DRILLING TO OBSERVE SUBGLACIAL CONDITIONS AND SLIDING MOTION

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ABSTRACT

Our ignorance of what happens at the bed of a glacier is the outstanding problem in glacier flow, and serious drilling efforts are necessary for its solution. Some of the problems encountered in a small-scale drilling project to make observations at the bed of a glacier are discussed. These include the problems of thermal and cable-tool drilling and bailing in dirty, actively-deforming temperate ice using back-packable equipment, the problems of borehole photography and water turbidity, and the possible effect of the borehole on the conditions observed.

Introduction

Although considerable progress has been made during the past 20 years in our understanding of the deformation of ice, our ability to predict the flow of a glacier, or to interpret its behavior in terms of climatic changes, is severely restricted by our ignorance of what goes on at the glacier bed. For the same reason, we know very little about the geomorphological processes of glacial erosion and deposition, and some hydrological problems such as water storage in glaciers and the production of sediment in glacially fed streams.

Because ice is a rather plastic material there are conditions under which the thickness of a glacier, and its flow as observed at the surface, are rather insensitive to what is occurring at its bed. Yet the thickness and flow of some other glaciers are probably to a large extent determined by subglacial processes. The list includes the surging glaciers, the large outlet glaciers, possibly some glaciers on volcanoes, and glaciers showing large seasonal variations in velocity.

The importance of the problem is recognized, and considerable theoretical work has been devoted to predicting what should happen at the bed of a temperate glacier; small-scale subglacial topography and water pressure play important roles. But at this stage the problem is essentially

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an experimental one. Because experiments are difficult, the theory has not been adequately tested, nor has it been shown that the type of interface which it assumes, clean ice lying on bedrock, is necessarily typical. Although some observations have been made in tunnels near terminal, marginal and icefall regions, drilling is the key to observation in the more typical deep regions of a glacier. In fact, one type of borehole experiment is already fairly common. The measured deformation of a borehole, integrated over its length, is subtracted from the measured surface velocity to give the velocity at which the glacier slides over its bed. Failure of the borehole to reach the bed, perhaps not uncommon, results in an overestimate of the sliding velocity.

Some problems encountered in a project to drill through a glacier and make direct observations at the bed with the help of borehole photography are described here.

Drilling

Our experiments were carried out during the summers of 1969 and 1970 in an area of Blue Glacier near the equilibrium line where the ice thickness is about 120 m. Blue Glacier is a temperate glacier on Mt. Olympus, Washington, U.S.A. Most of the drilling was done with 51-mm-diameter electrothermal drills similar to those described by Shreve and Sharp (1970). The technique was similar to that developed by Kamb and Shreve (1966) in that no casing was used. The holes, which tended to refreeze slowly, were maintained at a diameter of 60 mm with a special conically-shaped thermal drill. During the first summer we learned by borehole photography that a thin layer of debris accumulated beneath the thermal drill to a thickness of only 2 or 3 mm was sufficient to slow the thermal drilling rate, normally about 7 m/hr, by perhaps three orders of magnitude.

During the second summer we attempted to penetrate dirty ice with the help of a cable tool (Johnson, 1966). (A cable tool is essentially a heavy chisel which is repeatedly raised some tens of centimeters off the bottom with a cable and dropped.) The string of tools, consisting of swivel, jars, stem, and bit, was about 3 m long and weighed about 30 kg (Fig. 1). It was driven off a cathead, which for convenience was not connected directly to the wire cable, but via a rope clamped to it. The cable was continually adjusted so that there was some tension as the bit struck the bottom. A small cable winch, the cathead, and the sheave were all mounted on a wooden tripod (Shreve and Kamb, 1964, p. 115). We found it advisable to complete the cable-tool drilling fairly promptly. It can be difficult to re-enter a hole with a long string of tools after a period of days or weeks, depending on the rate of deformation of the ice.

The performance of this cable tool was rather poor, as illustrated by a drilling rate of only 1 m/hr in clean ice. We feel that this could have been considerably improved by increasing the 500 W used to power the cathead to a larger fraction of the 2000 W that was available. This is the power used in the electrothermal drilling. Another difficulty was that the bit was probably striking a fairly large area since no casing was driven to guide it, and the hole was usually enlarged by earlier attempts at thermal drilling in the dirty ice. Despite its inefficiency, layers of heavily debris-laden ice were successfully penetrated with this cable tool. It is interesting that a regular well-drilling cable-tool rig was used for experimental drilling in Athabasca Glacier in 1960 (W.S.B. Paterson, personal communication). Both the drilling speed and the weight of the equipment were at least an order of magnitude larger.

Water stood in all the holes in which cable-tool drilling was attempted. This permitted debris to be bailed out with a sand pump (Johnson, 1966). This is a simple device which, like the cable

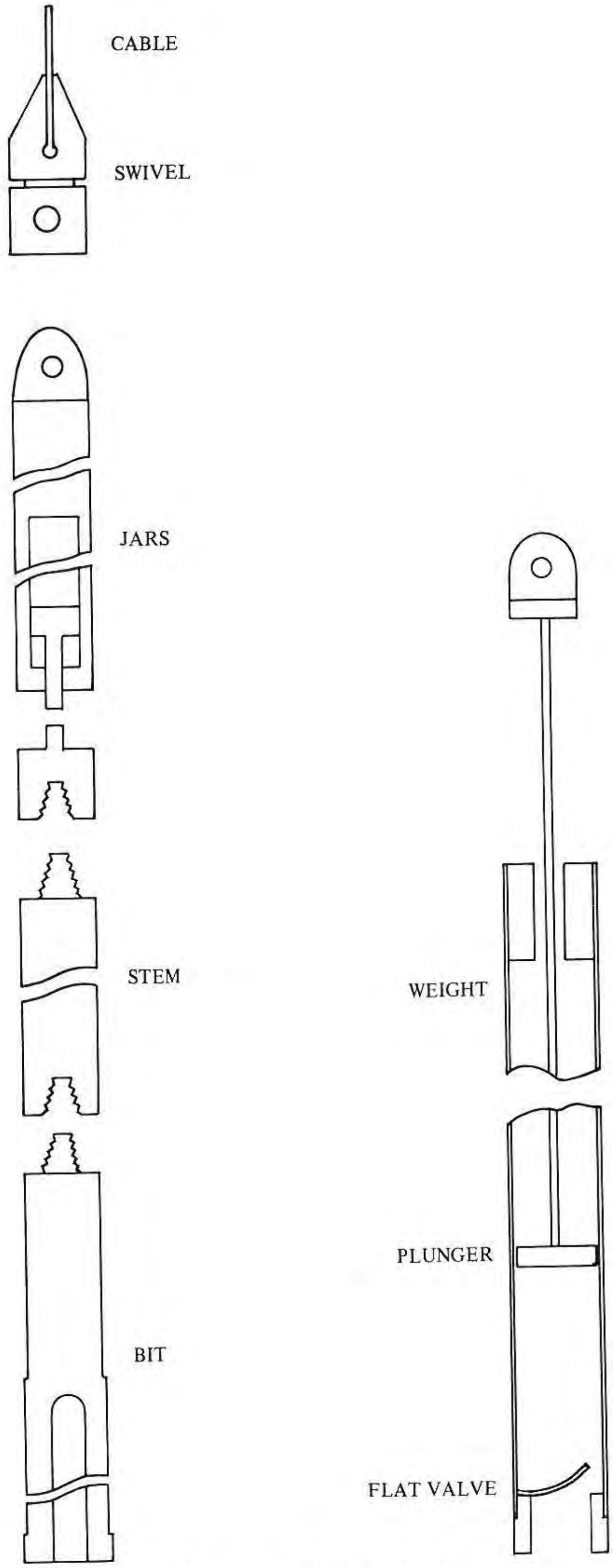

Figure 1. Cable tool (left) and sand pump (right). The bit, stem, and jars are respectively about 0.6, 2.0 and 0.5 m long; the maximum diameter of the bit is about 50 mm. The body of the sand pump is about 1.5 m long and 51 mm in diameter.

tool, is operated with a single cable. The pump is run into the hole with the cable attached to the plunger, which is therefore initially extended. When the pump body reaches the bottom and the cable tension is released, the plunger retracts under the influence of gravity. A strong jerk on the cable sucks debris into the bottom of the pump, where it is contained by a flat valve; we found that a sheet of neoprene worked best for this (Fig. 1).

Our sand pump worked well, except that it seemed to have difficulty in picking up all the debris in enlarged holes; this complicates the determination of undisturbed subglacial conditions. The sand pump seems to be a very useful tool even when no mechanical drilling is attempted. We found that after the thermal drill was stopped by debris, thermal drilling could often be continued after the bottom of the hole was cleaned with the sand pump.

All of the components used in these drilling techniques are portable, simple, and inexpensive. Large depths do not present a great problem because no casing or drilling pipe is used.

Borehole Photography

The boreholes and subglacial conditions were studied with a borehole camera. The instrument and its use have already been described, together with an air-lift system to pump turbid water from the bottom of the hole (Harrison and Kamb, 1973). A sketch of the camera is shown in Fig. 2. Turbidity caused by mechanical drilling and bailing is the most serious problem facing borehole photography. Even after the water pumped from the bottom of our holes became clear, by the time the air lift was run out of the hole and the camera run in (5 or 10 minutes), turbidity often prevented photography of the hole bottom. The problem decreased over a period of days or weeks until pumping immediately before photography was not required. No attempt to use a flocculent was made. We do not yet understand the physical processes involved in this turbidity problem.

Some of the capabilities of borehole photography have also been described (Harrison and Kamb, 1973). Perhaps the most striking is the observation of the motion of the ice with respect to the bed, as illustrated by Fig. 3. The observation of motion like this is probably an indication that the bed has been reached. Photos such as those of Fig. 3 are a stereo pair and therefore contain small-scale topographic information about the bottom, which is an ingredient of glacier sliding theory.

Effects of the Borehole

The presence of a borehole changes both the stress and the temperature environments. Depending upon the magnitudes of impurity and water pressure effects, either melting or freezing can take place (see Harrison, 1972). Other possible disturbances can be imagined. For example, say a borehole intersects the bed on the downstream side of a rock protuberance; this should be a low-pressure region. If the hole is water-filled, and the water does not escape due to surrounding higher pressure regions, there will be an excess pressure at the hole bottom which may cause the ice to separate from the bed. Disturbances such as these are probably not serious for most observations, as long as they are made immediately upon completion of the borehole. This points out the need to be able to handle the turbidity problem, which is most severe then.

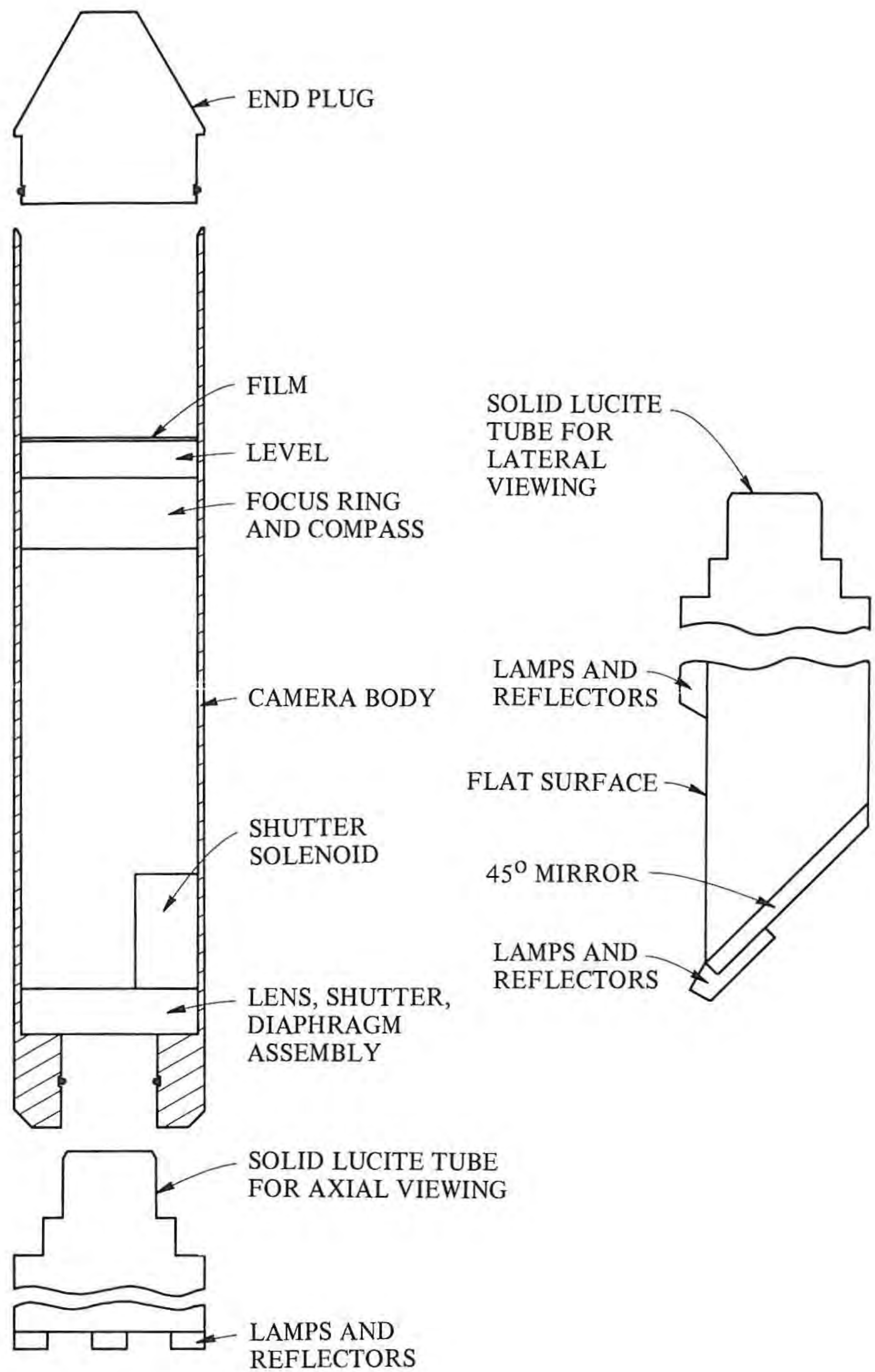

Figure 2. Borehole camera including tube for axial viewing at left; tube for lateral viewing at right. The outside diameter of the camera is 51 mm.

a

b

Figure 3. Photographs of the bottom of hole V1, 1969. (a) 7 September, 1245 hours, (b) 8 September, 1050 hours. The two bright areas in each photograph consist of ice attached to the borehole 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.

Conclusions

The capability of drilling in dirty ice is probably necessary to reach the bed of a glacier in many instances. The cable tool and sand pump, used together with thermal drilling, are very suitable for this, at least if no large rocks have to be penetrated. The efficiency of the cable tool system described here needs some improvement, since in order to determine "typical" subglacial conditions it is necessary to drill many holes.

When the necessary drilling capability is at hand, borehole photography is a powerful method of studying subglacial conditions and motion. The turbidity problem has been partially solved by pumping, but some further work on the origin and the precipitation of the suspended material is needed. Until this is done the use of a more elaborate camera or television system probably is not warranted.

Our experience indicates that the necessary improvements can probably be made without sacrificing the low cost and portability of the equipment.

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