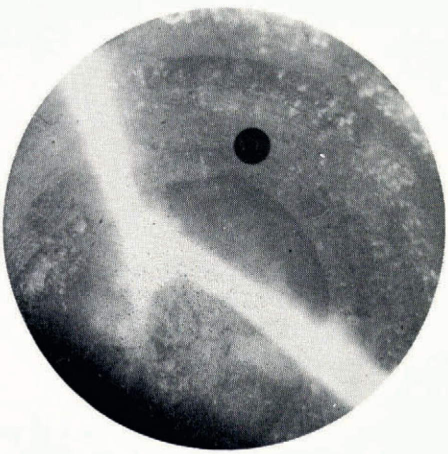

Fig. 9. Hole X, 1970. The bright areas consist of string that suspends a ball used to determine photograph scale; the ball is out of the field of view due to bore-hole curvature. The portion of the bed visible here has a diameter of about 105 mm.

black spot is the shadow of the level ball and it indicates a tilt of 10.5°. From the direction of tilt it follows that the up-glacier edge of the bore-hole bottom is seen near the center of the photograph. The hole is therefore shaped as sketched in Figure 10. This indicates that the initially vertical hole has tilted less near the bed than it has 0.9 m higher, a fact of significance in relation to the detailed distribution of deformation in the basal ice.

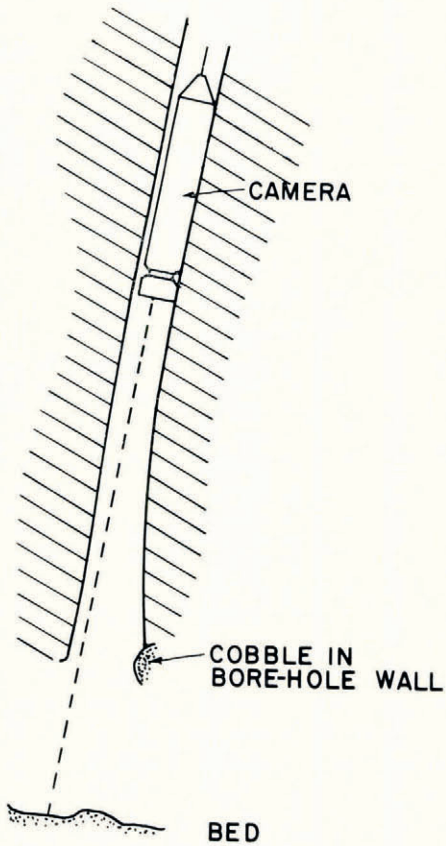

Fig. 10. Configuration of the bore hole and camera orientation as deduced from Figure 9. The bore hole was flared at the bottom during thermal drilling, and there is a gap between the base of the ice and the bed. The center of the camera is 0.9 m above the bed. The ice moves from left to right.

3. *Drilling*

Photography can give information important to the successful drilling of a bore hole. Figure 11a shows the bottom of a hole in which the thermal drilling rate had dropped by about three orders of magnitude. It shows, rather surprisingly, that this drop was caused by a thin layer of fine debris, and that it might be possible to continue thermal drilling after removing the debris with a suitable bailer. This is sometimes possible. Photography can often determine whether the bed has been reached; for example, it has not been in Figure 11a, although the thermal drill was essentially stopped. On another occasion, photographs of the bottom of a hole revealed rock but no sliding, suggesting that the bed had not been reached. This was verified by further mechanical drilling.

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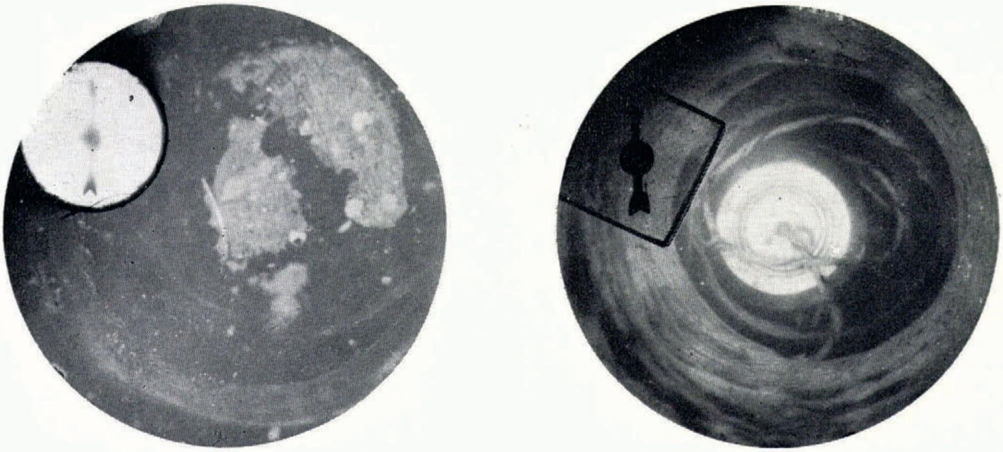
Drillers occasionally must fish for equipment lost in a bore hole, and photography may help by locating the position of the fish. Figure 11b shows the top of a thermal drill lost at 115 m depth; it was later recovered.



a b

Fig. 11. (a) Hole T1, 1969. Thin layer of debris at the bottom of a bore hole. The maximum dimension of the larger patch of debris is about 45 mm. An early version of the compass was used. (b) Hole V3, 1969. Top of lost thermal drill. Bore-hole diameter is about 60 mm.

Conclusions

Use of the glacier bore-hole camera shows that significant observations can be made of subglacial conditions, basal sliding motions, ice structure and bore-hole configuration. While the single-shot limitation of this particular instrument makes it more tedious to use than a bore-hole television system would be, it has the advantages of low cost, simple construction and maintenance, simple set-up and operation under field conditions, small weight, ready portability, and freedom from complicated electronic equipment. The main difficulty in the use of either a camera or a television system in studying the basal sliding phenomenon is water turbidity. This can be overcome by pumping, although considerable time and effort may be required, making it difficult to observe bore-hole phenomena that transpire immediately upon completion of drilling.

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