Glacial Geomorphology☆

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Introduction

The scientific study of glacial processes and landforms formed in front of, beneath and along the margins of valley glaciers, ice sheets and other ice masses on the Earth's surface, both on land and in ocean basins, constitutes glacial geomorphology. The processes include understanding how ice masses move, erode, transport and deposit sediment. The landforms, developed and shaped by glaciation, supply topographic, morphologic and sedimentologic knowledge regarding these glacial processes. Likewise, glacial geomorphology studies all aspects of the mapped and interpreted effects of glaciation both modern and past on the Earth's landscapes. The influence of glaciations is only too visible in those landscapes of the world only recently glaciated in the recent past and during the Quaternary. The impact on people living and working in those once glaciated environments is enormous in terms, for example, of groundwater resources, building materials and agriculture. The cities of Glasgow and Boston, their distinctive street patterns and numerable small hills (drumlins) attest to the effect of Quaternary glaciations on urban development and planning.

It is problematic to precisely determine when the concept of glaciation first developed. For centuries, people living in and close to mountains in the Northern Hemisphere understood that local glaciers expanded and retreated. Farmers and shepherds well understood over the generations that high pasture lands would become inundated by expanding valley glaciers. The large erratic boulders, at times their locations attributed to witches and mythical giants, were due to glaciers melting and retreating. The Icelanders, the alpine Europeans, as well as Norwegians, for example, had long understood the vagaries of valley glaciers. The Icelandic sagas contain direct references back into the 10th and 11th centuries of "dramatic" glacial advances and retreats. However, the larger concepts of catastrophic-sized glaciations or even global glaciations were on a higher level that touched upon philosophical and theological considerations.

The idea of larger ice expansion in Europe, for example, suggested a level of change on the Earth's surface that could be barely considered or contemplated. A few people, such as da Vinci, had almost, but deliberately, appeared to have evaded the question of larger ice masses. Such evidence, however, derived justifiable fears of prosecution and excommunication that left these early ideas hidden or, at best, unspoken. In Europe, in the Middle Ages up to the early mid-19th century, the very idea of a larger Global Glaciation was heretical. The Judeo-Christian mores of the time precluded such events as being only catastrophic and the very idea of a slowly expanding European Alpine ice mass into southern Germany and the Jura Mountains was simply implausible. There were stirrings in the Renaissance and the Enlightenment of the mid-18th century and a few individuals, such as James Hutton in Scotland, began to reconsider Earth History beyond biblical constraints. An example is the famous Scottish geologist, Hugh Miller, who, on grasping the idea of geological time over millennia rather the biblical 6 days, found a philosophical incompatibility that he could not easily live with.

The stirrings of the concept of a major European and eventually Global Glaciation is hard to pinpoint as to its founding. Popular belief has until recently been attributed the Swiss, Agassiz (1842) but new evidence would suggest that Jens Esmark (1824) in Norway had the idea and substantive field evidence much earlier (Hestmark, 2017). It can be argued that the recognition and/or realization of the Ice Age is one of the most incredible human discoveries in modern Geology (Krüger, 2013). By 1824 Jens Esmark had concluded that unquestionably parts of Scandinavia and other northern areas of Europe had been covered by vast glaciers because of colder climates due to the eccentricity of the Earth's orbit around the Sun. It was James Croll working in Scotland in the 1860s who then essentially formulated the concept of astronomical change leading to ice ages (ice house conditions) and

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interglacials (greenhouse conditions) (Croll, 1864), further later substantiated by Milankovic's solar forcing theory (Milankovic, 1930).

At first a single global Ice Age was accepted as likely and then an increasing awareness that multiple glaciations had occurred. By the early 20th century, Penck and Brückner (1901–09) from research in the southern German foreland, on the extensive river terraces that emanate northward from the alpine foreland, had established the concept of four major glaciations in the Pleistocene (Nilsson, 1983; Imbrie and Imbrie, 2005; Häuselmann et al., 2007; Graf and Burkhalter, 2016) (Fig. 1).

Running somewhat parallel to these findings in Europe and North America was the recognition that Pre-Quaternary Global Glaciations had occurred (Le Heron et al., 2018; Young, 2018). As early as 1855 in Shropshire, England a possible Permian glacial deposit was recognized (Ramsay, 1855). Later in India, Blanford et al. (1859) had noted the likelihood of glacial effects present in the "Talcheer Group" boulder beds.

Still the idea persisted of a single Ice Age that had been subdivided into four major events. These ideas remained extant well in to the 1960s and only when deep ocean drilling provided samples did this quadruple division become discarded.

It is interesting to speculate that when only a single Ice Age was recognized, many geologists, by the 1920s, lost interest in glacial studies especially in the United Kingdom. The discipline became the "haunt" of physical geographers and with that a geographical morphological perspective developed as glacial geomorphology, especially in the United Kingdom, became a substantial subdiscipline. The scientific approach adopted by "glacialists" in the mid-19th century was a combination of sedimentological and geomorphological expertise brought to bear upon the problem of understanding glacial feature and sediments. The early work by Gilbert (1906) for example, in the western United States, illustrates a strong process-based bias that remains even today as a superb example of a thoroughly scientific approach to understanding glacial features. By the early decades of the 20th century there began a movement toward a more morphological or "form-based" understanding of glacial features and an increasing de-emphasis of a sedimentological and process viewpoint. By the 1950s this de-emphasis had reached a level of imbalance such that glacial geomorphology perhaps overly relied upon the purely morphological analysis of glacial terrains (cf. Dury, 1983). For example, in tracing the history of drumlin research from the early 20th century there is a strong emphasis on the internal sediments found within drumlins related to glacial processes and to drumlin form (cf. Slater, 1926). Yet by the late 1950s drumlins were almost universally viewed as morphological features whose origin was considered almost exclusively as a function of drumlin shape (Chorley, 1959) while internal sedimentology was all but ignored. How this should be arrived at cannot readily be explained. Perhaps the demise of glacial studies within the larger field of geology where the advent of plate tectonic theory, for example, gained an increasing ascendancy and the fact that glacial studies were left almost entirely to geographers who had a much greater and ingrained sense of spatial patterns and morphological appreciation may be a partial explanation (Chorley et al., 1964; Grapes et al., 2008).

In the 1970s a process-based approach to understanding glacial geomorphology began to be reasserted. It is perhaps the apparent lack of explanatory power that was missing in the purely morphological approach that the need to understand the processes involved in the glacial system and its subsystems has re-emerged (cf. Spedding, 1997; Harrison, 2005; Tadaki et al., 2017). However, this philosophical/methodological dichotomy should not be construed as implying that either the morphological or the process-form approach can be regarded as superior to one another.

From the end of the Second World War and the start of the Cold War growing strategic interest in polar lands heralded a new period of studies of all forms of ice masses. Interest in Antarctica by the mid-1960s led to a vast accumulation of scientific data on

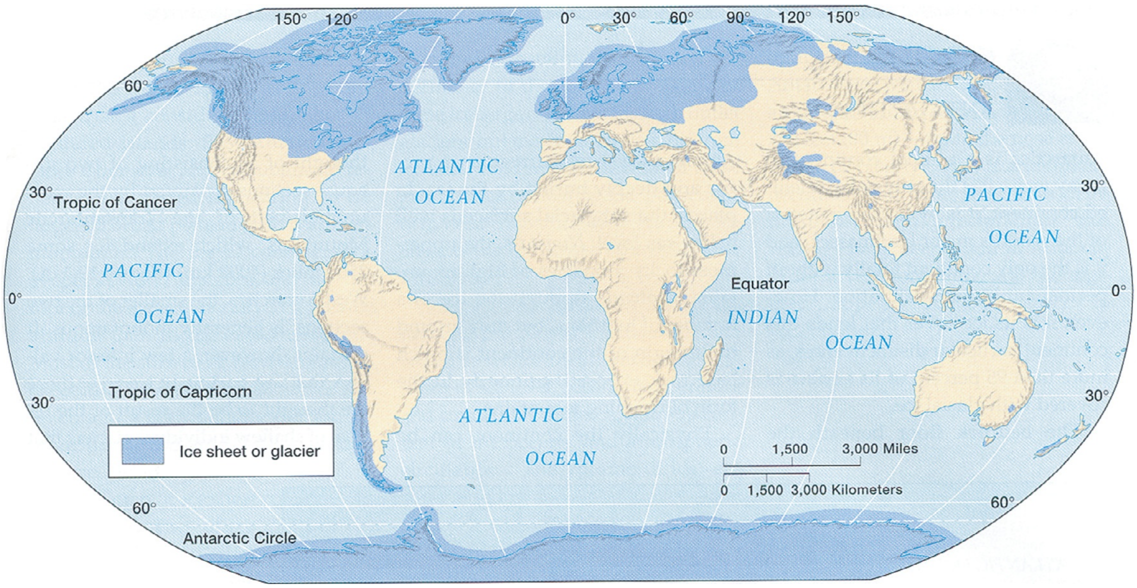

Fig. 1 Extent of global glaciation at approx. 18,000 years B_P. Modified from Lutgens, F.K., Tarbuck, E.J. and Tasa, D.G. (2014). Essentials of geology. Pearson Higher Ed, 608pp.

glaciology, sea-ice conditions, ice sheets and ice shelves. Increasingly, knowledge of present-day ice masses and ice physics and related glacial sediments and landforms began to be translated into a more comprehensive knowledge of past glacial sediments and landscapes. Research in Iceland, Svalbard, Greenland, Alaska, Scandinavia and the Baltic lands, as well as, Canada, for example, led to a better grasp of how glaciers operate and their impact on terrain that includes not only subglacial deposition but the effects of meltwater and associated sediments across glaciated lands. Similarly, an appreciation of glacial lake sedimentation and subaquatic processes, including glaciomarine processes and forms, has since emerged (Domack and Powell, 2018). One of the consequences of increased polar exploration especially, in Antarctica, Greenland, Alaska, Svalbard, the Canadian north and Iceland, has been the growth of glaciology as a distinct science devoted to understanding the physics, chemistry and climatology of ice masses (Cuffey and Paterson, 2010). Glaciology has made an enormous impact upon glacial geomorphology. Although often the two sciences seem to have moved along separate paths, the link between both has had a great benefit for the comprehension of glacial processes and landforms. This collaboration has been especially profound in Antarctica.

Glacial Landscapes

With the retreat of the last ice sheets to cover the Earth some 10,000 years ago to, in some places only 6000 years ago, a landscape emerged in the high and middle latitudes of the Northern Hemisphere that is both distinctive and characteristic of the impact of glaciation. Similar landscapes in South Island, New Zealand and in Patagonia in South America were equally impacted. The ice sheets eroded, transported and deposited vast quantities of sediments both on land and in the ocean basins. The surface topography of the continents today. For example in the northern states of USA and throughout Canada and northern Europe, was entirely modified with distinctive landscapes, sediments and landforms repeatedly overprinted as ice masses advanced and retreated many times over the course of the Pleistocene. With the rapid melting and retreat of the ice sheets, sea level quickly rose and, since the ice sheets had isostatically depressed the continental land masses, in many instances sea level rose above present levels, drowning large coastal areas. Much later continental land masses readjusted to the loss of the ice sheet load and slowly rose and raised shorelines and cliffs began to re-appear above sea level. These raised beaches and strandlines, for example, in Europe, North America as well as Australasia, became the colonization pathways for early humans (Meltzer, 2009; Reich et al., 2012; Williams, 2013; Posth et al., 2016).

Evidence in glaciated terrains of the effects of glacial erosion can be observed on bedrock surfaces in the form of glacial striae and chattermarks, and the effects of high pressure meltwater scour (cf. Stucki and Schlunegger, 2013). Evidence of glacial transport can be observed in the form of boulder trains and isolated erratic boulders left strewn across glaciated landscapes and in the provenance of glacial sediments. Finally, glacial sediments are ubiquitous in glaciated terrains. Also, many of these sediments in association with glaciated eroded bedrock or as distinctive features in themselves occur as landforms such as moraines, drumlins and eskers, glacial lake sediments, and as immense thicknesses of glaciomarine sediments.

Glacial geomorphology, as noted above, sets out to understand and interpret the topography and morphology of glaciated landscapes and their associated sediments and landforms by endeavoring to understand the myriad of processes that occur within the many sub-environments that make up any glacial system. To make sense of the complex sets of often spatially and temporally interlinked glacial sub-environments, it is critical that patterns and distinctive signature characteristics of these sub-environments be detected and understood. As Fig. 2 illustrates, there are many inter-related sub-environments; supraglacial, englacial, subglacial, terrestrial proglacial, subaquatic proglacial, and each of these environments can often be further subdivided. For example, the terrestrial proglacial subdivides into proximal and distal and within each can be isolated glaciolacustrine and glaciofluvial subunits. The sediment delivery systems (SDS) of these sub-environments are crucial in our understanding of glacial landscapes, landforms and sediments.

Perhaps one of the greatest problems in glacial geomorphology is in the partition and identification of glacial sub-environments since all too often an equifinality of processes and form emerges. The differentiation, for example, between englacial and supraglacial environments is all too often virtually impossible. Likewise, following glacier and ice sheet advance and retreat, intense overprinting led to sediment reworking and total or, in some places, partial removal and/or destruction of previous sediments and landforms. It is therefore a glacial geomorphologist's task to attempt to untangle the patterns and attributes of a glaciated landscape. One approach to this problem of overriding has been the development of a glacial landsystem approach whereby specific terrain "types" can be "isolated" and clearly demarcated (cf. Evans, 2014). Much as this method has its merits in terrains such as Iceland where primary glaciation has occurred in the relatively recent past, in other terrains such as the Prairies of North America or the North German Plain in Europe where repeated glacial overriding has occurred, landsystem methods are, in places, difficult to apply (cf. Kemmis, 1996; Benn and Lukas, 2006; Hughes, 2010; Böse et al., 2012).

Advances and Paradigm Shifts

In recent decades there have been several textbooks and academic reviews of glacial geomorphology that more than adequately summarize the "state" of the discipline at the time of writing. It is worth stepping back to take a broad view of the field and its recent progress. Like all sciences, progress is generally slow and incremental. However, occasionally methods or theories or "insights" set a discipline on new and exciting pathways. In glacial geomorphology, such pathways have and do occasionally occur that translate

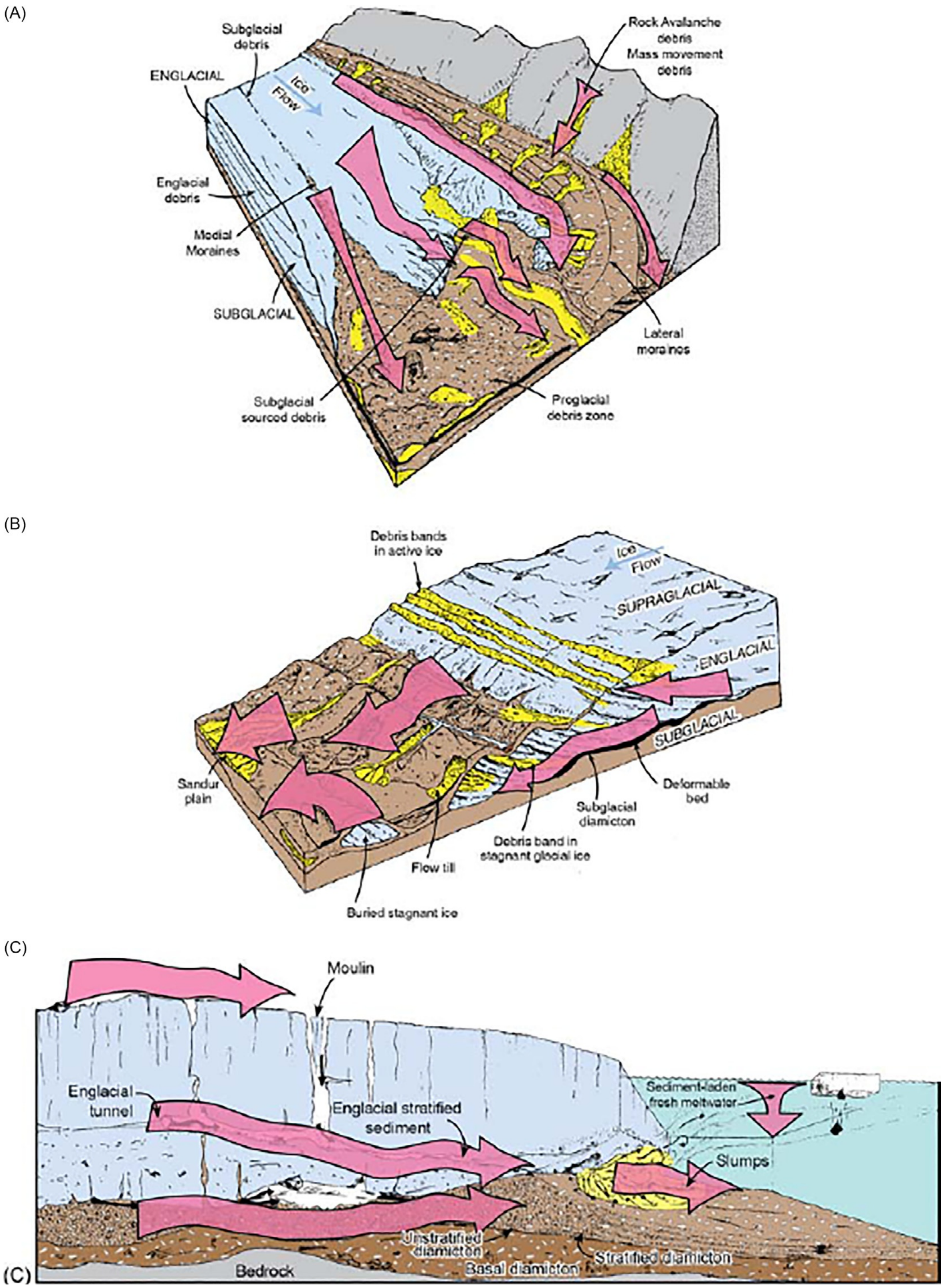

Fig. 2 Sediment delivery systems (SDS) within glacial environments: (A) SDS within valley glacial systems, (B) SDS within marginal ice sheet systems, and (C) SDS within subaqueous glacial environments. (A and C) Modified from Boulton, G.S. and Eyles, N. (1979). Sedimentation by valley glaciers; a model and genetic classification. In Schlüchter, C. (ed.), *Moraines and varves: Origin/genesis/classification*. Rotterdam: A.A. Balkema, pp. 11–23; (B) modified from Menzies, J., Hess, D.P., (2013). Depositional features. In Shroder, J.F. (ed.), *Treatise on geomorphology*. San Diego: Academic Press, pp. 127–140.

into major significant advances in knowledge that have profound "impacts." In no particular order such "changes," innovative new methods, or paradigm shifts have occurred in the past two decades, for example, dating methods, subglacial environments, geomorphological mapping, and glacial micro sediment analyses.

In the past, glacial geomorphology had to rely on such methods as radiocarbon dating, lichenometry and palynology (all superb tools within their limitations, to date materials found within sediments or on exposure surfaces (Walker, 2005)). Numerical dating methods are of fundamental importance in establishing independent chronologies (Wagner, 1998). These include the use of historical records, lichenometry, tephrochronology, varve chronologies, dendrochronology, amino acid geochronology, paleomagnetism, and radiocarbon, luminescence, K/Ar, Ar/Ar, U-series, terrestrial cosmogenic nuclide (TCN) surface exposure and fission track dating (Brigham-Grette, 1996). Dating glacial and associated sediments is essential in providing a temporal framework for accurate reconstructions of past climatic conditions and for helping to determine the nature and magnitude of glaciation for landscape evolution studies (cf. Fuchs and Owen, 2008). There are a few methods that can be utilized for the whole of the late Quaternary (c. 125 ka^{-1} ago to present). These methods have added enormously and continue to do so to our understanding of the chronology and stratigraphic frameworks but, at times, lack the precision limited by age constraints etc. (Jull, 2018). With the advent of other dating techniques, for example, optically stimulated luminescence (OSL) of sediments often at considerable depths and/or much older geological ages, a new window into glacial processes, landforms and stratigraphies have been opened (Lian and Roberts, 2006; Fuchs and Owen, 2008; Galbraith and Roberts, 2012; Arnold et al., 2015; Li et al., 2017). Luminescence dating, in contrast to the other dating methods, can be readily applied to most terrestrial sediments and can be used to date sediments on timescales from 10^1 to 10^5 years, encompassing the entire late Quaternary.

At around the same time the development of in situ terrestrial cosmogenic nuclide (TCN) method has revolutionized the study landscape evolution. Single or multiple nuclides can be measured in a single rock surface to obtain glacial erosion rates on boulder and bedrock surfaces, glaciofluvial incision rates, denudation rates of individual landforms or entire drainage basins, burial histories of rock surfaces and sediment (cf. Gosse and Phillips, 2001; Owen et al., 2006; Balco et al., 2008; Dunai, 2010; Portenga and Bierman, 2011, Darvill, 2013; Granger et al., 2013; Darvill et al., 2015; Dosseto and Schaller, 2016; Ganti et al., 2016). Using TCN the ages of climatic variations recorded by moraine and other glacial sediments can be directly determined (Harbor et al., 2006).

A major advance in TCN dating has been to develop a global network such as the "CRONUS-EU," and the American partner "CRONUSEarth" that have complied locations globally where production rates of terrestrial cosmogenic nuclides (mainly 3He, 10Be, 14C, 21Ne, 26Al, and 36Cl) can be determined with improved accuracy (*nb*. the production-rate calibration site (SPICE: the SP Flow Production-Rate Inter-Calibration Site for Cosmogenic-Nuclide Evaluations, Fenton et al., 2013). It is critical that these production rate values are robust and accurate (to ±5%). Glacial geomorphology is likely soon to be dependent for accuracy of dating and in understanding the effect so past climate change and thus future climates on exposure dating (cf. Balco, 2011).

In 1979 a theoretical paper by Boulton and Jones (1979) was perhaps the first indication that subglacial environments and the way they were understood up until that time needed to be re-evaluated with the beginning of the concept of subglacial soft deformable beds (cf. Alley et al., 1987; Boulton and Hindmarsh, 1987; Menzies, 1989; van der Meer. 1993: Van der Wateren, 1995; Murray, 1997; Truffer et al., 2000; Le Heron et al., 2005; Truffer and Harrison, 2006; Iverson, 2010; Walter et al., 2014). Allied to this concept has been the detection that the subglacial thermal regime in many ice masses is best described as polythermal (Cuffey and Paterson, 2010). Both these soft. Deformable beds and polythermal conditions, have, in combination, led to a recognition that ice mass velocity, ice surface profiles and, subglacial processes must be thoroughly reappraised (cf. Murray, 1997; Amundson et al., 2006; Rempel, 2008; Christoffersen et al., 2010). Not only are glacial sediments that form under these conditions likely to carry distinctive sedimentological signatures and structures but many landforming processes are likely to evolve land/bedforms in a differing manner than previously perceived. For example, explanations of the nature of Rogen moraine and drumlin styles of formation need to take such rapidly changing subglacial conditions into account where previously such conditions had never been contemplated. Where multiple till sequences had previously been considered evidence of multiple ice advances, it is now likely that one advance under deforming bed conditions might account for a similar stratigraphic package (cf. Menzies and van der Meer, 1998;

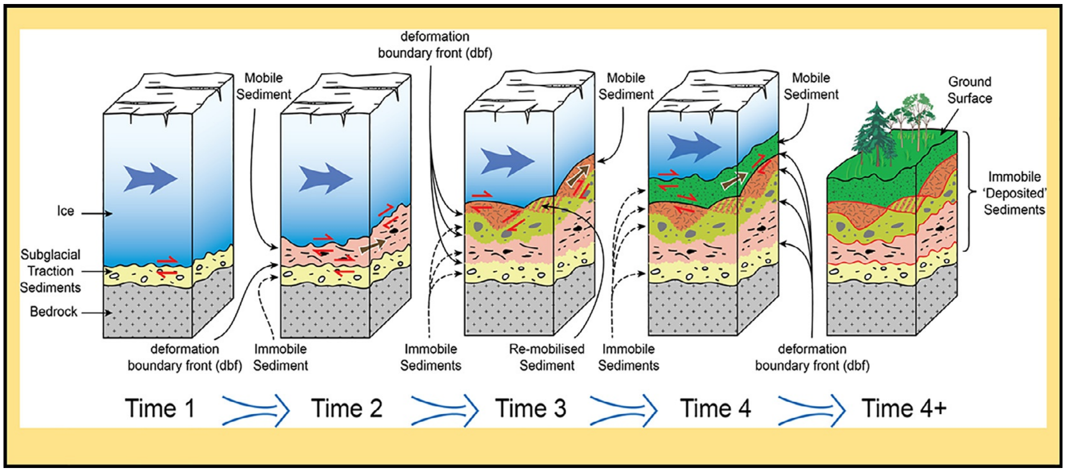

Fig. 3 A model of soft sediment subglacial deformation leading over time to the development of a stacked sequence of immobilized tills. Modified from Menzies, J., Paulen, R.C., McClenaghan, M.B., Rice, J.M.,Oviatt, N.M., Dhillin, N. (2018). Deformation 'boundary front' movements in subglacial tills – a microsedimentological perspective from till near Pine Point. Canada: NWT.

Phillips et al., 2018) (Fig. 3). However, much remains unknown concerning the impact and influence of subglacial soft beds in terms of the spatial and temporal variability of such beds and how this might affect and generate landform patterns (cf. Stokes and Clark, 2003; Ó Cofaigh et al., 2013; Margold et al., 2015; Stokes et al., 2016; Spagnolo et al., 2017) and distinctive sediment packages (cf. van der Meer et al., 2003; Menzies et al., 2006; Phillips et al., 2018). The concept of soft deforming subglacial beds and then vindication that such beds exist beneath modern ice masses and likely therefore occurred under Quaternary and Pre-Quaternary ice masses has been and remains one of the largest paradigm shifts in our understanding of ice masses and the subsequent landscapes developed (Fig. 4).

Closely related to the acceptance of soft deforming subglacial beds has been the recognition and re-introduction of the concepts behind glacial microsedimentology and glacial micromorphological analyses. It became apparent that if such soft subglacial beds had existed in the past, in the Quaternary or earlier, then some signature of such conditions should be evident in the glacial sediments themselves. To investigate such conditions, it was reckoned that distinctive sediment signatures and/or artifacts in the manner of distinctive microstructures and units should be present in these sediments. To that end independently from each other, several glacial geomorphology researchers began to manufacture resin-hardened thin sections of unlithified glacial sediments to view the "undisturbed" state of these sediments. This method had been used in Soil Science (Kubiëna, 1938; Jongerius, 1965; Brewer, 1976; FitzPatrick, 1984; Bullock et al., 1985; Stoops et al., 2010) but had rarely been adopted in glacial sediments (cf. Lundqvist, 1940; Sitler and Chapman, 1955; Lavrushin, 1976; van der Meer, 1987, 1996; Menzies and Maltman, 1992; Menzies et al., 2010; Menzies and van der Meer, 2018). Glacial micromorphology and microsedimentology are still in their developmental stages but already they are providing a wealth of data and new interpretations for glacial sediments that reveal processes and rheological changes that are crucial to the understanding of subglacial sedimentation processes (cf. Menzies et al., 2016; Woodward et al., 2017; Phillips et al., 2018). New methods, such as using X-ray computed microtomography (μmCT), are being utilized and further developed (cf., Tarplee and van der Meer, 2010; Tarplee et al., 2011; Cnudde and Boone, 2013; Bendle et al., 2015; Fouinat et al., 2017). The use of three-dimensional imagery with serial thin sectioning is also proceeding rapidly (Stroeven et al., 1999, 2002).

The fundamental objectives of glacial micromorphology and microsedimentology are to examine sediments at the microscopic level to derive insights into the processes of glacial erosion, transport, deposition, postdeposition and diagenetic processes. As the use of thin sections, μmCT images and SEM proceeds, the taxonomic classification, in place at present, can be expected to expand, alter and be re-evaluated. This microscopic examination of glacial sediments has bridged another frontier in glacial sediment understanding and has, as well as, adapting a new set of techniques, resulted in something of a paradigm shift in, for example, our understanding of subglacial tills and the mechanics of their deposition. As the grasp of subglacial rheological conditions has been better understood due to microscopic examination of undisturbed samples of these tills; so older till classifications, and with that

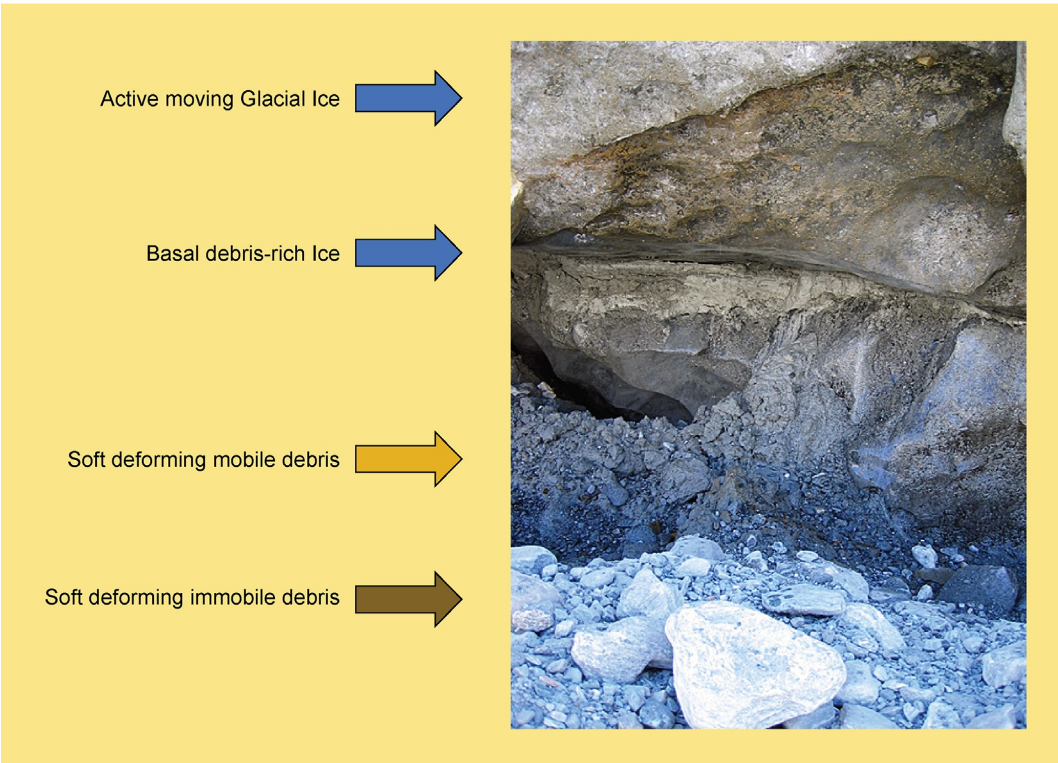

Fig. 4 Photograph beneath the Findelen Glacier, Valais, Switzerland showing soft sediment deformation in the subglacial environment. Note image is approximately 2.25 m height.

their stratigraphies, have had to be reviewed and revised. For some time now, it has been apparent that all subglacial tills other than those tills formed under virtually zero stress (melt-out tills in some instances (Larson et al., 2016)) and very high stress conditions (lodgement tills, Meer and Menzies, 2011) (Fig. 5) have been deformed in some manner (tectomicts, Menzies, 2012) and as such need to be re-evaluated and reclassified—evidence of a paradigm shift in thinking!

With the mapping of glacial sediments, landforms, and landsystems, new methods of data acquisition, storage, manipulation, analysis, and visualization have developed rapidly leading to a virtual paradigm shift in mapping methods. Gone largely are the slow ground mapping techniques of the past, yet such methods remain critical as critical ground truth checks. Too often in the recent past mapping has been done without ground mapping as a final check and some horrendous mistakes and misrepresentations have occurred (cf. Smith and Wise, 2007; Mitasova et al., 2012; McClenaghan and Paulen, 2018, p.526). Given that many research questions within palaeoglaciology are inherently spatially organized, mapping and surveying techniques have long been essential components of the glacial geomorphology. With the expansion of geospatial information technologies (GIT), these techniques have undergone enormous and rapid development and adoption. Geographic information systems (GIS) have become one of the most common frameworks for interpreting glacial environments (Napieralski, et al., 2007; Remondo and Oguchi, 2009; Lin et al., 2013; Pellitero et al., 2016; Wagner, 2018). GIS can be used to extract new geomorphic patterns and relationships from datasets (cf. Clark, 1993; Dunlop and Clark, 2006; King et al., 2007; Greenwood and Kleman, 2010). The potential use in glacial geomorphology of spatial analysis using GIS-based spatial analysis procedures integrating empirical datasets with numerical ice sheet models, either by overlay and visual comparison, or as boundary constraints on ice flow direction (glacial lineations), ice streaming (mega-scale glacial lineations (MSGL)), subglacial drainage (eskers, tunnel channels), or glacial/ice sheet spatial extent (end moraines, marginal meltwater channels) is enormous, and again, paradigm changing (cf. Livingstone et al., 2015; Margold et al., 2015; McClenaghan and Paulen, 2018) (Fig. 6).

Each of these "pathways" has opened up new understanding for glacial geomorphology. As are always the case such advances are not always universally accepted nor understood. Implementation is not always possible nor appreciated—"old" methods and ideas often expire slowly.

Glacial Erosion—Processes

The mechanics of glacial erosion have been relatively obscure for some considerable time. Much anecdotal evidence has typically been presented to "explain" the erosional processes as exemplified in landforms and other erosional aspects of glaciated landscapes but actual specific discussions on the processes are still relatively scarce over the past several decades (cf. Boulton et al., 1974; Boulton, 1974, 1996; Hallet, 1979, 1981; Riley, 1982; Drewry, 1986; Iverson, 1995; Hallet et al., 1996; Näslund et al. 2003). Since the turn of the century increasing interest in the mechanics of glacial erosion is certainly increasing (cf. Rea, 2007).

Glacial erosion of bedrock surfaces, intact bedrock units and sediments involve a range of processes, at times referred to as wear and attrition, that require a broad grasp of several closely allied components such as bedrock, glacial ice, glacial meltwater, sediment

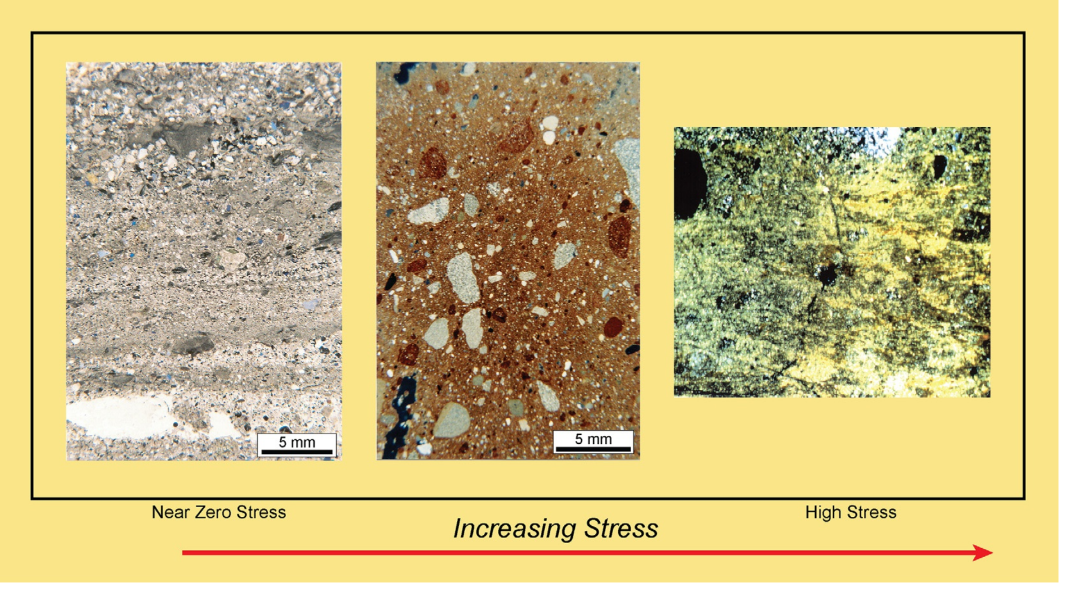

Fig. 5 Three photomicrographs of thin sections from left to right showing increasing stress levels. (A) Is a melt-out till from beneath the Matanuska Glacier, Alaska, United States, with very limited evidence in the form of microstructures of any deformation (cf. Larson et al., 2016). (B) Is a typical Pleistocene subglacial till from Oakville, Ontario, Canada, exhibiting the common microstructures of a deformed till (Eyles et al., 2011), and (C) is a subglacial till from near Moneydie, Perthshire, Scotland, that shows a unistrial plasmic fabric indicative of high stress deformation (Menzies and van der Meer, 1998).

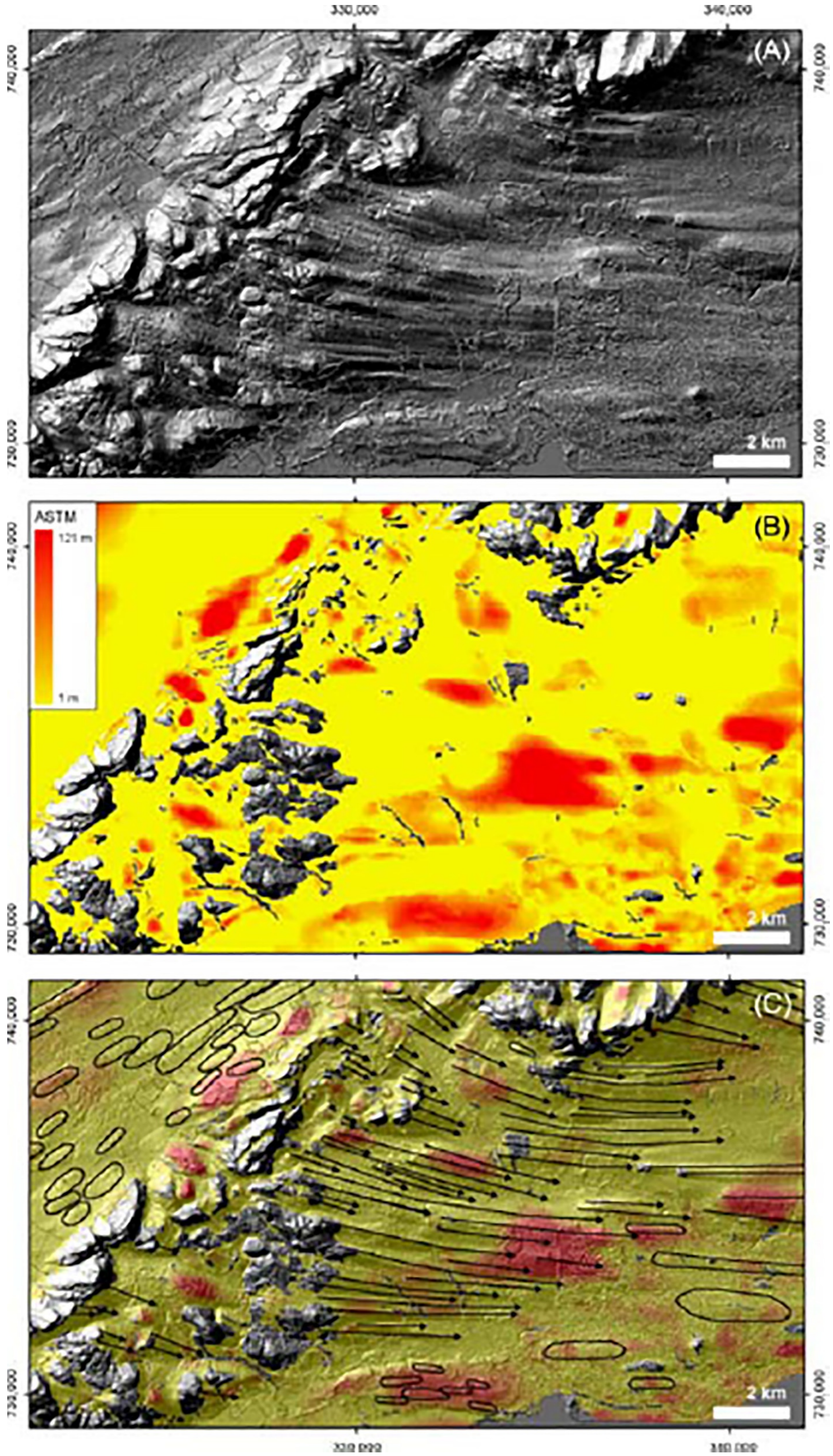

Fig. 6 An illustration of data fusion techniques. (A) Shaded-relief image (NW illumination, 43 vertical exaggeration) of a NEXTmap 5m digital surface model (DSM) from NE Scotland, revealing an assortment of streamlined landforms. (B) Advanced Superficial Thickness Model (ASTM) (in metres) overlain on DSM. (C) Visual fusing of DSM with ASTM data and discrete mapping of classical drumlins and crag-and-tails. After Clark, C.D., Hughes, A.L.C., Greenwood, S.L. and Ng, F.S.L. (2009). Size and shape characteristics of drumlins derived from a large sample, associated scaling laws. *Quaternary Science Reviews* **28**, 677–692.

conditions and pre-glacial bedrock conditions (cf. Olvmo and Johansson, 2002; Hooyer et al., 2012). Bedrock erosion can occur depending on lithology, bulk shear strength, fracture hardness, penetration toughness, moisture content, bedrock structure, fracture and joint geometry, and temperature (cf. Påsse, 2004; Staiger et al., 2005; Dühnforth et al., 2010; Krabbendam and Glasser, 2011; Leith, 2012; Leith et al., 2014; Pedersen et al., 2014). It is well documented in the wear and tribology literature (Rabinowicz, 1965; Scott, 1979; Orbanic and Junkar, 2008; Lian et al., 2018). Yet much of the means by which bedrock is actually eroded by ice is little studied nor understood. Published data such as bulk shear strength is of limited value in replicating real world situations, as tested cores are typically only few centimeters in dimension and any large crack or jointing spacing is eliminated as are variations in rock temperature and moisture content such that replication of field values is vastly over-estimated. Many parameters such as penetration toughness and fracture hardness are largely unknown for most bedrock types. Much more detailed data investigations are needed to clearly understand the bedrock aspects of glacial erosive processes.

The part played by the glacier ice in erosive processes is fundamental in terms of ice thickness, basal stress levels, basal ice velocity, the basal ice debris content and the temperature at the erosive interface (cf. Drewry, 1986, chapter 4; Glasser and Bennett, 2004; Herman et al., 2015; Koppes et al., 2015). Much remains to be understood about the impact of basal ice on erosive processes that deal with the specific mechanics of abrasion, plucking/quarrying and ice adhesion (Iverson, 2012; Ugelvig et al., 2016).

For too long the part played by meltwater in what might be better described as hydroabrasive processes due to sediment-laden flow was poorly acknowledged (Dahl, 1965; Shaw, 1988; Lowe and Anderson, 2003; Eyles, 2006; Jenkins et al., 2010; Beaud et al., 2016), as well as the main transport pathway for sediments within glacial systems (SDS) (Fig. 2). In terms of meltwater velocity and discharge events, the sediment content of the water, its temperature, glacial meltwater is a very effective erosive agent. Glaciated terrains exhibit superb examples of meltwater erosion in terms of P-forms, water abraded surfaces, tunnel valleys and networks. The depth of meltwater penetration below and active ice mass is a fundamental question when considering for example the depth of burial of nuclear waste (Chan et al., 2005; Lemieux et al., 2008; Iverson and Person, 2012; Neuzil, 2012). To date, evidence for hydromechanical changes caused by glaciation are limited and inconclusive. Estimates of the penetrative effect of glaciation range from several 10 s of metres to depths $\geq$300 m.

Until relatively recently, the role played by sediment as an erosive agent was largely ignored. The effectiveness of many erosive process whether by meltwater or direct ice contact is dependent to a great degree on the sediment acting at the erosive interface in terms of the sediment's lithology, and hardness (Rempel, 2008; Barcheck et al., 2018). For already deposited sediment, it becomes essential to understand the geotechnical nature of each lithofacies type (field data that are presently generally limited beyond engineering results, are woefully inadequate. Such data take little or no account of structural geometry or clast/boulder content when measuring bulk geotechnical components) to understand how sediment can be glacially eroded (cf. Boulton and Paul, 1976; Eyles, 1983, chapters 10–14; Clarke, 1987; Kavanaugh and Clarke, 2006; Rathbun et al., 2008; Iverson, 2010). Questions as to whether the sediments are already frozen before being eroded, if not, are likely fully saturated. Likewise, clast and boulder content and concentrations may drastically change rheological properties and need to be considered. Such detailed geotechnical knowledge, as of the present, is absent.

From anecdotal evidence, it is suggested the rates of glacial erosion vary enormously from one glaciated basin to the next (Drewry, 1986, p. 86). Erosion rates can be characterized through the detrital geochemistry of sediments found in deltas or submarine tunnel valley infills beyond ice margins (Cox et al., 2010). In terms of ice sheet glacial erosion rates there is a dearth of data. The general average rates of erosion suggested are in the range of 0.07–30 mm a^{-1} for valley glaciers. In areas of rapid rock uplift, a value of 1.0–100 mm a^{-1} has been suggested (Koppes and Montgomery, 2009; Olvmo, 2010). Using cosmogenic dating methods, Briner and Swanson (1998) suggested that rates under the Cordilleran Ice Sheet in western Canada were in the range of 0.09–0.35 mm a^{-1} but since beneath an ice sheet overlying rugged topography it is unlikely to represent the kind of values beneath other Pleistocene ice sheets. From East Antarctica erosion rates of 0.001–0.002 mm a^{-1} have been reported (Cox et al., 2010) whereas, in comparison, rates across West Antarctica although sparse and varied are often much higher (Smith et al., 2012). Rates in the Pine Island Glacier region are 0.6 ± 0.3 m a^{-1}, with an average current erosion rate of $\sim$1 m a^{-1}. This may be a function of topography and bedrock type although again the latter varies enormously across the ice sheet. Evidence from Antarctic a would suggest that much of the Antarctic interior may have been subject a total loss through erosion of <200 m of erosion.

The depth and degree of erosion reflects the presence or absence of warm-based ice and the consistency of ice flow direction (Hallet et al., 1996; Påsse, 2004). Near the continental margins selective linear erosion has overdeepened pre-existing relief (cf. Jamieson et al., 2010). Terrains close to ice streams have largely survived unmodified by glacial erosion if under cold-based ice. High erosion rates appear to result from steep thermal gradients in basal ice where basal ice velocity is high and warm-based ice prevails. It has been reported that erosion rates vary from 0.001 mm a^{-1} for polar cold-based ice and thin temperature plateau glaciers on crystalline bedrock to 0.1 mm a^{-1} for temperate, warm-based ice masses on resistant crystalline bedrock surfaces in Norway and Switzerland (cf. Olvmo, 2010; Beaud et al., 2016; Delaney et al., 2017). Whereas in Alaska under fast warm-based ice masses rates of 10–100 mm a^{-1} have been noted. These considerable variations reflect bedrock lithology, ice basal thermal states and the basal ice velocity, and pre-glacial bedrock and topographic settings. For both the Laurentide Ice Sheet (LIS) and the Fennoscandian Ice Sheet (FIS) rates of estimated erosion vary enormously (Kleman et al., 2008; Ebert et al., 2015). Estimates for both the LIS and FIS tend to use a global glacial cycle as a measure of the amount of erosion with rates ranging from 0.2 to 4–5 m but typically in the range of $\sim$1 mm a^{-1} (Sugden, 1978; Andrews and Miller, 1979; Boulton and Payne, 1992; Colgan et al., 2002; Påsse, 2004; Iverson and Person, 2012). Based upon physical evidence and theoretical considerations it is only too apparent that, in general, where ice sheets are cold-based minimal erosion occurs, in contrast to where warm-based ice, moving fast especially in ice stream pathways then erosion rates are appreciably higher.

Glacial Transport—Processes

Transport pathways in ice sheets and glaciers are well established (cf. Kirkbride, 1995; Alley et al., 1997). However, englacial and supraglacial transport identification in Quaternary and Pre-Quaternary sediments and rocks remains precarious at best. In subglacial environments, the development and activity of sediment fluxes transporting sediment toward the ice margin needs to be fully explored and understood. In models of subglacial deforming sediment, the sediment flux of subglacial sediment is mobilized as a function of strain, porewater pressure and effective stress levels, and is seen as a consistent supply source (Hindmarsh et al., 1989; Schoof, 2002; Dowdeswell et al., 2004, 2010; Christoffersen et al., 2010; Leysinger Vieli and Gudmundsson, 2010; Roberson et al., 2011). Subglacial sediment supply is a function of the production of "fresh" and "scavenged" sediment often sourced from areas remarkably close to the site of deposition (<15 km) (cf. Paulen and McMartin, 2010; Trommelen et al., 2013). For example, beneath the paleo-ice stream draining Marguerite Bay in West Antarctica, Dowdeswell et al. (2004) calculated a sediment flux rate, assuming a 1 m thick mobile subglacial sediment layer, of 4–28 $km^3/1000\ a^{-1}$ along a 35 km wide paleo-ice stream flowing at an ice velocity of approximately 0.5^{-1} km a^{-1} (cf. Boldt et al., 2013; Sergienko and Hindmarsh, 2013; Beem et al., 2014). These sediment flux rates equate to approximately $\sim$100–800 $m^3\ a^{-1}$ (Damsgaard et al., 2016; Luthra et al., 2016; Menzies et al., 2016; Barcheck et al., 2018).

Glacial Deposition—Processes

The mechanics of glacial deposition has been well studied for over a century, but issues persist in terms of the specific processes involved with many aspects of glacial deposition and allied bedform/landform development. Many general hypotheses on deposition are well established now only refinement is required, yet there are still further revelations in terms, for example, of the process of immobilization of subglacial sediments into till sheets or plains or a specific range of bedforms loosely classified as MSGL. There remain many unresolved issues and questions in subglacial geomorphology.

"Linkages" Within Glacial Geomorphology

It is evident that there are "linkages" within glacial geomorphology that may lead to new advances, innovations, and possibly paradigm shifts. There are many established links within the field of glacial geomorphology, while others need strengthened, and others that should be established and robustly "investigated." It is critical that these "linkages" be developed in what might be termed a multi-faceted corroborative process. "Linkages" exist or need to be developed between, for example, drumlins and other MSGL, glaciofluvial landforms, ice streams, tunnel valleys, overdeepened valleys and their infill, ice marginal environments from submarginal to proglacial, macro- and microsedimentology of glacial sediments, the relationships between oceanic and terrestrial subsystems (landsystems), glaciological models, dating techniques, precision and veracity, GIS imagery, glacial sediment rheology, and till taxonomy.

Established links: There would appear, for example, to be a strong link between drumlins and other MSGLs and ice streams that would suggest that fast moving temperate basal ice and a ready sediment flux related to basal ice stream conditions are "ideal" for drumlin and MSGL formation.

Links to be strengthened: There is strong evidence that a relationship must exist between till microstructure formation and evolution related to sediment rheology and basal ice conditions (cf. Menzies et al., 2018).

Links to be explored: For example, it is critical that interrelationships between bedforms, ice dynamics and glaciological models be further explored. Likewise, data gathered, for example, along margins and in and beneath active ice streams in Antarctica related to geomorphological forms is critical to advance our understanding of glacial bedform development and glaciodynamics.

Ultimately it is along the "margins" of these subareas of research interest that therein lies likely scientific advances. To that end a short list of issues that need to be considered in glacial geomorphology follows.

(a) In general, recognition and differentiation of subglacial and englacial lithofacies types persists as a continuing issue. The ability to discriminate between the varied sub-environments within which diamictons/tills can be deposited is an example. It remains problematic to distinguish between diamictons from subglacial and subaqueous environments in many critical instances. This is complicated by the fact that what are now subaqueous sediments were simply subglacial when deposited. The fact that a glacier terminates in water makes no difference to the bed contact.

(b) Macro- and microstructures within subglacial sediments develop under subglacial stress conditions. Considerable interest has been engendered in trying to understand the many complex structures both at the micro- and macrolevels found within all glacial diamictons (Menzies et al., 2016; Spagnolo et al., 2016; Phillips et al., 2018). At present only, limited explanations exist for these structures. A possible line of enquiry is that these structures are part of a continuum of forms developed at iterative stages as the sediment is emplaced.

(c) In glacial depositional terms, the impact of porewater and porewater pressures on sedimentation mechanisms, rates of sedimentation and the structures imprinted by porewater in sediments in terms of physical and chemical effects needs deeper investigation. Porewater, in directly influencing effective stress levels, must have a major part to play in glaciotectonism and sediment deformation at all scales. In translocating clays and soluble minerals, porewater alters the chemical signature and, in some instances, the geotechnical properties of some sediments. The extent of this impact remains only inferred. Related to porewater are the effects of high rates of saturated sediment deposition, overloading, glacial tectonism and neotectonism (cf. Phillips et al., 2018.

(d) It is typically stated that particles that have passed through the glacial system are distinctive in shape, surface morphology and size distribution, yet little research has closely investigated particle shape evolution, fracture mechanics and surface morphological imprinting other than in a limited sense. The fields of tribology and rock mechanics is a potential rich source of new insights into these aspects of particle development that need to be considered (cf. Zmitrowicz, 2003; Flowers, 2010; Iverson and Zoet, 2015).
(e) There is great need to relate glaciological parameters and therefore glaciological models to the depositional mechanics of subglacial and proximal glacial sediments on land and in the marginal ocean basins, both in terms of previously deposited sediments and subsequent sedimentation processes (cf. Sergienko and Hindmarsh, 2013; Stokes et al., 2013a,b; Hindmarsh, 2018).
(f) The value of dating techniques in stratigraphic correlation and surface age dating continues to require improvements in reliability and validity.
(g) Increasingly the combination of satellite imagery (GIS, Lidar, etc.) and ground-based glacial geomorphological mapping has retrieved many interesting interrelationships between ice streams and glacial bedforms (cf. Stokes et al., 2013a,b; Patton et al., 2015). It is essential to build geomorphological models that combine ice dynamics and subglacial bedform conditions and resultant forms accurately.
(h) It is essential that ice sheet and ice stream modeling is further refined to permit a better understanding of ice stream dynamics during advance and retreat phases.
(i) The timing of glacial events at a range of geomorphological scales still needs to be better understood in terms of the correlation between eustatic/isostatic changes at ice margins and in the proglacial zone.

Future Prospects

Subdividing glacial geomorphology into erosion, transport and deposition, both terrestrial and marine, allows an examination of progress in the discipline. Future endeavors might consider research under the following dominant areas of research in glacial geomorphology: glaciated terrains and past and present ice margins, and deep-time archives in ocean basins. Large areas of the glaciated continents and oceans have been mapped yet data remain hidden at depth both on land and in the ocean basins (e.g., Phillips et al., 2017). For example, in glacially overdeepened valleys on the North American and Eurasian continents and along coastal margins as far out as the edge of the continental shelves, there remain deep archives of sediment that still require close investigation (cf. Menzies and Ellwanger, 2015; Büchi et al., 2017a,b; Pomper et al., 2017; Swift et al., 2018). In Ontario, Canada there is increasing awareness of these deep archives and their relevance, for example, in tracing of groundwater flow patterns and detection of pollution plumes (cf. Gao, 2011; Steelman et al., 2017). In the Antarctic the Cape Roberts Project and ANDRILL have cored the continental margin to study the climatic and tectonic history of the continent (cf. Naish et al., 2007; Harwood et al., 2009). Related to deep archives in glacial marine sediments there is a remarkable correlation between methane hydrate destabilization which is increasingly suspected as an important positive feedback to climate change following past global deglacial periods. Such destabilization through the release of these gases may represent an important mechanism active during conditions of strong climate forcing such a global deglaciation (cf. Patton et al., 2016; Winsborrow et al., 2016).

The connection between glacial conditions in the past, today and in the future can be directly linked and applied to global climate change and global warming. Research in glacial geomorphology has reached new and exciting phases with the direct relevance of past and modern glacial environments to global environmental change and potential long-term implications for the Earth. With intensive study, especially over the past 50 years and the resultant accumulation of a vast data base of geomorphological terrain maps. Landform studies and glacial sediment inventories, glacial geomorphology remains a rich and vibrant science. Much remains to be discovered, re-assessed and new avenues of research pursued. Over the past decade there have been major advances in understanding large-scale mega-geomorphology especially in relation to glacial lineations over the beds of large former ice sheets (cf. Stokes and Clark, 2003). At around the same time the development of glacial microsediment research has heralded a new phase in glacial sedimentology (cf. van der Meer et al., 2003; Menzies et al., 2010). It is increasingly critical that a vertical integration of findings be developed that will permit a scalar incorporation of processes at differing scales, thus permitting an assimilation of glacial process mechanisms to be understood from the micro to the mega-scale. Glacial geomorphology can provide an improved understanding of past and present glacial landscapes and sediments that will be critical for humankind in the very near future.

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