Cover sheet

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PALAEO-ICE STREAM

Synonyms: not applicable

Definition: not applicable

Text:

Introduction

An *ice stream* is a region in a grounded ice sheet that flows at an order of magnitude faster than the slow-flowing ice that borders it. The term *palaeo-ice stream* is used to describe ice streams that no longer exist as a result of deglaciation. Ice streams have been referred to as the 'arteries' of an ice sheet (Bennett, 2003) because their high velocities are responsible for the vast majority of ice sheet discharge, despite representing a relatively small component of their surface area (Bamber et al., 2000). It is for this reason that they are viewed as a critical component of ice sheet mass balance and have important implications for sea level change (Shepherd and Wingham, 2007). The dynamic nature of ice streams is further emphasised by the relatively recent discoveries that they are capable of accelerating, decelerating, migrating, and shutting down over very short time-scales (e.g. Joughin et al., 2004; Conway et al., 2002).

Perhaps surprising, given their undoubted importance, is that ice streams are a relatively recent discovery. They were formally defined in the 1950s (Swithinbank, 1954) but only began to be intensively studied as late as the 1970s (e.g. Rose, 1979). Since that time, however, their identification in modern ice sheets has been enhanced by remote sensing techniques that enable a large-scale view of the flow features on the ice sheet surface (e.g. flow-stripes, crevasse patterns) and, more recently, the calculation of ice velocities and elevation (e.g. Joughin et al., 2004). These studies reveal that ice streams are typically large features (100s km long; 10s km wide) and possess very abrupt lateral shear margins, where intense crevassing is generated at the border with slow-flowing ice. Their rapid velocity is a defining characteristic and observations of their bed, whilst logistically very difficult, suggests that their motion is facilitated by a layer of saturated, deformable sediments that deform beneath the ice and offers minimal frictional resistance to basal sliding (Alley et al., 1986; Engelhardt and Kamb, 1998). Where subglacial sediment deformation is pervasive, high sediment transport rates are known to produce 'till' wedges at the terminus of the ice stream (Anandakrishnan et al., 2007).

Identification of palaeo-ice streams

Ice streams are a fundamental property of the flow structure of modern-day continental ice sheets and it can be assumed that they played a similar role in past (palaeo-) ice sheets. It was the recognition of their significance to ice sheet dynamics in the late 1970s and 1980s (e.g. Rose, 1979; Alley et al., 1986) that prompted several workers to attempt to reconstruct their location and behaviour in palaeo-ice sheets (e.g. Denton & Hughes, 1982; Dyke and Prest, 1987). These pioneering workers recognised that ice streams should leave behind geological/geomorphological evidence of their activity that would be very different from the slow-flowing regions of the ice sheet, and cited evidence of distinctive erratic dispersal trains with abrupt lateral margins (Hicock, 1988; Dyke and Morris, 1988). The discovery of highly elongated subglacial bedforms on palaeo-ice sheet beds, known as mega-scale glacial lineations (cf. Clark, 1993), was also linked to palaeo-ice stream activity. Despite these important advances, the identification of palaeo-ice streams was somewhat subjective, with a wide variety of evidence used to infer their location in former ice sheets (e.g. see review in Stokes and Clark, 2001).

Matthews (1991) highlighted the need for some objective criteria to identify palaeo-ice streams and Stokes and Clark (1999) later proposed some 'geomorphological' criteria, based on the characteristics of modern-day ice streams. These criteria are listed in Table 1 and, where several are identified together on a palaeo-ice sheet bed, are likely to indicate robust evidence of ice streaming.

Table 1: Geomorphological criteria for identifying palaeo-ice streams (from Stokes and Clark, 1999)

Contemporary ice stream characteristic	**Proposed geomorphological signature**
A. Characteristic shape and dimensions	1. Characteristic shape and dimensions (>20 km wide and >150 km long) 2. Highly convergent flow patterns
B. Rapid velocity	3. Highly attenuated subglacial bedforms 4. Boothia-type erratic dispersal trains (see Dyke and Morris, 1988)
C. Sharply delineated shear margins	5. Abrupt lateral margins (<2 km) 6. Ice stream marginal moraines
D. Deformable bed conditions	7. Glaciotectonic and geotechnical evidence of pervasively deformed till
E. Focused sediment delivery	8. Submarine accumulation of sediment, e.g. 'trough mouth fan' or 'till delta' , (only marine terminating ice streams)

The criteria, listed in Table 1, can be grouped together into a glacial landsystem, which represents the unique imprint (or 'footprint') of palaeo-ice stream activity (see Stokes and Clark, 2001). Indeed, numerous palaeo-ice stream imprints have now been recognised from all of the major palaeo-ice sheets from the last ice age (e.g. Laurentide, Scandinavian-Barents Sea, British-Irish; see special issue introduced by Clark et al., 2003) and even those from more ancient glaciations 100s of millions of years ago (Moreau et al., 2005). Palaeo-ice stream imprints have also been reported from predominantly bedrock terrain (e.g. Roberts and Long, 2003), including in mountainous areas (cf. Evans, 1996), based on the morphometry and pattern of streamlined erosional landforms.

Arguably, the best preserve palaeo-ice stream imprints have been identified on the sea-floor of the continental shelf surrounding modern-day ice sheets (e.g. in Antarctica) and associated with palaeo-ice sheets. Figure 1 shows an exceptionally well-preserve submarine palaeo-ice stream bed off the coast of northern Norway in Malangsdjupet. This ice stream 'footprint' contains many of the geomorphological criteria shown in Table 1.

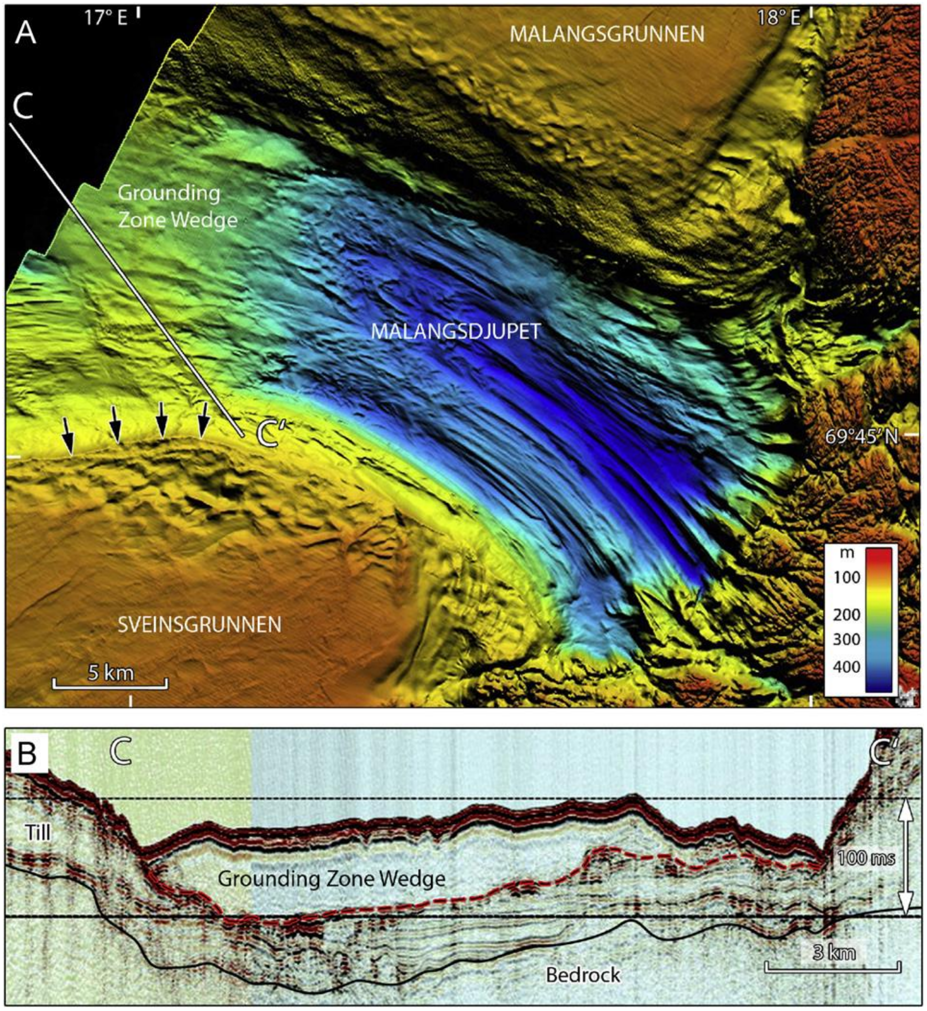

Figure 1: (A) Malangsdjupet palaeo-ice stream from the former Fennoscandian Ice Sheet. This ice stream bed contains almost all of the geomorphological criteria for a palaeo-ice stream imprint (see table 1) including the characteristic shape and dimensions with a convergent onset zone; highly attenuated mega-scale glacial lineations on the floor of the trough; and abrupt lateral margins with lateral shear margin moraines (identified with black arrows). The trough also contains evidence of focussed sediment delivery in the form of a grounding zone wedge, shown in a seismic profile in B (transect C to C' shown in A) Sun illumination from NE (from Ottesen et al., 2008)

Palaeo ice streams in marine settings (e.g. see Figure 1) have been shown to exhibit a characteristic evolution of subglacial bedforms along their length (Wellner et al., 2001; Ó Cofaigh et al., 2002). The inner shelf is usually characterised by bedrock drumlins, crag-and-tails and meltwater channels, which progress down-stream into more elongated drumlins and highly attenuated mega-scale glacial lineations in major cross-shelf troughs. Significantly, the deglaciation signature may also be superimposed on this pattern, offering crucial insights into the style of ice stream retreat (O Cofaigh et al., 2008). Where ice retreat was slow and steady, a series of closely spaced transverse recessional ridges are found superimposed on top of the mega-scale glacial lineations. Major still-stand positions are marked by the intermittent building of 'grounding zone wedges' (GZWs) and a series of such features, with no recessional ridges in between, is thought to represent an episodic retreat. Other imprints have been identified with very few recessional features (GZWs or recessional moraines) and with only a thin veneer of deglacial sediments. Such an imprint is thought to represent a rapid retreat of the ice stream (O Cofaigh et al., 2008).

The other broad approach to reconstructing palaeo-ice streams is through the use of numerical ice sheet models (e.g. Tarasov and Peltier, 2004). Incorporating ice stream processes into ice sheet models represents a major scientific and computational challenge, which has been described as "one of the key goals of theoretical glaciology" (Hindmarsh, 2009). The challenge for numerical ice sheet models is to be able to incorporate the physics of ice streaming and reproduce the 'known' location of palaeo-ice streams identified from geological/geomorphological evidence. This is a robust way in which the success of ice sheet models can be evaluated and tested (e.g. Stokes and Tarasov, 2010). Furthermore, there may be some palaeo-ice streams where evidence is either scarce, obscured, or yet to be discovered. Numerical ice sheet models have the potential to predict these palaeo-ice stream locations and guide the search for new discoveries.

Once identified, palaeo-ice streams hold huge potential for advancing our understanding of past ice sheet dynamics and their links to the ocean-climate system. If we can reproduce a robust reconstruction of palaeo-ice stream activity, it is possible to learn about their behaviour over much longer time-scales than present-day observations permit and their links to palaeoceanography and abrupt climate change. Moreover, the exposed beds of palaeo-ice streams permit access to the basal environment and facilitate investigation of subglacial sedimentary processes beneath ice streams, which is logistically very difficult beneath modern ice streams. The following sections briefly highlight the importance of palaeo-ice stream research in each of these key areas.

Palaeo-ice streams and past ice sheet dynamics

Any attempt to reconstruct the behaviour of a palaeo-ice sheet that ignores ice streaming is likely to be unrealistic. The large ice flux of ice streams has a profound impact on ice sheet configuration (e.g. thickness, margin extent, ice divide locations, etc.) and so it is important to know where and when they operated in order to reconcile ice sheet reconstructions with their geological evidence. A good example to illustrate this point is the former North American 'Laurentide' Ice Sheet (LIS).

Several workers reconstructed the low-surface profile of the LIS in many of its marginal areas, particularly where the underlying geology was characterised by relatively 'soft', fine grained sediments (e.g. Mathews, 1974). These areas of thin ice were in conflict with models of the LIS that required a thick, single-domed ice sheet, centred over Hudson Bay (e.g. Denton and Hughes, 1981). However, the low surface slopes of the ice sheet are easily explained by the presence ice streams whose rapidly velocity was induced by the deformation of soft water-saturated sediments (Fisher et al., 1985). Indeed, the higher velocities of these ice streams can also explain the lobate nature of the ice sheet margin and subsequent work has reported clear evidence of palaeo-ice stream imprints associated with such lobes (Patterson, 1998).

It has also been suggested that, once the LIS margin retreated back on to the more resistant (‘hard’) Canadian Shield rocks, ice stream activity was inhibited and ice sheet retreat was more stable (Clark et al., 1996). This geological control on ice streaming (which, incidentally, has also been suggested from work on modern-day ice streams: Winsborrow et al., 2010) has since been questioned; because robust evidence for ice streaming during deglaciation has been found on the Canadian Shield (Stokes and Clark, 2003). This discovery demonstrates that the spatial controls on ice streaming may be more complex than previously thought and highlights the importance of palaeo-ice stream research in contributing to our overall understanding of their behaviour. Indeed, a recent review by Winsborrow et al. (2010) identified seven potential controls on ice stream activity: topographic focussing, topographic steps, macro-scale bed roughness, calving margins, ‘soft’ subglacial geology, geothermal heat flux and subglacial meltwater routing.

Reconstruction of palaeo-ice stream histories is also an excellent approach to understanding the temporal controls on ice streaming. Modern-day observations of their behaviour are often limited to several decades, but reconstructions of palaeo-ice streams are capable of spanning thousands of years of activity. For example, whilst much research is focused on the mass balance of ice streams draining into the Ross Ice Shelf in West Antarctica, examination of the palaeo-ice stream tracks in their foregrounds indicates that they have been receding since the early Holocene and could continue to retreat even in the absence of further external forcing (Conway et al., 1999). Thus, palaeo-ice stream research can provide a useful context in which to assess the significance of relatively small changes in their behaviour that have been and will continue to be observed in modern-day ice sheets. Moreover, whilst it is known from contemporary ice stream research that ice streams are capable of switching positions and shutting down, research on palaeo-ice streams has revealed equally dramatic switches in ice stream position from one glacial cycle to the next (e.g. Dowdeswell et al., 2006) and even during deglaciation of a single glacial cycle (e.g. Stokes et al., 2009).

Palaeo-ice streams and subglacial processes

Although great progress has been made in understanding the subglacial environment beneath ice streams and the mechanisms that lead to their rapid flow (e.g. Alley et al., 1986; Engelhardt and Kamb, 1998), most information from the bed of modern-day ice streams is limited by the spatial and temporal resolution (e.g. indirect geophysical studies or borehole investigation). For this reason, many workers have recognised the potential that the now-exposed beds of palaeo-ice streams hold for understanding their basal processes. The sediments and landforms they have leave behind preserve important information regarding their basal processes and operation.

As noted above, the arrangement and morphometry of subglacial bedforms on palaeo-ice stream beds has been used to hypothesise that highly elongate bedforms are associated with fast ice flow (e.g. Clark, 1993; Stokes and Clark, 2002). Due to the inaccessibility of modern-day ice stream beds, this hypothesis has been difficult to test. However, advances in geophysical techniques have led to their recent discovery beneath Rutford Ice Stream in West Antarctica, providing the first conclusive evidence of this relationship (King et al., 2009). Moreover, because ice streaming results in such a distinct subglacial landscape (characterised by elongated subglacial bedforms), it should be possible to identify and investigate the nature of localised ‘sticky spots’, which are known to be important from studies of modern-day ice streams (e.g. Alley, 1993) but which, to date, have been very difficult to observe and characterise. Sticky spots should interrupt the predictable pattern of landforms that characterise a palaeo-ice stream bed and be easily recognisable (cf. Stokes et al., 2007). They should also be manifest in the sediments preserved on the palaeo-ice stream bed, which may even provide a ‘smoking gun’ of the mechanisms that led to ice stream shut-down. For example, Christofferson and Tulaczyk (2003) reported an unusual till sequence from beneath the Baltic Ice Stream in southern Scandinavia, consisting of a strong and well-consolidated till crust, underlain by weak and poorly consolidated till. They hypothesised that this sequence could be associated with the processes of basal freeze-on, whereby meltwater is extracted from the subglacial till and accreted to the base of the ice stream. Such a process can starve the ice stream of its layer of lubricating water, leading ice stream shut-down.

Palaeo-ice stream sediment transport and deposition

Palaeo-ice streams can be extremely powerful erosional agents, especially those that extend across continental shelves and operated over soft, deformable, marine sediments (Vorren and Laberg, 1997). These ice streams can be very efficient at eroding and transporting subglacial sediment and their sediment flux is comparable to the largest fluvial systems, despite their far shorter duration of operation. Moreover, the focussed sediment discharge towards the shelf edge can create huge depocentres, known as ‘trough mouth fans’ (Vorren and Laberg, 1997; Vorren et al., 1998). Significantly, investigation of the architecture of these trough mount fans has enabled investigators to reconstruct past sediment fluxes and the long-term record of ice stream activity (ice discharge, velocity), sometimes extending back through several glacial cycles (Vorren et al., 1998). For example, the Norwegian Channel Palaeo-Ice Stream in southern Norway is thought to have transported $>3.2 \times 10^4$ km^3 of sediment on to the North Sea Fan during the last 0.5 m.y., with extreme and punctuated sediment discharges as high as 1.1 Gt a-1 during the last glacial cycle (Nygård et al., 2007).

The extreme sedimentation rates associated with palaeo-ice stream trough-mouth fans also holds implications for geohazards, such as submarine debris slides and flows. It is known that the high sediment supply can lead to unstable deposits and an increased likelihood of slope failures in these areas, particularly after seismic activity and/or decomposition of gas hydrates (Vorren et al., 1998).

Palaeo-ice streams, palaeoceanography and abrupt climate change

Finally, the large ice flux of palaeo-ice streams also holds important implications for the delivery of icebergs and freshwater fluxes into the ocean. Ocean circulation (e.g. the North Atlantic thermohaline circulation) is highly sensitive to such influxes of freshwater and perturbation of these systems can lead to major and abrupt climatic changes (Broecker, 1994). Because ice streams have the capacity to drain large portions of an ice sheet relatively rapidly, they have the potential to deliver huge amounts of icebergs into the ocean and represent a key link in the coupling of the ice sheet and ocean systems. Episodes of ice streaming in Hudson Strait, for example, are thought to be responsible for several large iceberg export events into the North Atlantic between 60 and 10 ka (Broecker et al., 1992; MacAyeal, 1993). Evidence for these events comes from bands of ice-rafted debris in ocean cores, known as Heinrich layers, which have been specifically linked to sedimentary rocks beneath a palaeo-ice stream in Hudson Strait (Andrews and Tedesco, 1992). The influx of freshwater resulting from these events was sufficient to cause changes in sea surface temperature and salinity, which had a considerable impact on ocean circulation and northern hemisphere climate (Broecker, 1994). Although the trigger for these episodes of ice streaming remain unclear it is now recognised that they can be instrumental in driving abrupt changes in mid-high latitude climate and oceanography.

Elsewhere in the LIS, palaeo-ice streams have been implicated in similar iceberg discharge events, particularly at the north-western margin in the Canadian Arctic Archipelago (e.g. Stokes et al., 2005). Significantly, the timing of these events are similar to those issued from the Hudson Strait ice stream, hinting at the possibility that they were part of a pan-ice sheet destabilisation. The large marine-terminating ice streams at the northern margin of the Laurentide Ice Sheet are also thought to have contributed to the development of a thick (>1000 m) Arctic ice shelf, which may have occupied the Arctic Ocean several times during the Late Pleistocene (Polyak et al., 2001), further emphasising their important role in the ice sheet-ocean-atmosphere system.

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