The Ross Ice Streams:

A tale of piracy, bingeing and questionable stability

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Abstract

Ice streams are corridors of fast ice flow and their potential to discharge large quantities of ice from the interior into an ocean basin or withhold ice supply to the major ice shelves has major implications for the stability of the West Antarctic Ice Sheet (WAIS) and oceanic thermal and saline circulation. Accurate prediction of the future stability of the WAIS depends on an understanding of mechanics of their flow and the intrinsic and extrinsic environmental controls that turn it on and off.

This review presents some of the main issues arising from the intensive investigation of the Ross Ice Streams, the most dynamic element within WAIS and discharging 40% of its ice into the Ross Ice Shelf. It discusses ice stream significance; distinguishes between the Ross Ice Streams and other Antarctic ice streams; presents contemporary knowledge of ice stream morphology and dynamics, factors controlling ice streaming and ice stream velocities, spatial and temporal variations in ice stream behaviour and mechanisms of ice stream flow. Finally, it looks at the implications of recent mass balance measurements and recent work indicating a flow regime between those of the ice streams and the interior ice sheet.

The impression gained is of a continually evolving body of research characterised by an accumulation of knowledge but lack of consensus. The literature is riddled with contention, contradictory results, areas where knowledge remains sketchy, and conjecture. Undoubtedly advances in remote sensing technology will advance understanding, but more information is required on the variability in sedimentary properties over the bed of an ice stream: investigation of Palaeo-ice streams could provide a complementary and more accessible source of such information. Which theories one favours amongst the tales of ice stream piracy, bingeing and instability appear to be a matter of which research camp one resides in. Clearly this story will run and run.

Introduction

Over 90% of all ice and sediment discharged by the Antarctic Ice Sheet flows within fast-moving ice streams, typically hundreds of kilometres long, tens of kilometres wide and moving at speeds of 100 to 2000 m/year (Bentley, 1987; Bindschadler and Scambos, 1991; Bindschadler et al., 1996).

The 'pure' ice streams of the Siple Coast (Ross Ice Streams: Figures 1 and 2) of Antarctica are the most dynamic element within the West Antarctic Ice Sheet (WAIS), discharging 40% of its ice into the Ross Ice Shelf (Bennett, 2003). Since being mapped from airborne surveys and radar by Robin et al. (1970) and named, imaginatively, A to F[1] they have been intensively investigated. The substantial body of literature generated continues to evolve as improved technology, including GPS, satellite imagery and SAR interferometry, allow the collection of new data and refinement of previous studies.

This review presents the issues of importance to contemporary research and understanding. It introduces the significance of ice streams and the differences between the Ross Ice Streams and other Antarctic ice streams before exploring ice stream morphology and dynamics; onset, temporal and spatial behaviour; the mechanisms of fast flow; and the stagnation of Ice Stream C. Finally, the implications of recent findings connected with internal ice sheet flow and the mass balance of the Ross Ice Streams are discussed.

The Significance of Ice Streams

The potential of ice streams to discharge large quantities of ice from the interior into an ocean basin or withhold ice supply to the major ice shelves has major implications for the mass balance[2] of the ice sheet and oceanic thermal and saline circulation (Bennett, 2003). Episodes of ice streaming have been invoked as a potential forcing for high frequency millennial or sub-millennial climate change (Broecker, 1994), and their rapid flow rapidly transmits perturbations of flow upstream into the inland ice and downstream onto the ice shelves (Bindschadler, 1997).

Their occurrence and temporal and spatial stability is central to the dynamic behaviour of the present and future WAIS. Its future stability can only be predicted accurately with an understanding of the mechanics of ice stream flow and the intrinsic and extrinsic environmental controls that turn it on and off.

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[1] Ice Stream B was renamed Whillans Ice Stream in 2001 in honour of Professor Ian M. Whillans who was a major figure in the study of West Antarctic ice streams and died in May 2001 (Bennett, 2003). The other ice streams were renamed at the January 2003 meeting of the Advisory Committee for Antarctic Names (ACAN) in honour of glaciologists associated with their study.

[2] The rate of ice sheet volume change: it depends on the balance between snow accumulated on the ice sheet and ice discharged from it. Changes in ice sheet volume are directly linked to changes in global sea level (Bindschadler and Scambos, 1991).

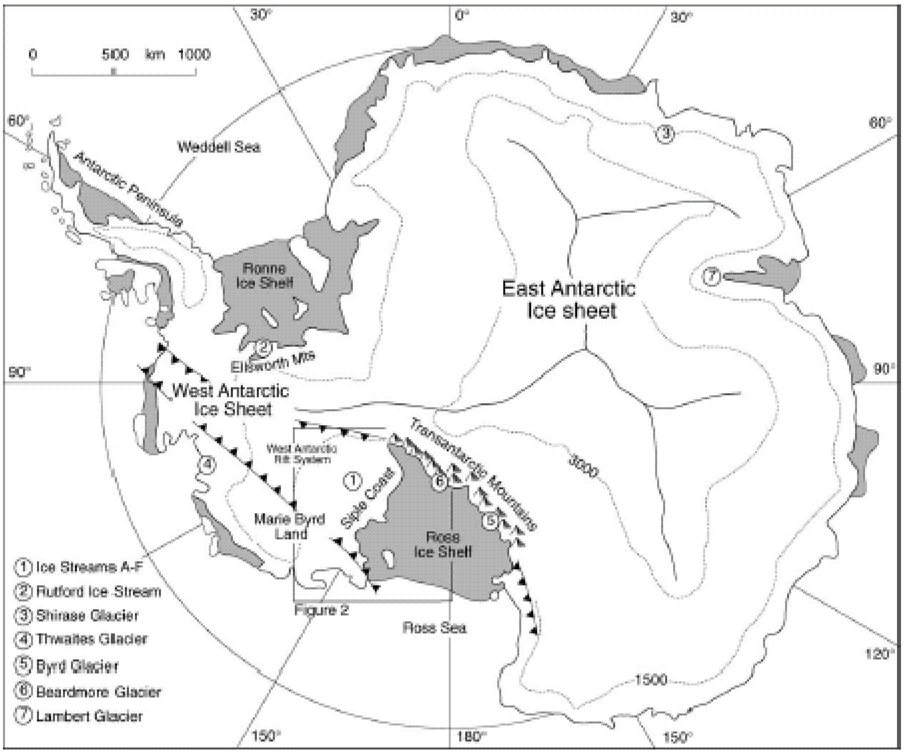

Figure 1. Map of Antarctica showing location of Ross Ice Streams A-F (Source: Bennett, 2003).

Pure and Topographic Ice Streams

Ice streams are parts of an inland ice sheet in which the ice flows more rapidly than the surrounding ice (Swithinbank, 1954). They act as transition regions between inland ice sheet flow and ice shelf flow (Bentley and Giovinetto, 1991; Bamber et al., 2000). The Ross Ice Streams are the only contemporary Antarctic examples of ‘pure’ ice streams (Bennett, 2003). They lack significant topographic control, being formed over a bed with very subdued topography. The ‘topographic’ ice streams found elsewhere in Antarctica are constrained by bed troughs of varying size and depth.

Ice flow tends to accelerate within topographically constrained corridors. In the absence of such corridors ice streams are associated with either corridors of rheologically weaker ice, within an ice mass, or with some form of lubricated bed, which facilitates rapid basal motion (RBM) (Bennett, 2003). An ice stream, In practice, may be both topographically constrained and have a lubricated bed and distinctions between pure and topographic become hazy. However, their physics helps distinguish them.

Ice streams lower the surface topography of an ice sheet. The drawdown associated with a pure ice stream is significantly greater due to the greater ice flow within it (Bennett, 2003). Glacier flow is driven by the down-slope weight of the ice and ice normally deforms with a basal shear stress in the range of 50-100 kPa. This gravitational driving force is supported on the glacier bed in an ice sheet flowing via sheet flow. The resultant basal shear stress drives glacier flow and peaks in Antarctic topographic ice streams between 50 and 100 km from the grounding line (the junction between floating and grounded ice).

Pure ice streams show a peak in gravitational driving stress at the head of the stream (the onset) followed by a downstream decline to values well below those necessary for significant ice deformation (e.g. 20 to 30 kPa) near the grounding line. Peak ice flow velocity does not coincide with peak glacial driving stress as in topographic ice streams (Bennett, 2003).

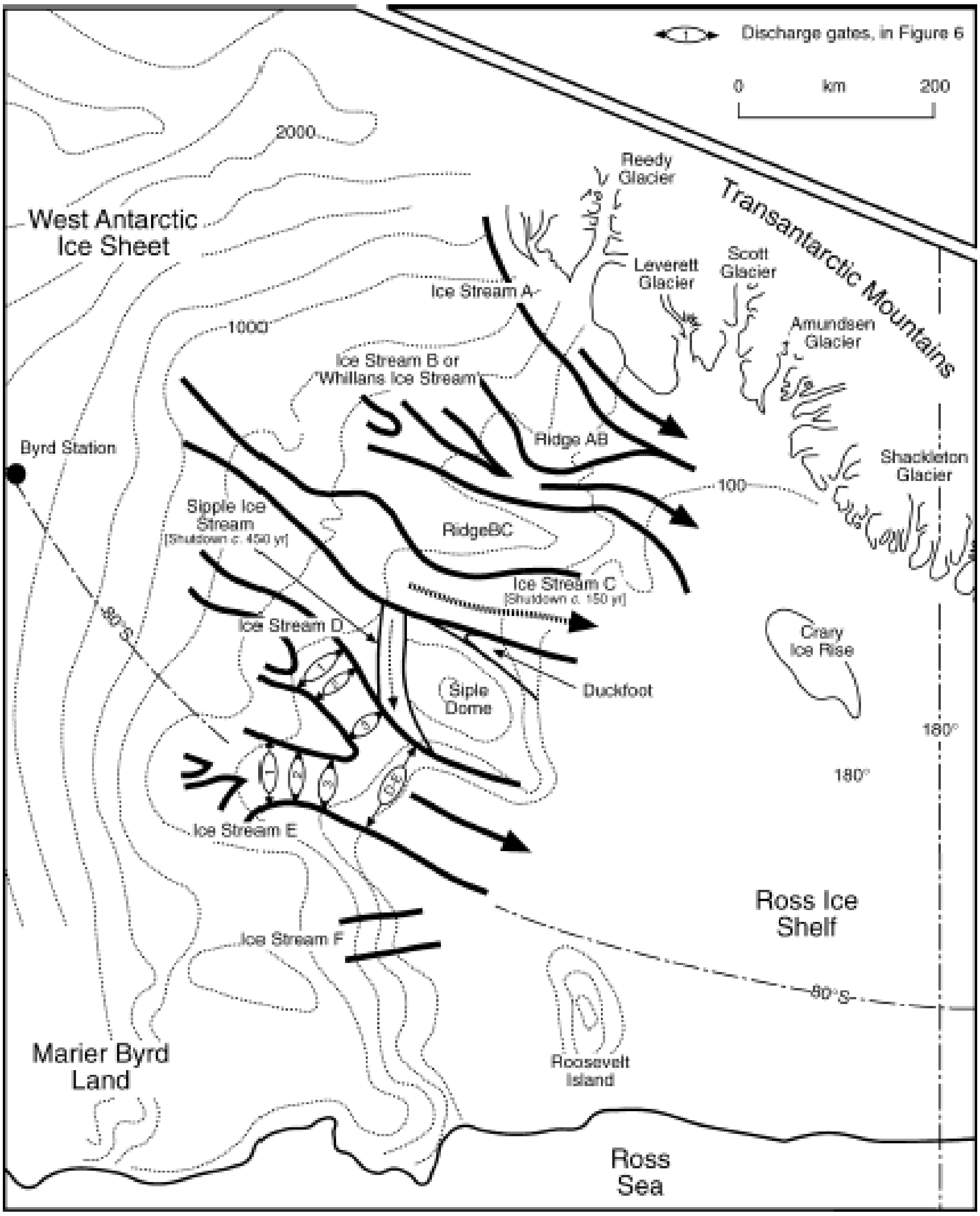

Figure 2. Map of the Ross Ice Streams (See Figure 1 for location: Source: Bennett, 2003)

Morphology and Dynamics of the Ross Ice Streams

The Ross Ice Streams have low surface slopes (order 10^{-3}: Alley and Whillans, 1991), widths of 30-80 km, lengths of 300 to 500 km and an average ice thickness of at least 1 km (Bennett, 2003; Oppenheimer, 1998). Velocities exceed 0.1 km/year and often rise to over 0.8 km/year (Shabtaie et al., 1987; Whillans et al., 1987; Bennett, 2003).

Distinct ridges, with crests up to several hundred metres above the ice streams and relatively large slopes (order 10^{-2}) towards the ice stream margins, separate the ice streams. Glacial till underlays both ice streams and ridges, but in the latter ice is frozen to the bed (cold-based), while in the streams ice is at pressure melting point. The junction between frozen and unfrozen basal ice occurs beneath the ice stream's shear margins.

Spatial and temporal distribution of ice stream flow velocity has been investigated using global positioning systems (GPS: e.g. Whillans et al., 1987), serial satellite images (Bindschadler et al., 1996) and, more recently, interferometric radar images (Joughin et al., 1999). Whillans Ice Stream exhibits spatial variation in velocity with a maximum of 827 m/year and typical rates of around 400 m/year. This compares to flows of as low as 5 m/year in the ice interfluves.

Since ice stream motion is produced at the base, velocity and associated strain components vary horizontally but not vertically (Raymond et al., 2001). An ice stream is characterised by a cross-flow transition from rapid motion in the ice stream to the slowly moving ice on either side. Velocity declines at a rapid but stream-dependent rate at the margins.

The shear margins support shear stress exceeding 100 kPa with consequent large strain rates (order 0.1 /yr), which cause intense frictional heating and 3 to 5 km wide zones of spectacular fracturing marking an ice stream's lateral margin. The margin shear stress can greatly exceed the basal shear stress (order 10 kPa). Consequently, a significant fraction of the down-slope weight of an ice stream can be supported from the sides. The shear zones are amongst the most prominent morphological features on the surface of the WAIS (Raymond et al., 2001).

An ice stream's upper section (trunk) is fed by a network of potentially competing tributaries, which may drain a common accumulation area (Joughin et al.,1999). Ice stream trunks are not particularly well constrained by subglacial topography (Shabtaie et al., 1987) but tributaries appear to be focused along subglacial topographic lows, with likely concentrations of thicker warmer ice, subglacial sediment or water (Joughin et al., 1999).

The complex spatial pattern of ice velocity across an ice stream's surface causes local thinning and thickening of ice in response to variations in the rate of strain resulting in various surface features (e.g. mottles, warps and flow stripes). These may provide clues to spatial variations in basal conditions. The lack of a universally clear relationship between basal and surface topographies (Whillans and van der Veen, 1993; Bindschadler et al., 1996) suggests that spatial variation in the ease of basal movement may be of greatest importance.

Onset of an Ice Stream

Conventionally, a clear distinction is made between the slow movement, predominantly through internal deformation within the ice mass, of the interior ice sheet (inland flow) and the streaming flow of the ice streams. Recent synthetic aperture radar (SAR) work by Bamber et al. (2000: Figure 3) has challenged this view but the generally accepted view is adopted for present purposes.

According to Alley and Whillans (1991), the transition between inland and streaming flows is almost certainly controlled by an initiation of RBM, which propagates kinematically upstream into the inland ice where velocity is dominated by the driving stress. Blankenship et al. (2001) define the onset of ice streaming as the transition zone bounded by these downstream and upstream limits.

Onsets are difficult to locate. Bindschadler et al. (2001) conclude that maximum driving stress is arguably the most reliable proxy indicator of onset location, while the use of surface features alone is convenient but unreliable. Two other proxy indicators, basal topography and geology or substrate, have been investigated and are discussed in more detail.

Basal Topography

In Antarctica fast flow initiates at a step in the bed elevation, with the exception of the Western Antarctica ice streams, which McIntyre (1985) noted do not follow this general correlation. Extensive bed-elevation mapping of ice streams A, B and C by Retzlaff et al. (1993) also failed to show any large gradients in basal topography in suspected onset regions. Although Bell et al. (1998) concluded that initial streaming flow of Ice Stream C coincided with a channel in the basal topography, it is uncertain that streaming was attained at this location (Bindschadler et al., 2001).

Underlying Geology

Observations suggest that some combination of saturated (and possibly mobile) sediments (e.g. Blankenship et al., 1986) and thin (lubricating) water layers or gaps (Engelhardt and Kamb, 1997) is necessary but perhaps not sufficient for the RBM of Whillans Ice Stream.

Whether RBM occurs via subglacial deformation or basal sliding over a thin water/sediment layer, or a combination of the two, there is strong reason to suspect a geological or substrate control on its initiation (Blankenship et al., 2001). Subglacial deformation depends on the availability of deformable sediment (Alley, 2000) and consequently strong correlation should occur between the onset of RBM and the tectonically controlled boundary of a sedimentary basin, or the extent of a sediment drape (Blankenship, 2001).

Basal water availability is important for sediment deformation and critical for subglacial sliding, and may be affected by variation in the geothermal heat flux (Blankenship et al., 2001). Accordingly, correlation may also be expected between onset of RBM and areas of enhanced heat flow, such as areas of subglacial volcanic activity (Blankenship et al., 1993) or areas composed of crustal blocks of varying thickness and thermal history (Stern and ten Brink, 1989).

Bell et al.[3] (1998), Anandakrishnan et al.[4] (1998), and Blankenship et al.[5] (2001) have presented evidence suggesting a strong coincidence in some, but not all, cases between the onset of RBM and the outcrop pattern of marine sediments and sediment-filled basins. Such evidence, along with evidence of the coincidence of the initiation of several ice stream tributaries with crustal zones with an enhanced geothermal heat flux (Blankenship et al., 2001), has been taken to clearly suggest geology as a spatial template for ice streaming (Alley, 2000).

However, caution is required in asserting that ice streams can only occur where there is a suitable geological template. Fast ice flow would tend to occur within basinal

[3] Used gravity and magnetic data.

[4] Used seismic evidence.

[5] Used seismic and aerogeophysical data.

troughs irrespective of the presence of deformable sediment (Bennett, 2003); the presence of additional controls is suggested by examples of sediment availability at the bed but the absence of ice streaming (Blankenship et al., 2001); and thermomechanical numerical models (e.g. Payne, 1995; Payne and Dongelmans, 1997) have succeeded in simulating ice stream flow characteristics over a uniform substrate.

Temporal and Spatial Behaviour of the Ross Ice Streams

RBM of a glacier depends on friction-reducing high basal water pressures. Consequently, ice velocities fluctuate in response to the varying of heat and melt budgets over hourly, diurnal and seasonal time scales (Willis, 1995). Contrastingly, McDonald and Whillans (1992) show Whillans Ice Stream to have a sub-annual scale velocity variability of less than 0.4%. However, importantly for considerations of WAIS stability, the Ross Ice Streams exhibit spatial and temporal instability, shift location and undergo cycles of varying flow activity on scales of more than 1 to 10s of years.

The Ross Ice Shelf provides a record of up to 1300 years of ice streams changing courses, velocities and margins (Fahnestock et al., 2000). Evidence of a major reorganisation of the Ross Ice Streams drainage about 420 years ago (Gades et al., 2000; Jacobel et al., 2000) illustrates the potential for an ice stream to switch on and off on time scales greater than 100 years. This potential is further evidenced by Ice Stream C, which currently has a flow rate of only 4 to 5 m/year.

Radar sounding of Ice Stream C has identified structures, typical of other ice streams, at depth indicating previous activity similar to that currently displayed by adjacent streams. Retzlaff and Bentley (1993) present evidence of stream shutdown through a wave of stagnation propagating upstream from the mouth (130± 25 years ago) to the head (30 years ago), although recent work by Jacobel et al. (2000) suggests a more complex event, revealing a step-wise migration of the northern margin 30-40 km to the south just prior to stagnation.

The ice streams also undergo longitudinal extension. Bindschadler (1997) presents an argument for the upstream migration of the ice stream onset, due to in-equilibrium of the ice stream head. Since WAIS ice stream lengths occupy a narrow range he suggests that the ice stream grounding line retreats in step with this inland migration. A tributary of Ice Stream B is migrating inland at 230 m/year (Price and Whillans, 2001), a rate that would see the ice stream head reaching the ice divide of WAIS in approximately 1400 years (Bennett, 2003).

Joughin and Tulaczyk (2002) reassessed the mass balance of the Ross Ice Streams using Interferometric Synthetic Aperture Radar (InSAR). They found strong evidence for ice-sheet growth of 26.8 +/- 14.9 Gton/year with an average thickening of ~25% of the accumulation rate. An earlier estimate, based on less precise ice-flow velocity measurements (Shabtaie and Bentley, 1987), of -20.9 +/- 13.7 Gton/ year implied that ice discharge exceeded accumulation by ~25%, causing ice sheet thinning and grounding line retreat. Much of the negative imbalance was attributed to Whillans Ice Stream, although negative imbalances were also found for the other Ross Ice Streams, with the exception of the stagnated Ice Stream C. Ice Stream C is the major contributor to the overall positive regional mass balance because of its negligible outflow but, importantly, Whillans Ice Stream is close to balance.

Several studies have documented a deceleration on Ice Stream A and Whillans Ice Stream. Since 1963, the mouth of Whillans Ice Stream has been widening at a rate of 137 ± 34 m/year with an associated drop in velocity from 967 m/year to 471 m/year in the mid-1980s (Bennett, 2003). The most current estimate yields a 23% deceleration from 1974 to 1997 (Joughin et al., In preparation: cited in Joughin and Tulaczyk, 2002), which accounts for 10.6 Gton/year (38%) of the total difference in discharge. Whether the slowdown of Whillans Ice Stream is part of a terminal decline or shorter-term fluctuation is not clear.

Changes in ice surface geometry and resulting drainage patterns have also contributed to Whillans Ice Stream being close to balance. There is evidence of "ice piracy”[6] as the drainage for Whillans Branch 2 has expanded to include some of the area that formerly fed Ice Stream C (Price et al., 2001) and possibly capture part of the catchment feeding Whillans Branch 1. Currently Whillans Branch 1 has a negative mass balance while Whillans Branch 2 has a positive mass balance, the latter probably being a relatively recent shift.

The regional positive imbalance has effectively developed within the last two centuries through Ice Stream C’s stagnation and Whillans Ice Stream’s observed deceleration. Consequently, it is driven by internal ice-stream dynamics rather than climate-related changes in accumulation or melt (Joughin and Tulaczyk, 2002).

In summary, variation in stream velocity over decades, the potential for stream stagnation and major drainage reorganisations all have major implications for the mass balance of this sector of the West Antarctic Ice. However, despite a large level of internal instability, the Ross Embayment system as a whole appears stable. Any major episode of instability should be recorded in the flow structure of the Ross Ice Shelf and, despite variation in the location and discharge from different ice streams, the system appears to have remained stable without any sign of a major reorganisation (Bentley, 1998).

Flow Mechanisms for the Ross Ice Streams

The mechanisms allowing the Ross Ice Streams to flow at such high rates despite low driving stresses are addressed through different conceptualisations and modeling approaches. Essentially, since rapid ice motion is concentrated at the bed an understanding of basal conditions is necessary.

Early ideas of either enhanced basal- and/or marginal-ice shear due to stress-induced recrystallisation (Hughes, 1977) or enhanced basal sliding associated with elevated basal water pressures (Rose, 1979) were put aside in the mid-1980s when seismic reflection studies discovered a 5-6m thick layer of soft sediment beneath Whillans Ice Stream. This layer of subglacial till had high levels of porosity consistent with an actively deforming sediment.

Ever since, the concept of subglacial deformation has been associated with rapid ice flow: the saturated sediment beneath ice deforms at a lower stress than ice and contributes up to 90 percent of a glacier’s forward movement (Boulton and

[6] In fluvial geomorphology “piracy” is defined as “the natural diversion of headwaters of one stream into the channel of another stream having greater erosional activity and flowing at a lower level” (Bates and Jackson, 1980: cited in Anandakrishnan et al., 2001)

Hindmarsh, 1987). Recent observations beneath Ice Stream B (Kamb, 2001), which indicate that basal sliding, or at least near surface deformation (within 3 cm of the ice base) accounts for most of the movement, question this association.

Regardless of the mechanism occurring basal hydrology is important. It determines the partitioning of flow between basal sliding and subglacial deformation and its temporal/spatial variation (e.g. Alley, 1989a, 1989b; Iverson et al., 1998; Boulton et al., 2001). Subglacial water pressure controls both sediment strength and the degree of coupling between the ice base and the bed. Subglacial hydrological observations beneath Ice Streams B, C and D (e.g. Kamb, 2001) suggest a basal water supply system capable of reducing basal friction through the supply of substantial quantities of water at a pressure approximately equal to the ice overburden. Interestingly, the hydraulic systems of inactive and active streams are very similar.

Boulton et al. (2001) developed a ‘slipstick’ cycle model of basal motion, based on rapid spatial and temporal variation in basal water pressure, embracing both basal sliding and sediment deformation at various depths. The slipstick cycle may operate under varying water pressure regimes and spatially variable hydraulic systems to potentially create areas where one area of an ice stream bed may be sliding while an adjacent one is in stick mode.

Recent observations aside, the modelling of ice streams requires the development of flow laws to adequately describe subglacial deformation. In recent years, debate about the nature and mechanics of subglacial deformation has resulted in two broad schools of thought: one advocating plastic description of subglacial sediments (e.g. Tulaczyk et al., 2000a, 2000b), the other maintaining that at larger scales the gross behaviour of tills is approximated by modelling them as a viscous fluid (e.g. Hindmarsh, 1997).

Plastic flow models restrict shear to a very shallow layer at the top of the till column, while viscous-type flow models predict the deformation of subglacial sediment over a much greater depth (Bennett, 2003). The former is consistent with the observations of Engelhardt and Kamb (1998) made beneath the Whillans Ice Stream; the latter with geological observations made by Hart et al. (1990).

Essentially, there is currently no agreement on what is the best model approximation of subglacial sediment flow (Bennett, 2003), but thermodynamic approaches to ice stream behaviour have successfully accounted for periods of fast flow and sheet flow, in which ice can only move slowly via internal deformation.

Thermodynamic Modelling of Ice Stream Behaviour

Tulaczyk et al. (2000a, 2000b) illustrate the potential sensitivity of till strength to basal melt rates and argue that till strength beneath an ice stream is thermally controlled. The weaker the subglacial sediment, the faster the ice stream motion, because a greater fraction of the driving stress must be supported by ice deformation in the shear margins (Tulaczyk et al., 2001).

Several thermodynamic models, focusing on the coupling between ice flow and heat generation, have illustrated the sensitivity of basal motion within an ice stream to thermal conditions (MacAyeal,1993; Payne, 1995; Tulaczyk et al., 2000b) and successfully simulated episodes of fast flow, with a self-limiting cycle of activity. This suggests that ice streams may be inherently cyclic in their behaviour, with switches between active ('purge') and inactive ('binge') phases occurring with a periodicity of several thousand years. The switching between fast and slow modes may be sensitive to a thermal trigger (Tulaczyk et al., 2000a). These models involve feedback loops and switches in basal thermal regime from melting to freezing. They support states of fast flow and sheet flow, and indicate that ice stream stoppages may be triggered by a prolonged period of thinning.

Ice flow within an ice stream causes viscous heating leading to a warm bed, which in turn accelerates ice flow. However, rapid ice flow in an ice stream will ultimately cause ice thinning, which may reduce the gravitational shear stress and bring cold ice closer to the bed, causing it to cool and switching the basal thermal regime from melting to freezing (MacAyeal, 1993; Payne and Dongelmans, 1997). Freezing-on of water to the ice base strengthens the subglacial till increasing basal resistance and decreasing ice stream velocity. Depending on the feedback between basal freezing and shear heating the freeze-on-driven ice-stream slowdown may lead to complete ice-stream shutdown (Tulaczyk et al., 2000). The ice stream is self-limiting and a period of ice accumulation is required before streaming can restart. In this model, the active part of an ice stream life cycle is ultimately limited by the efficiency with which it discharges ice.

The Role of Sticky Spots and Shear Margins in Controlling Flow

The discovery that the yield strength of the sediment beneath Whillans Ice Stream is only 1 or 2 kPa, compared to the 20 to 30 kPa imposed by the down-slope weight of the ice (Kamb, 1991; Tulaczyk et al., 2002a) implied the bed is unable to support the gravitational shear stress of the stream.

Alley (1993) suggests the basal shear stress of an ice stream may be supported disproportionately on localised regions or "sticky spots". He proposes that the drag induced by large bedrock bumps sticking into the base of an ice stream is the most likely cause of sticky spots, with discontinuity of lubricating till another possible cause but less effective in supporting the bed. Having proposed such a mechanism, he suggests it is unlikely to be the dominant control in Whillans Ice Stream. Anandakrishnan and Alley (1994) found a greater frequency of microearthquakes at the base of slow-moving Ice Stream C than at the base of Whillans Ice Stream. On this basis, they suggest a model of the base of an ice stream that consists of a weak unconsolidated till interspersed with discrete zones of higher strength of the order of 102 m^2 in area with a spatial density of $10/km^2$ and that the frictional character of these would control ice stream flow speed. However, MacAyeal et al. (1995), in investigating sticky spots below Ice Stream E, conclude that while sticky spots are significant in the overall force budget, they are not the dominant resistive stress.

Subsequent work (e.g. Echelmeyer et al.,1994); Jackson and Kamb, 1997; and Raymond et al., 2001) has subsequently established that the shear margins play an important role in retarding the flow of the ice stream and support a significant fraction of the down-slope weight of an ice stream. The redistribution of force in the margins means the speed of ice stream flow is sensitive to the width of flow causing intense frictional heating to be focused in the margins. In some circumstances, the high stress and energy dissipation in the margins may drive the margins of an ice stream outward allowing an increase of the discharge velocity and widening the ice stream discharge gate. Alternatively, reduction of stress and energy dissipation on the ice base inside the margins may cause the opposite tendencies, thus lowering ice stream discharge

(Raymond et al., 2001). The prediction of margin migration rates is unresolved and the widening and associated deceleration of Whillans Ice Stream suggests other flow control mechanisms are present.

It is not known whether margin migration is excluded by morphological and topographical bed constraints. The existence of undisturbed stratigraphy in Siple Dome between Ice Streams C and D indicates they have not been able to migrate into the ridge for many millennia (Nereson et al., 1996, 1998). Siple Dome's high base and an absent or very thin till layer (Gades et al., 2000) may possibly exclude streaming flow.

The Stagnation of Ice Stream C

Understanding the shutdown of Ice Stream C is relevant to the overall understanding of ice stream behaviour and stability of WAIS. Although inactive, it is underlain by a layer of unfrozen soft sediment and has a driving stress and basal hydraulic properties similar to the active Ice Stream B. The inference is that these neighbouring ice streams display contrasting behaviour because of mechanical differences at their beds.

Models of ice stream shutdown polarise into two broad viewpoints: it is either the consequence of part of an ice stream's life cycle resulting from rapid ice discharge, as illustrated by thermodynamic modelling; or the consequence of two adjacent streams interacting (Bennet, 2003).

Anandakrishnan et al. (2001) reviewed a range of hypotheses on causes of stagnation, which include surging, surging via basal water feedbacks, loss of lubricating till, ice-shelf backstress, ice piracy, water piracy, thermal processes and sticky spots. They favour the water piracy model, in which Ice Stream B captures the subglacial water that previously lubricated the bed of Ice Stream C inhibiting ductile deformation of the till. Anandakrishnan et al. suggest that a "combination of water-diversion, thermal processes at the bed, and sticky spots" (2001: 283) caused stagnation. The water piracy model combines two ideas: an ice stream's flow efficiency results in a flattening of surface gradient, which increases the importance of basal topography in driving subglacial water flow; and the lack of topographic control allows a reorganisation of subglacial flow towards Ice Stream B. Effectively the demise of the ice stream is brought about by its flow efficiency.

While this water piracy model has enjoyed some dominance it has been challenged by recent observations of Price et al. (2001) who question the chronology of evolution of the ice surface used by Anandakrishnan and Alley (1997a) to justify the model.

Bennett (2003) uses Anandakrishnan and Alley's (1997b) findings of supportive sticky spots under Ice Stream C to apply the slipstick model, discussed previously, and suggests that although similar basal water pressures exist beneath Ice Stream C and Ice Stream B, on average, there may be a higher percentage of the bed in stick mode under the former.

In summary, the actual causes of Ice Stream C's shutdown is not known but adoption of the view of cyclical ice stream stagnation suggests that other ice streams may shutdown.

A Flow Regime Between Stream Flow and Inland Ice Flow

Bamber et al. revealed complex flow patterns in the interior Antarctic ice sheet, with many tributaries of distinctly channeled flow and velocities of 80 to 100 m year-1 in the interior of drainage basins. These velocities are substantially slower than typical active ice stream velocities of 100 to 2000 m/year (Bentley, 1987; Bindschadler et al., 1996) but faster than the surrounding ice that is moving at about 30m/year. These findings suggest an undefined flow regime exists representing a continuous gradation between inland flow and ice stream flow. Importantly, small perturbation theory (Nye, 1963: cited in Bamber et al., 2000) suggests the dynamic response time of an ice mass is inversely proportional to its velocity. Consequently, parts of the interior of Antarctica may respond more rapidly to climate forcing than current model simulations suggest.

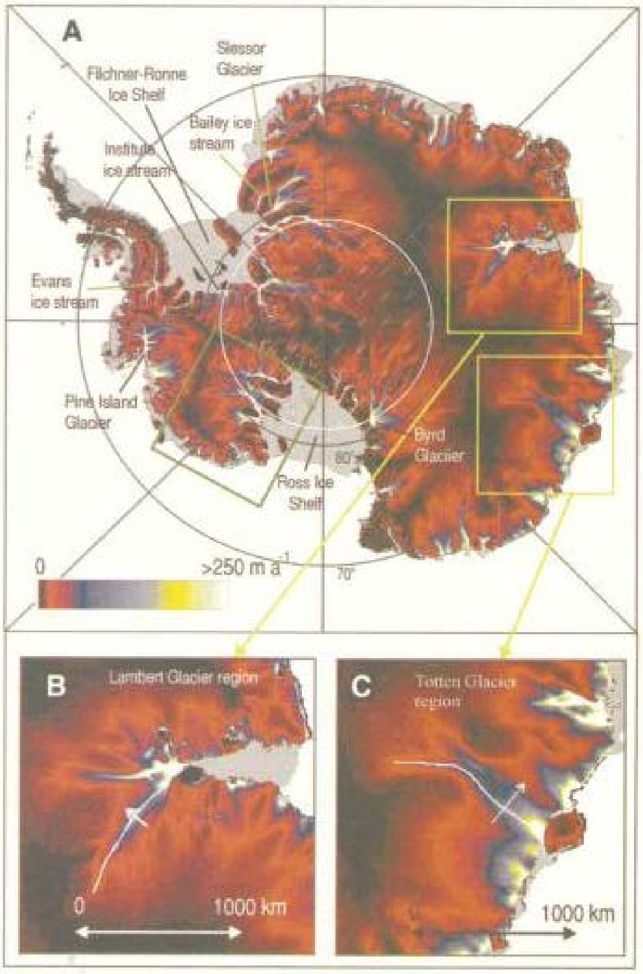

Figure 3. Balance velocities calculated for the grounded part of the Antarctic Ice Sheet showing complex flow patterns.

Description adapted from Bamber et al. (2000). (Figure Source: Bamber et al., 2000)

Implications of the Mass Balance of the Ross Ice Streams

The Shabtaie and Bentley (1987) estimate of a mass balance deficit implies ice sheet thinning and grounding line retreat. It also supports hypotheses of continued grounding-line retreat and possible collapse of WAIS (e.g. Bindschadler, 1998), with associated sea-level rise, based on extrapolation of grounding line retreat rate since the last glacial maximum (e.g. Conway et al., 1999).

Joughin and Tulaczyk (2002) offer alternative interpretations of the observed ice stream decelerations, taking into account the difficulty of ruling out decadal-scale or century-scale fluctuations in the slowdown of Whillans Ice Stream. They propose that their positive imbalance estimate and a trend toward a potentially larger imbalance suggest an ice sheet in advance rather than in retreat and may herald an end to the Holocene retreat of these ice streams.

The deceleration of Whillans Ice Stream may indicate an ice sheet response to a past imbalance. A likely overshoot in the restoration of balance resulting from continued unabated deceleration (Bindschadler, unpublished data: cited in Joughin and Tulaczyk, 2002) means, at least, a temporary shift to a positive mass balance. Such a shift might be well within the degree of ice-flow variability for the region over the last 1000 years (Fahnestock et al., 2000).

Alternatively, deceleration could indicate transition from a purge to a binge phase. Considering Ice Stream C's stagnation coupled with thermodynamic ice stream models' results, plausibly the current slowdown of Whillans Ice Stream could continue to a complete stagnation. The resultant reduction in discharge across the grounding line of the Ross Ice Shelf may have severe implications for the near-term stability of the ice shelf with any subsequent retreat or break up potentially affecting thermohaline circulation and the global climate (Joughin and Tulaczyk, 2002; Denton, 2000).

Conclusion

A comprehensive knowledge of ice stream dynamics is crucial to understanding their potential impact on the stability of an ice sheet and in turn on global climate and/or eustatic sea level rise. Any accurate prediction of WAIS stability depends on incorporating ice stream physics into models of the larger WAIS ice-flow systems.

The literature reviewed is characterised by an evolving understanding of these mechanisms but is riddled with contention, complex and contradictory data and discussions in various subject areas, such as shear margins, about which knowledge and understanding is limited. Contradictory data may be a result of cost and logistics restricting subglacial sampling regimes to limited point-specific data. Inaccuracies may occur in extrapolation of such data to enable the inference of basal conditions over the whole ice stream. Researchers may rely on evidence supporting their personal conceptualisation of basal processes, in the absence of definitive data.

Perceived complexities may be due to interpreting data that are effectively spatial and temporal snapshots of a complex system whereas the actual flow and character of an ice stream are the "time and space integrated products of this complex system" (Bennett, 2003: 322). Bennett uses this argument to suggest that an ice stream's average flow rate may be governed by the relative basal areas in each of the two modes of the slipstick cycle.

Ultimately more information is required on the variability in sedimentary properties over the bed of an ice stream Advances in remote sensing technology should advance knowledge and understanding, leading to improved sampling regimes that will allow more accurate extrapolation of observations. Alternatively, the investigation of Palaeo-ice streams could provide a complementary and more accessible source of such information.

The ability of the ice streams to affect the stability of the WAIS is subject to conjecture. Historical evidence of the stability of the Ross Ice Streams over 1300 years suggests a system exhibiting overall stability with a degree of ice flow variability within it. Previously negative and currently positive measurements of mass balance may be explained by thermodynamic models of self-regulating cycles of ice stream binge and purge and may be within the degree of flow variability inferred from the historical evidence. On the other hand models, such as Bindschadler's of grounding line retreat in step with inland migration of the ice stream onset, suggest the spatial and temporal instability of ice streams may induce instability of the WAIS. Clearly, the body of literature associated with the Ross Ice Streams will continue to grow for some time. This story will run and run.

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