Influence of subglacial drainage conditions on the velocity distribution within a glacier cross section

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ABSTRACT

Substrate properties and hydrological conditions at the base of Haut Glacier d'Arolla, Switzerland, are nonuniform. The thickness and grain size of subglacial sediment vary on length scales less than one ice thickness, whereas hydrological conditions vary seasonally and on length scales of about one ice thickness transverse to ice motion. There is a close relationship between the annually averaged velocity field and this nonuniformity of bed conditions. Basal motion dominates in an area with large water-level variations in boreholes, whereas ice deformation contributes significantly to total movement elsewhere. Localized enhanced basal motion occurs primarily in summer, especially during a July "spring event," but this motion is barely discernible in annually averaged surface velocity measurements, because transverse coupling suppresses surface expression of the basal motion discontinuity. These results highlight the need to include representations of bed nonuniformity in models of glacier flow and to consider ice deformation and basal motion as interdependent processes.

INTRODUCTION

Glacier movement is the sum of ice deformation, basal sliding, and deformation of subglacial sediments (Paterson, 1994). Rates of basal sliding and bed deformation are commonly modeled as a function of locally defined variables such as basal shear stress and subglacial effective pressure (Iken, 1981; Boulton and Hindmarsh, 1987), and cross-section flow simulations have assumed these variables are constant or vary only gradually in space and time (Nye, 1957; Reynaud, 1973; Harbor, 1992). However, borehole investigations show that substrate and subglacial hydrological conditions vary substantially and nonuniformly over length scales from less than one ice thickness to several ice thicknesses (Hantz and Lliboutry, 1983; Fountain, 1994; Fischer, 1995; Hubbard et al., 1995; Murray and Clarke, 1995; Smart, 1996). Hydrological conditions also vary on time scales from hours to years, as a function of changes in the configuration of subglacial drainage systems and variations in water inputs from surface melt and precipitation. These variations should affect rates of basal motion and create longitudinal and transverse stress gradients in the overlying ice. These stress gradients will influence rates of ice deformation and may create bridging effects that modify rates of basal motion across large areas of a glacier. In this case, the three motion processes cannot be regarded as independent, nor will they be driven only by local controls.

Although the importance of flow coupling through longitudinal stress gradients is widely recognized (Kamb and Echelmeyer, 1986), spatially and temporally variable transverse stress gradients have rarely been considered (Raymond, 1996). Before models that account for stress gradients arising from temporally and spatially variable basal motion (Hutter and Olunloyo, 1980; Balise and Raymond, 1985; Bahr and Rundle, 1996; Raymond, 1996) can be widely used, it is necessary to understand the length scales and causes of spatial variability in rates of basal motion. Appropriate distributions and scales of bed nonuniformity can then be prescribed as basal boundary conditions. As a step toward tackling this problem, we have investigated the influence of spatially variable bed properties and subglacial drainage conditions on the annually averaged velocity distribution within a transverse cross section of an alpine glacier.

FIELD SITE AND METHODS

Haut Glacier d'Arolla, Switzerland, is a 4-km-long, temperate valley glacier with a maximum thickness of about 180 m (Sharp et al., 1993; Fig. 1). Investigations of the glacier's hydrology and dynamics have included borehole studies of substrate and subglacial drainage conditions (Hubbard et al., 1995; Copland et al., 1997a; Gordon et al., 1997) on the eastern side of the glacier 1.5 km above the terminus (Fig. 1).

From 1992 to 1996, 121 boreholes were drilled with high-pressure hot water, most reaching the glacier bed. The glacier substrate was investigated by bed penetrometry, borehole video (Copland et al., 1997a), and observations in basal cavities and at the glacier margin. The distribution of borehole water levels (taken to indicate subglacial water pressures) was determined by manual measurements with an electrical conductivity probe (Ketterling, 1995) and continuous measurements with pressure transducers (Hubbard et al., 1995; Gordon et al., 1997). Glacier surface velocities were determined from repeat surveys of borehole tops and of stakes with permanently mounted reflector prisms (Fig. 1). Survey accuracies were ±6.5 to ±17 mm over the distances surveyed. The annual velocity distribution within the glacier was determined by repeat profiling (in August 1995 and 1996) of eight boreholes with a magnetically oriented borehole inclinometer (Blake and Clarke, 1992). Measurements were made at 1 m depth intervals, with a positional error of ≤0.5% of ice depth (Copland et al., 1997b). Boreholes were re-

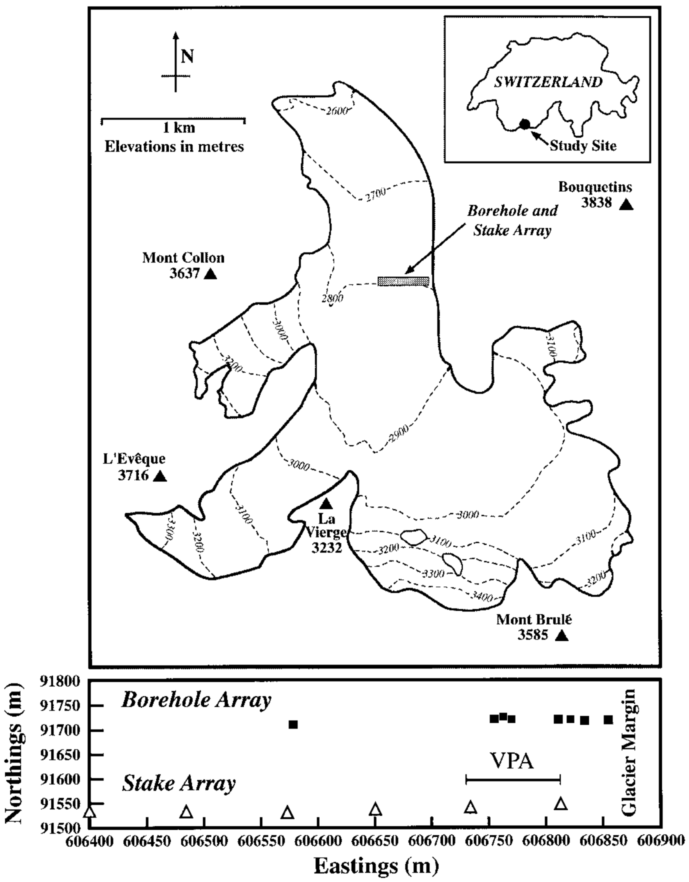

Figure 1. Map of Haut Glacier d'Arolla (lat 46°0′N, long 7°30′E), showing locations of stake and borehole arrays used to construct Figure 2 and the general position and extent of the variable pressure axis (VPA).

established in 1996 using cable-following drilling methods, but breakage and tangling of cables meant that only four boreholes reached within 5 m of the bed. All other boreholes were reopened to at least 50% of their original depth.

SUBSTRATE PROPERTIES

The nature of the glacier bed may influence basal motion processes, and substrate nonuniformity may cause spatial variations in basal motion rates (Bahr and Rundle, 1996; Fischer and Clarke, 1997). Bed penetrometer studies in six boreholes indicate up to 0.26 m of penetrable, unconsolidated sediment, and video observations in three boreholes show a bed of fine sediment with some larger clasts (Copland et al., 1997a). High turbidity at the base of many boreholes precluded more widespread observation of the bed but also suggests an underlying fine-grained substrate.

On the basis of turbidity variations and the rate of propagation of diurnal water-pressure waves away from the inferred location of a major subglacial channel, Hubbard et al. (1995) argued that sediments near the channel had been winnowed of fine-grained sediment. Penetrometer tests provide support for this idea, because penetration depths were 0.05–0.10 m in the channel region and >0.2 m to the east and west. Lower penetration depths may indicate a coarser or thinner sediment layer. Borehole observations therefore indicate that the glacier rests on an unlithified bed, and that the thickness and grain size of the sediments are spatially variable. Observations at the glacier margin, however, reveal striated and polished bedrock surfaces protruding through a layer of till. This suggests that the bed consists of sediment patches interspersed with bedrock bumps. Observations at the ice margin suggest that the length scale of these substrate variations is less than one ice thickness.

BOREHOLE WATER LEVELS

Borehole records from summer 1993 (Hubbard et al., 1995; Gordon et al., 1997) apparently show that large areas of the glacier bed had high and invariant water levels. Boreholes with significant diurnal variations were concentrated in a "variable pressure axis" (VPA, Hubbard et al., 1995, Fig. 2A). Water levels at the VPA center varied diurnally between minima at or near atmospheric pressure and maxima in excess of the local ice overburden pressure. With increasing distance from the VPA center, diurnal water-level minima rose and the maxima and/or amplitude of diurnal variations declined, until regions of stable, high-water levels were reached (Fig. 2A). Hubbard et al. (1995) argued that this pattern indicated a major subglacial channel at the VPA center. The VPA developed in the same area in four additional summers (1992, 1994–1996), although its width varied from ~70 m in 1995 to ~140 m in 1993 (Gordon, 1996).

At the end of the 1995 melt season, daily mean water levels rose rapidly in boreholes in the VPA. This occurred in late August on the eastern side of the VPA, but progressively later closer to the VPA center. Here it was preceded by four to five weeks of very low water levels following the cessation of surface melt. This suggests a progressive reduction in VPA width at the end of the melt season. After the melt season, water levels remained more or less constant, with minimal diurnal variability until at least mid-May 1996 when mean daily water levels began to fluctuate again and diurnal variability increased.

Thus, observations of borehole water levels suggest that the glacier bed is hydrologically nonuniform. Although large areas were subject to high and relatively constant water levels, a more restricted area showed diurnally variable water levels on a seasonal basis. This latter area appeared to be associated with a major subglacial drainage channel and is relatively narrow in a cross-glacier direction. As subglacial water pressure is believed to influence rates of basal motion (Iken and Bindschadler, 1986), and water-pressure variability can promote elastic stick-slip behavior beneath thin, gently sloping glaciers (Bahr and Rundle, 1996; Fischer and Clarke, 1997), nonuniform hydrological conditions at the bed should be reflected in the form of the velocity field within the overlying glacier.

ANNUAL VELOCITY DISTRIBUTION

The annually averaged velocity field included a classic parabolic pattern of surface velocities, with a broad area of relatively high velocities close to the centerline and a rapid decrease in velocity near the margin (Fig. 2, C and D). At the surface and at depth, the azimuth of the horizontal velocity vector lay within ±5° of the down-glacier direction in all but one borehole adjacent to the margin, in which a 40° rotation of the velocity vector with depth probably reflects motion past a bedrock bump on the valley side.

On either side of the VPA, both ice deformation and basal motion contributed to glacier motion, and there were strong vertical gradients in horizontal velocity in the lower 40%–50% of each profile (Fig. 2D). To the west of the VPA, basal motion exceeded 4m/yr and varied little across the glacier. To the east of the VPA, basal motion declined rapidly over a distance of about 100 m from ~8 m/yr at the edge of the VPA to <2 m/yr at the glacier margin. Within the VPA, basal motion dominated glacier flow and ice deformation was minimal (Fig. 2D). Peak velocities apparently occurred at about 50% of ice depth, and vertical gradients in horizontal ice velocity were minimal. Under worst-case error assumptions for the inclinometry, the apparent increase in velocity with depth in the upper 50% of the profile would be negligible, but the data would still show a clear basal sliding anomaly with an area of overlying ice that has minimal vertical variations in horizontal velocity. Although rates of basal motion in the VPA were substantially higher than surrounding areas, this difference is barely reflected in the surface velocity distribution. Transverse coupling between adjacent areas undergoing different rates of basal motion apparently induced compensating deformation patterns in the overlying ice, which suppressed any surface expression of the basal motion discontinuity.

SEASONAL AND SHORT-TERM SURFACE VELOCITIES

Surface velocities were measured at seasonal and short-term time scales during 1994–1995 along a transverse profile 180 m upglacier from the borehole array (Fig. 2B). Summer-averaged velocities were substantially greater than annually averaged and winter-averaged velocities, particularly in the VPA. 14% of the additional summer displacement occurred during a "spring event" in early July 1995, which lasted only 6% of the melt season. Maximum surface velocities during this event occurred in the region of enhanced basal motion identified by borehole inclinometry. This suggests that enhanced basal motion at an annual time scale is a consequence of events that occurred during the summer melt season, and that the annually averaged velocity distribution integrates the characteristics of quite different distributions developed at subannual time scales.

SYNTHESIS

Studies at Haut Glacier d'Arolla demonstrate that the glacier bed must be considered nonuniform at a range of spatial and temporal scales. Substrate characteristics appear to change at length scales of less than one ice thickness, and hydrological conditions vary on length scales of about one ice thickness in a direction transverse to ice flow. There may be some correlation between the distribution of subglacial drainage channels and the thickness and grain size of subglacial sediments. Although the extent of hydrological nonuniformity is seasonally variable, it exerts a major control on rates and processes of glacier motion. Basal motion occurred across the entire area of glacier bed mapped, but was enhanced in a narrow area which experienced large summer diurnal water-level fluctuations with peaks in excess of the local ice overburden pressure.

Surface velocity increased during the summer, especially during a spring event, when motion was clearly enhanced within the VPA. This suggests that the region of enhanced basal motion apparent in the annually averaged velocity distribution was largely a product of summer conditions. Although there were strong transverse variations in motion at the bed, such variations were barely discernible in the annually averaged surface velocity distribution. Transverse coupling between adjacent areas with contrasting rates of basal motion induced compensating patterns of deformation in overlying ice, reducing the amplitude of the motion discontinuity with increasing height above the glacier bed. This transverse coupling probably played an important role in increasing the summer velocity of ice in areas outside the VPA.

DISCUSSION AND CONCLUSIONS

Rates of basal glacier motion are believed to depend on subglacial water pressure, so maximum velocities would be expected in areas with water levels continuously in excess of the local ice overburden pressure. At Haut Glacier d'Arolla, basal motion was dominant in areas with highly variable summer water pressures, while ice deformation was also important in the areas with apparently high and constant water levels (Fig. 2). This discrepancy may be resolved if high and invariant borehole water levels do not provide a true measure of subglacial water pressure. If the transmissivity of the drainage system at the base of a borehole is too low to allow outflow of water introduced during drilling or from surface or englacial inputs, boreholes will remain full of water and will provide a misleading measure of subglacial water pressure.

Given that the effects of locally enhanced basal motion were apparently transmitted to adjacent areas via transverse coupling, it is evident that models of glacier flow should include some representation of the nonuniform hydrological conditions that are associated with this enhanced motion (Alley, 1996). There is also a need to clarify the relationship between subglacial water pressures and rates of basal motion. At present, it is not clear whether it was water pressure magnitude or water pressure variability that was re-

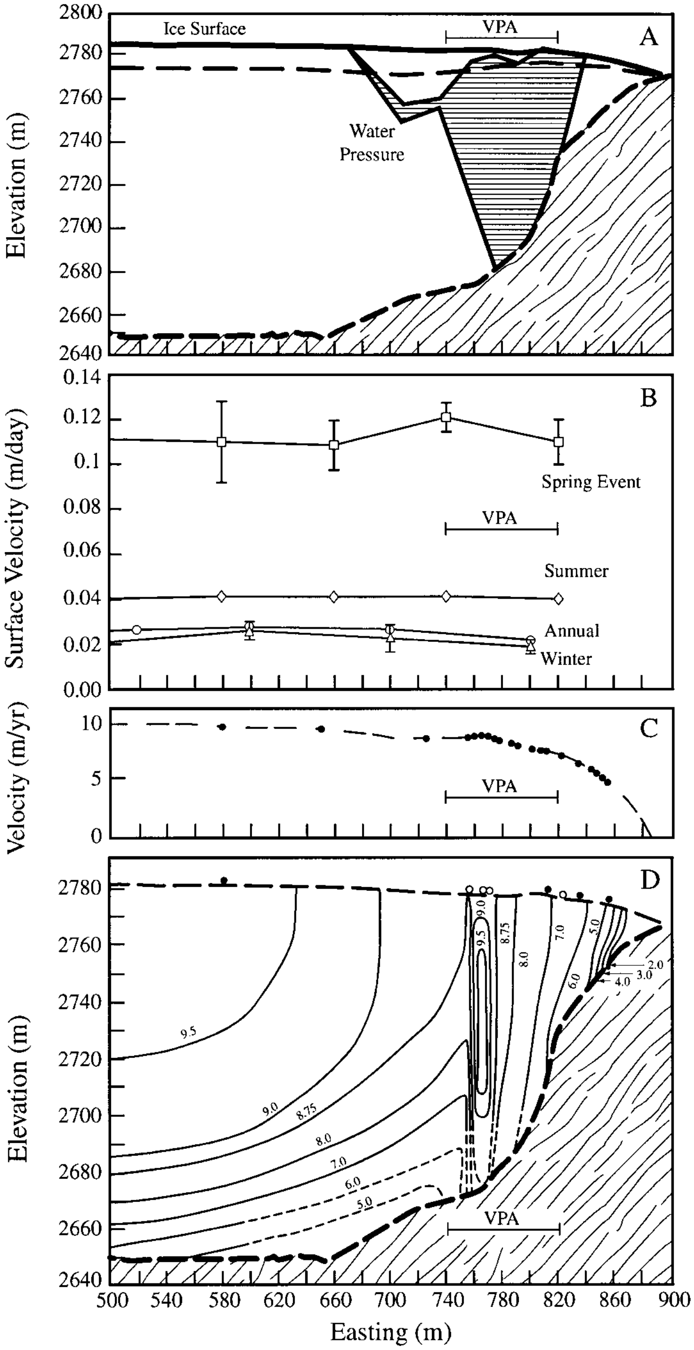

Figure 2. A: Half cross section of Haut Glacier d'Arolla at northing 91699. Shaded area defines range of maximum and minimum borehole water levels recorded on 17 August 1993. Dashed line represents local ice overburden pressure (in metres of water). B: Distribution of surface velocity based on surface stake measurements at annual, summer (22 June–27 August), winter (3–6 February), and spring-event (2–4 July) time scales in 1995, and approximate location of the variable pressure axis (VPA). Measurements were made along a transect at northing 91520 and are of the horizontal component of velocity in the flow direction. Summer and annual velocities have error bars smaller than the symbol size used to plot data points. C: Annual horizontal surface velocity based on displacements of borehole tops. D: Distribution of annually averaged (August 1995–August 1996) horizontal velocity within the half cross section at northing 91700. Note that only the last three digits of eastings are given and full values start with 606. Solid contours are well constrained by borehole data; dashed contours are extrapolated from boreholes that did not reach the glacier bed. Circles indicate positions of the tops of boreholes used in constructing the velocity contours. Solid circles are boreholes with data reaching close to the bed; open circles are boreholes with data extending at least 50% of ice depth, but not to the bed.

sponsible for enhanced basal motion. If subglacial water pressure magnitude is the control, then conventional wisdom suggests that basal motion should be maximum with high subglacial water pressure, because the glacier may decouple from its bed and slide relatively rapidly (cf. Iverson et al., 1995). However, the data do not rule out the possibility of maximum basal motion during subglacial water pressure minima when the glacier may be well coupled to its bed and able to readily deform subglacial sediments.

The velocity distribution depicted in Figure 2D differs from that found by Raymond (1971) at the Athabasca Glacier, Canada, although both show a combination of basal motion and internal deformation near the glacier centerline, with basal motion dominating near the glacier margin. The distinctive feature of the Haut Glacier d'Arolla data is the narrow zone of high basal motion in the region of the VPA. An important issue is whether this type of feature might also be present in other glaciers. Significant spatial variations in basal velocities apparently produce no discernible disruption of the classic parabolic pattern of annually averaged surface velocities (Harbor, 1992), so narrow zones of high basal velocity cannot be easily detected from annually averaged surface velocities. The only other borehole data for a glacier cross section, the Athabasca Glacier data, did not extend to the margins where features analogous to the VPA have been found on other glaciers (Hantz and Lliboutry, 1983; Fountain, 1994; Smart, 1996). Interestingly, attempts to model cross-section ice motion patterns using Athabasca Glacier data for calibration required adjustments of the basal boundary condition near the glacier margin (Reynaud, 1973; Harbor, 1992).

In conclusion, results from Haut Glacier d'Arolla provide new insight into both the form and controls on cross-sectional patterns of basal motion and internal deformation for a temperate valley glacier. The ice-motion pattern described here (Fig. 2) includes localized enhanced basal motion near the glacier margin in the region of what is believed to be a major subglacial channel. The marginal zone has not been closely studied in previous empirical work on valley glaciers, yet is critical in flow modeling. The Haut Glacier d'Arolla marginal zone appears to behave very differently from the simple variation in conditions often assumed in previous models.

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