



# Glacial geomorphology: Towards a convergence of glaciology and geomorphology

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**Abstract**

This review presents a perspective on recent trends in glacial geomorphological research, which has seen an increasing engagement with investigating glaciation over larger and longer timescales facilitated by advances in remote sensing and numerical modelling. Remote sensing has enabled the visualization of deglaciated landscapes and glacial landform assemblages across continental scales, from which hypotheses of millennial-scale glacial landscape evolution and associations of landforms with palaeo-ice streams have been developed. To test these ideas rigorously, the related goal of imaging comparable subglacial landscapes and landforms beneath contemporary ice masses is being addressed through the application of radar and seismic technologies. Focusing on the West Antarctic Ice Sheet, we review progress to date in achieving this goal, and the use of radar and seismic imaging to assess: (1) subglacial bed morphology and roughness; (2) subglacial bed reflectivity; and (3) subglacial sediment properties. Numerical modelling, now the primary *modus operandi* of ‘glaciologists’ investigating the dynamics of modern ice sheets, offers significant potential for testing ‘glacial geomorphological’ hypotheses of continental glacial landscape evolution and smaller-scale landform development, and some recent examples of such an approach are presented. We close by identifying some future challenges in glacial geomorphology, which include: (1) embracing numerical modelling as a framework for testing hypotheses of glacial landform and landscape development; (2) identifying analogues beneath modern ice sheets for landscapes and landforms observed across deglaciated terrains; (3) repeat-surveying dynamic subglacial landforms to assess scales of formation and evolution; and (4) applying glacial geomorphological expertise more fully to extraterrestrial cryospheres.

**Keywords**

Antarctica, geophysics, glacial geomorphology, glaciers, glaciology, ice sheets, numerical modelling, remote sensing

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## I Introduction

In this paper we define glacial geomorphology as the landforms, sediments and landscapes created and/or modified by glaciation, and the study of these features and their formative processes. Motivations for such studies are manifold. We live in a geological period, the Quaternary, spanning 1.8 Ma BP to the present, characterized by dramatic climate oscillations, in response to which glaciers and ice sheets throughout the globe have expanded and diminished many times. Understanding this history of glaciation, how the growth and decay of large ice sheets feeds back into further climate change, and quantifying ice-atmosphere-ocean feedbacks during past glaciations and deglaciations, are all key to elucidating the present and likely future responses of glaciers and ice sheets to ongoing changes in climate, and predicting the changes to sea levels and water resources that these will effect (eg, Shepherd and Wingham, 2007; Solomon *et al.*, 2007). Glacial geomorphology, in providing the evidence for determining former ice extents (eg, Dyke *et al.*, 2001; Glasser *et al.*, 2008) and dynamic configurations (eg, Clark, 1993; Stokes and Clark, 2001; Kleman *et al.*, 2008; Ó Cofaigh and Stokes, 2008; Rose and Hart, 2009), and in recording the processes that occur beneath ice masses both past and present (eg, Hindmarsh, 1993; Evans, 2003; Dunlop *et al.*, 2008; Stroeven and Swift, 2008), forms an essential component of this imperative. Glaciers and ice sheets are also effective agents of landscape evolution: highly active in erosion and landscape denudation, as evinced by mountainous 'alpine' landscapes (eg, Harbor *et al.*, 1988; Mackintosh *et al.*, 2006; Brook *et al.*, 2008) and regions of areal scouring (eg, Sugden, 1978; Lidmar-Bergström, 1997; Glasser and Bennett, 2004); and in deposition, as exemplified by the numerous tills (eg, Svendsen *et al.*, 2004) and glacial depositional landforms (eg, Eyles, 2006; Evans *et al.*, 2008) swathed across much of northern Eurasia and

America, legacies of the Last Glacial Maximum, ~21 ka BP. Improving our understanding of glacial erosional, depositional, and deformational processes worldwide is critical to gauging rates of landscape modification by ice masses, and quantifying the relative role that ice plays in global landscape denudation (Hallet *et al.*, 1996; Brocklehurst and Whipple, 2006; Aber and Ber, 2007; Stroeven and Swift, 2008, and references therein). From a more practical, 'applications-based' standpoint, a knowledge of the structure and distribution of glacial landforms and sediments is also highly useful in activities including gravel extraction, mitigation of natural hazards, and waste disposal (Gray, 1993; Bridgland, 1994; Talbot, 1999; Clague, 2008; Moore *et al.*, 2009).

In this article we reflect on some recent trends in glacial geomorphological research, and in particular the increasing engagement with understanding glaciation over larger and longer timescales afforded by advances in remote sensing and numerical modelling. Space limitations preclude a comprehensive review of the now vast field of glacial geomorphology (recent offerings from Benn and Evans, 2010, and Knight, 2006, provide good starting points), so we omit from this article any discussion of the vast contributions advances in dating methods have made to studies of deglaciation. Here we focus especially on developments made in techniques to image and interpret landforms, sediments and landscapes beneath modern ice sheets, which have perhaps received little synthesis to date in traditional geomorphological spheres, yet have much potential to inform the rapidly expanding field of studies and reconstructions of *former* ice sheets. We begin with an overview of some of the technological and theoretical advances which have facilitated an 'upscaling' of research in contemporary glacial geomorphology (section II). We then focus on the example of West Antarctica, reviewing the methods used to investigate the form and composition of the bed beneath the modern ice

sheet and the insights such studies provide. In section IV we discuss two examples of the ways in which numerical models use such data to advance our understanding of subglacial processes and landscape evolution. In section V we reflect on progress in contemporary glacial geomorphology, and tentatively propose some potential directions for future research.

## II Changing scales and methodologies in glacial geomorphology

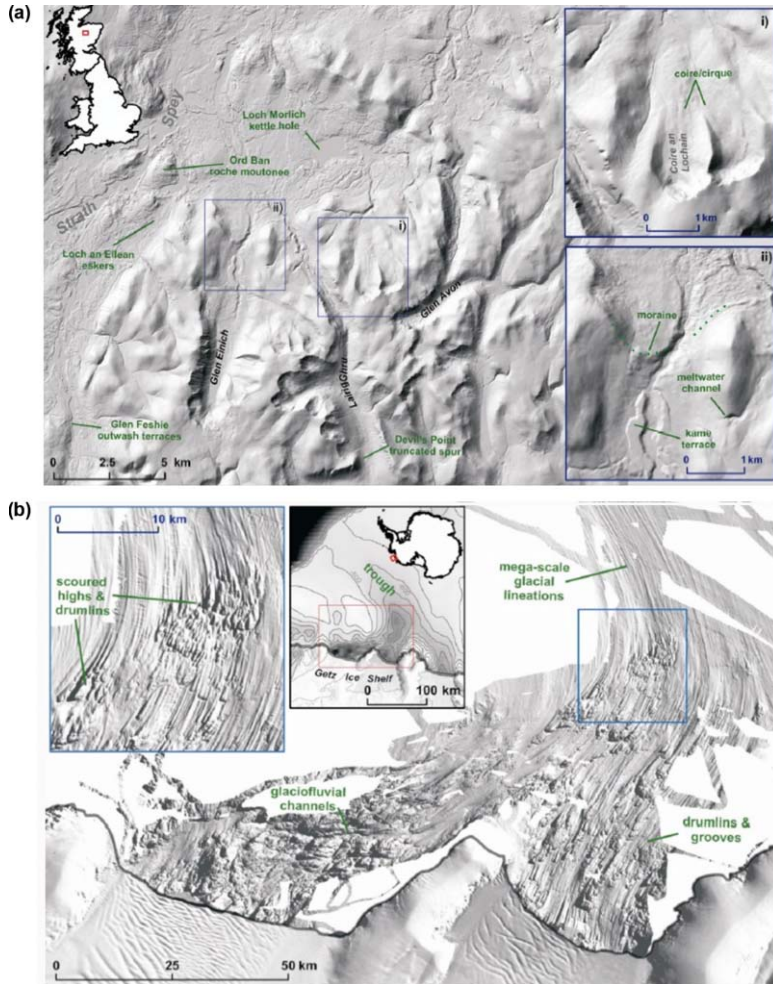
As in all aspects of geomorphology (cf. Church and Mark, 1980), scale is a critical concept in glacial research. The idea is illustrated with glaciological examples in Figure 1. In glacial geomorphology the term *landform* is typically used to describe features at local to sublocal (<10 km) spatial scales, which are created and persist over shorter temporal timescales (<10<sup>3</sup> years) than *landscapes*, palimpsests of landforms covering larger, regional to continental (~10<sup>2</sup>–10<sup>5</sup> km<sup>2</sup>) spatial scales, which must be considered over accordingly longer temporal timescales (cf. Sugden and John, 1976: 7). The critical point is that the *spatial* scale over which a landform or landscape develops tends to have a corresponding *temporal* scale; thus to study the evolution of entire ice-sheet-scale landscapes, such as landscapes diagnostic of the former Laurentide and Eurasian Ice Sheets, or the contemporary subglacial landscape beneath Antarctica, requires methodologies capable both of addressing spatial scales >10<sup>5</sup> km<sup>2</sup> and temporal scales >10<sup>4</sup> years.

Prior to the late 1980s, most glacial geomorphology was practised on deglaciated terrain at relatively local scales, with the majority of studies focusing on the genesis of individual landforms (cf. Boulton, 1987b). Traditional practices, with the primary aim of inferring past ice-extent and flow directions in individual localities, included geomorphological mapping of formerly subglacial and ice-marginal

landforms (eg, striae, drumlins, moraines); and fabric and compositional analyses of tills, either exposed in riverbanks, cliffs and/or quarries, or retrieved using sediment-coring techniques. While there was a burgeoning desire to link these disparate studies together to constrain glaciation over larger, regional to continental landscape scales, thereby to address long-term glacial landscape *evolution* (eg, Flint, 1971; Moran *et al.*, 1980; Denton and Hughes, 1981), the technology and theory to address these larger and longer scales of analysis were largely lacking.

Over the last 20 years, advances in remote sensing and numerical modelling have provided both the impetus and the tools for glacial geomorphologists increasingly to engage with elucidating glaciation over far larger spatial and temporal timescales than was previously possible. Remote sensing, especially from space, has allowed glacial landscapes clearly to be observed over far greater spatial scales than before (eg, Bamber, 2006; Kleman *et al.*, 2008), while numerical modelling has enabled hypothesis-testing over the correspondingly larger timescales (cf. Figure 1) required to understand the development and evolution of these spatially vast landscapes. We return to the role of numerical modelling in glacial geomorphology in section IV. The advances in remote sensing can be split into three groupings: spaceborne Earth observation; marine geophysics; and glacier geophysics.

The development of a suite of 'Earth observation' satellites, such as SPOT5 and ASTER, has enabled us, for the first time, to image landscapes effectively at up to continental scales (eg, Clark, 1997; Smith *et al.*, 2005). Especially striking has been spaceborne imagery of northern North America and Eurasia, which has aided delineation of the former ice-sheet extents (Napieralski *et al.*, 2007; Kleman *et al.*, 2008), and enabled researchers to visualize the essential coherence of different land systems diagnostic of former ice-sheet configurations (eg, Evans,



**Figure 1.** Illustrating the use of remote sensing to image glacial landforms and landscapes at a variety of scales. (a) 900 km<sup>2</sup> high-resolution (5 m) shaded relief map of the northern Cairngorm plateau and part of Strathspey near Aviemore, Scotland, an area extensively glaciated during the last stadial. Landforms characteristic of extensive glacial erosion over timescales  $>10^3$  years (eg, the Glen Einich and Lairig Ghru glacial troughs, truncated spurs, coires and roches moutonnées) can be discerned; superimposed over these are smaller landforms created over timescales of  $10-10^2$  years by glacial deposition (moraines), glaciofluvial action (meltwater channels, kames, eskers, outwash terraces) and deglaciation (kettle holes). Image generated from Intermap Technologies NEXTMap<sup>®</sup> digital elevation data, made using airborne synthetic aperture radar interferometry and provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC). (b) 40,000 km<sup>2</sup> medium-resolution (50 m) shaded relief map from ship-borne swath bathymetry, showing a landscape of former ice stream beds on the continental shelf of West Antarctica, submerged at up to 1000 m depth below sea level. The landscape is dominated by two ice stream troughs that converge into a single, 65 km wide, trough eroded into the continental shelf. Even the smaller-scale landforms in this landscape show the profound modifying effects of sustained fast glacier flow persisting over timescales  $>10^3$  years. Close to the modern grounding lines, an anastomosing network of channels has been carved into exposed bedrock by subglacial fluvial erosion, and bedrock has been streamlined.

2003). Illustrating the profound effect that remote sensing has had on scales of analysis, satellites have clearly imaged large-scale landforms (eg, megascale glacial lineations; Clark, 1993) that previously went unrecognized because they appear too fragmented on the smaller scales of aerial photographs of field investigation. Perhaps more than any other factor, such imagery has strengthened our appreciation that large parts of the Earth's terrestrial landscape have fundamentally been shaped by the growth and decay of major ice sheets; and the consequent ability to synthesize previously disparate observations of landforms and local-scale models, and upscale to continental-scale models of (de)glaciation, has fuelled a shift away from the more traditional smaller-scale 'alpine glaciation' studies towards those with a larger-scale 'ice-sheet-glaciation' emphasis. A particularly dynamic growth area of glacial geomorphology now concerns the identification of 'palaeo-ice streams' across deglaciated terrain (Stokes and Clark, 2001; Ó Cofaigh *et al.*, 2002; Clark *et al.*, 2003; Graham *et al.*, 2007a). Such research has at its core the philosophy that the composition and distribution of exposed subglacial landforms and sediments impart vital clues concerning what has controlled the flow, and changes in flow, of former ice streams and glaciers. Understanding these controls is vital, as satellite-derived ice-velocity observations have demonstrated that arterial fast-flowing ice streams account for the vast majority of overall ice flux in modern ice sheets (Joughin *et al.*, 2002; Rignot, 2006; Rignot and Kanagaratnam, 2006), hence understanding their behaviour is at the heart of elucidating overall ice-sheet evolution.

Significant related advances further consolidating the turn towards ice-sheet-scale geomorphology over the last 20 years have been made in 'ship-borne' remote sensing, more commonly termed marine geophysics (Dowdeswell and Scourse, 1990; Dowdeswell and Ó Cofaigh, 2002). At the Last Glacial Maximum, terrestrial ice sheets extended onto the continental shelves off Antarctica, North America (including Greenland) and Eurasia. While the submergence of these subglacial landscapes has facilitated the excellent preservation of features (see, for example, Larter *et al.*, 2009), it has also meant that their detection and detailed study have had to await the development of technology capable of imaging landforms and landscapes effectively beneath several 100 m of seawater. Over the last two decades the capability to achieve this goal has developed at a rapid pace, and marine geophysical techniques including multibeam swath bathymetry, side scan sonar, TOPAS subbottom profiling and multichannel seismic reflection profiling have all been refined and increasingly implemented to map, in sometimes astounding detail, a plethora of glacial landforms and sediments off Antarctica (eg, Anderson *et al.*, 2002; Lowe and Anderson, 2003; Mosola and Anderson, 2006; Nitsche *et al.*, 2007; Dowdeswell *et al.*, 2008; Larter *et al.*, 2009; Smith *et al.*, 2009), Greenland (eg, Ó Cofaigh *et al.*, 2004; Evans *et al.*, 2009) and the North Atlantic (Dowdeswell *et al.*, 2006; Nygard *et al.*, 2007; Ottesen *et al.*, 2008). Mirroring the work utilizing spaceborne instrumentation to image terrestrial deglaciated landscapes, a common drive has been to reconstruct former ice-stream flowpaths, geometry and dynamics from the landforms and sediments thus imaged (eg, Evans

**Figure 1. (Continued)** Downstream, there is a transition to drumlin swarms, often clustered between isolated, scoured bedrock highs or interspersed with megascale glacial lineations (MSGSL). As sediment cover becomes continuous farther downflow, only MSGSL persist, converging and reaching far onto the continental shelf. Image after Larter *et al.* (2009); see also Nitsche *et al.* (2007); ice shelf imagery from LIMA mosaic.

*et al.*, 2006; Ó Cofaigh and Stokes, 2008; Larter *et al.*, 2009).

Using both the onshore and offshore work on deglaciated terrains, a range of landforms or landform assemblages characteristic of former ice-streaming within a regional ice cover (Clark, 1994) have been identified: (1) drumlins and flutes, hills or ridges of glacial till elongated along the axis of ice flow (Boulton, 1976; Menzies, 1979; Clark *et al.*, 2009); (2) megascale glacial lineations (MSGLs), elongate ridges of sediment also aligned along flow similar to the above but with much larger dimensions, which may in many cases consist of amalgamations of the above (Clark, 1993; King *et al.*, 2009); (3) deformation tills, thicknesses of unconsolidated sediments containing a directional deformational signature (eg, Dowdeswell *et al.*, 2004; Ó Cofaigh *et al.*, 2005); and (4) the absence of such features on intervening regions interpreted as areas of slow or sheet flow (Kleman *et al.*, 2008). An outstanding challenge is to invert from this glacial geomorphology the former ice-sheet conditions responsible for imprinting these landforms, sediments and landscapes (eg, Glasser and Bennett, 2004; Kleman *et al.*, 2008), and, to test such ideas rigorously, the related challenge has therefore arisen of imaging the corresponding landforms, sediments and landscapes beneath modern ice streams. This is a challenge that is steadily being addressed through glacier geophysics.

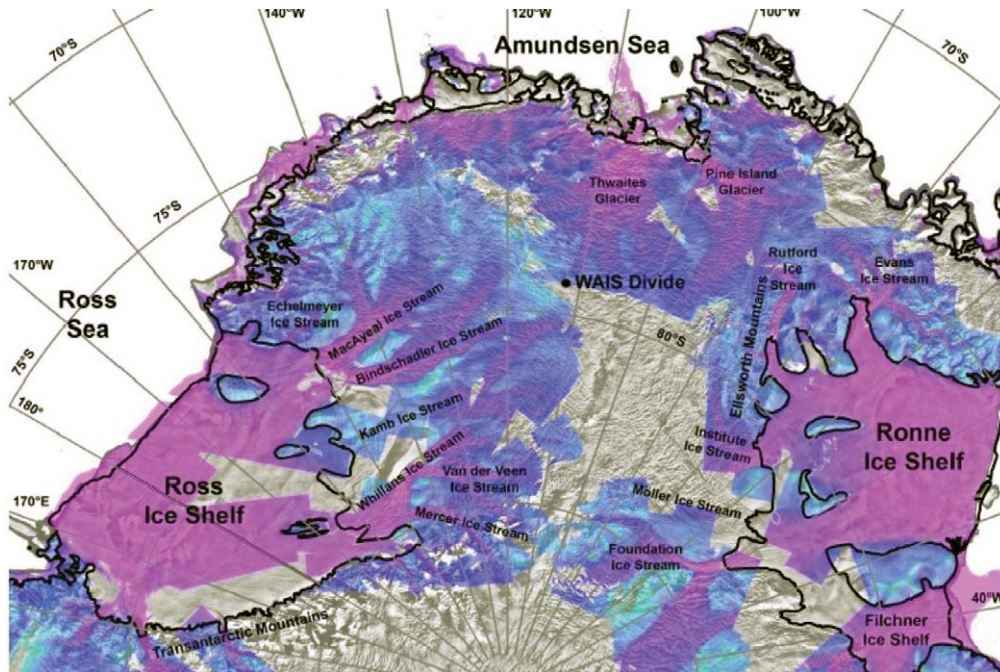
Compared with the bulging archive of imagery of exposed ice-sheet beds obtained from Earth observation and marine geophysics over the last 20 years, progress in using geophysical techniques to image modern ice-sheet beds has been less marked. This is certainly not due to apathy on the part of glaciologists; rather, it is because the task of 'seeing through' ice thicknesses of several km to gain comparable imagery of ice-sheet beds remains at the frontier of geophysical ability. A less significant, but still important, consideration is that access to the

remote interior regions of ice sheets, especially in Antarctica, while steadily increasing, remains extremely restricted, limiting opportunities to gather data and refine methods. Nevertheless, geophysical methods applied over modern ice sheets have steadily developed to a stage at which they are beginning to produce geomorphological data directly comparable with that retrieved over deglaciated terrains.

### III Imaging subglacial conditions across West Antarctica

#### *I Location*

West Antarctica is shrouded by the world's only remaining marine ice sheet. Here, the term 'marine' specifically refers to the predominant grounding of the West Antarctic Ice Sheet (WAIS) below present (and iso-adjusted) sea level, an attribute hypothesized as leaving it especially vulnerable to rapid flotation and collapse in response to rising sea levels and thinning (Mercer, 1978; Pollard and DeConto, 2009). Knowledge that the WAIS holds the equivalent of ~3.3 m of sea-level rise (Bamber *et al.*, 2009), coupled with satellite observations of its highly dynamic behaviour, comprising dramatic thinning and ice-acceleration in some parts (eg, Joughin *et al.*, 2006; Wingham *et al.*, 2006a; 2009; Bamber *et al.*, 2007; Rignot, 2008; Rignot *et al.*, 2008), has motivated research into the fundamental controls on ice-stream behaviour in West Antarctica since the early 1970s (Hughes, 1977; Bentley, 1987; Alley and Bindschadler, 2001). Belief, evermore backed up by theory, that the key to dynamic changes in ice-stream behaviour lies at the bed (eg, Alley *et al.*, 1986; MacAyeal, 1992; Schoof, 2006), has fuelled numerous efforts to 'view' basal conditions beneath the WAIS. With the exception of a handful of boreholes (Engelhardt *et al.*, 1990; Engelhardt and Kamb, 1998), this research has relied entirely on applications of glacier geophysics.



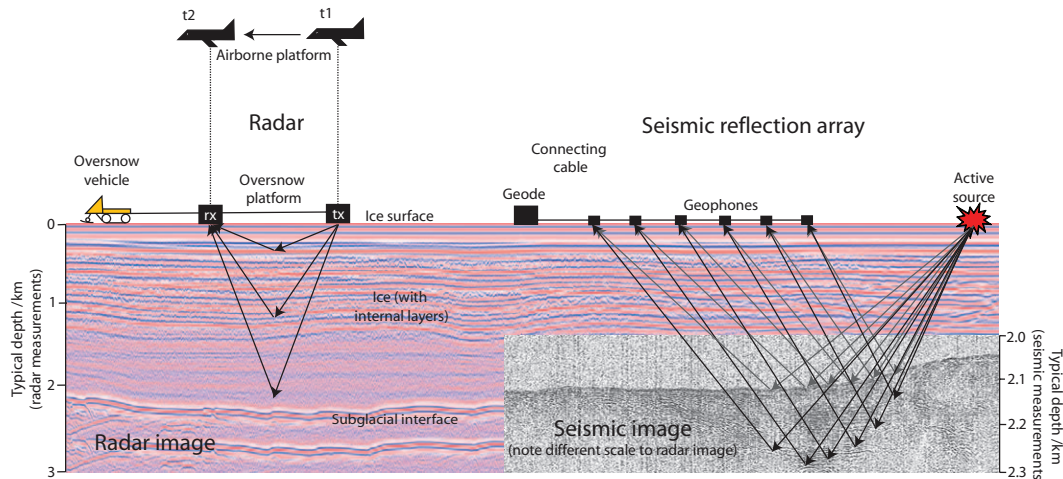
**Figure 2.** Location map of the West Antarctic Ice Sheet, showing the main geographical features mentioned in the text, notably the major ice streams and glaciers that drain into three catchments: the Ross Ice Shelf, the Ronne Ice Shelf, and the Amundsen Sea. The background image (shades of grey) is MODIS mosaic imagery from Haran et al. (2006); superimposed over this is a mosaic of satellite-derived ice surface velocities (after Edwards, 2008); the black line indicates the approximate grounding line as mapped in the Antarctic Digital Database (<http://www.add.scar.org:8080/add>).

The WAIS is drained predominantly by three catchments at the apex of which is the WAIS Divide (the site of a current deep-ice coring project; Figure 2). The Ross catchment drains ice westwards across the Siple Coast to the Ross Ice Shelf via a series of ice streams some of which have little or no obvious topographic control: from south to north these are Mercer, Whillans, van der Veen, Kamb, Bindschadler, MacAyeal and Echelmeyer Ice Streams, formerly known as Ice Streams A, B1, B2 and C to F). The Ronne catchment feeds ice to the Filchner-Ronne Ice Shelf: significant drainage conduits include Evans, Institute, Möller and Rutford Ice Streams, the latter of which is fringed and topographically constrained by the neighbouring Ellsworth massif. Ice flow from the Amundsen catchment is unprotected by a large ice shelf,

and is routed predominantly via Pine Island and Thwaites Glaciers (Figure 2).

## 2 Methods

While much of glacial geomorphology has proceeded from smaller to larger scales of landform and landscape analysis (section II), it could be argued that efforts to sound and image the basal interface beneath the WAIS have followed the converse trend, with the principal pacemaker being technology. Prior to the development and application of ice-penetrating radar systems, what little knowledge existed either of subglacial topography or subglacial conditions was obtained from very widely spaced point-seismic reflection soundings (Bingham and Siegert, 2007b) or gravity surveys, many of which were conducted under the auspices of the



**Figure 3.** Schematic diagram showing methods of radar and seismic-reflection acquisition over ice. Radar systems, which exploit electromagnetic waves, may be operated either from airborne or oversnow platforms and are particularly valuable for acquiring internal layers and bed echoes over large areas. Seismic-reflection profiling, which employs elastic waves, has the additional asset of being able to penetrate into the sub-bed material and extract information on basal sediment properties. Note that the radar image (pink/blue) and the seismic image (grey) are not to the same vertical scale, and both images are vertically exaggerated; the horizontal scale is  $\sim 100$  km.

International Geophysical Year programme between 1957 and 1960 (eg, Bentley, 1971; and see Naylor *et al.*, 2008). However, the development of airborne ice-penetrating radar systems during the 1950s and 1960s rapidly opened the door to more comprehensive sounding of continental- and regional-scale bed topography throughout the 1970s, and in the last 30 years aerogeophysical surveying has been refined such that acquisition includes not only simple topography but also physical information concerning the characteristics of subglacial material. Building on the continental/regional insights thus gained, oversnow radar systems, often operated at lower frequencies than airborne systems, have been applied to interrogate basal properties over more localized scales. Parallel developments in seismic data acquisition have been critical to determining the nature of the subglacial interface beneath parts of the WAIS.

*a Airborne radar investigations.* Geophysical radio detection and ranging (radar) investigations over

ice sheets exploit the transparency of cold ice to electromagnetic waves in the high to very high frequency (HF/VHF/megahertz) bands. All ice-penetrating radar (IPR; also known as radio-echo sounding or RES) systems comprise a transmitter that emits electromagnetic waves and a receiver that records their reflections (or ‘echoes’) off any surfaces evincing a contrast in dielectric properties; these surfaces include the ice surface, internal layers (englacial horizons with common properties in density, chemistry and/or ice-fabric) and, of most direct interest to the geomorphologist, the ice-bed interface (Figure 3). Indeed, it was the realization that the bed could easily be sounded through thick ice using radar that initially prompted early ‘radioglacialogists’ to mount radar systems within aircraft, creating for the first time a viable means of constraining subglacial morphology across the vast ice-shrouded tracts of Antarctica and Greenland (Bailey *et al.*, 1964; Gudmandsen, 1969; Robin *et al.*, 1977; Drewry, 1983; Bogorodskiy *et al.*, 1985). The principal motivation for these



early measurements was simply to sound the vertical position of the bed, thereby ascertaining the volume of ice stored in the terrestrial ice sheets; across the WAIS systematic surveying designed for this purpose was conducted in the late 1960s and throughout the 1970s (Robin *et al.*, 1977; Drewry, 1983). An early hint that radar systems could retrieve not only topography *per se*, but also information pertaining to *properties* of the basal interface, was provided by the observation that particularly bright bed-echo strengths occurred over putative subglacial lakes (Oswald and Robin, 1973). From the 1980s onwards, airborne radar surveys explicitly designed to support coordinated field activities (eg, Alley and Bindschadler, 2001; Payne *et al.*, 2006) have generated further data sets that have thus been interpreted *both* for bed topography *and* basal properties. In parallel, revolutionary developments in navigation (notably Global Positioning Systems, GPS) and digital data acquisition have enabled significant progress to be made in data resolution and accuracy, such that modern systems can sound the bed at intervals of  $\sim 20 \pm 1$  m (Vaughan *et al.*, 2006; cf. 1.8–3 km in Drewry, 1983).

Airborne radar systems therefore provide perhaps the most effective means of constraining subglacial geomorphology on regional to continental scales. However, few, if any, airborne radar surveys in Antarctica have been couched explicitly in terms of addressing subglacial geomorphology; rather, their findings, for the most part, have been presented in geophysical or process-glaciological arenas. A key question for the geomorphologist, therefore, is: what parameters extracted by radar across modern ice sheets are useful in helping to interpret formerly glaciated landscapes? To date, the answer may be divided into two categories: (1) subglacial topography itself, specifically addressed by analysing bed roughness along radar survey tracks; and (2) radar-derived bed-compositional properties, a proxy for which is the strength of the radar-returned power, or bed reflectivity.

Simply constraining the ‘shape’ of the subglacial landscape, and smaller-scale landforms (without yet addressing their composition, discussed below), is an important goal in West Antarctica. At the continental scale, airborne radar measurements of ice thickness (supplemented by other methods) have been used to compile the ‘BEDMAP’ digital elevation model (DEM) of subglacial topography (Lythe *et al.*, 2001). BEDMAP provides first-order indications of the relations between major WAIS ice streams and basal topography: Rutford Ice Stream is clearly underlain by a well-defined subglacial trough; the Siple Coast ice streams, however, display a much less clear, in some cases negligible, correspondence with basal topography. The DEM therefore displays very clearly that whereas in some places ice streams have clear topographic control elsewhere other factors drive ice-stream configuration. However, while BEDMAP is highly useful in this and the other regards for which it was intended (eg, Arthern and Hindmarsh, 2003; Llubes *et al.*, 2003; Pollard and DeConto, 2009), its 5 km grid resolution precludes capturing most individual glacial landforms, even at the larger scales of features now identified with remote sensing on deglaciated landscapes, such as MSGL. Moreover, its reliance on interpolation between survey tracks, especially in data-sparse regions (cf. Welch and Jacobel, 2003), limits its use in terrain analysis techniques. However, the constitutive airborne radar tracks themselves, along which the bed *has* been sounded at high resolution ( $\sim 20$  m to 3 km), have been interrogated for smaller-scale variations in the shape or texture of the ice-sheet bed, a property commonly termed bed roughness.

Bed roughness can be defined qualitatively as the vertical variation of an ice-sheet bed with horizontal distance, and has been quantified from radar-derived bed echoes in several ways. One approach is to characterize bed roughness based on the standard deviations of individual bed-elevation points from an interpolated bed surface

(Rippin *et al.*, 2006). Taylor *et al.* (2004) developed a technique for assessing bed roughness based on power spectra derived from Fast-Fourier-transforming bed-elevation profiles; this has been exploited by Siegert *et al.* (2004a) and Bingham and Siegert (2007a) to quantify bed roughness across several West Antarctic ice streams. The above methods have utilized only raw bed-elevation profiles sounded by radar; various attributes relating to the strength of radar-returned echoes (or bed reflectivity, which we discuss in more detail below) have also been interpreted as variations in bed roughness (Peters *et al.*, 2005; Rippin *et al.*, 2006). Significantly, an intercomparison of eight different algorithms for assessing bed roughness has demonstrated that regardless of the particular method used similar regional-scale patterns are derived (D. Rippin, personal communication). Thus, for example, beds beneath areas of streaming (fast) flow are typically 'smooth' (ie, little vertical variation with horizontal distance), while beds beneath intervening areas of sheet (slow) flow are often 'rough' (Siegert *et al.*, 2004a). Bingham and Siegert (2009: their Figure 3) present schematically a framework for the geomorphological interpretation of bed roughness patterns across Antarctica. The underlying concept is that smoother beds reflect regions that have experienced more subglacial modification (erosion and/or deposition/deformation) by warm-based fast-flowing ice, perhaps aided by a softer preglacial lithology, whereas rougher beds evince greater preglacial landscape preservation, frequently corresponding with cold-based slow-flowing ice (eg, interior regions and 'ice ridges' between ice streams) and/or subglacial orogenies. An outstanding challenge is to apply parallel methods to former ice-sheet beds, and in so doing set up a methodological framework for using 'roughness signatures' in the currently glaciated continental-scale landscape as analogues for their equivalents in deglaciated landscapes.

The use of airborne radar to derive information on the *composition* of modern ice-sheet beds

typically focuses on a proxy termed 'bed reflectivity' (also known as bed-echo strength, or bed-reflection power, BRP), wherein variations in the amplitude of the radar echo from the bed, corrected for ice thickness and internal ice properties, have been interpreted as variations in the composition of the basal interface. Such variations arise due to differences in water content, subglacial geology and/or the roughness of the subglacial interface, so that, in principle, brighter (dimmer) bed reflectivity can be used to identify areas of wet (dry/frozen), hard (soft/unconsolidated) and/or smooth (rough) beds. The approach was pioneered by Shabtaie *et al.* (1987), who examined airborne radar data over Mercer, Whillans and Kamb Ice Streams, and argued that bed reflectivity varied inversely with freezing at the bed. Seismic studies (discussed in section III.2.c) showing that much of West Antarctica is underlain by unconsolidated packages of sediments led Bentley *et al.* (1998) to reinterpret variations in radar-derived bed reflectivity over the same region as contrasts between wet and frozen subglacial till. More recently, Peters *et al.* (2005) have drawn up a table of airborne-radar-derived bed reflectivities for different subglacial materials. This scheme accounts for the fact that rougher beds will scatter the radar signal and weaken the bed reflectivity; a property exploited by Rippin *et al.* (2006) in using bed reflectivity as a proxy for bed roughness itself.

In addition to bed reflectivity, which focuses on the amplitude of the signal returned from the bed, researchers are now beginning to recognize that other parameters, such as the length and phase of the radar pulse returned from the bed, may also be related to the nature of subglacial sediments (Rippin *et al.*, 2006; Murray *et al.*, 2008; see also Doake, 1975).

*b Oversnow radar investigations.* In several parts of the WAIS, oversnow radar systems have been deployed to gain further insights into subglacial morphology and composition. The operation of

oversnow systems is essentially the same as for airborne radar, but with the transmitter and receiver mounted on, or towed behind, oversnow vehicles (Figure 3). Where the key advantage of airborne radar lies in its ability to acquire data over the larger scales of landscape analysis, oversnow radar is typically used to acquire higher-resolution data in targeted areas of especial interest, often suggested in the first instance by spaceborne remote sensing or airborne radar surveys. In addition to the advantages of improved spatial resolution and the elimination of losses through the air, many oversnow radars can also be operated at lower frequencies than airborne systems, enabling better penetration through thick ice to subglacial landforms.

Drawing upon a range of bed reflectivities derived for subglacial materials from frozen permafrost to a film of liquid water (Gades, 1998), several oversnow-radar surveys have demonstrated sharp contrasts in bed reflectivity crossing the margins from ice streams (high reflectivity) to ice ridges (low reflectivity) across the Ross ice streams (Gades *et al.*, 2000; Catania *et al.*, 2003; Raymond *et al.*, 2006). These authors have attributed the higher bed reflectivities beneath ice streams to water-saturated tills and the lower bed reflectivities found interstream to frozen or patchy, thin tills; some calibration of these results has been provided by comparing bed reflectivities with measurements of water content and basal sediment in nearby boreholes (Catania *et al.*, 2003). Within an ice stream itself, Jacobel *et al.* (2010) found on the Kamb Ice Stream that, although bed reflectivity is generally high, it is possible to have isolated areas of low reflectivity that correspond to 'sticky spots' of localized slow flow, which can be picked out from spaceborne observations and where borehole studies have found dry beds (Engelhardt, 2004). Hence, although the till beneath modern ice streams is widespread, it appears to have heterogeneous properties that correspond strongly with the configuration of ice streams and the distribution of

instream sticky spots. These findings support the detailed analysis of till characteristics in deglaciated regions to identify former regions of ice streaming and ice-stream sticky spots (eg, Christoffersen and Tulaczyk, 2003; Stokes *et al.*, 2007).

The use of oversnow radars in West Antarctica to image subglacial landforms on scales that tally with those imaged across former ice-sheet beds (eg, Stokes and Clark, 2006; Larter *et al.*, 2009) is a field still in relative infancy. Traversing the grounding line of Whillans Ice Stream, Anandakrishnan *et al.* (2007) imaged an 8 km long, up to  $\sim 80$  m deep subglacial sedimentary wedge (or 'till delta'), the existence of which probably serves to stabilize the current grounding-line position (Alley *et al.*, 2007). Relict wedges of similar dimensions, with upstream MSGL, have been observed across the floor of the Ross Sea between the Ross Ice Shelf and the continental shelf, likely evincing relict stages of grounding-line retreat dating back to the Last Glacial Maximum (Domack *et al.*, 1999; Mosola and Anderson, 2006). Driving a radar in grids over the onset region of Rutford Ice Stream (and also deploying seismic methods, discussed in the following section), King *et al.* (2007) imaged several subglacial bedforms and supplied the first evidence from a contemporary ice stream of a direct relationship between bedform shape and ice-stream flow-velocity, inferred only previously from geomorphological analyses of palaeo-ice-stream beds (Ó Cofaigh *et al.*, 2002; Stokes and Clark, 2002; Wellner *et al.*, 2006). Indeed, subsequent radar surveying across a downstream fast-flowing ( $\sim 375$  m a<sup>-1</sup>) sector of the same ice stream confirmed this association, revealing MSGL beneath the modern ice stream indistinguishable from those found on the beds of palaeo-ice streams in northern Canada (King *et al.*, 2009). These studies have demonstrated the potential that radar-imaging of landforms beneath the modern ice sheet offers for testing rigorously ideas concerning landform/ice-dynamics associations previously only

postulated from studies of deglaciated terrain. However, as yet there remain tantalizingly few such observations from modern ice streams with which to test theories of elongate glacial landform development.

*c Seismic investigations.* The use of seismic techniques constituted the first application of geophysics to glaciology (Mothes, 1926, after Clarke, 1987) and, in the early (pre-radar) days of Antarctic science, seismic shot-depths provided the first (albeit sparse) measurements of ice thickness across the WAIS (eg, Bentley and Ostenso, 1961). Because seismic techniques exploit different phenomena – elastic rather than electromagnetic waves – the information they generate concerning subglacial conditions is complementary to that obtained by radar; indeed, seismic techniques retrieve some subglacial properties that radar cannot. Notably, the principal limitation of radar techniques over modern ice sheets is the inability of electromagnetic waves (in most cases) to penetrate *beneath* the subglacial interface. Elastic waves, by contrast, travel easily through ice *and* can image sub-bed structures (Figure 3). This has become an especially significant attribute following the widespread uptake in glacial geomorphology of the deforming-bed paradigm (eg, Boulton and Hindmarsh, 1987; Hart, 1995; Maltman *et al.*, 2000; van der Meer *et al.*, 2003), the key tenet of which is that where glaciers and ice streams are underlain by unconsolidated sediments, subglacial deformation of those sediments, particularly when wet, may facilitate fast flow. There is therefore a need to image sub-bed conditions and elucidate the composition and internal structure of subglacial sediments in both modern and palaeo settings, and such information beneath modern ice sheets can only be extracted by seismic methods.

One of the most common seismic techniques applied to elucidate basal conditions in West Antarctica has been normal-incidence seismic reflection sounding (hereafter shortened to

seismic reflection sounding). A comprehensive introduction to this methodology and its applications is given in Smith (2007). For each measurement, the equipment comprises a source that emits elastic waves, typically a small explosive, and an array of detectors, typically a spread of geophones hand-planted just beneath the snow surface, each of which picks up reflections of the elastic waves from subsurface reflectors, most obviously the ice-bed interface but also from sub-bed sediment layers (Figure 3). Useful parameters for the glacial geomorphologist that are derived from the method include: (1) sub-bed reflectors, indicative of subglacial sedimentary structures; (2) acoustic impedance of the subglacial material, evincing subglacial sediment properties; and (3) small-scale subglacial topographic features, analogous to Quaternary glacial landforms. With respect to the latter point, the spatial resolution of seismic measurements is often better than that obtained by radar (eg, King *et al.*, 2007).

The first intensive use of seismic reflection sounding to delineate subglacial conditions in West Antarctica was conducted in 1983/84. Blankenship *et al.* (1986) picked out two clear reflectors below Whillans Ice Stream, an upper reflector corresponding to the ice-bed interface, and a lower reflector corresponding to the bottom of a metres-thick subglacial sediment layer. Subsequent modelling of the relation between elastic-wave velocity and porosity based on laboratory experiments suggested that the subglacial sediment layer was relatively porous (~40%) and too weak to support the shear stress exerted by the overlying ice; thereby providing the first evidence that a significant component of the flow of streaming ice may be attributed to active deformation in an underlying layer of dilated sediments (Alley *et al.*, 1986; 1987; Blankenship *et al.*, 1987). The dilatancy of this till layer was later confirmed by drilling into it (Engelhardt *et al.*, 1990), and further seismic reflection sounding similarly disclosed the existence of dilatant subglacial sediments beneath

the neighbouring Kamb Ice Stream (Atre and Bentley, 1993).

The significance of subglacial sediments to the onset of ice streams and the configuration of the tributaries that feed them was first investigated using seismic reflection sounding by Anandakrishnan *et al.* (1998), who showed that the margin of streaming flow in the upper reaches of Kamb Ice Stream was coincident with the boundary of a regional-scale deep subglacial sedimentary basin. Further extensive seismic experiments in this region have confirmed that tributaries of both Kamb and Bindschadler Ice Streams overlie significant sedimentary packages (Peters *et al.*, 2006). A transect from the ice-sheet interior into a tributary of Kamb Ice Stream shows a progression from no-sediment to discontinuous-sediment to continuous-sediment, while the upglacier and lateral extensions of Bindschadler Ice Stream correspond strongly with the extent of continuous subglacial sediments. Both of these observations imply a significant subglacial sedimentary influence on the onset and overall configuration of ice streaming (Peters *et al.*, 2006).

The seismological study of Kamb Ice Stream by Atre and Bentley (1993), which also included seismic reflection sounding over the slow-flowing Engelhardt Ice Ridge, demonstrated that subglacial sediment porosities typically range from 30 to 45%. The lower porosities correspond to lodged (non-deforming) sediment; shear of the sediments causes dilation inducing porosity increases to 40% or above. These interpretations have subsequently been calibrated with direct analyses of sediments spot-sampled from the bed using ice drilling and piston coring (Tulaczyk *et al.*, 1998; Kamb, 2001). Significantly, Atre and Bentley (1993) further demonstrated that porosity may be approximated by the acoustic impedance (compressional wave speed times density) of the bed material. Since the acoustic impedance of the bed material is a function of that in the ice and the seismic reflection coefficient at the basal interface, and

following a widely held assumption that the acoustic impedance of the basal ice is a constant over typical scales of seismic-reflection analysis (a few to a few tens of km), subsequent work has used the seismic reflection coefficient at the basal interface as a proxy for the existence and composition of subglacial sediments. Beneath Rutford Ice Stream this technique has been deployed extensively to distinguish areas of ice underlain by actively deforming, wet dilatant sediments and adjacent areas of lodged sediments over which the ice flow is interpreted as being dominated by basal sliding (Smith, 1997a; 1997b; Smith and Murray, 2009). Atre and Bentley (1994) and Vaughan *et al.* (2003) have further supported the idea that ice streams are underlain by actively deforming tills juxtaposed with 'patches' of lodged sediment, the proportions of which may go some way towards explaining the dynamic behaviour of the overlying ice – greater proportions of deforming tills relative to lodged tills promote streaming, while areas of lodged till within ice streams may act as 'sticky spots'. Where subglacial seismic reflection coefficients are particularly high (but with a reversed polarity corresponding to low acoustic impedance), they may evince directly the presence of subglacial water: King *et al.* (2004) reported one such instance in which they identified water-filled canals up to 200 m wide flowing overtop and between actively deforming saturated subglacial till. It was not, however, possible to resolve in this study whether the individual 'canals' extracted by the seismic data corresponded to individual canals 200 m wide or alternatively lateral amalgamations of several narrower canals.

While much seismological research in West Antarctica has concentrated on discerning the distribution and properties of subglacial sediments, seismic-reflection data have also been used to image subglacial landforms. For example, seismic profiling conducted across Whillans Ice Stream demonstrated that the subglacial sediment is organized into flow-parallel flutes

as much as 13 m deep and 1000 m across (Rooney *et al.*, 1987). By far the most extensive seismic investigations of subglacial landforms, however, have been conducted within the Rutford Ice Stream catchment. Smith (1997a) reported on the acquisition, in 1991, of a seismic profile orthogonal to ice flow in the main trunk of the ice stream, and interpreted a 400 m wide 50 m high bedrock obstacle (therein named 'The Bump') as a drumlin on the basis of its cross-sectional dimensions and an inferred composition of soft, deforming till. In that study Smith did not possess data on the length (along-flow) of the inferred drumlin but contended it would likely be longer than it were wide due to streamlining of drumlinoid features by ice flow; a subsequent seismic profile collected 10 km upstream appeared to support this (Smith, 1997b), while recent extensive radar surveying across the region has confirmed the widespread existence of streamlined bedforms beneath this section of the ice stream (King *et al.*, 2009). The seismic-reflection acquisition undertaken in 1991 (Smith, 1997a) was repeated at the same geographical location in 1997 and 2004, and revealed that this drumlin and adjacent features experienced active erosion and/or deposition during the intervening periods (Smith *et al.*, 2007). The 1991-identified drumlin (The Bump) underwent little change between the first two surveys, but was eroded by 2–3 m between the second and third surveys. More arresting, however, were changes that took place over an adjacent 500 m wide portion of the bed: between 1991 and 1997 this part of the bed experienced a lowering of 6 m, equating to an average erosion rate of  $1 \text{ m a}^{-1}$ ; yet between 1997 and 2004 the same section evinced no erosion but a mound of material 100 m wide and 10 m high appeared in the middle. With dimensions and soft-sediment characteristics again typical of drumlins investigated in deglaciated regions, this was interpreted as the first observation of a drumlin actively forming beneath a contemporary ice mass (Smith *et al.*, 2007). The appearance of this

drumlin within a seven-year period, together with the observations of rapid erosion rates between repeat-surveys, demonstrates the dynamism present in the subglacial environment, and in particular within subglacial sediments, such that significant changes to subglacial depositional landforms may occur over timescales of a few years or less. Smith *et al.* (2007) posited that the drumlin may have formed either by sediment filling a groove in the ice above the bed, or due to an instability mechanism in the underlying till proposed by Hindmarsh (1998) and which forms the basis of numerical modelling discussed in section IV. We revisit the significance of repeat surveying in advancing geomorphological understanding in section V.

Results from most of the seismic reflection surveys undertaken over the last two decades on Rutford Ice Stream, covering  $\sim 140 \text{ km}^2$  across the main trunk, have been collated in Smith and Murray (2009). This has shown that cross-stream bed topography is characterized by streamlined mounds of deforming sediment aligned along the ice flow direction, superimposed onto the bed in regions both of basal sliding and sediment deformation. With mean dimensions of 22 m (height), 267 m (width) and extending for at least 1–2 km, these features have all been interpreted as drumlins and at least one MSGL. Notably, these bedforms are considerably elongated compared with the drumlins, crag-and-tail features and ribbed moraines imaged with radar and seismics 160 km upstream in the onset region (King *et al.*, 2007), again supporting the hypothesis that bedforms become more elongated with distance downstream (see section III.2.b). Notably, using seismic reflection, King *et al.* (2007) were also able to image depositional surfaces *within* drumlins, beneath the subglacial interface itself. The dips of the internal depositional surfaces, predominantly down-flow and across-flow, were taken to indicate the active migration of these bedforms along the direction of active ice flow, consistent with hypotheses of drumlin formation

presented by Boulton (1987a) and Dunlop and Clark (2006).

#### IV Numerical modelling in glacial geomorphology

Over the last two decades, the science of glaciology has increasingly employed numerical modelling as its primary *modus operandi* for investigating the dynamics of ice sheets (eg, Oerlemans, 1984; Hindmarsh, 1993; Hughes, 1995; Payne *et al.*, 2000; Huybrechts, 2002; Pattyn *et al.*, 2008; Pollard and DeConto, 2009). The chief attraction of modelling lies in the ability to reduce ice-sheet behaviour to a series of physical relationships, thereby to simulate 'observations' of ice-sheet fluctuations over the geological timescales through which many of the controlling processes operate and which render their direct observation impossible. Glacial geomorphology has a key role to play in such efforts by providing, beneath modern ice sheets, information on subglacial conditions, and, in areas of former ice coverage, an archive of palaeo-ice limits and palaeo-ice-flow directions, which may be used both as input to models or as an independent 'validation' on their output. There is therefore significant potential for glacial geomorphologists to apply modelling techniques directly to the testing of hypotheses of glacial landscape evolution and glacial landform development, some recent examples of which we now review.

Perhaps due to the traditional paucity of subglacial geomorphological data, and/or the inability, until recently, of ice-sheet models to represent ice-streaming phenomena (see Payne *et al.*, 2000; Pattyn *et al.*, 2008; Hindmarsh, 2009), no modelling investigation of ice-sheet-scale ice dynamics has yet been tied explicitly into the glacial geomorphological record in West Antarctica. Relevant progress is, however, being made on two fronts. The first of these is investigating ice-sheet/landscape interactions on hypothetical substrates. Jamieson *et al.*

(2008), for example, applied the Glimmer ice-sheet model (see Rutt *et al.*, 2009) with an erosion component to investigate the influence of ice-sheet erosional processes on the evolution of a hypothetical landscape over a scale similar to that of Antarctica. This study has highlighted more than ever the key importance of correctly parameterizing basal sliding in ice-sheet models: under low basal-slip conditions bed morphology exerts a much greater influence on ice flow because ice cannot respond readily to thermal instabilities; this suggests that the permeability of subglacial material may be a primary influence on streaming flow. This theoretical approach has also suggested that as ice sheets continue to erode a preglacial substrate the resultant development of overdeepenings beneath ice streams may ultimately aid stabilization of the ice-sheet's configuration of fast-flow units (Jamieson *et al.*, 2008). This is an important consideration for the interpretation of palaeo-ice sheets and in particular palaeo-ice-stream landscapes, and leads into the second relevant approach: applications of ice-sheet models to investigating the flow and form of palaeo-ice sheets.

In recent years there has been a profusion of numerical modelling studies applied to reconstructing the limits, dynamics and basal conditions of palaeo-ice sheets in the Northern Hemisphere (eg, Arnold and Sharp, 2002; Marshall and Clark, 2002; Siegert and Dowdeswell, 2004; Hooke and Fastook, 2007; Boulton *et al.*, 2009). Research on the former British Isles Ice Sheet (BIIS) provides an excellent example of the direct usage of glacial geomorphology in this regard. Over the last decade, high-resolution digital elevation models of northern Britain and Ireland have shown clearly an abundance of lineated subglacial bedforms such as MSGL distributed both onshore (eg, Evans *et al.*, 2009) and offshore (eg, Graham *et al.*, 2007a), supporting the contention that the BIIS was characterized by several cold-based upland areas of slow flow, drained by a series of fast-

flowing warm-based ice streams into divergent 'lobes' spread across the North Sea and the Atlantic continental shelf. Ice-sheet modelling has provided a methodology both to link what were previously many disparate hypotheses of regional glaciation into a coherent picture of Pleistocene glaciation and retreat, and to investigate quantitatively the formation of particular land systems across the British Isles. For example, Boulton and Hagdorn (2006) explicitly directed a thermomechanically coupled numerical ice-sheet model, driven by a proxy climate, to explore the properties that would best produce an ice-sheet configuration consistent with the existence of ice lobes in the North Sea and Irish Sea basins identified previously by offshore surveying. The lobes could only be explained with the explicit inclusion in the model of fast-flowing 'ice-stream' units, achieved by imposing high basal slip in areas coincident with the existence of 'soft' marine sediments offshore. The overriding form, if not the details, of this 'dynamic, fast-flow' ice configuration was supported by further modelling conducted by Hubbard *et al.* (2009), in which the temporal variability of ice streams in the BIIS was also explored. Hubbard *et al.*'s simulation suggests that the BIIS was highly dynamic, with its ice-stream units experiencing both spatial migration and temporal 'binge-purge' cycles analogous to those seen in Antarctica today (Retzlaff and Bentley, 1993; Catania *et al.*, 2006). Modelling by Evans *et al.* (2009) further complements this work, paying particular attention to explaining large-scale cross-cutting bedforms prevalent across many parts of the British Isles by reconstructing the evolving ice-sheet configuration during recession of the BIIS from the Last Glacial Maximum. What has been particularly striking about these recent modelling efforts are: (a) the explicit engagement with glacial geomorphological records both in providing data on palaeo-flow rates and directions which are testable using ice-sheet modelling, and in providing comprehensive data sets against which model

results can be validated; and (b) the need to incorporate dynamic, fast-flow phenomena, analogous to those witnessed in modern ice sheets, resulting in reconstructions more consistent with the glacial geomorphological record than have previously been achieved. Indeed, in displaying properties such as ice-streaming units, low longitudinal slopes and margins grounded predominantly below sea level, the picture that emerges from recent models concerning the last BIIS is not dissimilar to that of the WAIS today. The outstanding challenge that now lies ahead is to apply similar techniques to elucidate the links between glacial geomorphology and ice-sheet dynamics beneath modern ice sheets, such as the WAIS. This task will be aided by the improved retrieval of glacial geomorphology beneath the modern ice sheet (as discussed in section III) to complement the growing archive of offshore subglacial bedforms.

While numerical modelling is therefore being much applied to the larger and longer scales of glacial geomorphological analysis (cf. Figure 1), the same cannot be said with respect to studies focusing on the scales of individual glacial landforms. As we noted in section II, the deep heritage of glacial geomorphology lies in local landform studies on deglaciated terrains, arising principally out of the interest of Northern Hemisphere mid-latitude populations in the processes that shaped their natural environment (Sugden and John, 1976: 1). Such interest has spawned a prodigious array of research papers concerning glacial landforms, often characterized by competing hypotheses presented to account for their genesis and modification (eg, Bennett *et al.*, 1998; Wilson and Evans, 2000; Lukas, 2005; Graham *et al.*, 2007b). To date, however, numerical modelling has rarely been employed to resolve such debates. A notable exception is a recent study by Dunlop *et al.* (2008). These authors developed a physically based numerical model (BRIE: Bed Ribbing Instability Explanation) that describes the development of ribbed (also known as rogen) moraines, transverse



subglacial ridges distributed across deglaciated terrains for which many alternative formation mechanisms have been proposed (see Dunlop and Clark, 2006, and references therein). Incorporating physical relationships derived by Hindmarsh (1998), Fowler (2000) and Schoof (2007), BRIE encapsulates the principle that ribbed moraine results from natural instabilities in a deforming bed, leading to the spontaneous development and preferential growth of waveforms at the subglacial ice-till interface. The true value of this approach to investigating landform (in this case, ribbed-moraine) formation and evolution lies in the use of the model to test rigorously predictions against observations: thus Dunlop *et al.* were able to predict ribbed-moraine characteristics (such as typical dimensions and between-moraine wavelength) resulting from glaciologically plausible inputs (such as effective pressures and ice velocities drawn from contemporary ice sheets), and to validate their predictions against a large database describing the spatial properties of these landforms (Dunlop and Clark, 2006). This successful application of modelling techniques to address smaller-scale bedform development sets a significant precedent: indeed, with geophysical techniques now progressed to the stage at which individual landforms may be imaged beneath several km of ice (eg, King *et al.*, 2007; 2009; Smith and Murray, 2009; and other examples in section III), and with glaciological theory persistently maintaining the significance of subglacial morphology in controlling regional ice dynamics, an understanding of subglacial geomorphology at the scale of individual landforms is increasingly being recognized as imperative to issues of larger-scale landscape evolution and ice dynamics.

In summary, numerical modelling techniques are increasingly being adopted by glacial geomorphologists to explain landscape and landform genesis and evolution across deglaciated terrains. Most such applications to date have focused on the larger and longer scales of analysis describing landscape evolution beneath ice

sheets, reflecting the greater engagement with the 'larger-scale' in contemporary glacial geomorphology (discussed in section II). Modelling allows rigorous testing of hypotheses of landscape evolution over geological timescales which cannot directly be observed; but is also showing promise for resolving the many competing hypotheses of individual landform generation that bedevil the traditional literature pertaining to 'smaller-scale' landform studies. The strength of applying models to deglaciated terrains is that model input can be fed by, or output directly judged against, rich observational records unobscured by contemporary ice cover. An outstanding challenge is to link the findings from such studies into improving our understanding of the myriad subglacial landscapes and landforms we are now only beginning to unmask beneath contemporary ice sheets, such as the WAIS.

## V Discussion: Future challenges in glacial geomorphology

Addressing the multidisciplinary nature of modern geomorphology, Church (2005) suggested that progress in geomorphology as a whole is increasingly being achieved through the application of fundamental mathematical and physical principles. Responding to this, Summerfield (2005) argued that a greater engagement with longer timescales, processes and associated methods was required too. From a 'glacial' perspective, these comments echo Sugden's (1976: 1) call from over 30 years ago for 'a more glaciological type of geomorphology and a more geomorphological type of glaciology', to address a growing schism between glaciologists, largely trained in mathematics or physics, who placed greater stress on theory and smaller-scale process-studies, and field geomorphologists, largely trained in geography or geology, who placed greater import on description and evolution of landforms but had engaged to some extent with continental-scale glaciation. In this

short review we have argued that glacial geomorphology has already, to a considerable extent, travelled along the path towards greater quantification and vastly widening scopes of spatial and temporal analysis, in no small part facilitated by the remarkable advances that have taken place, and continue to take place, in remote sensing and numerical modelling. Glacial geomorphological research in Antarctica, interfaced with research on palaeo-ice sheets, exemplifies these trends, and future progress is contingent on continuing the interdisciplinary collaboration that has developed between the geographers and the geologists, the geophysicists and the engineers, the mathematicians, physicists and the earth (system) scientists, who now address contemporary glacial geomorphological debates. As Bamber (2006) has noted, remote sensing has not made field observations redundant; rather it remains crucially dependent on them – and in the case of acquiring bed data in Antarctica the remote sensing itself is necessarily conducted by field scientists. Similarly, numerical modelling, while in itself an exercise in abstracting physical conditions, is fundamentally reliant for its first principles on our ability to observe what is happening and therefore on our continued ingenuity in acquiring observational records at a variety of scales through a combination of field, remote sensing and geophysical techniques.

In this final section we reflect on some potential avenues for future research in glacial geomorphology and consider some of the challenges that lie ahead. We present four points, explicitly inspired by our own research interests in Antarctica; these are not to be taken as an exhaustive list of future research directions but rather intended to stimulate further discussion among the community concerning where future research can be directed.

- (1) It is clear that developments in remote sensing and numerical modelling have afforded us an unprecedented opportunity

to engage with glacial landscape evolution on much larger spatial and associated temporal scales than was previously possible. There is a clear need to pursue this: both of the world's remaining ice sheets are undergoing dramatic rates of change, and understanding ice-sheet (de)glaciation is fundamental to predicting the significant changes in global sea level and water resources that may result. Glacial geomorphology comprises the key evidence from which we can invert former ice-sheet histories and processes, to predict contemporary ice-sheet behaviour; yet the interpretation of former ice dynamics from the subglacial bedforms and sediments left behind following deglaciation remains limited by a dearth of observed analogous features beneath modern ice masses. Beneath the WAIS glacial geophysical techniques are showing increasing promise for retrieving subglacial conditions, and the coverage of such data needs to be expanded further to gain a better overall picture of basal conditions. This acquisition will take time – polar fieldwork, incorporating, for example, radar and seismic surveying, ideally supplemented by sampling basal sediments via ice drilling, can only be performed during the brief summer window each year, and is by its nature an expensive pursuit. In the mean time, it is worth reflecting that many insights into ice-sheet-scale processes have been gained, and continue to be gained, from studies of smaller-scale glacier behaviour. For example, physical laws of basal motion and deforming-bed behaviour have been informed and constrained by observational studies conducted in artificial subglacial tunnels or using down-borehole probes at several mid-latitude valley glaciers (eg, Hubbard, 2002; Cohen *et al.*, 2005; Rousselot and Fischer, 2005; Kavanaugh and Clarke,

2006; Hart *et al.*, 2009). Moreover, small glaciers can provide more accessible sites for the testing and further refinement of geophysical techniques capable of imaging modern ice-mass beds (eg, Kulesa *et al.*, 2006; King *et al.*, 2008). Viewed in this context, valley glaciers may be considered 'natural laboratories' for testing ideas and equipment, and developing laws applicable to the larger and longer scales of ice-sheet evolution and deglaciation. Numerical modelling, in drawing together the fundamental principles of ice behaviour at all scales of analysis, provides the framework within which the physical laws developed from valley-glacier studies can be upscaled and applied to ice-sheet-scale research.

- (2) Although there has been steady progress to date in imaging both the morphology and composition of subglacial landforms, sediments and landscapes beneath modern ice sheets, there is much ground yet to cover in this field. One clear goal is simply to survey subglacial conditions in regions where such data remain lacking (cf. Lythe *et al.*, 2001). However, an even greater emphasis needs to be placed on applying geophysical surveying techniques to imaging subglacial landforms and properties on the scales that are now routinely being captured over deglaciated terrains by Earth observation and marine geophysics; and such a goal will be aided considerably by continued dialogue between researchers predominantly working in formerly and currently glacierized environments. There are at least two facets to this statement. First, research on former ice-sheet beds, and in particular over palaeo-ice streams, where access is not limited by overlying ice, has been particularly revealing for our understanding of modern ice-sheet basal processes (eg, Clark, 1993; Larter *et al.*, 2009). Nevertheless, many

of the assumptions developed therein concerning bedform genesis and evolution, and processes of basal sediment deformation, remain unobserved and therefore not rigorously tested in the contemporary environments to which they apply. Future research on palaeo-ice sheet beds, in particular identifying land systems associated with, for example, ice-stream sticky-spots or ice-stream onset-regions, could direct glacier geophysicists to appropriate locations to search for analogues beneath contemporary ice streams; and the imaging of analogous glacial land systems beneath modern ice cover can then be used to test hypotheses of their development and evolution that have been posed solely from studies of deglaciated terrain. Second, this glacial geomorphology needs to be extracted beneath modern ice sheets at a range of scales. Beneath the WAIS, regional- to continental-scale coverage of subglacial topography and subglacial sedimentation is steadily accumulating (Peters *et al.*, 2005; Holt *et al.*, 2006; Vaughan *et al.*, 2006); and studies of macro-scale subglacial roughness offer some potential to compare modern and former ice-sheet beds quantitatively (eg, Bingham and Siegert, 2009). At more local scales, further imaging of subglacial landforms that correspond with bedforms and bedform assemblages observed on palaeo-ice streams offers promise for improving modelling of past and future ice-dynamic behaviour (King *et al.*, 2009; Smith and Murray, 2009). At even smaller scales, glaciological theory has persistently stressed the importance of smaller scales of bedform, and the 'controlling obstacle size' (20 cm to 1 m) in controlling basal friction, even beneath ice streams several km thick (Weertman, 1957; Hubbard and Hubbard, 1998); thus far we do not possess the geophysical capability to image any part of an ice-sheet bed

with this resolution, and to do so would represent a significant geophysical breakthrough. Recent studies have demonstrated the great potential of combined radar and seismic surveying to infer a range of basal conditions at a range of scales beneath modern ice streams (King *et al.*, 2007; Murray *et al.*, 2008); seismic data provide detailed local information on subglacial topography, bed reflectivity (elastic waves) and sub-bed structure, where radar data provide complementary data on subglacial topography and bed reflectivity (electromagnetic waves) and can be used effectively to upscale spatial coverage.

- (3) Given the temporal variability that has been observed both in ice stream flow (Retzlaff and Bentley, 1993; Siegert *et al.*, 2004b; Catania *et al.*, 2006) and ice-stream subglacial water systems (eg, Wingham *et al.*, 2006b; Fricker *et al.*, 2007), it is prudent to note that almost all of our observations of the geomorphology of modern ice-sheet beds are based on single temporal ‘snapshots,’ ie, almost nowhere has the bed been imaged more than once using the same method. Yet Smith *et al.* (2007) have demonstrated, by repeat seismic-surveying the same 3.5 km profile traversing a 2 km deep part of the Rutford Ice Stream, West Antarctica, that the subglacial interface beneath a modern ice stream is capable of remarkable evolution over 6/7-year intervals (see section III.2.c). The observation is significant because it shows the sheer rapidity (a few years or less) with which an ice stream can reorganize its subglacial sediment. To improve modelling of the formation and evolution of subglacial landforms and landscapes it is clearly necessary to elucidate further the essential dynamism of subglacial geomorphology beneath ice sheets and especially ice streams, and this objective can only be supported by

practising further repeat surveying in targeted regions of interest. In other words, there may now be as much, if not more, scientific value in ‘four-dimensional’ radar/seismic surveying of some ‘already explored’ regions of the WAIS, than in searching for virgin territory to survey. In this context, pre-existing survey data from some of the more well-constrained WAIS ice streams (eg, Whillans, Kamb, Rutford, PIG) can provide the baseline for future surveys of the same regions that will help to determine the temporal evolution of the basal geomorphology.

- (4) Ice is far from a uniquely terrestrial commodity, and indeed spaceborne sensors are enabling us to view extraterrestrial geomorphology with ever increasing accuracy. One of our nearest neighbours, Mars, has two polar ice caps, composed of cold (dry) ice and therefore presently incapable of making a geomorphological imprint on the planet’s surface. Nevertheless, Martian geomorphology is replete with evidence that the planet’s history has been one of multiple glaciations, and preliminary analyses of high-resolution imagery have shown, for example, that: (1) a number of highland regions are characterized by landforms analogous to glacial landforms on Earth, such as MSGL, cirques, and roches moutonnées (Head *et al.*, 2006; Banks *et al.*, 2008); (2) substantial Boreal and Austral ice sheets, capable of basal melting and perhaps subglacial sediment deformation, may once have extended to the Martian mid-latitudes (Kargel and Ström, 1992; Head *et al.*, 2003); and (3) the former ice sheets probably contained significant ice-streaming units, evinced by deep channels and longitudinal flutes within them (Lucchita, 2001; Kite and Hindmarsh, 2007). As we are attempting on Earth, perhaps Martian glacial geomorphology can similarly be used to invert for

former ice-sheet behaviour and can support burgeoning interests in Martian process-glaciology (Phillips *et al.*, 2008; Prockter *et al.*, 2008), which may ultimately feed back into our understanding of terrestrial glaciation. The larger and longer scales of analysis now regularly taken into consideration by those concerned with ice-sheet (de)glaciation on Earth have equipped the same community with many of the skills necessary to engage much more deeply with extraterrestrial glacial geomorphology.

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