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Glacier hydromechanics: early insights and the lasting legacy of three works by Iken and colleagues

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ABSTRACT. The association between basal hydrology and glacier sliding has become nearly synonymous with the early work of Almut Iken and colleagues. Their research published in the *Journal of Glaciology* from 1981 to 1986 made an indelible impact on the study of glacier hydromechanics by documenting strong correlations between basal water pressure and short-term ice-flow variations. With a passion for elucidating the physics of glacier-bed processes, Iken herself made fundamental contributions to our theoretical and empirical understanding of the sliding process. From the theoretical bound on basal shear stress, to the inferences drawn from detailed horizontal and vertical velocity measurements, the work of Iken and colleagues continues to inform the interpretation of data from alpine glaciers and has found increasing relevance to observations from the ice sheets.

INTRODUCTION

Hydromechanical processes operating at the glacier bed are responsible for some of the most intriguing ice-flow phenomena, including glacier surging (e.g. Kamb and others, 1985) and ice streaming (e.g. Alley and others, 1986). Since its inception, the *Journal of Glaciology* has been a repository for works addressing glacier hydromechanics with such seminal contributions as those of Weertman (1964), Lliboutry (1968) and Budd and others (1979). Among the most influential and highly cited works on this topic are several by Almut Iken and colleagues dating to the 1980s. These pioneering works collectively examine the intimate coupling between basal hydrology and ice dynamics and its power to explain measurable phenomena, such as seasonal uplift of the glacier surface (Iken and others, 1983) and short-term variations in glacier flow speed (Iken, 1981; Iken and Bindschadler, 1986). In celebration of the publication of the 200th issue of the *Journal of Glaciology*, we look back at the insights hatched in these three papers and trace their influence to the present day. These works remain staples for those with a passion for alpine glacier dynamics and are being rediscovered by those seeking to unravel some of the ice-sheet observations so newsworthy in recent years.

BACKGROUND AND CONTEXT

At the time the work of Iken and colleagues was published, it had been over 20 years since Weertman (1957) introduced his sliding theory based on regelation and enhanced creep around obstacles at the bed. The notion of sliding as a contributor to overall glacier motion had been recognized previously (e.g. Gerrard and others, 1952; Haefeli, 1957), with its study dating back to the mid-1800s (Hopkins, 1845, 1849). Lliboutry (1958) introduced ice–bed separation (cavitation) into sliding theory, thus formally admitting a primary role for basal water pressure. Weertman's (1964) work became the basis for a sliding law of the form $u = C\tau^p/N^q$ (e.g. Budd and others, 1979; Bindschadler, 1983; Fowler, 1987), still in use today, with sliding speed u, constant C which depends on bed geometry, basal shear stress τ, effective pressure N and positive constants p and q often set to 3 and 1, respectively. Subsequent work in the late 1960s and 1970s would generalize sliding theory and extend it to a variety of idealized bed configurations (e.g. Nye, 1969, 1970; Kamb, 1970; Morland, 1976a; Fowler, 1979).

At the same time, a variety of conceptual models of englacial and subglacial water flow were emerging that would shape our picture of glacier drainage for decades to come. The year 1972 alone saw the publication of theories describing water flow along englacial potential gradients (Shreve, 1972), in a thin film at the bed (Weertman, 1972) and in ice-walled conduits (later 'R-channels') (Röthlisberger, 1972). These works were contemporaneous with the early studies of jökulhlaups (e.g. Björnsson, 1974; Nye, 1976) and complemented observational studies of englacial or subglacial hydrology which were focused largely on attempts to measure basal water pressure (e.g. Mathews, 1964; Hodge, 1976).

It was in this context that Iken began her career in glaciology. As a student with Fritz Müller at McGill University her earliest work was carried out on White Glacier in the Canadian Arctic as part of the Axel Heiberg Island Expedition (Iken, 1972, 1974; Müller and Iken, 1973). She was given, according to some of her contemporaries, the obscure and unrewarding assignment of trying to measure short-term velocity fluctuations of White Glacier. Conventional wisdom held that the glacier should be frozen to its bed, hence free of such variability. In 1967, Iken conducted stake surveys at 3 hour intervals over 2 weeks in the ablation area of White Glacier and detected diurnal variations in flow speed (Iken, 1974). This ignited her interest in the theoretical and observed relationships between water pressure and sliding velocity, to which she would dedicate much of her career. Her research would take her back to the Alps and eventually to Alaska and Greenland.

INSIGHTS FROM SELECTED WORKS

This section highlights three of the most enduring works of Iken and her colleagues. These were chosen in part for their numerous citations, but primarily based on a 'focus group' approach to identifying the most influential *Journal* papers and the favourites of *Journal* readers.

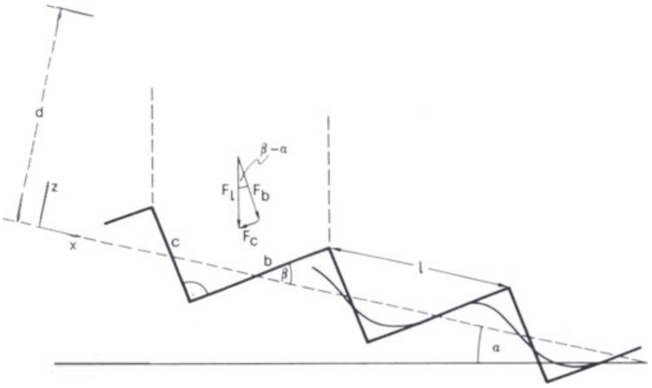

Fig. 1. Diagram illustrating the derivation of the limiting water pressure of stability. An ice slab of thickness *d* is resting on a stepped bed with a mean slope α (Iken, 1981).

Modelled water-pressure effect on sliding (Iken, 1981)

Motivated by observations of short-term velocity variations in glacier flow speed (Iken, 1978) and the relationship between measured vertical and horizontal velocities (Iken and others, 1983), Iken (1981) constructed an idealized model to investigate the relationship between subglacial water pressure and glacier sliding. Although water pressure had been linked to basal motion through several proposed mechanisms (e.g. Lliboutry, 1968; Jones, 1979), the observations motivated the idealization of the glacier bed as an impermeable undulating surface. Building on the theoretical work of Lliboutry (1968, 1979) and Kamb (1970), Iken (1981) aimed specifically to examine the effect of water pressure on sliding during the transient stages of cavity development.

Assuming a perfectly lubricated glacier bed, a linear ice rheology and instantaneous water supply or drainage, Iken (1981) employed a finite-element code for stress–strain analysis developed originally at Eidgenössische Technische Hochschule (ETH) for tunnel construction. Both sinusoidal and quasi-sinusoidal bed shapes were considered (undulations of 20 m wavelength and 1.5 m amplitude), with an ice thickness (310 m) and bed slope (4°) chosen to resemble those of Unteraargletscher, Switzerland. While the finite-element code was reasonably amenable to this problem, several manual interventions were required including: (1) an iteration to ensure consistency between a given water pressure and the affected bed area; (2) careful positioning of the nodes at the downstream end of the cavity roof to insure bed-parallel ice motion at the point of contact; and (3) a trial-and-error approach to defining correct steady-state cavity configurations for a given water pressure. Iken was among the first to employ finite-element methods to solve glacier flow problems (e.g. Iken, 1977), in part because of the extraordinary patience required; iterations were performed manually with punch cards until convergence was reached.

The results of this modelling effort clearly illustrated sliding enhancement in response to an applied water pressure between the 'separation pressure' p_s (e.g. Lliboutry, 1968; Nye, 1969; Kamb, 1970), defining the onset of ice–bed separation, and the 'limiting' or 'critical' water pressure $p_1 = \rho g d \sin(\beta - \alpha)/\sin\beta$ derived by Iken (Fig. 1), beyond which unstable sliding was predicted to occur. At the onset of cavity formation, simulated ice flow near the bed became more plug-like; flow speeds exceeded those modelled when the cavities reached steady state, where ice–bed separation was at its maximum (cf. figs 4b, 5b and 6a in Iken, 1981). A small decrease in water pressure precipitated a dramatic change in the modelled flow field, including transient reverse sliding above the stoss face of the downstream obstacle. This intriguing latter prediction remains neither confirmed nor refuted by observations, though some forms of reverse glacier motion have been documented (e.g. Harrison and others, 1986).

Iken (1981) drew several important conclusions related to the effect of bed geometry, cavity extent and water pressure on sliding velocity: (1) bed configurations with lower separation pressures (e.g. obstacles with steep lee faces) produce a stronger sliding velocity response to water pressure; (2) sliding sensitivity to water-pressure increases with the area over which the water pressure acts and also depends on the orientation of the area; (3) if this area remains constant, sliding speed increases linearly with water pressure for a Newtonian ice rheology; and (4) sliding is most sensitive to water pressure at the inception of cavity formation, rather than when cavities reach their maximum steady-state sizes. Thus, sliding speed is predicted to be highest during the early stages of cavity growth.

Iken (1981) concluded that 'sliding velocity is neither simply a function of the subglacial water pressure nor of the size of cavities but depends on both variables', and speculated that observations of early season glacier acceleration may be the manifestation of unstable sliding at water pressures below overburden. She suggested that the limited duration of these events may be related to limited water supply and imperfect hydraulic connectivity across the glacier bed. Future observations, including those of Iken and Bindschadler (1986), would reveal stable sliding at pressures greater than the critical pressure, pointing to a role for basal friction as suggested by Iken (1981) and later modelled by Schweizer and Iken (1992) and to global force-balance controls on the sliding process (e.g. Cuffey and Paterson, 2010).

Seasonal uplift and basal water storage (Iken and others, 1983)

Up to 0.6 m of surface elevation increase was observed at the beginning of the melt season on Unteraargletscher by Iken and others (1983) using a combination of optical survey data and photographs from an automatic camera. The authors speculated that a similar 'uplift' may have been observed on Unteraargletscher as early as 1842/43 by Louis Agassiz (Agassiz, 1847). In 1975, theodolite measurements of poles arranged in four transverse profiles were undertaken at intervals from 2 hours to 3 days. At the pole where the highest-resolution measurements were made, errors were controlled such that vertical positions were known to 2 mm. The data showed stable downward stake movement over winter giving way to a prolonged period of summer uplift, which was punctuated by several uplift events associated with periods of enhanced melt. Iken and others (1983) clearly documented the coincidence of maxima in horizontal velocities and maxima in vertical velocities, rather than vertical displacements (Fig. 2; fig. 3 in Iken and others, 1983). That horizontal velocity maxima occurred during uplift appeared to confirm the principal finding of Iken (1981).

Iken and others (1983) interpreted these observations as the result of cavity growth at the glacier bed in response to pressurized water, pointing to the dominant influence of water pressure on glacier sliding speed. They came to this conclusion by systematically ruling out the following as leading explanations for the observed uplift: temporal variations in longitudinal strain rate, increases in glacier volume due to crevasse formation, expansion of intragranular veins and dilatation of subglacial sediments. This rigorous approach to attribution was characteristic of Iken's work throughout her career. In seeking to explain how a minimum of 0.3 m of water could be stored in cavities at the bed without precipitating unstable sliding, Iken and others (1983) calculated that sinusoidal undulations of 0.56 m in amplitude covering most of the glacier bed could accommodate the water; however, they speculated that the cavities were probably more compact than this and perhaps asymmetric in shape, with more steeply inclined stoss faces. The data in Figure 2 have become the classical empirical demonstration of 'hard-bedded' sliding.

Observed water-pressure effect on sliding (Iken and Bindschadler, 1986)

Iken and Bindschadler (1986) put the theoretical underpinnings of basal sliding (e.g. Lliboutry, 1968, 1979; Kamb, 1970; Iken, 1981; Fowler, 1986) to the test with simultaneous measurements of borehole water level and surface velocity at Findelengletscher. This temperate valley glacier, located in the Pennine Alps of Switzerland, was chosen because of its observed sensitivity to changes in water input (e.g. Iken, 1978). Ice-surface velocities were obtained from sub-daily optical surveys of velocity stakes arranged in four rows transverse to ice flow. These measurements were not automated, hence their temporal resolution was proportional to surveyor effort. Twenty-five boreholes were drilled to the bed over a laterally confined ~1 km section of the glacier, using hot-water drilling capability that Iken was instrumental in developing (Iken and others, 1977). Borehole water levels were monitored with membrane gauges and Goerz 'Miniscript' recorders. These recorders employed pens and rolls of paper and had the advantage, according to Iken, of allowing one to easily verify their operation and inspect the data. Checking the Miniscript was usually the first task of the morning and in at least one case, when exceptionally high water levels were recorded, prompted a round of survey measurements before breakfast.

Hydraulic connections with the englacial/subglacial drainage system were observed in 11 of the 25 boreholes, and water levels in the connected holes were found to be roughly parallel to the ice surface across the borehole array. Diurnal cycling of water levels commenced in early June, with daily peaks generally being synchronous across the array and lagging the local peak in surface melt by 6–8 hours. Multi-day variations in horizontal velocity at the stake locations were strongly correlated to borehole water levels. Iken and Bindschadler (1986) emphasized this correlation between flow speed and basal water pressure, but commented little on the precise phasing between the two during transient events. The data they presented showed velocity maxima generally occurring during rising water pressures, though this relationship was not a tidy one.

When Iken and Bindschadler (1986) plotted one of these velocity records from the central study area against water level averaged over four of the connected boreholes (Fig. 3; fig. 6 in Iken and Bindschadler, 1986), a relationship emerged that encapsulates the central result of this study. This relationship becomes asymptotic where basal water pressure approaches the ice overburden pressure, and appears to hold over a wide range of water levels and for data collected over different time periods and in two different years.

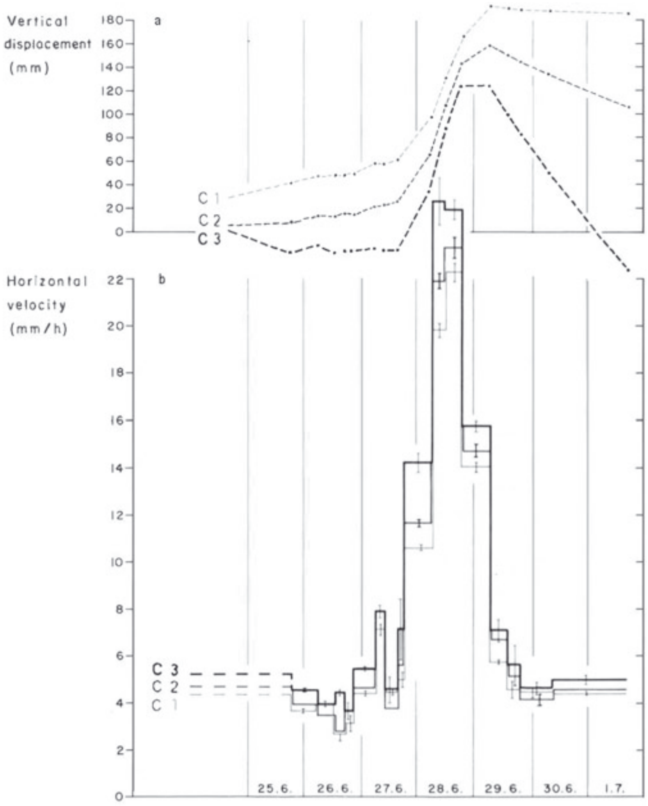

Fig. 2. Detailed theodolite measurements of glacier movement indicating an 'uplift'. (a) Vertical displacement of three poles, C1 to C3; C1 is near the glacier margin, C3 on the medial moraine. (b) Horizontal velocity of the same poles (Iken and others, 1983). Data from Unteraargletscher, 1975.

Iken and Bindschadler (1986) interpreted these data, along with the results of dye-tracing tests and electrical conductivity measurements, as evidence for drainage through a system of interconnected cavities (e.g. Lliboutry, 1968, 1979) where cavity growth is a function of subglacial water pressure (e.g. Iken, 1981). To arrive at this interpretation, they ruled out decoupling of the glacier sole from the bed by flotation, based on the measured water pressures being too low, and pervasive sediment deformation, which would not explain the persistence of the functional relationship at low water pressures. The stability of the relationship in time required that the basal shear stress and the fraction of the bed subject to water-pressure variations remained roughly constant. The rapid borehole response to several waves of high basal water pressure was interpreted as reflecting the enlargement of cavities and, in cases of water pressure meeting or exceeding overburden, rapid bed separation. The low propagation speeds of these pressure waves (~50–180 m h^{-1}) also pointed to a system capable of water storage along a tortuous flow path. The behaviour described above contrasted with that documented by Iken and others (1996) for the central region of Gornergletscher, Valais, Switzerland, where the presence of a subglacial sediment

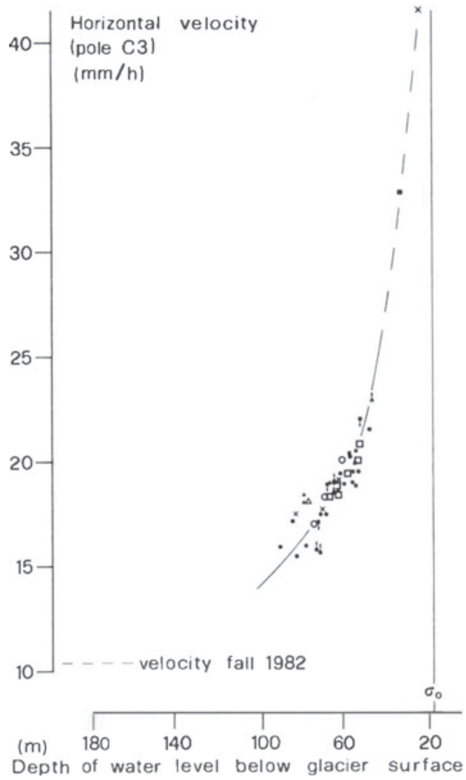

Fig. 3. Velocity of pole C3 as a function of the subglacial water pressure (shown as depth of water level below surface). The water pressure, equal to the ice-overburden pressure σ_0 at the centre line, corresponds to a depth of water level of 18 m below the surface. Different symbols refer to different periods (Iken and Bindschadler, 1986). Data from Findelengletscher, 1980–82.

layer was inferred from the damped and delayed response of the drainage system to hydraulic perturbations.

The data in Figure 3 were compared with theoretical predictions, namely the sliding speed over a perfectly lubricated sinusoidal bed for a constant basal shear stress. Empirical estimates of the separation pressure p_s corresponded to water levels of 140–180 m below the surface and were obtained from Figure 3 by extrapolating the relationship to a horizontal tangent at low water levels. Values of bed roughness $a/\lambda \sim 0.02$ were obtained for the empirical separation pressures according to $p_s = \sigma_0 - \lambda\tau/\pi a$, where σ_0 is the ice overburden pressure, λ and a are the wavelength and amplitude of sinusoidal bed undulations, respectively, and $\tau \approx 1$ bar is the basal shear stress. These roughness values were deemed consistent with the visible bedrock undulations of the proglacial area, but when used to calculate the limiting or critical pressure for a sinusoidal bed, $p_c = \sigma_0 - \lambda\tau/2\pi a$, predicted unstable sliding at pressures that were far too low. The data in fact suggested a critical pressure very near the ice overburden pressure. Iken and Bindschadler (1986) isolated the assumption of perfect basal lubrication as the leading shortcoming in their theoretical calculations and suggested that friction due to basal debris may play a significant role in reducing the basal shear stress that contributes to sliding. They concluded with one of the rarely mentioned but inevitable truths regarding the interpretation of field data: 'In order to reach conclusions, it was often necessary to generalize the results of measurements made at a very limited number of points and, furthermore, to decide sometimes what was typical or irregular.'

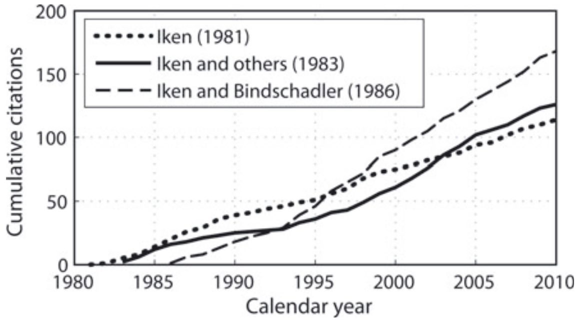

Fig. 4. Cumulative citations over time according to the Web of Science® citation index.

In a germane follow-up study, Iken and Truffer (1997) made similar measurements to those of Iken and Bindschadler (1986) on Findelengletscher during its advance in the early 1980s and its subsequent retreat. They found a different relationship between borehole water level and glacier flow speed than that plotted in Figure 3. Data from 1985, at the end of the advance, and from 1994, during the retreat, were distinct from one another and plotted below the data from 1980–82. By 1994, the variation in glacier velocity with water level was less than that of 1980–82 by about an order of magnitude. Iken and Truffer (1997) attributed this change in the relation between water level and sliding speed to a change in the nature of the subglacial drainage system over time, in which the connectivity between cavities had decreased. In effect, unconnected areas of the glacier bed buffered the velocity response to basal water pressure: high sliding rates were inhibited by limited water access to cavities, while the lowest sliding rates were precluded by isolated water pockets failing to drain.

LEGACY

Figure 4 presents a superficial analysis of the legacy of the works summarized above. With over 100 documented citations each, these papers have had a persistent influence over the years. The citing studies run the gamut from surging and tidewater glaciers (e.g. Kamb and others, 1985; Fowler, 1989; O'Neel and others, 2001; Fatland and Lingle, 2002; Vieli and others, 2004) to theoretical modelling of basal processes (e.g. Meyssonnier, 1989; Zmitrowicz, 2003; Raymond and Gudmundsson, 2005; Calvo and others, 2006; Sayag and Tziperman, 2009) to the interpretation of conditions beneath paleo ice sheets (e.g. Dardis and Hanvey, 1994; Piotrowski and Tulaczyk, 1999; Brennand, 2000). Although the absolute number of citations within ice-sheet studies is still few, it is interesting to note that recent studies of Antarctic ice streams (e.g. Gray and others, 2005; Fricker and others, 2007; Joughin and others, 2009) and Greenland outlet glaciers (e.g. Joughin and others, 2008; Shepherd and others, 2009; Bartholomew and others, 2010) continue to draw upon these works.

Attribution is possible for some of the inflections in the cumulative citation curves (Fig. 4). For example, the flurry of papers related to Variegated Glacier in Alaska (e.g. Kamb and others, 1985; Raymond and Malone, 1986) contributes to the rise in cumulative citations to Iken (1981) from 1985 to 1989. Output from the Haut Glacier d'Arolla (Switzerland) project from 1996 to 1999 (e.g. Nienow and others, 1996; Harbor and others, 1997) is also visible in this record.

The Arolla project and numerous papers from Unteraargletscher (e.g. Gudmundsson and others, 1999; Schuler and others, 2004) contribute to the increase in citations to Iken and others (1983) between the mid-1990s and 2005, along with works from Trapridge Glacier (Yukon, Canada) and Bench Glacier (Alaska) among others. Citations to Iken and Bindschadler (1986) are more difficult to characterize, because they are broadly distributed across studies. However, Figure 4 illustrates clearly that the relevance of this work has increased, rather than decreased, over time. Below I highlight a few of the research areas impacted by the works profiled here. This review is far from comprehensive, drawing only upon a subset of works that cite one or more of the three papers.

Alpine glacier hydromechanics

Nowhere has the trio of works by Iken and colleagues been more influential than in the study of alpine glacier hydromechanics. These studies span a range of subjects from 'spring events' (e.g. Anderson and others, 1999; Kavanaugh and Clarke, 2001; Mair and others, 2001) to jökulhlaups (e.g. Björnsson, 1998; Russell and others, 2006; Sugiyama and others, 2007) to glacier erosion (e.g. Hooke, 1991; Iverson, 1991; Harbor, 1992; Jamieson and others, 2008; MacGregor and others, 2009). Short-term to seasonal variations in velocity as observed by Iken and colleagues have been documented around the world on both temperate (e.g. Naruse and others, 1992; Raymond and others, 1995; Nienow and others, 2005; Purdie and others, 2008) and polythermal glaciers (e.g. Hooke and others, 1985; Jansson, 1995; Copland and others, 2003; Rippin and others, 2005; Bingham and others, 2006). A review of this work through the early 1990s is given by Willis (1995).

Glacier surges furnish a dramatic example of flow variations, and accordingly references to the work of Iken and colleagues can be found in the numerous papers related to the 1982–83 surge of Variegated Glacier (e.g. Kamb and others, 1985; Kamb and Engelhardt, 1987; Raymond and Harrison, 1988). Iken's (1981) conceptualization of the sliding process is akin to Kamb's (1987) linked cavity model used to explain the surge mechanism for Variegated Glacier. Many features of the antecedent mini-surges of 1978–81 were likened to observations from Findelengletscher and Unteraargletscher: transient uplift and subsidence of the glacier surface, propagating waves of high basal water pressure and velocity and the correspondence of peak uplift rates with peak velocities (Kamb and others, 1985; Kamb and Engelhardt, 1987). A notable exception was the maximum in observed velocities and pressures, the latter exceeding the limiting pressure calculated by Iken (1981) at which sliding was predicted to become unstable. One explanation given for this was limited hydraulic connectivity during mini-surges, such that high-pressure water was confined to patches of the bed (Kamb and others, 1985).

Hydromechanical events reminiscent of the observations on Unteraargletscher and Findelengletscher have been documented on both temperate and polythermal glaciers from Haut Glacier d'Arolla in Switzerland (e.g. Mair and others, 2003) to John Evans Glacier in the Canadian High Arctic (e.g. Bingham and others, 2006). In some cases these events appear to be driven by basal water pressure as interpreted by Iken and Bindschadler (1986) (e.g. Copland and others, 2003), while in others the water pressure responds to a predominantly mechanical forcing (e.g. Kavanaugh and Clarke, 2001). Basal hydromechanical events can temporarily alter the force balance of the glacier (e.g. Howat and others, 2008), highlighting the limitations of the standard sliding law where the driving stress is assumed to be balanced locally by basal drag. In several cases Iken's (1981) modelling results have been used specifically to explain the occurrence of peak horizontal velocities during rising water pressures (e.g. Nienow and others, 2005). For example, Blake and others (1994) documented diurnal peaks in sliding velocity, measured at the bed of Trapridge Glacier during rising water pressures measured in a nearby borehole. Fischer and Clarke (1997) proposed a stick–slip relaxation process to explain this, whereby elastic strain in the ice is released when rising basal water pressure causes episodic decoupling of the ice from the underlying till.

Velocity perturbations driven by basal hydrology are not confined to land-terminating glaciers (e.g. Meier and others, 1994). For example, ONeel and others (2001) found flow speed near the terminus of LeConte Glacier, Alaska, to respond to surface melt and precipitation, in addition to ocean tides. Both Columbia Glacier in Alaska (Kamb and others, 1994) and Hansbreen in Spitsbergen (Vieli and others, 2004) exhibited velocity variations in response to surface water input as documented for many land-terminating glaciers; however, velocity correlated better with water storage than pressure in both cases.

Many glaciers such as Unteraargletscher in Switzerland (Sugiyama and Gudmundsson, 2004), Storglaciären in Sweden (e.g. Jansson, 1995) and Kennicott Glacier in Alaska (Bartholomaus and others, 2008) exhibit behaviour similar to that documented by Iken and others (1983) and Iken and Bindschadler (1986). Some studies, however, do not find a straightforward relationship between sliding speed and basal effective pressure and yet are not inconsistent with the observations of Iken and colleagues in other respects. For example, at Bench Glacier, Harper and others (2007) observed accelerated motion associated either with enhanced ice–bed separation or elevated hydraulic connectivity at the glacier bed, but unaccompanied by low effective pressures.

MacGregor and others (2005) noted that the onset of the spring acceleration event at Bench Glacier coincided with a maximum in global englacial storage and that the propagation of the event was accompanied by a pattern of uplift and subsidence not unlike that observed by Iken and others (1983). Anderson and others (2004) used the 'tilted staircase' model of Iken (1981) to interpret a similar GPS dataset from Bench Glacier, where the relationship between calculated bed separation and sliding speed was explained in terms of cavity growth and collapse prior to the development of a channelized drainage system (see also Kessler and Anderson, 2004). Using a sliding law of the general form proposed by Iken and Truffer (1997), Anderson and others (2004) inferred water pressures from their data that were naturally averaged over the relevant spatial scale. There is clearly a relationship between water and sliding at Bench Glacier, but one that does not lend itself easily to a functional description in terms of measured borehole water pressure.

It would be raising a false dichotomy to suggest that the work of Iken and colleagues supports a relationship between sliding and water pressure to the exclusion of storage volume. The results above only serve to reinforce the significance of the connectedness of the drainage system (e.g. Iken and Truffer, 1997; Hanson and others, 1998), the scales of heterogeneity over which glacier processes naturally average (e.g. Kamb and others, 1994) and the relative influences of local vs non-local forcing (e.g. Rippin and others, 2005).

Ice-sheet hydromechanics

The extension of the early work of Iken and colleagues to the larger scale of the ice sheets is hardly surprising, given that they exported ideas about subglacial hydromechanics from the Swiss Alps to Greenland. Their work on Jakobshavn Isbræ (Iken and others, 1993; Funk and others, 1994; Lüthi and others, 2002) remains the only work to have documented glacier-bed conditions through direct borehole observations, which included evidence of an active subglacial drainage system. Iken and colleagues combined measurements and modelling (Iken and others, 1993; Funk and others, 1994; Lüthi and others, 2002) to infer a thick layer of rapidly deforming temperate ice at the base of Jakobshavn Isbræ. Their findings helped explain the fast flow of the ice stream and its lack of seasonal variation (Echelmeyer and Harrison, 1990).

Since the early 2000s, there have been a number of studies documenting a distinct coupling between hydrology and dynamics particularly on land-terminating glaciers in Greenland. GPS data have revealed diurnal, weekly and seasonal variations in surface velocity along the western margin of the ice sheet that have been interpreted as responses to variable meltwater input to the bed (e.g. Bartholomew and others, 2010). Relatively coherent weekly variability in surface velocity was found by Van de Wal and others (2008) over a 60 km stretch of the Kangerlussuaq ('K') transect, where the ice is 1000–1500 m thick. They related acceleration on this timescale to the rate of surface meltwater production, rather than the absolute volume of meltwater. This observation indirectly supports Iken's (1981) conceptual model of sliding with cavitation.

Shepherd and others (2009) documented diurnal variations in horizontal flow speed and ice-surface elevation over several days in 2007 on the land-terminating Russell Glacier in western Greenland. They associated these variations with diurnal meltwater input, while they attributed longer-term flow variations to lake drainage events. On the basis of these observations, Shepherd and others (2009) proposed that alpine glaciers may be a reasonable analogue for Greenland in a warming climate. This suggestion seems to be confirmed by Bartholomew and others (2010) for another transect inland from the Russell Glacier terminus, where the data look much like those in Figure 2, velocity magnitudes excepted. Although some of the outlet glaciers along Greenland's western margin exhibit strong sliding responses to meltwater input reminiscent of alpine glaciers, they also appear to behave like alpine glaciers in adjusting their drainage systems to water flux (e.g. see Willis, 1995, for a review). This would explain their responsiveness to meltwater variability, rather than total volume in some cases (e.g. Van de Wal and others, 2008; Schoof, 2010).

In Antarctica, discovery of saturated deformable sediments beneath fast-flowing ice streams in the early 1980s (e.g. Blankenship and others, 1986) led researchers to consider the influence of water pressure on basal flow processes in an environment isolated from surface meltwater. Although the hard-bedded cavity-dominated drainage systems envisaged by Iken and colleagues would seem a far cry from the deforming beds of the Siple Coast ice streams, much of this work began by considering the fundamentals of sliding theory and observations from alpine glaciers (e.g. Bentley, 1987; Alley, 1989, 1993; Engelhardt and others, 1990; Harrison and others, 1993; Engelhardt and Kamb, 1997). Iken's (1981) theoretical bound on basal shear stress surfaced in a recent study of Pine Island and Thwaites Glaciers in the mass-shedding Amundsen Sea sector of West Antarctica. Joughin and others (2009) noted a consistency between this bound and properties of the plastic-bed model they used which produced the best agreement between the modelled and measured extents of acceleration and thinning above the grounding line.

Other recent Antarctic work harks back to the observations of Iken and others (1983) by attributing short-term vertical deflections of the ice surface to the movement of subglacial water. Gray and others (2005) first observed this in Antarctica (cf. Fatland and Lingle, 2002) on Kamb and Bindschadler Ice Streams using interferometric synthetic aperture radar (InSAR) data. The short-term nature of the deflections and the spatial coincidence of uplift/subsidence with subglacial hydraulic potential minima led to the interpretation of these data as reflecting transient water storage and release. Similar phenomena have since been interpreted from ice-surface deflections on other ice streams and in other regions of Antarctica, painting a highly dynamic picture of sub-ice-sheet drainage (e.g. Fricker and Scambos, 2009).

The sliding law

Adaptations to the classical form of the sliding law have been made, for example, to account for tangential forces (friction) at the bed (e.g. Morland, 1976b; Schweizer and Iken, 1992) and to allow for unstable sliding above a critical pressure less than the overburden (Iken and Truffer, 1997; Truffer and Iken, 1998). Much effort has also been devoted to understanding basal motion in the presence of unconsolidated sediments (e.g. Alley, 1989; Iverson, 1999).

An important recent development in sliding theory revisited Iken's (1981) derivation of the 'limiting' or 'critical' pressure, which implies that basal shear stress cannot exceed a maximum value for a given effective pressure and bed geometry. Interpreted physically, cavity water pressure limits the stress that can be concentrated on the stoss faces of bed obstacles as sliding with cavitation occurs. This is significant because it invalidates the traditional form of $u = C\tau^p/N^q$ as a general sliding rule. In Iken's (1981) original notation, $p_1 = p_0 - \tau/\tan\beta$ (equation 2), where p_1 is the limiting pressure, p_0 the overburden pressure, τ the basal shear stress and β the maximum slope of the stoss faces of bedrock obstacles with respect to the mean bed slope (Fig. 1). Rewriting gives $\tau \leq N \tan\beta$. Schoof (2005) showed that this relationship, which he termed 'Iken's bound', could be extended to more realistic bed geometries and incorporated into a new sliding law (see also Fowler, 1987). Gagliardini and others (2007) extended Schoof's (2005) work to nonlinear ice rheology and locally infinite bed slopes (i.e. bed obstacles that are perpendicular to mean bed slope) and proposed a friction law of the form $\tau/N = D\chi^{1/n}/(1 + \alpha\chi^m)^{1/n}$, where $\chi = u/(D^n N^n A_s)$, u is sliding speed, n is Glen's exponent and D, A_s, m and $\alpha = \alpha(m)$ depend only on bed geometry if properly chosen. Although such laws are more complicated to implement than the traditional sliding relation, they are now being incorporated into numerical ice-flow models (e.g. Bueler and Brown, 2009; Pimentel and others, 2010).

CONCLUDING REMARKS

Iken and colleagues have contributed to our understanding of glacier hydromechanical processes from both theoretical and empirical perspectives. This places Iken among an elite few to have made seminal contributions in both glaciological theory and field observation. She is uniformly praised by her colleagues as a scientist with strong physical insight and a deep understanding of the processes she studied. The research methods of the day were labour-intensive, whether through the use of punch cards for numerical modelling or manual theodolite measurements recorded in a field book to track sub-daily variations in glacier flow speed. Such circumstances required a degree of patience and perseverance perhaps less familiar to those of us in the cluster computing and GPS generation of glaciology. The insights of Iken and her colleagues were therefore, in part, a product of extraordinary energy and endurance in the field. Subsisting on a simple diet featuring potatoes, oatmeal and a good supply of Swiss chocolate, Iken herself was a tireless field surveyor. This made possible the high temporal-resolution measurements that revealed such phenomena as glacier uplift and short-term acceleration. She had an appreciation for simple measurements throughout her career and was accordingly always equipped with a wristwatch, a multimeter and a roll or two of 'Puma band' (Swiss substitute for duct tape).

Nearly three decades ago Iken (1981) showed us that there is a theoretical bound on the shear stress that can be supported by the glacier bed, a result that is just beginning to transform the way we represent the basal boundary condition in ice-flow models. With her colleagues she documented ice-surface uplift as a result of transient water storage at the bed and showed that maximum sliding speeds were achieved during cavity growth. These insights have been used to interpret short-term velocity fluctuations, among other data, from the Alps, Scandinavia, Svalbard, New Zealand, Kamchatka, Alaska, Yukon, the Arctic, Patagonia and the Himalaya as well as from past and present ice sheets. From surging and tidewater glaciers to the ice streams of Greenland and Antarctica, this work continues to provide a basis for interpreting the hydromechanical processes that operate under ice. Given the prominent role of dynamics in our current study of the cryosphere's response to climate, we can expect the influence of this work to persist for years to come.

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