BORE-HOLE INSTUMENTS TO MEASURE GLACIER BASAL MOTION

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Abstract. The processes that control the partitioning of glacier basal motion between sliding at the ice-bed interface, and deformation of subglacial sediments represent a major unsolved problem in glacier mechanics. A lack of both direct observations of glacier basal motion, and an adequate rheological description of subglacial sediments, have held back attempts to resolve such problems. However, direct observation of the mechanics of glacier basal motion is possible via the use of instrumented bore-holes. We detail the construction and installation of two types of sensors which may be used *in situ*, to measure basal sliding, and the physical properties of basal sediments. To illustrate the use of these sensors we describe results collected at Bakaninbreen, a surging glacier in south-east Svalbard. Sliding rates are shown to be consistently higher up-glacier of the surge front, and negligible down-glacier of it. Sediments from beneath the glacier have a yield stress in the range 17–87 kPa, and a viscosity in the range 1.1×10^{10}–4.3×10^{10} Pa s.

INTRODUCTION

Glacier basal motion can occur by several processes; where ice rests on a rigid substrate, the majority of basal motion is thought to result from sliding at the ice-rock interface; where ice rests on unconsolidated sediments, basal motion can additionally be caused by deformation of these sediments, and by ploughing of clasts through the upper layers of the bed (Alley, 1989a). *In situ* observations at the margin of Breidamerkurjökull, Iceland show that up to 90% of glacier surface velocity may be accounted for by deformation of water saturated, subglacial sediments (Boulton and Jones, 1979; Boulton and Hindmarsh, 1987). Seismic reflection studies and coring on the fast-flowing Antarctic Ice Stream B have also revealed the existence of a water-saturated, highly porous subglacial sediment layer several metres thick (Alley *et al.*, 1986; Engelhardt *et al.*, 1990). Deformation of these sediments may explain how fast flow velocities are maintained in the absence of large driving stresses. However, the details of basal motion where ice is moving over an unconsolidated deformable bed remain elusive (Alley, 1989b).

Hot-water drilling techniques allow access to the beds of ice masses. Humphrey *et al.* (1993) observed an actively deforming basal till layer some 65 cm thick beneath Columbia Glacier, south-east Alaska. Iverson *et al.* (1994) also suggest that active deformation is occurring beneath Storglaciären, Sweden, while observations at the bed of the surge-type Trapridge Glacier, Yukon Territory have shown that deformation of subglacial sediments may account for up to 60% of the glacier's forward motion (Blake *et al.*, 1994). Direct observation of the glacier bed is possible via instrumented bore-holes; such instrumentation forms the basis of the work we are currently undertaking in Svalbard (Murray and Porter, 1994). We aim to address the following questions:

1. How is glacier flow partitioned between sliding and sediment deformation?
2. How does ice-sediment coupling vary spatially and temporally?
3. How does the basal water system affect ice-bed coupling?
4. What are the rheological properties of the basal sediments?

In order to achieve these aims we need to separately assess the contribution of sliding, ploughing, and sediment deformation to glacier basal motion, and to assess changes in these contributions over time and space. In this paper we give full details of two of our subglacial sensors that allow measurement of glacier basal motion by sliding, and measurement of the rheometric properties of basal sediments. We detail the construction, calibration, and installation of the sensors, and outline basic interpretation of the resulting data. The sensors are based on designs that have been tried and tested on Trapridge Glacier (Blake *et al.*, 1992; Blake *et al.*, 1994; Fischer and Clarke, 1994).

INSERTION OF SUBGLACIAL SENSORS

Bore-holes are drilled using a hot-water ice drill to the glacier bed. Once the bore-hole is complete a percussion hammer, as described by Blake *et al.* (1992), is used to insert sensors into basal sediments. The hammer consists of a 2 m long tubular stainless steel body (Fig. 1). Surrounding this body is a sliding steel striker which can be raised by a single steel wire operated from the glacier surface, and then dropped onto an anvil. When the striker hits the anvil a percussive force results that is used to drive the sensor into the basal sediments. The insertion of an instrument is performed as follows. With the hammer and instrument at the bed the operator pulls gently on the hammer wire to take up any slack, and then to raise the striker above the anvil. The striker is then allowed to drop freely onto the anvil. Our experience suggests that allowing the striker to fall from approximately 0.5 m is adequate to allow instrument insertion. By repeating this action many times the instrument is driven into the bed. The same wire can be used to retrieve the hammer from the bed by pulling on it until the striker reaches the upper stop; at this point continuing to pull on the wire will lift the hammer up the bore-hole. The hammer is best retrieved by simply walking away from the bore-hole maintaining hold of the storage reel until the hammer is just below the surface; a second operator should then lift the hammer clear of the bore-hole to prevent the hammer wire from kinking. During the hammering procedure one of two attachments are screwed onto the hammer below the anvil, either a steel finger or a tubular steel sheath (Fig. 1) dependant on which sensor is to be inserted. Details are discussed below for each individual sensor type.

The depth of sensor insertion into subglacial sediments is monitored during the insertion procedure. Once the sensor and hammer are in place at the bottom of the bore-hole the signal wire of the sensor is held taut and this wire is marked with tape at the level of the ice surface. A further tape mark is made 0.5 m above this first mark. As the sensor is hammered into the sediment, the distance between the ice surface and the uppermost tape mark is reduced. Hammering is normally continued until the sensor ceases to advance, however, where basal sediments are especially soft care should be taken not to drive sensors beyond the bottom of the bore-hole. Our experience suggests that over two hundred hammer blows may be required. Once insertion is complete, the distance between the uppermost tape mark and the ice surface is taken to be the minimum insertion depth of the sensor into the subglacial sediment; the hammer can then be withdrawn.

We believe this measurement to give minimum insertion depth for two reasons. First, subglacial sediment may be disturbed when the drill reaches the bed, especially as the operator typically keeps the drill running at the bed for several minutes to confirm that progression of the drill has ceased; second, the combined weight of the sensor and the percussion hammer is considerable, and we expect them to settle some distance into the disturbed subglacial sediments under their own weight before hammering commences.

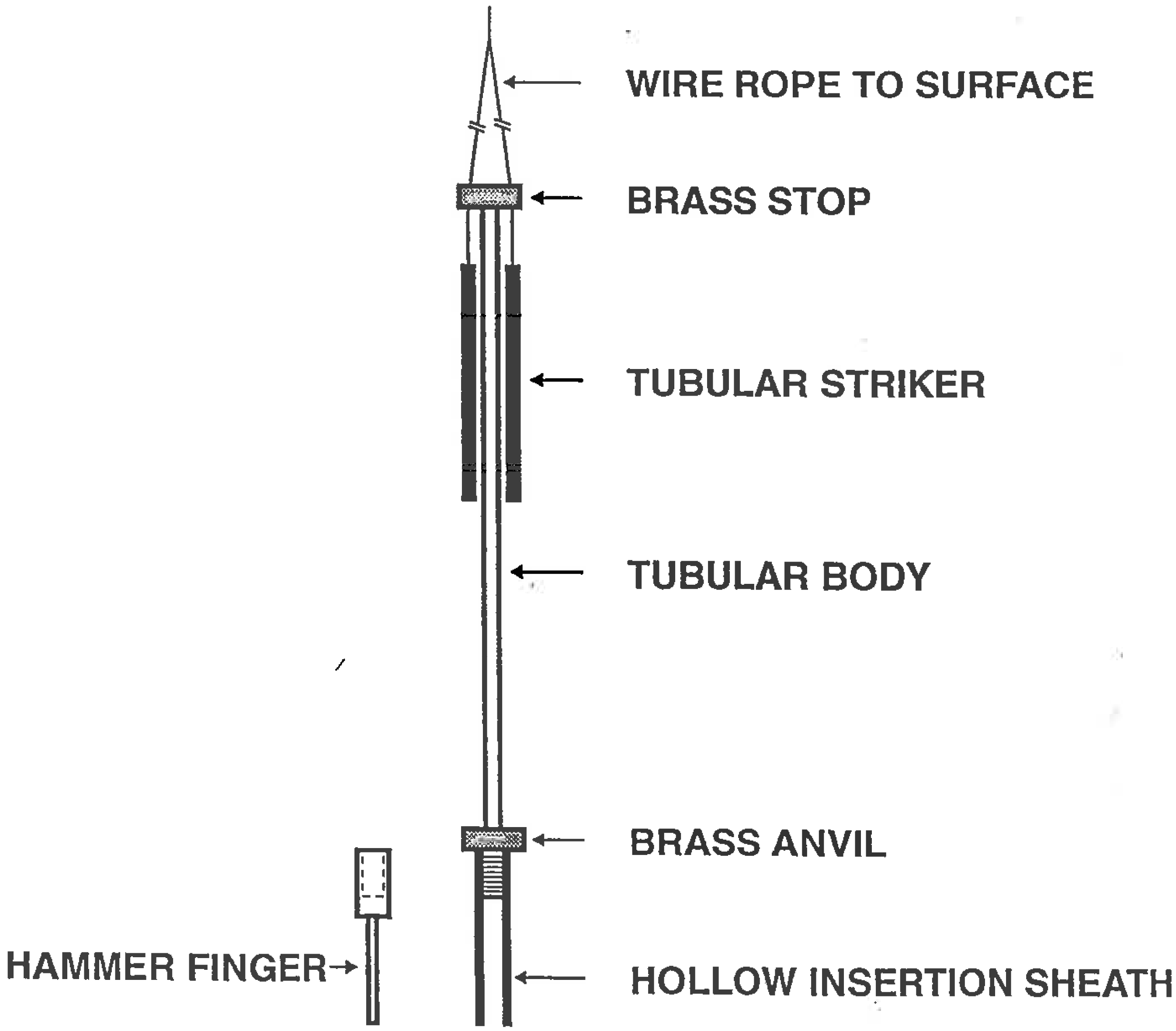

Figure 1. Schematic diagram of the percussion hammer used to insert sensors into basal sediments. The hammer can be fitted with either an insertion sheath, for flexible instruments, or a finger used to insert rigid devices. After: Blake *et al.*, 1992.

MEASUREMENT OF PLOUGHING: PLOUGHMETERS

The ploughmeter enables us to assess subglacial ploughing, and the properties of subglacial sediments such as viscosity and yield strength, and can also be used to indicate rates of glacier sliding and sediment texture (Fischer and Clarke, 1994; Fischer and Clarke, in press). The device consists of a steel rod onto which strain gauges are bonded near one end. The ploughmeter is hammered into the bed, such that all strain gauges are fully immersed into the subglacial sediment. The upper section of the device then becomes trapped in the ice, and the lower portion is dragged through the underlying sediment, effectively acting as an ice-entrained clast (Fig. 2a). This 'ploughing' action sets up stresses within the ploughmeter, that cause changes in the resistance of the strain gauges.

Construction details

Our ploughmeters are based on the design described by Fischer and Clarke (1994). The basis of the ploughmeter is a 2 m long steel rod, machined to a point at one end (Fig. 2b). At the other end, a guide hole is drilled to a diameter suitable to accept the insertion finger of the percussion hammer. Strain gauges are bonded onto the steel rod near the tip. As the ploughmeter bends, the resistance of each strain gauges changes; by wiring the device in a full-bridge arrangement this change in resistance unbalances the bridge and produces a corresponding voltage change. The rod and gauges are sheathed in a protective P.V.C. tube and the void between the tube and the rod is filled with epoxy resin. The P.V.C. tubing (Fisons TWR 670-2928) has internal and external diameters of 25 mm and 28.25 mm respectively. The resin and tube protect the gauges and associated wiring against mechanical damage and water ingress. A resin with a low viscosity, low shrinkage, and high strength is essential; we chose an S.P. Systems three part resin (SP620) for these reasons. The resin is also transparent (albeit pale yellow) when cured, allowing inspection of the bridge circuits after casting. At the base of the ploughmeter a metal cap is bonded to the tip to protect the sandwich structure during its insertion.

Correct surface preparation is essential to ensure good bonding of strain gauge to ploughmeter. The area of the steel rod where the strain gauges will be situated is lightly machined, in order to polish and roughen the surface slightly. Immediately prior to bonding, the surface is roughened at 45° to the measurement axis using fine abrasive paper. The surface is then cleaned using isopropyl alcohol. The strain gauges (TML PLS-20-11) are bonded to the steel rod using Cyanoacrylate adhesive (TML CN adhesive). The centre of the gauge is located 0.1 m from the pointed end; it is this end that will be inserted into the basal sediments. Connecting terminals (TML TF-2S) are used to facilitate wiring and soldering of the bridge circuits. Both the terminals and strain gauges are bonded in the same fashion. First, location lines are marked onto the steel rod. The gauge is then placed face down on a cleaned surface, such as a glass plate, and a strip of transparent adhesive tape

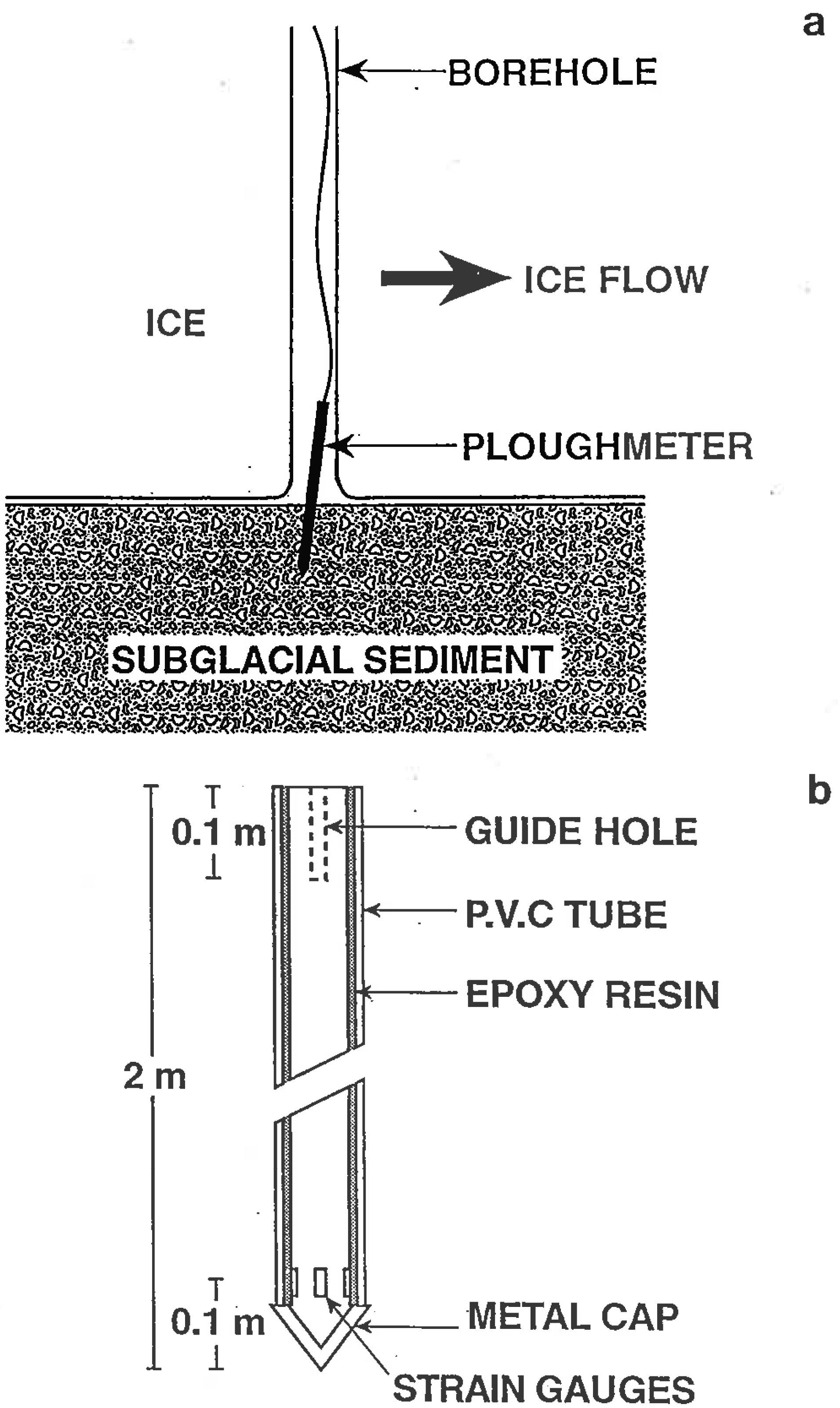

Figure 2. Subglacial ploughmeter. (a) Ploughmeter in place in bore-hole; the upper portion of the device becomes trapped in the ice. As the glacier slides over its bed, the lower portion of the ploughmeter is dragged through the basal sediments, and the resulting force is registered as changes in the resistance of strain gauges bonded onto its lower tip. (b) Dimensions and construction details of the ploughmeter. After: Fischer and Clarke, 1994.

is placed on top of the gauge sticky side down. Location lines corresponding to those on the steel rod are drawn on the tape. The tape and the strain gauge are then gently peeled away from the glass plate. The tape and gauge are placed onto the rod in alignment with the location lines, and then the portion of the tape on which the strain gauge is situated is gently lifted from the steel surface leaving part of the tape attached to the rod in the correct location. Cyanoacrylate adhesive is applied to the underside of the gauge, and then the tape and gauge are 'rolled' back down into position on the rod. It is important not to apply an excessive quantity of adhesive to the gauge, however, sufficient must be applied so that all air bubbles are expelled, and the adhesive spreads out as the gauge is rolled onto the rod. The gauge should not be bent excessively during these procedures as damage can result. Firm finger pressure is applied for one minute. Three minutes later the tape can be gently peeled away from the gauge. It is usual for the lead wires to adhere to the surface of the metal; they should be gently lifted away from the excess adhesive. The terminal connectors are bonded using the same procedure, and, if desired, can be bonded at the same time as the strain gauges.

Fifteen minutes after bonding, the bridge circuits can be connected (Fig. 3). Two bridge circuits are constructed, each consisting of two strain gauges located directly opposite each other on the ploughmeter, and two precision resistors. The nominal resistance of the strain gauges is 120Ω; 121 Ω precision metal film resistors (R.S. 164-889) are used to complete the two bridge circuits. The two bridges are linked using common excitation and ground wires. Each bridge has two further wires leading into the multiplexer. The lead wires from the strain gauges are soldered onto the terminal connectors and cut down to length. All other internal wiring uses insulated solid core copper equipment wire (*e.g.*, Farnell 140-418). After wiring, the resistance of each bridge circuit should be checked: the resistance across the ground and excitation leads should be approximately 60 Ω; across any two of the remaining wires the resistance should be approximately 120 Ω; the resistance across strain gauge lead wires should be approximately 75 Ω. Once the signal wires (6 core telephone cable, R.S. 368-508) are attached to the ploughmeter, these resistance will rise (for 200 m of wire the rise is of the order of 40 Ω). For this reason calibration should be carried out with signal wires attached. The instrument cable is directly spliced onto the internal wires about two thirds of the way up the ploughmeter. This cable is doubled back on itself along a length of approximately 0.30 m and is then taped firmly to the ploughmeter to prevent direct strain on the internal wiring or strain gauges. It is essential to avoid any shorting between the wires of the bridge circuits and the steel rod. For this reason plastic tape is used to insulate areas where solder joints and bare wires are exposed. Heat shrink or sleeving is used wherever possible.

The next step in construction is to sheath the ploughmeter in P.V.C. tubing and to fill the void between the rod and the tubing with epoxy resin. The metal surfaces of the

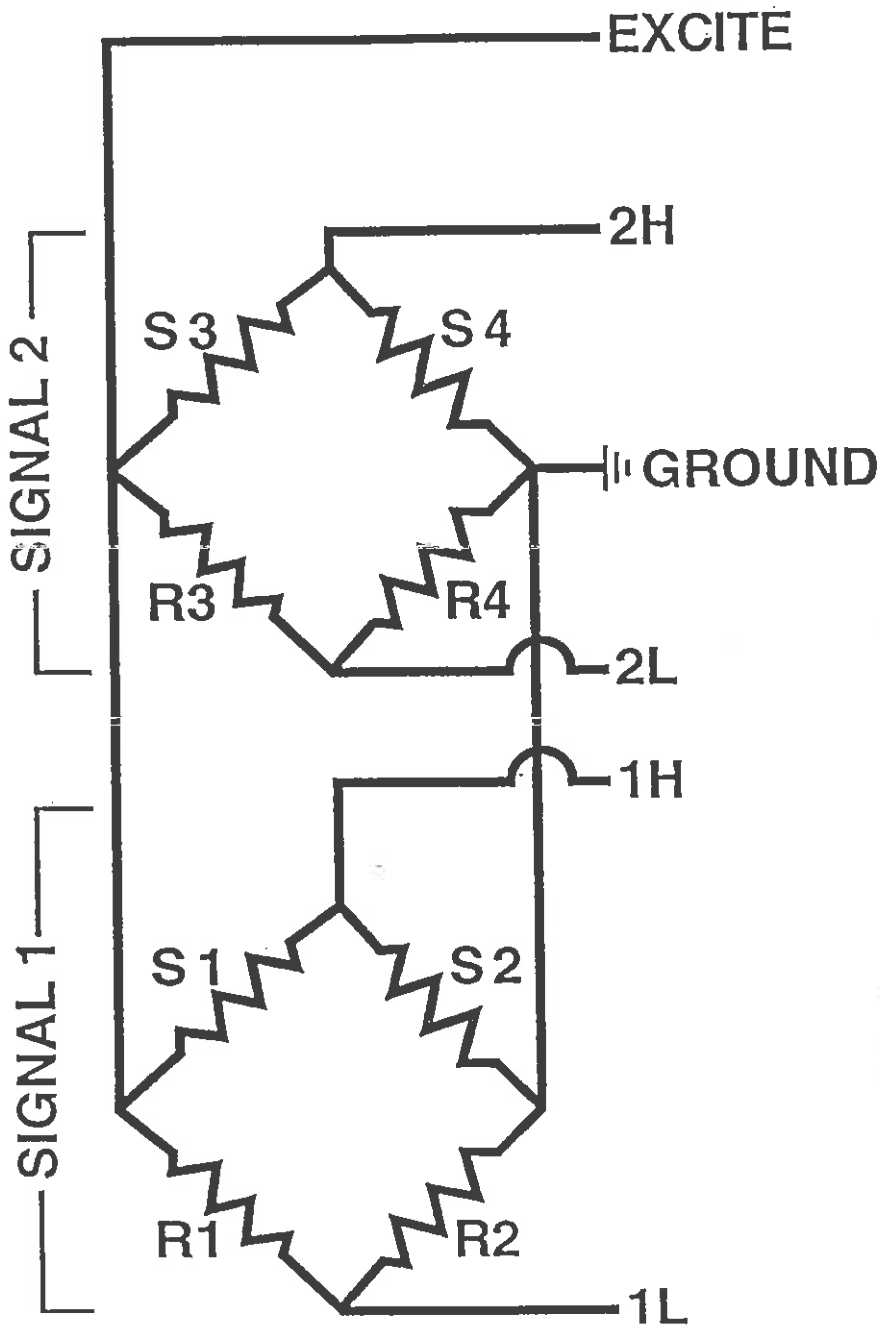

Figure 3. Ploughmeter wiring diagram showing resistors and strain gauges arranged as two full bridge circuits. 'S' denotes strain gauges (120 Ω unstrained) and 'R' denotes bridge completion resistors (121 Ω. The bridges are completed by 121 Ω precision resistors.

ploughmeter should be roughened using glass paper and cleaned, in order for the resin to bond well. A hose clip is used to clamp the P.V.C. tube to the ploughmeter to prevent resin leakage during casting. Because the void between the tubing and the steel rod and wiring is so small, especially where the telephone wire is doubled back on itself, the resin is injected through the walls of the tubing. The resulting holes are sealed using insulating tape which can be removed once the resin has cured. Care should be taken to prevent resin entering the guide hole at the top of the instrument during casting.

Calibration

Calibration is carried out in the manner described by Fischer and Clarke (1994). The ploughmeter is laid on a flat surface with its bottom end overhanging by approximately 0.20 m so that all of the strain gauges are beyond the edge of the surface. This edge then acts as a pivot point. The ploughmeter is clamped at the pivot point, and at its far end using a bench vice and 'G'-clamp. The ploughmeter is then loaded by hanging weights as close to its tip as is practical. We used a metal bucket attached via a short climbing sling to achieve this. The ploughmeter is wired to a Campbell Scientific CR-10 datalogger and loaded incrementally. It is then rotated to the next angle, reclamped and reloaded. We used a total loading of 300 N in 10 N weight increments applied every fifteen degrees between 0° and 360°. We used an excitation voltage of 250 mV (Table 1) and averaged five measurements across each bridge at every load. A device that combines a protractor and plumb line allows us to rotate the ploughmeter with an accuracy of ±1°.

The data collected during calibration consists of voltage pairs from each bridge circuit at every load and rotation angle. Output from both bridges is required to define angle and load. Voltages V_{p1} and V_{p2} from the ploughmeter bridges at load L and rotation ϕ have been shown to fit surfaces of the form

$$P_1(L,\phi) = A_{p1} L \cos(\phi + B_p) + C_{p1} \tag{1a}$$

and

$$P_2(L,\phi) = A_{p2} L \sin(\phi + B_p) + C_{p2} \tag{1b}$$

(Fischer and Clarke, 1994); the constants A_{p1} and A_{p2} scale the amplitude of the predicted output at each load, B_p reflects the arbitrary choice of the device zero for rotation, and C_{p1} and C_{p2} represent the output at zero load. The calibration constants A_{p1}, A_{p2}, B_p, C_{p1} and C_{p2} are calculated by inverting the calibration data by repeated use of the procedure UNCMIN (Kahaner *et al.*, 1989, p. 370). Both surfaces are fitted simultaneously to minimise the fitting parameter E;

$$E = (P_1 - V_{p1})^2 + (P_2 - V_{p2})^2. \tag{2}$$

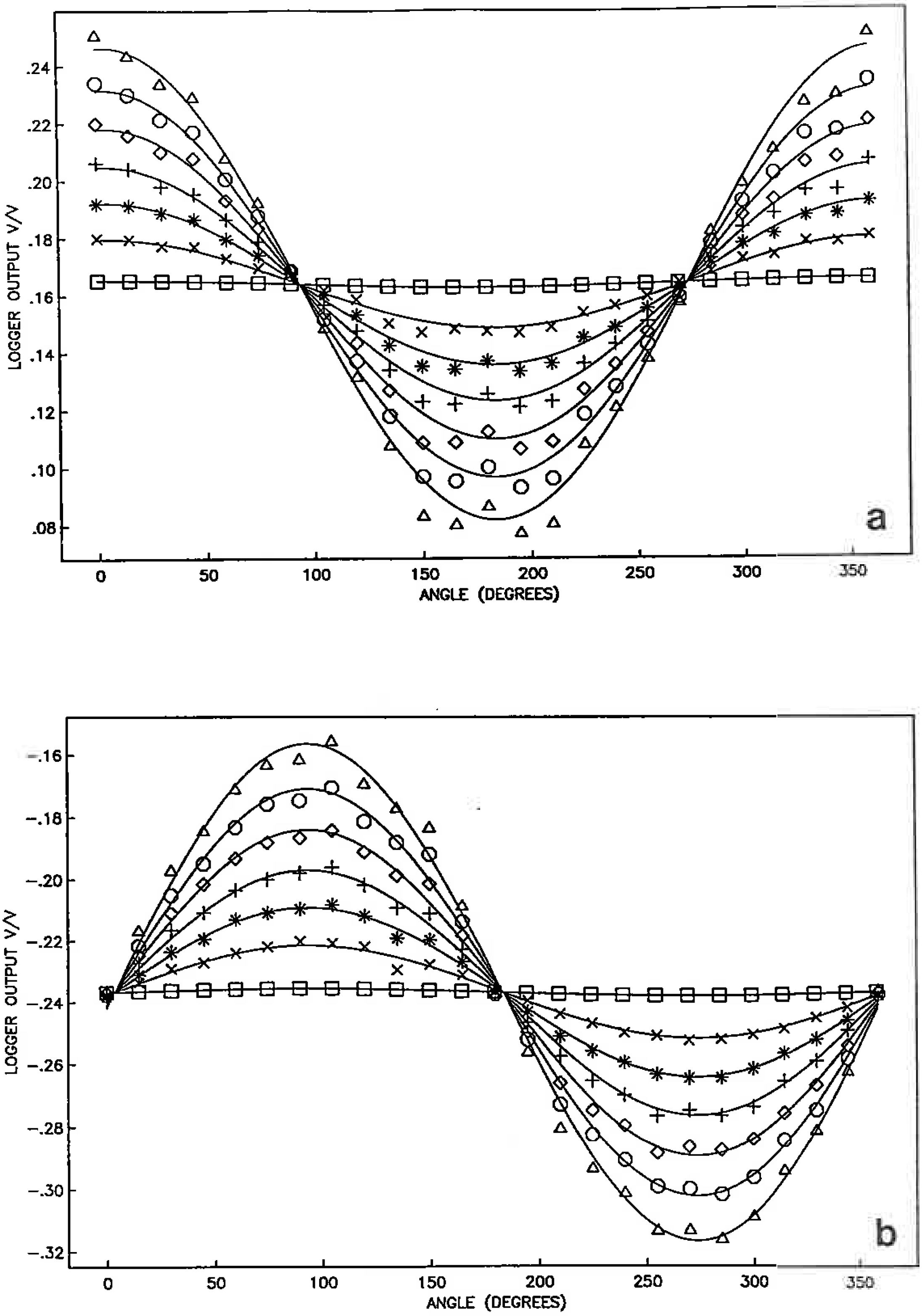

Figure 4. Sample output from a ploughmeter calibration. Calibration data are shown as points, and the fitted surface (equation 1) is shown as a series of sine and cosine curves cutting the surface at fixed forces. Both surfaces are fitted simultaneously so as to minimise the fit error (equation 2). (a) Output from bridge 1 and (b) output from bridge 2.

Once these parameters have been calculated the load and corresponding angle can be calculated from any voltage pair by simultaneous solution of equations $1a$ and $1b$. A sample calibration is shown in figure 4.

Sensor installation

To enable insertion of ploughmeters, the hammer finger is attached to the percussion hammer. The finger fits into the guide-hole drilled in the end of the ploughmeter, but the guide-hole is shorter than the length of the finger so that hammering applies force directly onto the steel rod of the ploughmeter. A minimum of two people are required to insert the device. The hammer and ploughmeter are placed beside the top of the bore-hole and the hammer wire and sensor cable are laid out side by side on the ice to a distance slightly greater than ice depth at the drilling site. One person then controls the hammer wire and instrument cable from the far end, while the second lowers the ploughmeter into the bore-hole holding the instrument cable. The hammer is then inserted into the guide hole of the ploughmeter by this person, who holds the weight of both hammer and sensor on the *instrument cable*. The full weight of both the hammer and device are taken on the instrument cable by the first operator, who walks slowly towards the bore-hole, still maintaining weight on the instrument cable and simply controlling the hammer wire. This procedure gently lowers the ploughmeter and hammer towards the bed, and ensures that the hammer finger remains in the guide hole. The output voltages from both bridges of the ploughmeter can be monitored using a datalogger during the hammering process.

Sample results

Bakaninbreen is a surge-type glacier situated in the high arctic archipelago of Svalbard. The glacier began surging in 1985, and a steep ramp has formed where fast moving active surge ice meets inactive stagnant ice (the surge front). The surge has continued through the period 1986-1994, and in 1994 a program to instrument the bed of the glacier with a combination of devices to investigate basal conditions, and the mechanisms of motion was begun (Murray and Porter, 1994). This program included extensive hot-water drilling and the installation of a suite of sensors to measure glacier basal motion both above and below the surge-front. Figure 5 shows the magnitude and direction of force recorded by three ploughmeters beneath Bakaninbreen. 94PL05 and 94PL04 were both installed above the surge-front and are subject to larger applied forces than 94PL02 situated below the surge-front, presumably due to the faster sliding of the surging ice resulting in higher ploughing forces. During drilling above the surge-front we experienced what we interpret to be several spatially extensive sediment horizons some 20–30 m above the bed. These englacial layers are thought to represent subsurface continuation of thrust features observed at the surface (Hambrey *et al.*, in press). 94PL04 was the first sensor installed above the

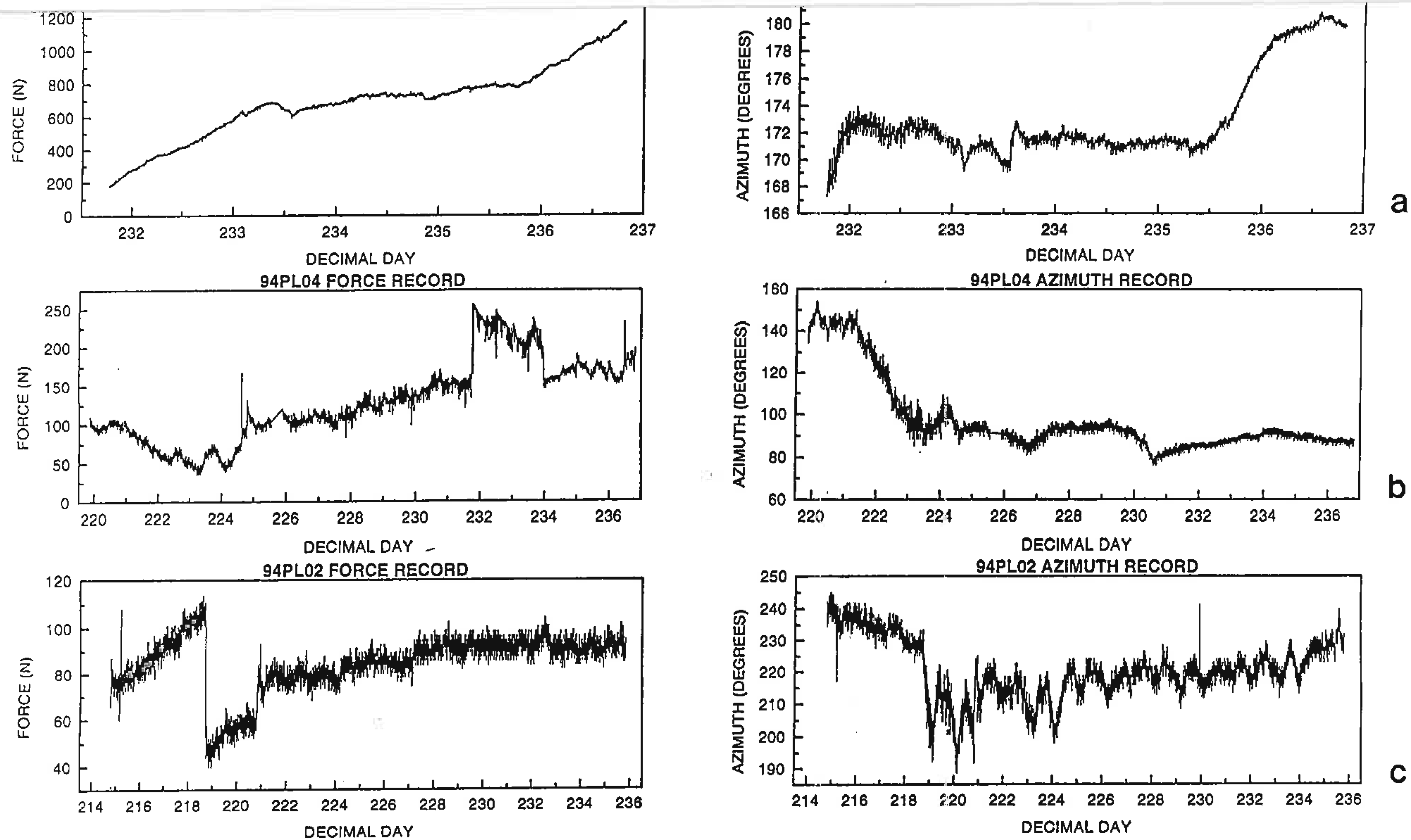

Figure 5. Sample ploughmeter records. (a) Force and azimuth records for ploughmeter 94PL05 inserted into basal sediments up-glacier of the surge-front at Bakaninbreen, Svalbard. (b) Force and azimuth records for ploughmeter 94PL04 believed to have been inserted into an englacial sediment layer. (c) Force and azimuth records for ploughmeter 94PL02 inserted into basal material at Bakaninbreen, Svalbard down-glacier of the surge-front.

surge-front. The hole drilled to accommodate this sensor reached a depth of 114 m which we initially believed to be the bed. The subsequent realisation that the bed is at a depth of approximately 120 m suggests that this sensor has not been installed at the bed, but is emplaced in an englacial sediment layer. The force experienced by this ploughmeter is also relatively low (Fig. 5b) indicative of slow relative displacement and thus possibly of placement in an active englacial thrust feature.

Interpretation

If we assume that the principal direction of forcing is down-glacier we can decompose the force record into down-glacier and cross-glacier components (Fig. 6). This calculation assumes that the ploughmeter is held rigidly in the glacier ice. An alternate interpretation would be to assign some, or all, of the variation in azimuth to instrument rotation. For example it might be reasonable to assign long term variations to rotation of the device, and short term variations to a genuine cross-glacier force component. This assignment can easily be made, and figure 6 also shows the effects of assigning 50% and 100% of the variation to rotation.

In order to determine the rheometric properties of the subglacial sediments an appropriate rheometric model must be used. If we assume that the basal sediment acts as a viscous fluid, then we can calculate an apparent viscosity for the material. An indenter ploughing through a viscous fluid experiences a distributed force, f, over its length which is proportional to the viscosity of the fluid, μ and the velocity of the indenter u,

$$f(z) = \mu u \mathcal{L}(a, c), \tag{3}$$

where $\mathcal{L}$ is a length scale which is a function of both the length of the indenter c, its radius a as well as its geometry. For an ellipsoid indenter the length scale $\mathcal{L}$ is given by

$$\mathcal{L}(a, c) = \frac{4\pi}{\ln(2c/a + 1/2)}, \tag{4}$$

whereas for a cylinder it is given by

$$\mathcal{L}(a, c) = \frac{2\pi}{\ln(2c/a)} \frac{2\ln(2c/a) - 1/4\ln[1 - a^2/c^2]}{\ln(2c/a) + 1} \tag{5}$$

(Fischer and Clarke, 1994). In order to equate this distributed force with the point loading used in the ploughmeter calibration we calculate the bending moment that results from each scenario at the position of the strain gauge. Then, since strain is proportional to this

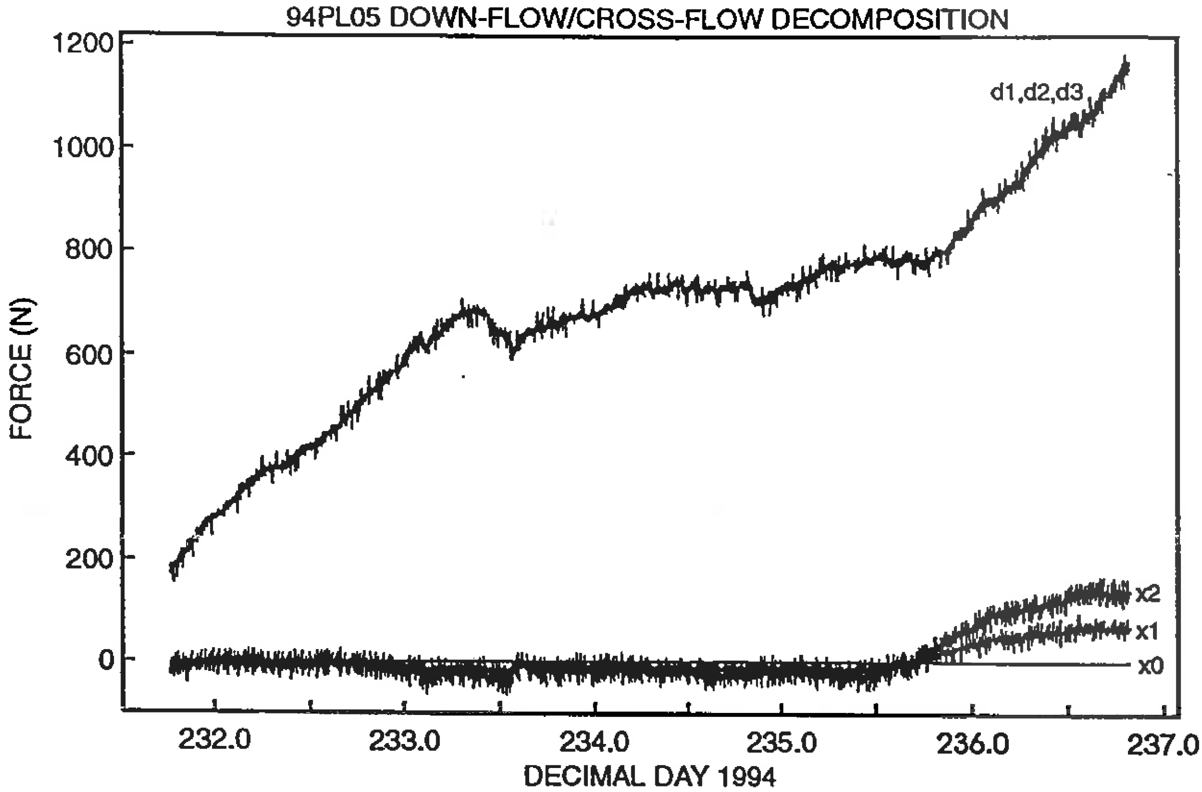

Figure 6. Down-flow / cross-flow decomposition of the force record for ploughmeter 94PL05, showing the effect of partitioning the force signal between rotation of the device and cross-flow motion. Such partitioning has virtually no effect on the down-flow component; traces d1, d2 and d3 are superimposed on top of one another. Cross-flow traces x1 and x2 are very similar in form, but differ in amplitude. Trace x0 represents 100% ploughmeter rotation, trace x1 represents 50% rotation and 50% cross-flow motion, and trace x2 represents 100% cross-flow motion.

moment, the output of the device will be equal for equivalent bending moments. Consider a ploughmeter of radius a inserted into the basal sediments to a depth c, with its strain gauges situated a distance z_g from its tip. The force distribution is given by equation 3, and either equation 4 or 5 depending on the assumed geometry, with the velocity u being the relative velocity between the ploughmeter and the bed material (Fischer and Clarke, 1994). If the glacier is moving by basal sliding alone, then for an ellipsoid geometry

$$\begin{aligned} M(c - z_g) &= \int_c^{c-z_g} f(z - (c - z_g))dz \\ &= \mu u \frac{4\pi}{\ln(2c/a + 1/2)} c z_g. \end{aligned} \tag{6}$$

During calibration the equivalent bending moment is given by

$$M(z_g) = L z_g, \tag{7}$$

such that the apparent viscosity of the till can be calculated from

$$\mu = L(u \frac{4\pi}{\ln(2c/a + 1/2)} c)^{-1}. \tag{8}$$

If the glacier basal motion is not comprised wholly by sliding, but sediment deformation is also occurring, then the relative velocity of the ploughmeter through the sediments will vary with depth. Assigning a portion of the basal motion to deformation will reduce u, and therefore increase the apparent viscosity of the till. To calculate an estimate of the viscosity of the basal till at Bakaninbreen we take the basal velocity to be equal to the average sliding velocity measured by a sliding sensor above the surge front, and use the force record for 95PL05 (Fig. 5). We obtain viscosity estimates that range from a minimum of 1.1x10^{10} Pa s (resulting from maximum insertion depth c, and minimum loading L) to a maximum of 4.3x10^{10} Pa s (resulting from minimum insertion depth c, and maximum loading L). By using the mean force experienced, and the mean insertion depth we obtain a mean basal sediment viscosity of 1.9x10^{10} Pa s. Because equation 3 incorporates the relative velocity between the ploughmeter and sediment we can calculate an approximate velocity for 95PL04 which is emplaced in englacial sediments. We assume that the rheology of these sediments is in the same range as those calculated for the basal sediments; the resulting relative velocity between sediment and ploughmeter is 0.02 - 1.6 ma^{-1}. We cannot distinguish between the cases of extrusion of sediment along the englacial feature, and movement of ice in a geometry similar to a thrust fault.

An alternative rheological model is that till is behaves as a Bingham fluid; in this case the yield stress of the material can be calculated. Again the bending moment of the distributed force experienced by the ploughmeter once it is inserted is equated to the equivalent calibration scenario. With the same geometry as previously described, the force distribution is given by

$$f(z) = 4a(2+\pi)k, \tag{9}$$

so that the bending moment at the position of the strain gauge is

$$\begin{aligned} M(c - z_g) &= \int_c^{c-z_g} f(z-(c-z_g))dz \\ &= 4a(2+\pi)kcz_g \end{aligned} \tag{10}$$

where k is the yield strength of the till (Fischer and Clarke, 1994); thus the yield strength of the till can be calculated from

$$k = \frac{L}{4ac(2+\pi)}. \tag{11}$$

Using these approximations the yield strength of the till at Bakaninbreen is 17–87 kPa, with a mean value of 29.9 kPa.

MEASUREMENT OF SLIDING: DRAG-SPOOLS

Drag-spools are simple devices used to give us an approximate indication of the rate of glacier sliding, helping us to partition glacier motion between sliding at the ice-bed interface and sediment deformation. Our 1994 and 1995 sensors were supplied by Icefield Instruments; final assembly and calibration were carried out in Leeds.

The drag-spool consists of a miniature multi-turn potentiometer attached to a spool around which is wound approximately three metres of thin nylon string. This string passes out through a perspex housing via a guide tube, and is attached to a brass insertion tip. This tip is anchored in the subglacial sediment, while the drag-spool itself remains frozen and fixed into the bore-hole. As the glacier moves over its bed the anchor remains fixed within the sediment and string is paid out from the spool as the displacement between the spool and anchor increases (Fig. 7a). This unspooling action turns the potentiometer and therefore alters its resistance. Using a half bridge arrangement, the resultant voltage change can be monitored and related to displacement. Differentiating the displacement with respect to time allows calculation of sliding velocity.

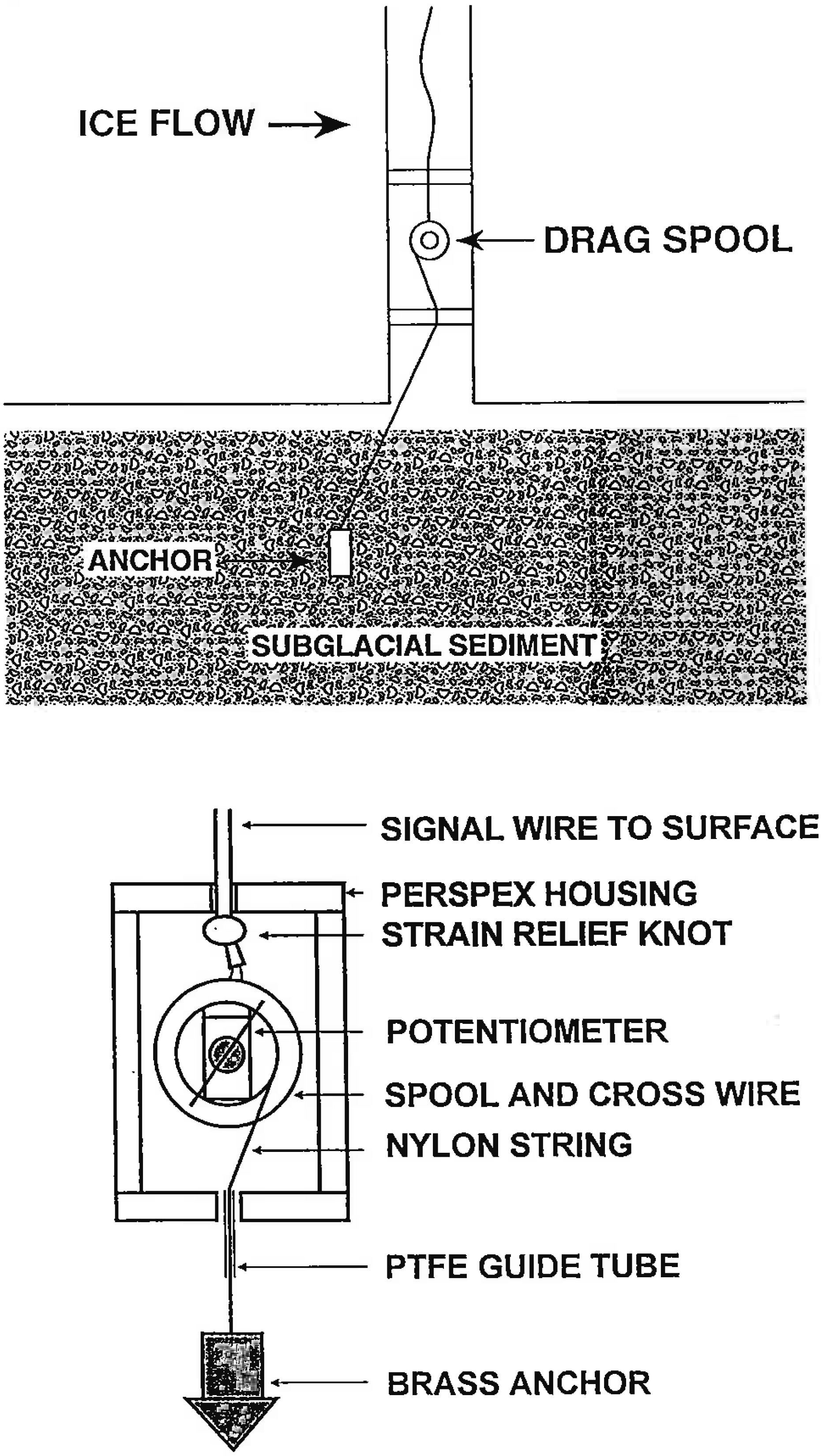

Figure 7. The subglacial drag-spool. (a) Drag-spool in place in bore-hole. The drag-spool remains in a fixed location in the bore-hole, while the anchor remains fixed in the glacier bed. As the glacier slides forward, string is paid out from the drag-spool. (b) Construction details of the drag-spool. As string is paid out in response to glacier sliding, the spool is turned altering the resistance of the miniature potentiometer. After: Blake *et al.*, 1994.

Construction details

At the heart of the drag-spool is a 25-turn 5 Ω miniature potentiometer. The potentiometer is situated at the centre of a spool, and is attached to the spool by a stiff wire fixed radially across the adjustment screw of the potentiometer (Fig. 7). The spool has a radius of 0.03 m and sits inside a small perspex housing. The string exits the perspex housing via a short length of PTFE tubing (R.S. 399-798) used to reduce friction and prevent chafing of the string. This tubing is glued into place using an epoxy adhesive. Two-core telephone cable (R.S. 368-485) is used to transmit signals to the glacier surface. The wire enters the drag-spool via a small hole in the top of the assembly, and is knotted to prevent the wire pulling out of the instrument. This hole is sealed with epoxy adhesive.

Calibration

Calibration is carried out with the full length of signal wire attached to the drag-spool. A three-metre tape is laid out along the bench, while the drag-spool, set to its lowest resistance, is clamped so that no movement can occur while the string is paid out. Sufficient string is left free to allow for the attachment of the insertion tip, and to allow the drag-spool housing to reach the top of the hammer finger when the insertion tip is placed on its end. The string is marked close to the drag-spool housing with insulating tape. The end of this tape is used as a reference point and is aligned with the zero mark on the measure. The sensor is wired as a half bridge to a Campbell CR-10 datalogger using a 1 kΩ precision resistor (R.S. 165-769) to complete the bridge circuit. This resistor should be the same resistor that will be used when the drag-spool is wired to the logger in the field. The string is then pulled out from the drag-spool, and the voltage recorded at each increment. We used an excitation voltage of 250 mV (Table 1), and paid out the string in increments of 0.01 m; our calibration uses the average of ten measurements at each increment. The relationship between displacement and output voltage is non-linear (Fig. 8) due to the non-linearity of the potentiometer and changes in the apparent radius of the spool as the string is unwound. We fitted these data to polynomial curves of increasing order until further improvement in the fitting parameter became negligible. The final form achieved was of eighth-order

$$D = \alpha_0 + \alpha_1 V + \alpha_2 V + ... + \alpha_8 V^8, \tag{12}$$

where D is string payout distance, $\alpha_1 ... \alpha_8$ are calibration constants, and V is the signal measured from the drag-spool (Fig. 8).

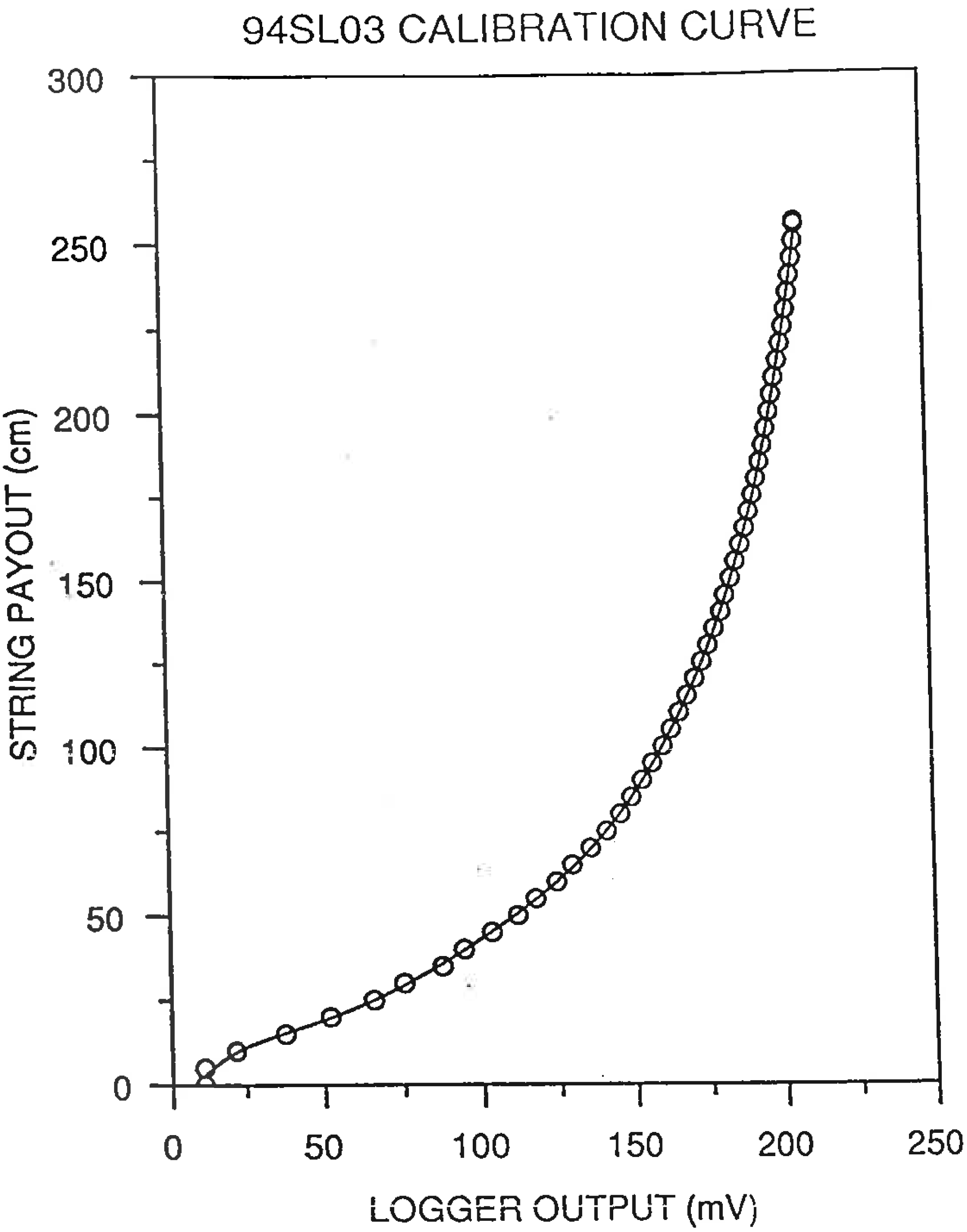

Figure 8. Sample output from calibration of a drag-spool. Calibration data are shown as open circles, and the fitted polynomial (equation 12) is shown as as a continuous line.

Sensor installation

Before insertion the drag-spool is prepared by packing the housing with a non-conducting grease (*e.g.*, Vaseline) to prevent water ingress and to lubricate the spool. The cover plate is then firmly taped onto the drag-spool housing, and a hollow guide tube with a slightly larger diameter than the insertion finger is taped onto the housing. This procedure is carried out in the field in case the string becomes unspooled during transit, and can be repeated if the sensor insertion is unsuccessful. For the insertion the hammer finger is attached to the percussion hammer. The hammer finger is fed through the guide tube, and the insertion tip is tied onto the drag-spool string so that once the tip is placed onto the end of the hammer finger the string is taut. The hammer wire and instrument cable are laid out and controlled in a similar manner as for ploughmeter insertion, however, the instrument cable is not strong enough to support the weight of the hammer and so the hammer and instrument are lowered down the bore-hole holding the weight on the ***hammer cable***. It is essential that the instrument cable is held taut as the hammer is lowered into the bore-hole so that the tip does not fall off the finger as the hammer and instrument are lowered; it may be easiest for a person standing at the bore-hole to control this second cable as the first operator walks towards the hole. The instrument cable should also be kept taut as the hammer is raised back up the bore-hole to reduce the risk of the hammer snagging the cable resulting in the possibility of either pulling the tip out of the bed, or tearing the drag-spool from its anchor. During the insertion procedure, the resistance of the potentiometer is monitored to observe any string payout that may occur. Finally, to complete the insertion, the instrument cable is gently raised until the device resistance rises slightly to ensure that the tip has 'caught' in the subglacial sediment. Inevitably, a few centimetres of string become unspooled during this procedure. The instrument cable is then anchored taut, by tying it to an ice screw, until the drag-spool and cable become frozen into the bore-hole.

Sample results and interpretation

Once installed the drag-spool is a one-way instrument; string can be pulled from the spool, but cannot be fed back into the instrument case. For this reason the resistance of the instrument, and hence measured voltage, should be an increasing function of time. However field readings show some periods of time when the voltage decreases (Fig. 9), although the overall signal increases with time. These periods suggest that the signal is subject to noise, which is perhaps most likely to be thermal in origin. We therefore process the data in such a way as to remove any periods of voltage fall. Note that these periods do not correspond to up-glacier flow; any increase in relative displacement, regardless of direction, will increase the signal; any decrease in displacement would be recorded as a constant signal level.

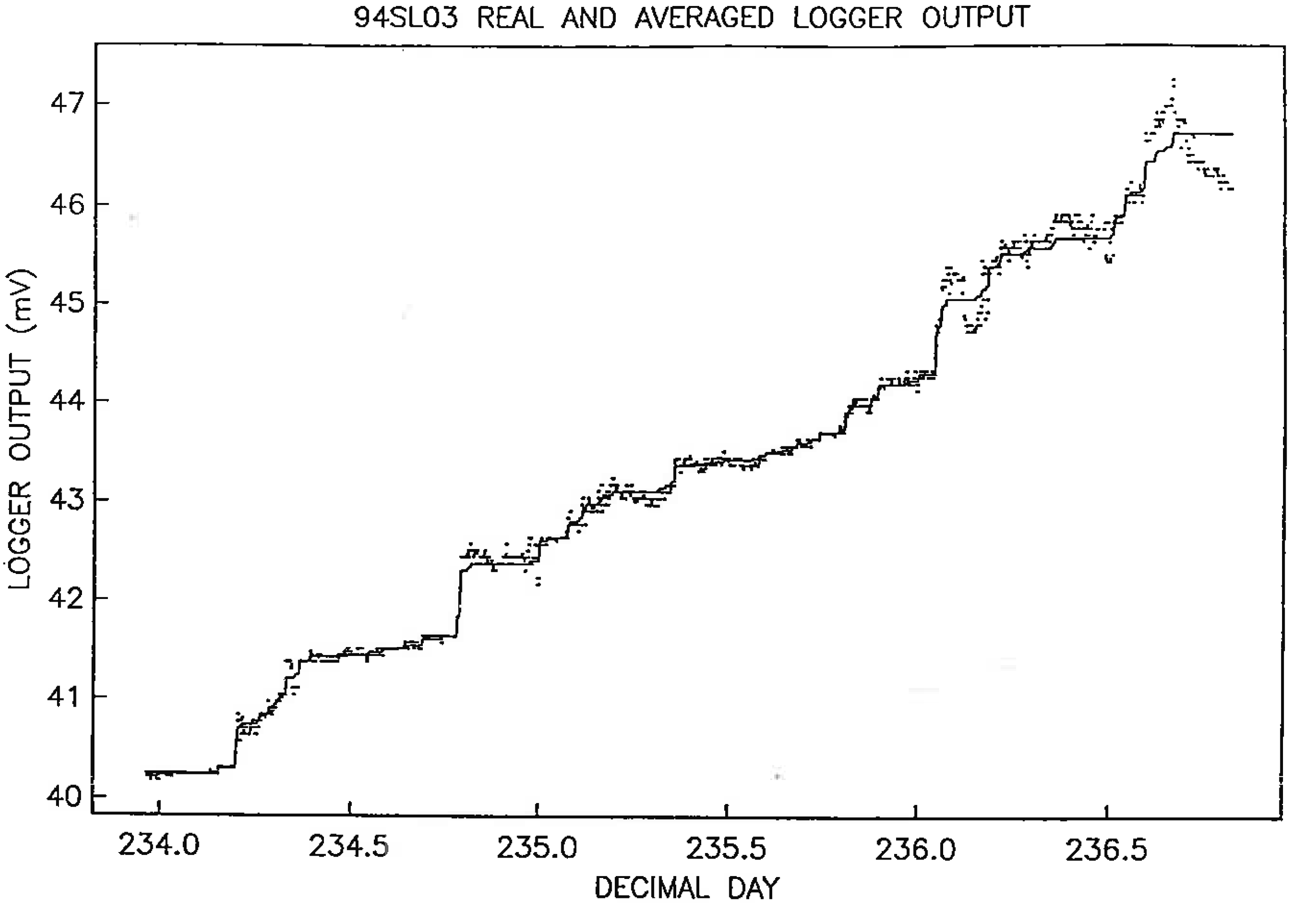

Figure 9. Drag-spools can produce a noisy signal. Raw field data (individual points) and fitted average (solid line), details of this averaging procedure are given in the main text.

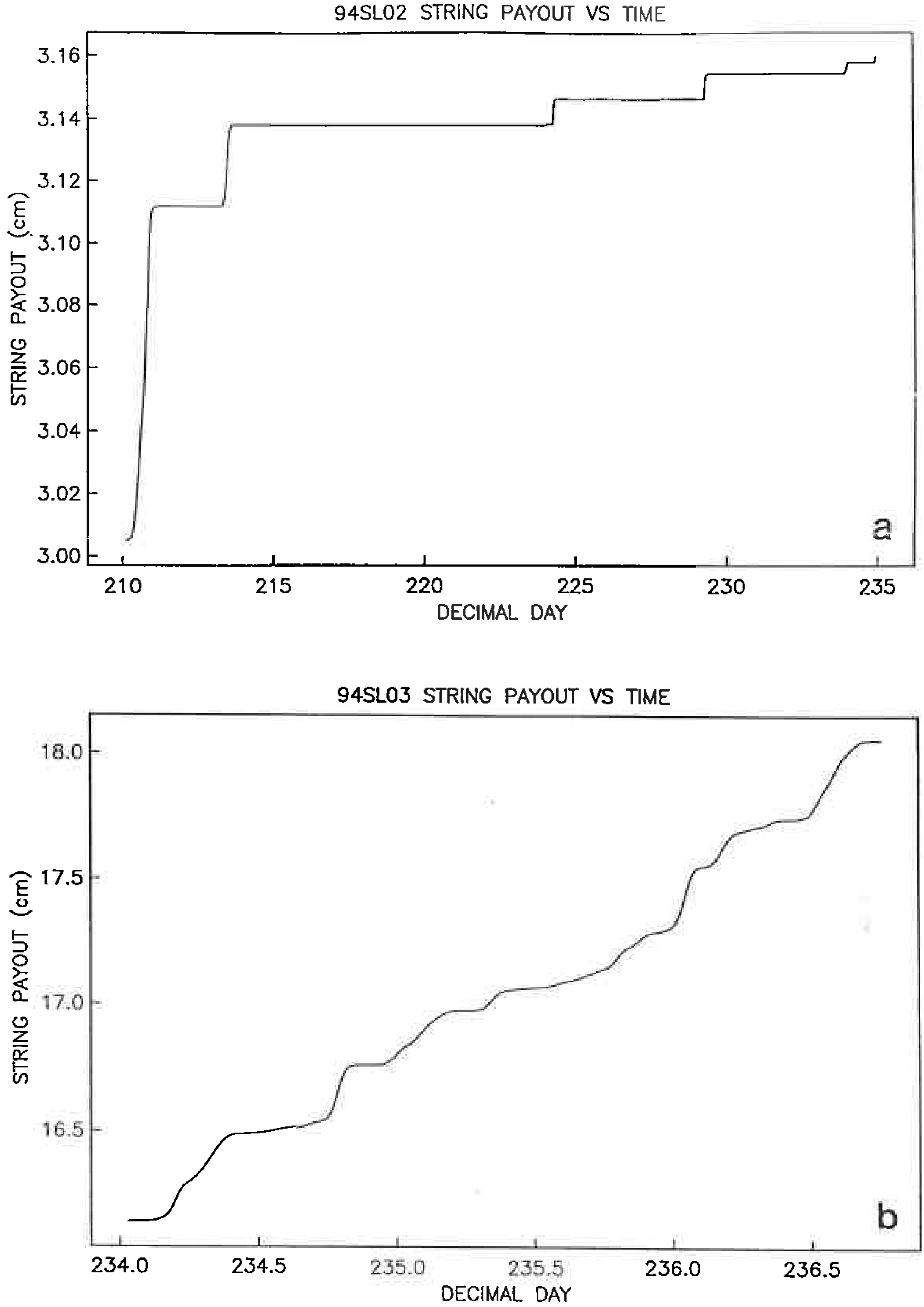

Figure 10. Sample string payout (a) drag-spool 94SL02, situated down-glacier of surge-front and (b) drag-spool 94SL03, situated up-glacier of surge-front.

Therefore to remove this noise, three strictly increasing lines are fitted through the data in the following manner (Fig. 9). First, the most rapidly increasing displacement is calculated. The basis of this line is that it increases immediately the data increase, and once a level is reached the line is not allowed to fall again. Second, the least rapidly increasing displacement is calculated. The basis of this line is that it does not rise until all the remaining data is above that level. The average of these two lines is then used to place a third line through the data that represents our best fit of a strictly increasing function through them. This third line is the one we use in subsequent calculations. String payout distances can then be calculated using equation 12. These values can be used to calculate sliding rate. A gaussian smoothing filter, normalized to prevent data rescaling, is applied to remove sharp steps resulting from the averaging process. We then use a standard three-point centred-difference operator to calculate the differential and hence sliding rate. Errors in the calculated sliding rate could result from two effects. First, any deformation of sediment between the base of the glacier and the depth of anchor insertion will cause additional string to pay out and thus increase calculated sliding rate. Second, if the anchor ploughs through the basal sediments the calculated sliding rate will be decreased. In common with Blake *et al.* (1994) we believe that the force required to release string from the spool is so low that the second effect will be negligible. Thus we believe our sliding rate to be a maximum value.

At Bakaninbreen, string payout rates (Fig. 10), and therefore sliding rates, are considerably higher above the surge-front where surging ice is moving down-glacier. The total string payout from a drag-spool located below the surge-front over a seventeen day period was 0.15 cm (Fig. 10a). Above the surge-front, a total string payout of 1.92 cm over a three day period was observed (Fig. 10b). Sliding rates above the surge-front are consistently higher when compared with the record from drag-spools located below the surge-front.

THE NATURE OF THE ICE-BED INTERFACE

In our discussion above we have depicted a glacier bed where a clear distinction can be made between clean glacier ice and basal sediments; the reality is likely to be much less distinct. First basal ice is unlikely to be clean, especially where the glacier overlies a sedimentary bed; basal material will be incorporated into bulk glacier ice by a number of mechanisms including thermal accretion, sliding by regelation, folding, faulting, and thrusting. Thus, even beneath a warm-based glacier the ice–sediment transition may be gradual rather than abrupt. The vertical extent of basal ice containing dispersed or stratified sediments varies with glacier dynamic and thermal regime, but may be up to tens of metres (Hubbard and Sharp, 1989). Because of potentially high, and often stratified, sediment content some doubt as to sensor placement at the bed must always exist. Furthermore the rheology of basal ice is both highly variable and anisotropic. Because of these factors care should be taken in the interpretation of results from sensors such as those we have described. Notwithstanding these cautions, our understanding of glacier basal motion can only be increased by bore-hole instruments such as those we have described.

CONCLUSION

We hope that this paper has provided sufficiently detailed information to allow others to construct and install subglacial sensors of similar design. The use of these subglacial sensors *in situ*, especially in combination with measurements of hydraulic pressure at the bed and surface velocity measurements, will give a valuable insight into the mechanical and hydraulic conditions at the base of any glacier.

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Campbell CR10 Ploughmeter Calibration Program Instruction:

Instruction Number P6: Full Bridge.

Parameter Number:	Description:
01:1	1 Repetition .
02:1	2.5 mV slow rejection range.
03:1	Logger input channel number 1.
04:1	Excitation channel number 1.
05:250	250 mV excitation voltage.
06:3	Input location 3 for first measurement.
07:1	Multiplier of 1.
08:0	Offset of 0.

a

Campbell CR10 Drag Spool Calibration Program Instruction:

Instruction Number P4: Excite, Delay, and Measure

Parameter Number:	Description:
01:1	1 Repetition .
02:34	250 mV 50 Hz rejection range.
03:1	Logger input channel number 1.
04:1	Excitation channel number 1.
05:50	Delay in hundredths of a second (half a second).
06:250	250 mV excitation voltage.
07:3	Input location 3 for first measurement.
08:1	Multiplier of 1.
09:0.0	Offset of 0.

b

Table 1. Campbell Scientific CR-10 datalogger commands to run (a) ploughmeter and (b) drag-spool.

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