Bedrock mega-grooves in glaciated terrain: a review

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Abstract

Bedrock mega-grooves are assemblages of straight and parallel troughs eroded in bedrock, typically over 1,000 m in length; most sites occur within the limits of the Last Glacial Maximum, both on- and off-shore. In this paper, we review the current understanding of these important yet enigmatic landforms and propose a framework for their future research. Mega-grooves are important to our understanding of ice sheet dynamics, ice–bedrock interactions and bedrock landscape evolution in glaciated areas. The overall straightness of mega-grooves across the landscape, their parallel alignment to palaeo-ice flow direction, and occurrence below the general land-surface level, has led to their unanimous interpretation as landforms of subglacial erosion. Scenarios proposed for mega-groove formation focus on either glacier ice or subglacial meltwater as the principal agent of erosion, yet none offers a comprehensive explanation. At locations where mega-grooves occur along lines of structural geology, their location, formation and morphology were largely controlled by the bedrock characteristics. Where no underlying structural control is apparent, mega-grooves were likely initiated through glacial abrasion, and subsequently modified through a range of erosional processes, potentially involving multiple morphogenetic agencies and feedbacks operating between bedrock topography and basal ice flow. In the absence of absolute dates, morphostratigraphic analyses suggest mega-groove survival through multiple glacial cycles. No specific ice-flow characteristics have been identified as a condition for bedrock grooving, but it has been suggested that some bedrock mega-grooves are related to ice streaming, which deserves further study. An initial analysis of bedrock grooves with seemingly similar morphology at a range of scales hints at a bedrock – groove landform size continuum, which could be a useful framework for exploring process landform relationships. Future research could usefully focus on quantitative analysis of mega-groove morphology, augmented with detailed field analysis of landform relationships to bedrock structure and lithology, and thereby potentially provide further insight into the age and glaciological significance of these landforms.

Key words: mega-groove; glacial erosion; bedrock geology; landform size continuum; meltwater

1 Introduction

Bedrock mega-grooves are series of straight troughs eroded in bedrock, typically over 1,000 m long and up to 10s of metres deep. Mega-grooves display a consistent parallelism throughout their length, without cross-cutting. The essential characteristic of a grooved area is aptly summarised in a pioneering study by Smith (1948: p 507) who noted “the impression thus created is that of ground deeply scored by a giant rake” (Figure 1). Over the past hundred years, a number of mega-groove sites have been reported worldwide from areas covered by former Quaternary ice sheets, both onshore (Smith, 1948; Witkind 1978; Wardlaw et al., 1969; Funder, 1978; Heikkinen and Tikkanen, 1989; Bradwell, 2005; Bradwell et al., 2008; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Eyles, 2012; Krabbendam et al., 2016) and offshore (Lowe and Anderson, 2003; Heroy and Anderson, 2005; Bradwell and Stoker, 2015). While most sites are found within the limits of the Last Glacial Maximum (LGM) ice sheets, bedrock mega-grooves of an inferred glacial origin have been reported at some localities lying well outside these limits (Figure 2) and used to reconstruct ancient glaciations, such as in the Sahara (Fairbridge, 1974), Australia (Perry and Roberts, 1968) and Argentina (López-Gamundí and Martínez, 2000), as well as in the wider Solar System on Mars (Baker and Milton, 1974, Lucchitta, 1982;). More recently, bedrock mega-grooves have also been inferred from beneath the Greenland ice sheet (Jezek et al., 2011).

The location of mega-grooves and their accordant alignment with other streamlined landforms indicative of former ice-flow direction is usually taken to indicate that they are related to former glaciation. This, together with their parallel conformity and straightness over long distances, has prompted most geomorphologists to propose a subglacial origin for these landforms, traditionally related to quarrying and abrasion (Carney, 1910; Smith, 1948; Zumberge, 1955; Wardlaw, 1969; Witkind, 1978; Goldthwait, 1979; Lowe and Anderson, 2003; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Eyles, 2012; Krabbendam et al., 2016). An alternative school of thought invokes the erosive action of meltwater rather than glacier ice, both on Earth (Baker and Milton, 1974; Tinkler and Stenson, 1992; Shaw, 2002; Bradwell, 2005, Munro-Stasiuk et al., 2009) and Mars (Baker and Milton, 1974). The lack of consensus with respect to the origin of bedrock mega-grooves exists not only between these two schools of thought, (i.e. glacial *versus* glacifluvial), but also within. For example, advocates of glacial erosion propose various scenarios for mega-groove formation, with specific mechanisms that have included prolonged abrasion over multiple cycles of glaciation (Roberts et al., 2010); lateral plucking under fast-flowing ice (Krabbendam and Bradwell, 2011); and glacial abrasion by fast flowing, debris-rich basal ice (Goldthwait, 1979; Eyles, 2012). Such views are not necessarily conflicting, as they apply to site-specific characteristics related to geology, geomorphology and glacial history. However, few attempts have been made to systematically examine the characteristics of mega-grooves from different settings and assess whether a complex set of conditions and mechanisms could account for their formation, or whether they might be explained by a single mechanism or scenario.

In the last decade, a renewed interest in the analysis of bedrock mega-grooves in a glaciological context has led to the emergence of new research questions, which explore the link between mega-grooves and palaeo-ice streams (e.g. Bradwell et al., 2008; Heroy and Anderson, 2005; Krabbendam and Bradwell, 2011; Eyles, 2012, Krabbendam et al., 2016). The geomorphic signature of ice streams consists of an assemblage of landforms with diagnostic characteristics. In particular, onset zones of fast-flow have bedrock landforms with high length: width ratios and a convergent flow pattern, and are often replaced down-ice by an area of deformed sediment (Stokes and Clark, 1999). Where mega-grooves occur in conjunction with streamlined landforms indicative of fast ice flow, it has been suggested that they belong to the same palaeo-ice stream landsystem for example on the Antarctic continental shelves (Lowe and Anderson, 2003; Wellner et al., 2006), in Scotland (Bradwell et al., 2007; Bradwell and Stoker, 2015), Canada (Eyles, 2012) and also in Norway (Ottesen et al., 2008). At these locations, mega-grooves occur in areas interpreted as the onset zones of fast ice-flow (ice streams), and their formation has been attributed to enhanced and focused glacial erosion assumed to take place in such zones.

Addressing the uncertainties relating to mega-groove formation and their glaciological significance would lead to a better understanding of the subglacial environment in terms of spatial variability of subglacial forms and processes, and persistence of bedrock forms beneath ice sheets. This paper presents a systematic review of the existing body of knowledge on mega-grooves in order to assess the proposed mechanisms of formation and the glacial and geological scenarios in which grooves were likely initiated. First, we review the terminology related to bedrock grooving and provide an historic overview of mega-groove research (Section 2). In Section 3, we review the physical characteristics of mega-grooves and their relationships to bedrock geology. The mechanisms proposed for mega-groove formation, and possible time frames of development are presented in Section 4. In the discussion (Section 5) we (i) evaluate the role of geological structure in mega-groove formation, (ii) undertake an initial assessment of mega-grooves in relation to a possible bedrock landform size continuum, and (iii) assess the influence of glaciological conditions on groove formation. Emerging from this critical review, we propose a series of suggestions for future research.

2 Terminology and history of research

2.1 Terminology

A series of terms have been used over the decades to refer to bedrock corrugations in glaciated terrain, including ‘megaflutes’, ‘flutings’, ‘fluted terrain’ (Gravenor and Meneley, 1958; Funder, 1978, Heikkinen and Tikkanen, 1989), ‘giant grooves’ (Smith, 1948; Witkind, 1978; Goldthwait, 1979) and ‘megagrooves’/’mega-grooves’ (Bradwell, 2005; Munro-Stasiuk et al., 2005; Bradwell et al., 2008; Benn and Evans, 2010). Of these, some terms have been used with a wider meaning. For example ‘lineations’ and ‘flutings’ can refer to landforms in unconsolidated sediment or unknown substrates, and mean either ridges and/or troughs (Baeten et al., 2010). It is important that a specific descriptive terminology be designated for large-scale grooves from glaciated terrain, which occur in bedrock, in order to ensure clarity and unity in scientific communication. It is also important to maintain an awareness of terminology used in the past, in order access references to these landforms in older publications.

Deriving and developing terminology in geomorphology should aim to help differentiate between landforms, particularly those of similar shape and/or process – form regimes. In this respect, bedrock mega-grooves bear morphological similarities with mega-scale glacial lineations (MSGLs: cf. Clark, 1993; King et al., 2009). The latter are typically much longer, generally formed in unconsolidated glacial sediments (cf. Spagnolo et al., 2014), and can exhibit cross-cutting patterns (Clark, 1993; Bradwell et al., 2007; Benn and Evans, 2010). While corrugations in both types of substrate have unequivocally been linked to glaciation, uncertainties regarding their formation and glaciological significance persist. Indeed they are likely different landforms, with an altogether different morphogenesis, so it is important that differing terminology is used consistently to refer to each type. Because MSGL is a well-established term for highly elongate glacial lineations in unconsolidated sediment (Clark, 1993; Clark et al., 2003; King et al., 2009; Spagnolo et al., 2014), it is preferable to avoid the term ‘lineation’ when the substrate is bedrock. Whenever the substrate is unclear, the term ‘fluting’ may be more appropriate, especially as it has been previously employed to describe troughs and ridges collectively in a landscape context (e.g. Gravenor and Meneley, 1958; Lawson, 1976; Funder, 1978; Heikkinen and Tikkanen, 1989) and does not inherently define the nature of the substrate. However, flutings or ‘flutes’ commonly occur at a much smaller scale than both MSGL and bedrock mega-grooves (Ely et al., 2016).

Ideally, terminology should capture key physical characteristics of landforms in order to be as descriptive and intuitive to envisage as possible. In the case of mega-grooves, one key characteristic is their occurrence in bedrock and, in this respect, the word ‘groove’ is semantically appropriate, as it means a long, narrow cut or depression in hard material (Soanes and Hawker, 2005). However, ‘groove’ by itself has long been used for general reference to a wide size-range of subglacially-formed troughs in bedrock, (Dahl, 1965; Gjessing, 1965; Flint, 1971). Therefore, a quantifier is required alongside ‘groove’ when referring to large-scale landforms, in order to render their extraordinary length, which is another key physical characteristic. In older studies, large-scale grooves are referred to as “giant grooves” (e.g. Smith, 1948; Wardlaw et al., 1969; Witkind, 1978; Goldthwait, 1979), and while this expression is still in use (Grosswald and Hughes, 2002), the more morphometrically precise term ‘mega-grooves’ has gradually replaced it (e.g. Bradwell, 2005).

The term ‘megagroove’, as explicitly proposed by Bradwell et al. (2008) to refer to large-scale bedrock grooves formed through glaciation, was quickly adopted by the scientific community and has been widely used in the last decade in glacial geomorphology, solely to refer to these landforms (Roberts et al., 2010; Krabbendam and Glasser, 2011; Eyles, 2012; Benn and Evans, 2010;Krabbendam et al., 2016). Although both ‘mega’ and ‘giant’ communicate the large size of the grooves, the prefix ‘mega’ is preferable for the following reasons: i) it can give a technical rather than literary value to the word ‘groove’(i.e. 10^6 mm according to the International System of Units), which improves clarity in scientific communication; ii) it allows for classification in the wider range of grooves with similar morphology and instantly conveys the hierarchic place that these landforms occupy in the range, which can be useful in the context of a landform size continuum; iii) unlike ‘giant’, ‘mega’ is not a superlative, so it leaves open the nomenclature scale if yet larger grooves are yet to be named (e.g. giga-grooves). The hyphenated version ‘mega-groove’ is preferred because it maintains a better focus on the semantic value of each component and allows for some flexibility in usage. In conclusion, we regard the term ‘mega-groove’ as best suited to refer to large-scale bedrock grooves in glaciated terrain, as it conveys concisely and comprehensively the current knowledge of these landforms, while avoiding ambiguity in relation to others.

2.2 A brief history of research

The history of mega-groove research spans less than a century, during which time there has been a gradual broadening of the scientific interest related to these landforms. To our knowledge, mega-grooves are first mentioned in land survey reports carried out by Geological Surveys in Canada and the USA (Gilbert, 1873; Bell, 1867). Early papers with a specific focus on mega-grooves are based on observations that were rather incidental to broader geological projects, and the authors implied that the motivation to describe such landforms lay in their unusual nature and rare occurrence. For example, Smith (1948, p 503) explicitly states that his study on mega-grooves in the Northwest Territories (NT), Canada “is based on observations made while serving as a geologist on the Canol Project […]. Ground observations were […] purely incidental to studies of petroleum geology”. Notably, Smith’s (1948) paper has been the benchmark for later descriptions and interpretations of bedrock mega-grooves, because subsequent studies used it as a basis for morphologic and genetic comparisons (e.g. Zumberge, 1955; Gravenor and Meneley, 1958; Wardlaw et al., 1969; Witkind, 1978; Funder, 1978; Heikkinen and Tikkanen, 1989; Jezek et al., 2011). Mega-groove studies published throughout the 20th century describe the physical characteristics of landforms in detail, in conjunction with their relationship to bedrock geology. Such descriptions are based on data from direct field observations and from aerial photographs, but little is mentioned about the glaciological context (e.g. Smith, 1948; Wardlaw et al., 1969; Funder, 1978).

It was not until the beginning of the 21st century that the glaciological conditions in which mega-grooves formed received considerable attention (Lowe and Anderson, 2003; Wellner et al., 2006; Bradwell et al., 2008). Initially, new sites were reported and analysed with the advent of new survey techniques, such as satellite imagery and digital elevation models onshore (Bradwell et al., 2008; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Eyles, 2012; Krabbendam et al., 2016) and bathymetric surveys offshore (Lowe and Anderson, 2003;

Wellner et al., 2006; Eyles, 2012; Bradwell and Stoker, 2015), and geophysical techniques beneath modern ice sheets (Jezek et al., 2011) (Figure 3). In addition, some older sites were revisited and previous interpretations challenged with respect to the agents and processes involved in groove formation (Munro-Stasiuk et al., 2005; Krabbendam and Bradwell, 2011; Eyles, 2012). Most of the more recent studies attempt to explain mega-groove formation in a wider, regional context of ice flow, whether past (Lowe and Anderson, 2003; Wellner et al., 2006; Eyles, 2012; Bradwell and Stoker, 2015) or present (Jezek et al., 2011), and they link groove formation to specific characteristics of ice flow in terms of velocity. It could even be argued that the scientific interest in bedrock mega-grooves has been rekindled recently by their glaciological interpretation as subglacial features formed in the onset zones of -ice streams (Bradwell et al., 2008; Eyles, 2012; Krabbendam et al., 2016). The potential link between ice streams and bedrock mega-grooves has certainly given these enigmatic landforms increased visibility in glacial research at a time when ice streams, ancient and modern, have been receiving more attention (Bamber et al., 2000; Rignot and Kanagaratnam, 2006; Winsborrow et al., 2010; Kleman and Applegate, 2014; Stokes et al., 2016; Stokes, in press; Eyles et al., 2018).

In summary, the scientific interest in mega-grooves has broadened from the detailed documentation of their physical characteristics, to include their glaciological significance in a wider, regional context of palaeo-ice flow and based largely on remote sensing data. Yet how these landforms were actually initiated and whether or not they are produced by multiple glaciations remain poorly understood.

3 Characteristics of mega-grooves

In this section we review the principal physical characteristics of mega-grooves reported in the literature in terms of morphology, morphometry and topographic setting, as well as relationships to bedrock geology. The aim here is to build a database of physical characteristics of mega-grooves, in order to facilitate identification of key physical features and patterns of occurrence. Such data will serve as a basis to test hypotheses of mega-groove formation. Table 1 summarises the key data on mega-grooves described in the literature, and their location is mapped on Figure 2.

3.1 Morphology and morphometry

Mega-grooves typically occur as series of parallel corrugations in bedrock. In most cases mega-grooves are strikingly rectilinear across the landscape (Figure 1) (Smith, 1948; Funder, 1978; Lowe and Anderson, 2003; Bradwell, 2005, 2008; Eyles, 2012), although in some places they can show a slight sinuosity in planform (Zumberge, 1955; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Jezek et al., 2011), or exhibit a broad curve (Smith, 1948). An exceptional case are the mega-grooves described by Witkind (1978), which curve round the northern spur of the Mission Range, Montana, US (Figure 4). Witkind (1978) suggests that the overall curvature reflects changes in former regional-ice flow direction in contact with local mountain glaciers, although groove occurrence along bedrock joints is also mentioned at this site. Grooves of similar size tend to maintain their parallelism regardless of whether they are rectilinear, slightly sinuous or crescentic in planform, with the exception of the mega-grooves in Assynt, NW Scotland, which splay out slightly in the palaeo-ice flow direction (Figure 5A and B) (Bradwell, 2005).

Mega-grooves usually have an up-and-down long profile, with bedrock knobs and ridges along their floors (Witkind, 1978; Heikkinen and Tikkanen, 1989; Eyles, 2012). In Assynt, NW Scotland, they tend to deepen up-slope, and some terminate abruptly against a steep cliff in the middle of the slope (Bradwell, 2005). The long-profile, as well as the actual depth, have proven difficult to assess at sites where a thick layer of till is present inside the grooves (Witkind, 1978), or if their floor is occupied by lakes (Wardlaw et al., 1969), muskeg, vegetation (Smith, 1948), or peat (Bradwell, 2005). The typical depth is, however, in the range of 10 – 20 m (Table 1). In cross-profile, mega-grooves are typically U-shaped (Witkind, 1978; Funder, 1978; Heikkinen and Tikkanen, 1989; Bradwell, 2005; Eyles, 2012; Krabbendam et al., 2016), although at some localities the cross-profile can vary between V- and U-shaped (Smith, 1948; Bradwell et al., 2008), or parabolic with steep, concave sides (Bradwell et al., 2008) (Figure 6).

[*insert table 1*]

Mega-grooves are typically 1,000-2,000 m in length, Exceptionally long grooves, of up to 12,000 m, have been reported in the Mackenzie River valley, Northwest Territories, Canada (Smith, 1948), and some that are tens of kilometres have been identified on the Antarctic continental shelf (Wellner et al., 2006). At some locations, mega-grooves are unbroken along their length (Smith, 1948; Funder, 1978; Bradwell, 2005), which contrasts with other sites where either the ridges or the mega-grooves are discontinuous (Krabbendam et al., 2016; Heikkinen and Tikkanen, 1989). Length can also vary widely within the same area. For example, the grooves north of Ullapool in Scotland have been reported to range between 500 and 3,000 m (Bradwell, et al., 2008). In Montana, US, Witkind (1978) noted that a string of two or three grooves joined up longitudinally, thus giving the false impression of extreme length. The width of mega-grooves is typically in the range of 20-200 m, and tends to remain constant within the same groove (e.g. Mission Range, Montana; Witkind, 1978), but varies considerably between sites and sometimes within the same site (Table 1). Regarding groove spacing (or wavelength), some studies report that mega-grooves are regularly spaced (e.g. at 45 m: Funder, 1978; Bradwell, 2005), or that spacing varies within a certain interval (e.g. 10-20 m, Bradwell et al., 2008), whereas other studies do not report this metric (see also Table 1). Gravenor and Meneley (1958) identified two peaks in mega-groove spacing for the five sites they investigated in north-east Alberta, at 90-120 m and 180-215 m, respectively, which occur regardless of the nature of the substrate.

Mega-grooves typically occur in undulating lowland areas with local relief generally below 400-600 m (Smith, 1948; Gravenor and Meneley, 1958; Heikkinen and Tikkanen, 1989; Funder, 1978; Eyles, 2012). They have been reported to occur in all positions on slopes relative to ice-flow direction (e.g. lee, stoss, across-slope), although local trends have been noted. For example, in Ontario, Canada, mega-grooves are present on the slopes tilted to the south-west, which follow the shallow dipping plane of bedrock strata which coincided with regional ice-flow direction (Eyles, 2012). In Finnish Lapland, mega-grooves incise the summits of fjells (local granite hillocks) and fade over intervening lowlands only to re-emerge on the next hill, thereby being traceable over long distances in straight lines over the landscape (Heikkinen and Tikkanen, 1989) (Figure 7).

Given the above descriptions of the size and shape, Bradwell et al. (2008) defined mega-grooves as being "large-scale, linear, erosional features with negative topographic expression formed by glaciation, regardless of their genesis". Here, we add to this definition a semi-quantitative reference based on characteristic morphometric values reported in the literature and summarised in Table 1. Thus bedrock mega-grooves are:

Series of parallel and closely-spaced bedrock grooves, straight to slightly curvilinear in planform, which occur in glaciated terrain. Typically mega-grooves measure over 1,000 m in length, have length:width ratios between 20:1 and 50:1, and length:depth ratios higher than 100:1.

Although the shape and size of the intervening ridges often mirror those of the grooves (Funder, 1978; Eyles, 2012), we argue that it is mainly the grooves that represent the geomorphological process of subglacial erosion, whereas the ridges are partial remnants of the initial land surface into which the grooves were incised (c.f. Smith, 1948). There are a few other common features among mega-groove sites that have not been included in the above definition. For example, all sites tend to occur towards the margins rather than the centre of ice sheets (Figure 2), and also in areas of relative lowland, close to the local base level (Section 3.1). While such attributes may have some relevance with regards to mega-groove formation, as yet they are not considered diagnostic features for these landforms.

3.2 Relationships to bedrock geology

Any relationships between mega-grooves and bedrock geology, in terms of lithology and structure, have the potential to explain how the bedrock properties could account for mega-groove formation. Here, published accounts of mega-grooves are reviewed in relation to bedrock geology, and this reveals a clear first-order classification between those that appear to be related to underlying structure and those that do not.

3.2.1 Lithology

Mega-grooves from glaciated terrain have been reported in a variety of lithological settings: carbonate sedimentary rocks (NT Canada – Smith, 1948; Manitoba, Canada – Wardlaw et al., 1969; Georgian Bay, Canada – Eyles, 2012; Novaya Zemlya, Russia – Grosswald and Hughes, 2002), metasedimentary rocks (Ullapool, Scotland – Bradwell et al., 2008; Montana, US – Witkind, 1978; Ontario, Canada – Krabbendam et al., 2016), conglomerates (East Greenland – Funder, 1978), metamorphic rocks (Assynt, NW Scotland – Bradwell, 2005; West Greenland – Roberts et al., 2010), and also in old and highly metamorphosed shield rocks (Alberta, Canada – Gravenor and Meneley, 1958, Finland – Heikkinen and Tikkanen, 1989; West Antarctica – Lowe and Anderson, 2003; Wellner et al., 2006; Ontario, Canada – Krabbendam et al., 2016). In some places, mega-grooves occur in areas of mixed sedimentary and igneous lithologies (e.g. Isle Royale in Michigan, US – Zumberge, 1955; Tyne Gap, England – Livingstone et al., 2008; Ungava Peninsula, Canada – Krabbendam and Bradwell, 2011). The largest mega-grooves reported occur in the submerged crystalline bedrock of Sulzberger Bay, on the Antarctic continental shelf, where they attain depths of over 100 m and lengths of over 40,000 m (Wellner et al., 2006).

Our review of the literature suggests that the type of bedrock is not a defining factor in mega-groove location, but a direct lithological control over mega-groove formation has been inferred in some cases at a local scale, based on the susceptibility of rocks to erosion. For example, in the Mackenzie River valley, Northwest Territories, Canada, the deepest and widest grooves occur in the Bear Rock formation, a late-Silurian/early-Devonian porous and cavernous brecciated limestone, and in the Devonian reef limestone; whereas harder limestones of roughly the same age have either poorly developed grooves or none (Smith, 1948). On the islands in Georgian Bay, Ontario, the grooves are best-developed in softer, lagoon carbonate facies, in contrast to other carbonate rocks (Figure 8A) (Eyles, 2012). In addition, the presence of bioherms, which are hard bedrock mounds more resistant to erosion than the surrounding rock, enabled differential erosion through split flow, as envisaged by Eyles (2012) (Figure 8B).

At a number of sites of mixed bedrock lithology, it has been noted that mega-grooves occur exclusively or preferentially on certain rocks. For example, a mega-groove field in East Greenland is strictly confined to areas of Røde Ø Conglomerate (Figure 9), which lithologically forms an insular occurrence surrounded by gneissic metamorphic rocks (Funder, 1978). There, the transition between the grooved and non-grooved area is sharp and coincides with the change in lithology, which indicates lithological control over mega-groove formation. Similarly, in Assynt, NW Scotland the grooves are more numerous and better developed in Cambrian quartzite than in adjacent areas to the south and west, underlain by Moine schist and Torridonian sandstone, respectively (Figure 5A) (Bradwell, 2005).

At the other extreme lie cases in which lithology seems to have been insignificant in mega-groove formation, for example in the Manitoba, Interlake region, Canada, where the granitic bedrock adjacent to the grooved carbonate rocks also bears mega-grooves (Wardlaw et al., 1969). A similar observation has been noted in north-east Alberta, Canada, where mega-grooves cut indiscriminately across lithological boundaries, with hard pegmatite dykes having been 'grooved' to the same depth as adjacent 'softer' metasediments (Gravenor and Meneley, 1958). This shows that erosion rates can be entirely unaffected by the differential resistance of variable and juxtaposed rock types. In west Greenland, on the other hand, the ridge-and-groove topography is the result of differential erosion between two rock types, whereby the grooves are developed in the metamorphic parent rock and the mafic dyke intrusions stand proud as ridges (Roberts et al., 2010) (Figures 3A & 10 G).

To summarise, mega-grooves do not occur preferentially on any particular lithology. The degree of influence that bedrock lithology exerts on mega-groove development varies between very high and very low. It is suggested that certain types of rock are more susceptible to glacial erosion than others, but such susceptibility has not been assessed quantitatively.

3.2.2 Structure

Studies that analyse the relationship between mega-grooves and bedrock structure often do so in terms of groove alignment relative to the strike and dip, and also to joints and folds. The results fall into two categories: mega-grooves which bear no apparent relationship to any structural lines and cut through structural boundaries (Smith, 1948; Gravenor and Meneley, 1958; Funder, 1978; Bradwell, 2005), and those that follow structural lines (Zumberge, 1955;

Bradwell, et al., 2008; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Krabbendam et al., 2016).

Structurally-independent mega-grooves are aligned at an angle to the strike of bedrock strata (Smith, 1948; Gravenor and Meneley, 1958; Funder, 1978; Bradwell, 2005; Eyles, 2012; Krabbendam et al., 2016) and comprise two subgroups: one is formed by mega-grooves in homogenous bedrock (Figure 10 A) and the other by mega-grooves which cut through geological boundaries (Figure 10 B). The former are confined to single rock formations, with classic examples from Georgian Bay, Ontario, Canada, eroded into Palaeogene carbonate strata (Figure 10A) (Eyles, 2012; Krabbendam et al., 2016), and also those in Cambrian quartzite from Elphin, Scotland (Figure 5A) (Bradwell, 2005). This subgroup also includes mega-grooves in gneissic rocks, where former structural discontinuities were greatly attenuated through intense metamorphism, thus resulting in a relatively homogenous lithology (Figure 11) (Heikkinen and Tikkanen, 1989, Krabbendam et al., 2016). The other subgroup comprises mega-grooves that cross-cut lithological and/or structural boundaries, most typically where two different rock types come into contact, for example west of the Franklin Mountains, Northwest Territories, Canada (Figure 1) (Smith, 1948; Krabbendam et al., 2016) and Alberta, Canada (Gravenor and Meneley, 1958). At Elphin, Scotland, the longest groove crosses three consecutive lithologies from east to west, namely Cambrian quartzite, Torridonian sandstone and Lewisian gneiss (Figure 5A) (Bradwell, 2005). Structural cross-cutting occurs lithologically homogenous bedrock at Harefjord, east Greenland, because the dip and strike varies greatly within the grooved area (Funder, 1978) (Figure 9).

Among mega-grooves controlled by bedrock structure, they most commonly occur in layered bedrock strata, where the grooves are parallel to strike and palaeo-ice flow direction (Zumberge, 1955; Heikkinen and Tikkanen, 1989; Livingstone et al., 2008; Krabbendam and Bradwell, 2011; Krabbendam et al., 2016). Their cross profile is typically asymmetric, with the steeper side cutting across strata ends, and the shallower side following the dip surface of the bedding plane (Figure 10C) (Zumberge, 1955; Heikkinen and Tikkanen, 1989; Krabbendam and Bradwell, 2011). These are suggested to have formed primarily as a result of lateral plucking (Zumberge, 1955; Krabbendam and Bradwell, 2011) (see Section 4.1.2). In most cases, this morpho-structural relationship is obvious on remotely-sensed images at sites where the mega-grooves and ridges follow the lineaments of folded or tilted bedrock strata, thus explaining their slightly sinuous aspect (Figure 12) (e.g. Zumberge, 1955; Livingstone et al., 2008; Krabbendam and Bradwell, 2011; Krabbendam et al., 2016). Structural underpinning in mega-groove location can occur in various other forms. For example, in Manitoba, Canada, in an area of folded carbonate strata, some mega-grooves correspond to synclines, whereas the separating ridges are remnants of anticlines (Figure 10D) (Wardlaw et al., 1969). In Assynt, NW Scotland some grooves are reported to occur along fault lines (Figure 5A) (Bradwell, 2005), and the mega-grooves in the Mission Range, Montana, US are thought to have formed along pre-existing joints in the bedrock, which directed the action of glacial erosion (Figure 10E) (Witkind, 1978).

From the mega-groove sites reported in the literature, we note that around 70% are controlled in some way by the bedrock structure (Table 1). Mega-grooves that occur independent of bedrock structure are limited to relatively few clear examples, namely four sites in the Mackenzie river valley, Northwest Territories, Canada (Smith, 1948), Harefjord, East Greenland

(Funder, 1978), Assynt, NW Scotland (Bradwell, 2005) and two sites in Ontario, Canada (Eyles, 2012; Krabbendam et al., 2016). At some localities, the relationship with the bedrock structure is less clearly addressed (Gravenor and Meneley, 1958; Wardlaw, 1969; Heikkinen and Tikkanen, 1989) or not even mentioned. This is likely due to difficult direct access to the bedrock in submerged areas (e.g. continental shelves; Lowe and Anderson, 2003; Wellner et al., 2006; Heroy and Anderson, 2005), beneath contemporaneous glaciers (Jezek et al., 2011) or on Mars (Lucchitta, 1981). Sites of structurally-independent mega-grooves may be more numerous than is currently known and lie undiscovered due to lack of visibility in areas highly modified by human activity, buried beneath glacial sediments (see Section 5.3), or submerged.

4 Mega-groove formation

There is general consensus that mega-grooves are formed beneath ice sheets. This is based on their occurrence in glaciated areas and parallel alignment to ice-flow directions, which can often be inferred from alignment with other subglacial landforms, such as rock drumlins, streamlined ridges (Smith, 1948; Bradwell et al., 2008; Krabbendam et al., 2016; Eyles, 2012), and MSGLs (Lowe and Anderson, 2003). Jezek et al. (2011) found that bedrock mega-grooves beneath the Greenland ice sheet are aligned parallel with the local ice-flow lines, as inferred from measurements at the ice surface (Figure 3D and E). It is significant that most sites are found in areas documented to be well within the reconstructed limits of the most recent, Marine Isotope Stage 2 (MIS2) glaciation (Figure 2), and which have also been repeatedly glaciated during the Quaternary. Exceptions are sites in Argentina (López-Gamundí and Martínez, 2000), Australia (Perry and Roberts, 1968) and the Sahara (Fairbridge, 1974), where mega-grooves lie well outside the limits of the Quaternary glaciations but within glacial limits attributed to ancient, pre-Quaternary glaciations. At these locations they occur alongside other glacial landforms and are interpreted to have formed at the same time (Perry and Roberts, 1968; Fairbridge, 1974; López-Gamundí and Martínez, 2000).

While there is unanimous agreement that bedrock mega-grooves in glaciated terrain are landforms of subglacial erosion, there is disagreement regarding the agent of erosion. The predominant and traditional idea relates the formation of mega-grooves to direct glacial erosion by ice (Chamberlin, 1888; Carney, 1910; Smith, 1948; Zumberge, 1955; Goldthwait, 1979; Wardlaw, 1969; Boulton, 1974; Witkind, 1978; Lucchitta, 1981; Lowe and Anderson, 2003; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Eyles, 2012; Krabbendam et al., 2016), whereas a more recent and entirely different interpretation claims that erosion of bedrock grooves of various sizes was carried out mainly, if not entirely, by subglacial meltwater (Baker and Milton, 1974; Sharpe and Shaw, 1989; Kor et al., 1991; Tinkler and Stenson, 1992; Shaw, 2002; Bradwell, 2005; Munro-Stasiuk et al., 2005; Munro-Stasiuk et al., 2009).

4.1 Glacial erosion

The proponents of a glacial origin for mega-grooves base it on several aspects: i) the morphologic similarity and close association between mega-grooves and smaller grooves, including striations (e.g. Chamberlin, 1888; Carney, 1910; Wardlaw et al., 1969; Boulton, 1974);

ii) the parallelism with the direction of ice flow; and iii) the remarkable straightness that mega-grooves maintain over the landscape (Smith, 1948; Eyles, 2012). Smith (1948, p 510) captured the latter aspect when pointing out "the inability of any other known process to produce grooving of the type described, with discordant relations to structural trends and to topographic and drainage features." Some studies mention glacial erosion without suggesting a particular mechanism for groove formation (Gravenor and Meneley, 1958; Funder, 1978; Heikkinen and Tikkanen, 1989; Wardlaw et al., 1969; Jezek et al., 2011). Others refer to positive feedbacks in erosional processes as ice flowed over topographic highs (Heikkinen and Tikkanen, 1989) or in the onset zones of ice streams, where fast ice flow was initiated over the bedrock and enhanced erosion along flow-parallel lines (Bradwell et al., 2008; Krabbendam and Bradwell, 2011; Eyles, 2012; Krabbendam et al., 2016). A few studies discuss scenarios whereby bedrock properties, in conjunction with the glacial conditions, favoured a particular mechanism of glacial erosion (i.e. abrasion *versus* plucking), thus leading to mega-groove initiation (Chamberlin, 1888; Carney, 1910; Smith, 1948; Zumberge, 1955; Witkind, 1978; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Eyles, 2012). Either way, glacial erosion in bedrock takes place through the two essentially distinct mechanisms of abrasion and plucking.

4.1.1 Glacial abrasion

Abrasion is performed by rock fragments and debris present at the glacier sole, which incise the bedrock and wear it down as they are being dragged along by the ice (Chamberlin, 1888; Carney 1910; Goldthwait, 1969; Sugden and John, 1976; Boulton, 1974; Iverson, 1990; Rea, 1994). Glacial abrasion is advocated by a number of authors as the principal mechanism for mega-groove formation (e.g. Chamberlin, 1888; Smith, 1948; Boulton, 1974; Goldthwait, 1979; Witkind, 1978; Lowe and Anderson, 2003; Roberts et al., 2010; Eyles, 2012). In studies based on empirical evidence, there is often a strong indication that abrasion was controlled by lithology to a large extent (see section 3.2.1), either through a generally higher susceptibility of bedrock to erosion, especially the Palaeozoic carbonate rocks around the Canadian shield (Chamberlin, 1888; Carney, 1910; Smith, 1948; Goldthwait, 1979; Eyles, 2012; Eyles and Putkinen, 2014), or through differential erosion in areas of juxtaposed lithologies of different hardness (Roberts et al., 2010). In Georgian Bay, Ontario, Eyles (2012) argued that the prevailing mechanism for groove formation was enhanced abrasion by fast-flowing ice loaded with basal debris, which underwent flow separation around bioherms (see Section 3.2.1). This mode of ice flow explains the formation of streamlined bedrock ridges separated by straight and U-shaped grooves (Figure 8B). In West Greenland, the grooves and ridges formed as a result of the two different lithologies experiencing different rates of erosion over time (see Section 3.2.1) (Roberts et al., 2010). Goldthwait (1979) inferred abrading glacier ice when he described an erosive agent of enough plasticity to mould itself to the grooves, but possessing enough rigidity to grip and hold in place rock particles while moving over considerably long distances. Witkind (1978) proposed glacial abrasion for the formation of the mega-grooves in Montana, US, based on the abundant presence of striated surfaces with highly polished and rounded bedrock knolls.

In order to explain the development of mega-grooves as a series of long, parallel features independent of structural control, some authors advocated the existence of englacial debris banding (Carney, 1910; Smith, 1948; Gravenor and Meneley, 1958; Bradwell et al., 2008). Banding refers to some internal organisation of debris within glacier ice, capable of concentrating the erosive power along parallel lines. This idea was expounded in Carney (1910, p. 644), whereby the grooves on Kelleys Island, Lake Erie, were envisaged as the product of former "localization of tools and a constant supply of them in the basal area of the ice". Bradwell et al. (2008) expressed the same view when referring to the mega-grooves north of Ullapool, Scotland, although the a subsequent interpretation of lateral plucking as the main mechanism of groove formation rendered banding unnecessary (Krabbendam and Bradwell, 2011). The regular spacing of mega-grooves prompted Gravenor and Meneley (1958), to suggest that grooving in Alberta, Canada occurred due to some internal organisation of ice flow, rather than to any geological controls, (see Section 3.1). Focussed abrasion is proposed by Krabbendam et al., (2015) as the main mechanism of mega-groove formation in a homogenous lithology, based on the likely accumulation of subglacial debris into bedrock troughs, where it enhances the efficiency of glacial erosion and leads to the enlargement of grooves (Figure 13 A)(see Section 5.1.2).

In summary, glacial abrasion has been specifically proposed as the principal mechanism of mega-groove formation in geological settings with uniform lithology, where no structural control is apparent.

4.1.2 Glacial plucking

Plucking involves the dislocation of rock fragments subglacially, triggered by the development of low-pressure cavities in the lee of bedrock protuberances (Carol, 1947; Gordon, 1991; Rea, 1994). The dislocation takes place along lines of structural weakness, such as joints and bedding planes, thus explaining the presence of a steep vertical surface. Not surprisingly, in areas where glacial plucking was proposed as the main mechanism of groove formation there is a strong relationship between mega-grooves and bedrock structure. Zumberge (1955) argued that glacial plucking, rather than abrasion, was the process that enhanced the pre-glacial stepped topography on Isle Royale, Michigan, USA. He pointed out that the specific geological setting, comprising well-bedded lava flows intercalated within beds of conglomerate and flow breccia, which strike parallel to the palaeo ice-flow, in addition to the presence of vertical hexagonal joints, must have been a favourable setting for plucking. Zumberge (1955) pioneered the idea of lateral plucking, a concept further developed by Krabbendam and Bradwell (2011). The difference between lateral plucking and plucking in its traditional sense is in the attitude of the strata, in that a loosened block has to undergo rotation around its vertical axis in order to be dislocated and removed by the ice, rather than just horizontally translated away from the bedrock (Krabbendam and Bradwell, 2011) (Figure 13B). The resulting mega-grooves typically have an asymmetric cross-profile (Figure 10C and 13B) (see section 3.2.2). This mechanism of mega-groove formation has been invoked at several localities, namely Ullapool (Scotland), Ungava Peninsula (Canada) and the Tyne Gap, England (Krabbendam and Bradwell, 2011), the Kaladar area, Canada (Krabbendam et al., 2016), and Isle Royale, Michigan, USA (Zumberge, 1955). With the exception of Ullapool, Scotland, the mega-grooves occur at outcrop scale and they follow the strike of the bedrock strata, making the structural underpinning obvious even on small-scale satellite images (Figure 12). At some sites, the bedrock is of mixed lithology, varying from hard, igneous intrusions to relatively soft sedimentary rocks, like mudstone, which is why a pre-glacial initiation of the current stepped topography was suggested to have formed through differential subaerial erosion (Zumberge, 1955; Krabbendam and Bradwell, 2011) (see Section 5.1.1). The mega-grooves north of Ullapool, Scotland, occur in lithologically-homogeneous and well-jointed metasandstone, and their initiation is attributed to highly effective lateral plucking on the steep, north-facing slopes, where the bedrock has a higher density of joints (Krabbendam and Bradwell, 2011) (see Section 3.2.2). According to Smith (1948), the rocks in the Mackenzie basin, Canada, would have been susceptible to different styles of erosion, enabling one mechanism to prevail over the other. Thus, the brecciated and coralline limestone is suggested to have been prone to plucking, while abrasion was probably more effective on the harder Devonian limestone (Smith, 1948). At one locality Smith (1948, p. 509) notes: “an abrupt change in appearance may be observed in passing from one type of rock to another”.

In summary, glacial abrasion and plucking have been proposed as the main mechanisms of mega-groove formation, taking into account how the bedrock geology could have influenced each mechanism. Abrasion is often linked to the assumed susceptibility of rocks to this type of erosion, although no geotechnical assessment of what classifies rocks into ‘hard’ or ‘soft’ with regards to abrasion has been carried out in the published studies as far as we are aware (see Table 1). Plucking is regarded as more effective on jointed bedrock, to allow for rock dislocation. In all cases where lateral plucking is invoked as the main mechanism of groove formation, the grooves occur in layered bedrock strata and ice flow was parallel to the bedrock strike.

4.2 Meltwater erosion

Several authors have regarded the large-scale bedrock grooves in Ontario, Canada, as the product of erosion by meltwater released catastrophically in high volumes during subglacial mega-floods (Sharpe and Shaw, 1989; Shaw and Gilbert, 1989; Kor et al., 1991; Tinkler and Stenson, 1992; Shaw, 2002; Munro-Stasiuk et al., 2005; Munro-Stasiuk et al., 2009). The grooves occur in the metamorphic rocks along the south-western margin of the Canadian Shield, as well as in Palaeozoic carbonate bedrock, which borders the shield along its southwestern margin. Most of these bedrock grooves are an order of magnitude smaller than mega-grooves (see section 5.2), including those at Kelleys Island, which is why they have not been included in the mega-groove inventory in Table 1. However, we present the discussion regarding a glacifluvial origin for all bedrock grooves that occur in series of straight and parallel individuals because it has implications for the more general problem of bedrock-groove formation (see Section 5.2).

The proponents of groove erosion solely by meltwater base their model on the close association of grooves with abundant linear and non-linear P-forms, like cavettos, potholes, schielwannen, mussel gouges and scour marks transverse to former flow direction (Kor et al., 1991; Tinkler and Stenson, 1992; Munro-Stasiuk et al., 2005). Specifically, the scenario proposed for groove-erosion by subglacial meltwater involves fast-moving water vortexes impinging against the bedrock in roughly straight lines and eroding by plucking, abrasion and cavitation within short time frames. The evidence invoked is the presence of sharp-edged rims of some of the grooves through analogy with those commonly occurring in fluvial environments (Kor et al., 1991; Munro-Stasiuk et al., 2005), where they are interpreted as being directly formed through turbulent meltwater flow (Whipple et al., 2011). In addition, elongate bedrock ridges with a higher up-ice end, flanked by grooves, are interpreted as being formed by meltwater erosion through split flow (Figure 13C). Indeed, most authors regard P-forms as being formed through a combination of glacial and glacifluvial processes, where meltwater may have played a major morphogenetic role, whether in the form of water-saturated till (Gjessing, 1965; Goldthwait, 1979; Kor et al., 1991) or as a pressurised fluid flowing at the glacier – bedrock interface (Dahl, 1965; Gray, 1981; see also Benn and Evans, 2010 for a brief review). Significantly, Boulton (1974) reported observations that suggest a pure glacial origin for schielwannen formed through split flow of debris-rich ice around bedrock high points, where the normal pressure is higher than that on the surrounding surfaces. These results show that meltwater is not a prerequisite for the formation of P-forms.

Bradwell (2005) interprets the mega-grooves in Assynt, NW Scotland, as Nye channels formed through meltwater erosion in bedrock The grooves are in the form of large parallel furrows eroded in quartzite, aligned east-west, parallel to the flow direction of the former ice sheet. Groove formation through erosion by glacier ice is rejected on the basis that it fails to explain the abrupt termination of some of the grooves in mid-slope. Bradwell (2005) envisaged initial bedrock hydrofracture by meltwater jets released under glaciostatic pressure from the underground cavity system in the carbonate bedrock, present to the east of the grooved area, followed by erosion through known fluvial processes. He attributed other, smaller-scale landforms (e.g. scallops, potholes) to meltwater erosion and assigned the striations in the area to subsequent glacial erosion, during deglaciation or phases of advance.

A glacifluvial origin for mega-grooves has sometimes been dismissed on the basis that it cannot explain the straightness of the grooves (Witkind, 1978; Eyles, 2012). At the same time, the potential effectiveness of subglacial fluids under hydrostatic pressure in eroding sinuous channels is acknowledged by some authors (e.g. Chamberlin, 1888; Witkind, 1978).

In summary, a purely meltwater origin for bedrock mega-grooves, as proposed by a number of authors, refers to large-scale bedrock grooves that occur in close association with P-forms in Ontario, Canada; and also to the mega-grooves in Assynt, NW Scotland. Although there is little consensus, both glacial and glacifluvial proponents often recognise a mixed signature of ice and water erosion in mega-groove morphology, but no quantitative contribution of each agent has yet been established.

4.3 Timescales of formation

The chronology of bedrock mega-groove formation is poorly constrained and the few studies that address this aspect (see Table 1) base it on landform morphometry and principles of morphostratigraphy, rather than absolute dating techniques. Establishing the chronology of these landforms is important because it offers a time frame for the study of groove formation, with direct implications for establishing rates of erosion and landscape evolution.

Most authors who suggest that mega-grooves formed during multiple glacial cycles advocate glacial erosion for their formation based on the assumption that a long time is required for it to act upon the bedrock in order to produce grooves of such dimensions (Smith, 1948; Gravenor and Meneley, 1958). In West Greenland, Roberts et al. (2010) present a scenario whereby mega-groove formation could have spanned more than one glaciation. The site is close to the present ice sheet margin and comprises bedrock grooves and ridges with uninterrupted continuity over several kilometres (Figure 3A); this contrasts with the fragmented ridge topography to the east, which clearly records changes in ice-flow direction. Based on this contrast, Roberts et al. (2010) interpreted the grooves and ridges close to the ice margin as being formed through prolonged glacial erosion as the glacier ice advanced repeatedly over the area in the same direction, likely through multiple glaciations.

In Finnish Lapland, mega-grooves occur alongside, and are aligned sub-parallel to, glacifluvial landforms (i.e. eskers and meltwater channels). The presence of numerous suites of glacifluvial landforms was interpreted as evidence for frequent changes in ice-flow direction during the latest stages of deglaciation, which led to the conclusion that the mega-grooves were in existence before then, possibly forming earlier in the last glacial cycle (Heikkinen and Tikkanen, 1989).

None of the studies so far provide an absolute age for mega-grooves, but overall results suggest that mega-grooves were in existence before the last glaciation and that they may be much older, possibly spanning more than one glacial cycle.

5 Discussion

5.1 The influence of geology on bedrock grooving

A clear and useful distinction can be established between geology-controlled *versus* geology-independent mega-grooves (Figure 10). Geological control refers here to the bedrock structure that facilitated the formation of some mega-grooves, often in combination with the lithology (Section 3.2.2). Where mega-grooves occur in connection to the bedrock structure, their location, morphology and formation are relatively straightforward to explain, whereas structurally-independent mega-grooves remain poorly understood.

5.1.1 Mega-grooves controlled by the bedrock structure

Most mega-grooves reported in the literature as being structurally-controlled occur in tilted layered strata and both their location and morphology directly reflect the underlying bedrock structure (see Section 3.3.2). The geological underpinning of mega-groove location can also be reflected in the topographic contrast between grooved areas developed in layered rock strata and the non-grooved topography of adjacent areas of a different geology. Classic examples are the groove-bearing belts of meta-sedimentary rocks in Ungava Peninsula, Canada surrounded by areas of Precambrian shield, with a typical non-streamlined, cnoc-and-lochan topography (Figure 12) (Krabbendam and Bradwell, 2011; Krabbendam et al., 2016). Morphologically, mega-grooves in layered strata have an asymmetric, stepped cross-profile (Figure 10C) (see Section 3.2.2), but the tectonic and geological scenarios in which the rocks were formed and tilted can induce variations in the general topography of the grooved terrain, as well as in groove morphology. For example, tilted strata bearing grooves and ridges can be eroded flanks of large synclines and/or subsiding basins, like the Michigan/Lake Superior basin. There, the stepped, groove-and-ridge topography of Isle Royale (Zumberge, 1955), representing the basin's north-western flank, is matched by similar topography on the opposite side, at Keweenawan Peninsula, on the southern bank of Lake Superior (Halls, 1969). In contrast, at Kaladar, Ontario, the syncline is smaller and the fold tighter. Therefore, the ridges have steeper sides and the lithological symmetry between the two flanks of the syncline is more obvious (Figure 10F) (Krabbendam et al., 2016). Large-scale grooves in layered strata occur on the Isle of Mull, Scotland, where the grooves represent the result of differential erosion between stacked lava flows (Figure 14) of Palaeogene age (Williamson and Bell, 2012). At this location the grooves formed due to mixed lithological and structural causes. In principle, mega-grooves can occur in any form of layered strata, which may have undergone folding, tilting, overturning, faulting, or other tectonic movement throughout their geological history, before groove formation. Less commonly, mega-grooves have been reported to occur along other lines of structural 'weakness', like faults (Bradwell, 2005) and joints (Witkind, 1978; Eyles, 2012). A well-jointed rock is generally more susceptible to glacial plucking, than a more massive, yet mechanically weaker rock. This is because joints are prone to enhanced weathering due to easier access of water, which contributes to reducing the rock's overall resistance to mechanical stresses.

With respect to groove formation, we hypothesise that this is primarily the result of entrainment and transport of pre-existing loosened bedrock, whether in the form of loose debris or Tertiary regolith. A weathering mantle with abundant loose debris would have developed during the Tertiary, and would have been readily available for entraining into, and removal by, glacier ice and meltwater at the onset of early Quaternary glaciations. The mere removal of pre-glacial debris by any denudation agent may have sufficed to uncover a groove-and-ridge topography already present on the underlying bedrock structure, as also suggested by Zumberge (1955) (Figure 10 C-G). Indeed, glacial abrasion may not need to be invoked as a prerequisite for groove initiation. Subsequent processes of subglacial erosion almost certainly enhanced the grooves (see also Section 5.1.2). Of these, lateral plucking is likely to have been the most efficient (see Section 4.1.2), but the role of abrasion could have been more significant than currently thought, because the plucked rock fragments could have further acted as abrasion tools.

In summary, structurally-controlled mega-grooves are likely to be encountered in any geological terrain where glaciers flowed parallel to structural lines, most commonly in tilted, layered rocks. The location of the mega-grooves would have been dictated by the bedrock structure, and their morphology closely controlled by it. The role of glacial erosion was primarily to reveal a pre-existing grooved terrain already partially developed on the backbone of the bedrock geology, rather than to initiate the grooves. The grooves were then subjected to further modification by various erosion mechanisms in subaerial and subglacial environments, most likely through multiple glacial/interglacial cycles.

5.1.2 Mega-grooves independent of the bedrock structure

Structurally-independent mega-grooves are unanimously interpreted as landforms of erosion in bedrock, due to their occurrence below the general land surface, which forms a series of accordant surfaces or intervening ridges (Figure 10) (Smith, 1948; Heikkinen and Tikkanen, 1989; Bradwell, 2005; Eyles, 2012; see also Section 4 and Table 1). The full formation of structurally-independent mega-grooves remains difficult to explain. Various mechanisms have been suggested, with a focus on either glacial or glacifluvial erosion (see Sections 4.1 and 4.2). It is possible that some structural control was inherent in the bedrock layer where the mega-grooves were initiated, which has since then been removed by erosion, while the grooves continued to deepen into the underlying rocks. This would be difficult to prove, but a thorough investigation of the geological history in grooved terrain may at least offer some clues regarding the feasibility of such a scenario.

In the absence of any indication of geological control, we share the view of others (Chamberlin, 1888; Carney, 1910; Smith, 1948; Witkind, 1978; Bradwell et al., 2008; Eyles, 2012) that the main process in the initiation of mega-grooves, was that of abrasion by glacier ice, given their straightness over the landscape and typical U-shaped cross-profile (Figures 6A, 8 A and B, 10 A and B) (see section 4.1.1). It is unlikely that straight and parallel grooves of this size could have been initiated in bedrock by fast-flowing water vortexes as implied by the proponents of catastrophic subglacial mega-floods (Sharpe and Shaw, 1989; Shaw and Gilbert, 1989; Kor et al., 1991; Tinkler and Stenson, 1992; Shaw, 2002; Munro-Stasiuk et al., 2009; see also section 4.2). While water vortexes have the ability to erode channels in bedrock (Whipple et al., 2011), they would have had to advance in straight and parallel lines, over long distances and wide areas, in order to erode parallel grooves. The suggested formation of the mega-grooves in Assynt, NW Scotland, as Nye channels may explain certain features (see section 4.2), but it remains difficult to reconcile with the parallelism of the individual grooves. Although Nye channels can form assemblages covering wide areas, and could have formed as a result of migration of subglacial drainage routes, their overall pattern is typically dendritic or anastomosing (Sharp et al. 1989; Sugden et al. 1991; Booth and Hallet 1993; Ó Cofaigh 1996). We consider that meltwater erosion more likely modified bedrock grooves *after* they were already initiated, either subglacially or subaerially during deglaciation. Ultimately, the older the landforms, the more numerous the agents and processes that are likely to have modified them (e.g. glacial, glacifluvial and fluvial erosion, chemical dissolution, subaerial weathering, paedogenesis and slope processes during interglacials). It is therefore useful to treat mega-groove formation in two stages, firstly *initiation* followed by *modification*, in order to understand the potential action of different morphogenetic agents and processes (see Section 5.2).

A key aspect is that once a bedrock groove is well-enough established (see Section 5.2), it is more likely to become self-perpetuating rather than prone to obliteration through subsequent erosion due to positive feedback mechanisms that reinforce ice flow pathways and enhance erosion during successive glaciations. Small-scale bedrock perturbations have been shown to direct basal flow lines at the ice-bedrock interface, regardless of the regional ice-flow direction (Boulton 1974, 1979; Rea et al. 2000; Roberts et al., 2010). Basal sliding along the groove pathway could be enhanced by increased meltwater production, due to increased availability of heat. On an uneven bedrock surface, geothermal heat flow lines are perpendicular to the surface, assuming the thermal conductivity is uniform and isotropic, as would be the case in homogeneous bedrock. Thus, geothermal heat flow lines converge towards the centre of bedrock depressions, (Nobles and Weertman, 1971; Drewry, 1976), and a higher amount of heat is delivered into the groove relative to the surrounding area (Figure 15). This heat is directly proportional to the depth of the groove, so more heat is produced as the groove grows in size. Enhanced basal sliding, combined with the potential that grooves have for concentrating loose, subglacial rock debris released through basal melting (Boulton, 1974; Roberts et al., 2010; Krabbendam et al., 2015), could enhance abrasion and, therefore, landform development.

Interestingly, no cross-cutting has been reported between mega-grooves, otherwise frequently reported to occur between smaller bedrock grooves (Chamberlin, 1888; Iverson, 1990; Rea, 1994; Rea et al. 2000), which suggests that once a bedrock groove is well enough established, it may be a persistent landform even under ice sheets with shifting flow directions. This idea is strengthened by the presence of striations and other small grooves superimposed on the mega-grooves at an angle (Funder, 1978; Wardlaw et al., 1969; Witkind, 1978), which testify to changing ice-flow directions while mega-grooves were already in existence. Hence, 'average' glacial conditions for mega-groove formation appear to have persisted for much longer than the conditions under which smaller grooves (see Table 2) were formed. Similarly, the long axes of roches moutonées are often a product of prolonged, average basal flow conditions, whereas their striation sets and plucked faces can display early- and late-stage variability in flow direction in response to ice sheet build-up and decay (Roberts and Long 2005; Lane et al., 2014). This fits in with the notion that basal flow direction during 'average' glacial conditions is predominantly the same during each glacial cycle, and points to long-term evolution of mega-grooves.

In summary, structurally-independent mega-grooves were most likely initiated through glacial abrasion and subsequently modified by geomorphic agents in addition to, or other than, glacier ice. Once initiated, a mega-groove is prone to self perpetuation due to feedbacks operating between the bedrock topography and enhanced basal-ice flow lines, which makes it a persistent landform even beneath ice sheets with shifting flow directions.

5.2 A bedrock-groove landform size continuum?

Recent studies have identified a morphology and size continuum of glacial landforms in unconsolidated sediment, confirmed through quantitative analyses (Ely et al., 2016).Fewer studies explore this topic for bedrock grooves (e.g. Chamberlin, 1888; Boulton, 1974). However, the available observations would appear to indicate that discrete grooves with similar morphology, namely U-shaped, straight and elongated grooves, occur at different scales (Chamberlin, 1888; Boulton, 1974; Rea, 1994). Furthermore, Eyles & Putkinen (2014, p 131) recently stated that "morphologically, the bedrock mega-grooves are essentially giant striations". This hints at the possible existence of a bedrock-groove size continuum, which would need to be confirmed before being used as a framework for further exploration of process – form relationships. First, it is important to establish the evidence for the existence of grooves of different sizes, what scale range these sizes span, and the place of mega-grooves in a hierarchy of landforms. As a preliminary exploration, basic morphometric values for bedrock grooves were simply extracted from published studies and are presented in Table 2, together with a general description of related grooves in ~~bedrock.It~~bedrock. It is apparent that studies of bedrock grooves tend to focus on certain size ranges and also that grooves from each size range have specific characteristics. Thus there appear to be four classes of grooves, here referred to with the relevant prefix of micro-/meso-/macro-/mega- (Figure 16 and Table 2).

The smallest features are micro-grooves (or striations), which occur as elongated and shallow troughs in bedrock, in series of parallel individuals (Figure 16A), typically parallel to ice flow. Cross-cutting is common (Figure 16 B), attesting to changes in ice-flow direction and they are generally interpreted in the literature as the product of glacial abrasion (e.g. Chamberlin, 1888; Iverson, 1990; Rea, 1994). The grooves of intermediate sizes typically occur in association with P-forms, and a closer analysis of this association reveals that the meso-grooves occur *among* P-forms of similar magnitude (Figure 16C-D) (Dahl, 1965; Gjessing, 1965; Gray, 1981), whereas macro-grooves have P-forms present *inside* them (Figure 16E). Various scenarios have been proposed to explain the formation of meso- and macro-grooves, ranging from fluvial (Dahl, 1965; Sharpe and Shaw, 1989; Kor et al., 1991) to glacial (Boulton, 1974), and sometimes a combination of the two (Gjessing, 1965; Gray, 1981). Most authors recognise a strong fluvial signal in their formation, based on their slightly sinuous shape in planform, as well as associations with other P-forms The latter are thought to have required turbulent flow, which cannot be attained by ice alone. Mega-grooves, in contrast, have mostly been associated with glacial abrasion (see section 4.1.1). A similar classification can be inferred from that presented by Sugden and John (1976), where streamlined depressions in bedrock are shown to range from striations to grooves, with P-forms present in the mid-range (Figure 17).

[*Insert table 2*]

Table 2 is a useful framework to further explore the potential for a bedrock-groove size continuum. It clearly shows that bedrock grooves from glaciated terrain range from the finest and shortest striations to kilometres-long mega-grooves, and that grooves at all scales occur in series of parallel individuals. Further work is now required to test whether the size and shape grade gradually from one type to another and whether length: width ratios exhibit consistency (cf. Ely et al, 2016). If features show a single population of grooves of different shapes and size, which merge together smoothly, this would hint at an overarching formative mechanism, as has recently been reported for ribbed moraines, drumlins and MSGLs (Ely et al., 2016). Alternatively, it may be that there are clear breaks between these different types, which would indicate separate classes and potentially different scenarios of formation. Either way, it is unlikely that mega-grooves have "grown" from millimetre-deep striations, because striations are not deep enough to 'trap' debris and focus erosion. It is equally unlikely, if not impossible under known subglacial conditions, that mega-grooves could have achieved their current size as a result of bedrock abrasion caused by one large boulder in traction. Most likely, mega-grooves were initiated as small bedrock grooves large enough to sustain their self-perpetuation. In other words, there may be a bedrock - groove size continuum where one end-member is a mega-groove and the other is a groove larger than a striation. The question is then what is the minimum size required of a bedrock groove to trigger the positive feedback mechanisms which lead to self-perpetuation (see Section 5.1.2), and is there a critical depth/width/length of a bedrock groove that enables or limits further landform growth? These questions could be approached through modelling experiments of subglacial bedrock erosion at a small scale.

Another fundamental question for understanding the origin of mega-grooves is: how did the initial grooves form? Could a single large boulder in basal traction erode the bedrock efficiently enough as to initiate a mega-groove? So far, most estimates of subglacial bedrock abrasion assume abrading clasts much smaller than boulders (Boulton, 1974; Drewry, 1976 and Iverson et al., 2003). A mathematical assessment of bedrock abrasion by large boulders could be used in the first instance to generate a range of scenarios for the initiation of mega-grooves. Such scenarios would imply a ubiquitous presence of large boulders across the landscape at the time of mega-groove initiation, in order to explain typical landform occurrence in series of individuals. The Tertiary weathering mantle could provide an explanation for the availability of boulders. Significantly, on sandstone bedrock areas unaffected by Quaternary glaciations and subjected to millions of years of weathering in a warm climate, large corestone boulders are widely present in the landscape (see Ollier 1984, 1991; Taylor and Eggleton, 2001 for reviews). Ultimately, a reappraisal of the pre-Quaternary geological history combined with fieldwork at key locations (see also Section 5.4) could help to assess the potential role of the Tertiary regolith in mega-groove formation. Any mathematical analysis of groove initiation needs to account for specific lithological characteristics responsible for the susceptibility of rocks to abrasion, as well as the relative hardness between the bedrock and the abrading clasts. Laboratory experiments show that high-porosity rocks are more prone to grooving, as whole grains become dislocated due to intergranular cement failure (Lee and Rutter, 2004). Smith's (1948) observation that the deepest mega-grooves occur in highly porous limestone and the most shallow in well-consolidated limestone (see Section 3.2.1) could form the starting point for a quantitative exploration of mega-groove initiation through glacial abrasion.

It is intuitive to envisage how, once initiated, a mega-groove is further eroded by different mechanisms and agents (see section 5.1.2). If mechanisms other than glacial abrasion and plucking are responsible for modifying a groove into a mega-groove, then what are the boundary conditions required by a particular mechanism of erosion to act, and what are the thresholds beyond which others take over? It is apparent from the data presented in Table 2 that the geomorphic signature of glacifluvial erosion seems more obvious in grooves in the middle size ranges, (i.e. meso- and macro-grooves), whereas the end members of the range (i.e. striations and mega-grooves) are regarded by most authors as bearing predominantly the signature of erosion by glacial ice (*cf* Sugden and John, 1976). If mega-grooves do lie in a bedrock groove size continuum, then it may be possible to understand their evolution by analysing smaller grooves at different stages, prior to becoming mega-grooves.

In summary, the occurrence of bedrock grooves with seemingly similar shape, spanning a vast range of scales from micro- to mega-grooves, hints at the existence of a landform size continuum, but further morphometric analyses are needed to test this. The ubiquitous presence of large boulders across the landscape prior to glaciation could explain mega-groove initiation through abrasion, and Tertiary weathering mantles are one option for the supply of such tools. The initial grooves were likely further modified by various agents, both glacial and non-glacial to gain their current dimensions. If confirmed, the bedrock-groove landform size continuum would offer a useful framework for exploring process – form relationships, which could help understand groove evolution within a size spectrum.

5.3 Glaciological conditions

There are a number of cases where mega-grooves have been mapped as part of larger suites of landforms indicative of ice streaming, based on their spatial association with characteristic features, such as MSGLs and rock drumlins (Lowe and Anderson, 2003; Eyles, 2012; Bradwell and Stoker, 2015). It has been argued that many marine-terminating palaeo-ice stream landsystems comprise large areas of streamlined features, including bedrock mega-grooves. Typically bedrock mega-grooves merge down-stream into long trains of MSGLs that extend to the edge of the continental shelf, where they typically terminate at a large fan of stratified deposits (e.g. Bradwell and Stoker, 2015; Stokes, 2018). General observations regarding the position of mega-grooves in such landsystems, as well as their association with other streamlined bedrock forms that exhibit a convergent pattern, have led to the interpretation that mega-grooves occur in the onset zones of ice streams (Lowe and Anderson, 2003; Wellner et al., 2006; Bradwell et al., 2008; Eyles, 2012; Bradwell and Stoker, 2015; Krabbendam et al., 2016), and are the result of enhanced and focused erosion at those locations (Bradwell et al., 2008; Krabbendam and Bradwell, 2011; Eyles, 2012; Krabbendam et al., 2016). However, the association between mega-grooves and ice streaming is not obvious at all sites. Mega-grooves at several locations were not initially linked to any particular glaciological conditions or ice-stream landsystem (Smith, 1948; Gravenor and Meneley, 1958; Wardlaw et al., 1969; Funder, 1978; Witkind, 1978; Heikkinen and Tikkanen, 1989). This might be because these studies pre-date the full-recognition of ice streams in the palaeo-record (Stokes and Clark, 2001) which have since then been mapped in much greater detail (e.g. Northwest Territories, Canada – Smith, 1948, Margold et al., 2015a, b). Therefore, there is now scope for a re-appraisal of the glaciological conditions at these sites. However, other mega-groove sites are still not associated with any glacial landsystems (Funder, 1978; Witkind, 1978; Heikkinen and Tikkanen, 1989) or have been shown to occur in ice sheet areas of 'normal' flow conditions (Roberts et al., 2010), so it is difficult to identify any links between groove formation and specific ice-flow velocity at these locations. The mega-grooves in Assynt, NW Scotland, have a divergent pattern in the direction of the palaeo-ice flow (Figure 5B), contrary to the typically convergent associated with ice-streaming onset (Stokes and Clark, 1999). This points to the initiation of mega-grooves being unrelated to ice stream onset even though they are located in an area of fast-flow onset (Stoker and Bradwell, 2005). The study of Roberts et al. (2010) in West Greenland shows that it is primarily the differential erosion of contrasting lithologies through prolonged glaciation, rather than fast ice flow, which initiated and maintained the grooved terrain (see section 4.3 and 5.1.2). Thus, overall, the literature points to no specific glaciological conditions (e.g. ice flow velocity, thickness) as a requirement for mega-groove formation. As yet, bedrock mega-grooves cannot be unequivocally associated with fast-ice flow, unlike MSGLs which are now generally regarded as being formed under fast ice-flow conditions (Stokes and Clark, 2002; King et al., 2009).

A further complication with respect to bedrock mega-grooves and ice streams is the existence of mega-lineated areas within palaeo ice-stream landsystems, covered by a discontinuous cover of till, where there is some disagreement regarding the type of substrate in which the grooving occurs. Thus, some areas in Alberta, Canada, have been interpreted as bedrock mega-grooves (Krabbendam et al., 2016), while the Canadian Geological Survey mapped the same lineations as till flutings, or MSGLs, because the till is thicker than 5 m (Paulen and Plouffe, 2009; Fenton et al., 2013; Canadian Geoscience Map 195, 2014). Sometimes the transition in substrate from bedrock to unconsolidated sediment can be difficult to establish. Empirical evidence for flutings composed of mixed bedrock and till (Gravenor and Meneley, 1958; Atkinson et al., 2014) show that bedrock can be present at, or close to, the surface within MSGLs. Indeed, it is possible that MSGLs overlie fluted bedrock, especially where the till cover is relatively thin, which implies that the underlying bedrock is grooved. This could mean that areas of grooved bedrock are much more extensive than currently documented. Another possibility is that the stoss end of MSGLs could contain bedrock bumps similar to crag-and-tails, with ’tails‘ buried under till. On the one hand, the bedrock – till interplay in fluted terrain makes it challenging to establish the actual spatial extent of the grooved bedrock. On the other hand, such complex terrains likely contain information related to landforms that could help decode a potentially diachronous geomorphic signature of palaeo-ice stream activity.

5.4 Further research

Future research into the origin of bedrock mega-grooves could fruitfully address several key aspects of their formation.

First, a rigorous reappraisal of geological detail would be instrumental in the search for any geological controls on mega-groove initiation. This would involve an assessment of structural geology and lithological characteristics in detail, as well as an attempt to reconstruct the characteristics of the Tertiary regolith mantle. The latter could help infer lithological characteristics that were present at the time of mega-groove initiation and potentially relevant to glacial abrasion.

Second, detailed geomorphic mapping of mega-grooves followed by morphometric analyses are necessary to enable quantitative approaches to process – form relationships. Quantifying landform distribution and dimensions has led to some important progress in our understanding of other subglacial bedforms (Clark et al., 2009; Ely et al., 2016), and this type of analysis could be extended across all bedrock-groove size ranges (Table 2) in order to establish whether a morphology and size continuum exists.

Third, empirical data from key locations is needed to assess groove evolution and efficiency of various erosion mechanisms. Particularly promising are localities where mega-grooves cut through structural and lithological boundaries, and where the groove profile is reported to change as a result (e.g. Smith, 1948; Bradwell, 2005). Comparative observations at these sites and Schmidt hammer tests could give an indication of how different rock types lend themselves to erosion and which erosion mechanism is likely to be most efficient. Other key points are the termini of mega-grooves, which could offer clues as to whether and how bedrock grooves increase in length. At locations where mega-grooves merge into MSGLs, field survey using ground-penetration radar could help gain an understanding of how such transitions occur and help establish the role of mega-grooves in the context of ice streaming.

Fourth, numerical modelling could be used to test scenarios of groove formation and help gain insight into boundary conditions for rates of erosion. Cosmogenic nuclide dating could help constrain differential erosion between the groove base and the adjacent ridge (Briner and Swanson, 1998; Young et al., 2016). Not least, the increasing amount of data retrieved from modern subglacial environments is likely to help refine our understanding of processes at the ice – bedrock interface and thus support research into the origin of mega-grooves.

6 Conclusions

Bedrock mega-grooves are series of predominantly straight, long and parallel troughs in bedrock that occur in terrain formerly or currently occupied by ice sheets. In this paper, we review the literature pertaining to these landforms in order to assess our current understanding, identify aspects which require further investigation, and propose a general framework for further research. Historically, mega-groove research spans less than a century, in which the focus has widened from understanding groove formation based on empirical observations, to landform interpretation in a wider, regional context of palaeo-ice flow and, potentially, ice streaming. Generally, mega-grooves measure >1,000 m in length, have length:width ratios between 20:1 and 50:1, and length:depth ratios >100:1. They typically occur in lowlands, towards the periphery of the most recent mid-latitude ice sheets, both on- and off-shore, but have also been reported beneath modern ice sheets (Jezek et al., 2011).

There is a clear distinction between mega-grooves controlled by the bedrock structure and those independent of it. Structurally-controlled mega-grooves represent around 70% of all reported sites and occur in areas where palaeo-ice flow was parallel to lines of structural geology. The most common examples are those in layered tilted rocks, where the grooves are parallel to strike, and where their location, formation and morphology are directly explained by the underpinning bedrock structure. Mega-grooves independent of bedrock structure are unrelated to the orientation of bedrock dip and strike, often cut through geological boundaries, and their location and formation remain as yet unexplained. At present there is no consensus with regards to the formation of structurally-independent mega-grooves, but most site-specific case studies strongly suggest that they are subglacial landforms initiated through glacial erosion. Other factors have been identified that may have been important at different stages in mega-groove formation, namely the pre-glacial relief, the presence of Tertiary regolith, the presence of meltwater at the glacier – bedrock interface, ice-flow conditions, ice – bedrock feedback mechanisms, subaerial processes, and time. The age of mega-grooves is poorly constrained, but they have likely survived through multiple cycles of glaciation. At several locations, mega-grooves have been mapped and interpreted as onset zones of fast ice-flow in palaeo-ice stream landsystems, and their formation attributed to presumed high rates of basal ice velocity and erosion. However, the exact relationship between ice stream flow and bedrock erosion is currently insufficiently understood for firm conclusions to be drawn regarding ice streaming and mega-groove formation.

Bedrock grooves with similar morphology, ranging in length from millimetres to kilometres have been identified from published studies, where they tend to be treated in the context of their specific size range and of which four classes emerge in the literature. It is possible that mega-grooves belong to a landform size continuum, and this would offer a context for process – form relationships and feedbacks to be explored and help understand groove evolution from small to large. It is suggested that the next steps in mega-groove research focus on:

i) detailed mapping of key physical features to enable morphometric analyses. These are necessary to derive a quantitative definition for mega-grooves, to test the existence of a bedrock groove size continuum and to constrain numerical modelling experiments;

ii) scrutiny of the current bedrock geology at a small scale, as well as an attempt to reconstruct the Tertiary regolith, in order to investigate any geological controls on groove formation;

iii) field survey through geomorphological mapping, sediment analyses and geophysical techniques at key locations, to assess the likelihood of different erosional processes in mega-groove formation and to explore the link between ice-flow velocity and mega-grooves;

iv) numerical modelling to test scenarios of groove initiation and help gain insight into boundary conditions for rates of erosion, alongside the application of absolute dating techniques.

Collectively, the data gathered from these lines of investigation should help address current uncertainties regarding mega-groove formation and advance overall understanding of these landforms and their glaciological significance.

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Table 1 Mega-groove characteristics related to basic morphometry, geology and glaciology from sites across the world, extracted from published studies. N/M = not mentioned; LIS = the Laurentide ice sheet; words in bold represent a summary of the text in the cell; the metrics for length, width and relief are average values with maximum values in brackets.

Site & References	Length (m)	Width (m)	Relief (m)	Mega-grooves in relation to			Evidence of glaciation	Hypotheses of formation
				Terrain	Bedrock lithology	Bedrock structure		
Northwest Territories (NT), Canada Smith (1948)	30-1,500 (12,000)	< 50	< 30	Ten sites (A-J) across the broad and irregular 130 km^2 lowland bordered by mountains, between the Great Bear Lake and the Mackenzie River; boggy terrain. Grooves: clusters of parallel individuals on tops and stoss sides of slopes; mostly straight, diverge a few degrees (J); broad curvature (C). Ridges: continuous; minor variations in size and shape at crest level; fragmented (B); “en echelon offsets” (G); drumlinised (D). **10 sites in Arctic lowland**	Silurian - Lower Tertiary sedimentary basin. Mega-grooves reach maximum depth in a brecciated limestone, porous to cavernous (lower-Devonian Bear Rock formation) and in Devonian reef limestone; Poorly developed grooves in the harder Devonian and massive Silurian limestone. **Limestone**	Grooves oblique or perpendicular to bedrock strike; parallel to strike (E, F). The cross profile is mostly U-shaped. **Discordant**	Grooved areas close to the margin of Laurentide Ice Sheet (LIS) at its maximum extent; patchy glacial deposits containing erratics; grooves aligned with regional ice flow direction; The Pleistocene glaciation changed the regional drainage pattern; current Mackenzie valley interpreted as a Lateglacial marginal meltwater channel. **Margin of LIS**	Differential glacial erosion controlled by lithology. An estimated 40-80% of the rock layer was removed through erosion from well-developed grooves; model of groove evolution with adjacent grooves merging over time. **Glacial erosion**
Harefjord, East Greenland Funder (1978)	50-2,000	45	1–5	About 50 parallel ridges and grooves on the gently undulating lowland at 50-250 m a.s.l., along the north shore of Harefjord, inner Scoresby Sund; fluted area ca 6 km^2. The crest of ridges conforms to general topography. Two till ridges, up to 1.5 m high present. **Arctic lowland**	Grooved area confined to an insular outcrop of Røde Ø Conglomerate surrounded by pre-Cambrian metamorphic rocks. Coarse sandstone and conglomerate with gneiss phenoclasts, possibly deposited during a period of faulting activity in the Lower Permian. **Røde Ø Conglomerate**	Grooves cut across beds of sandstone and conglomerate with varying orientations; possibly depositional cones. The ridges have a rounded top and the grooves a U-shaped profile. **Discordant**	Parallel to the Quaternary ice-flow direction. Striations parallel to ridges, also at 20°angle; no cross-striations Thin and patchy till veneer; numerous erratic boulders. Bedrock forms obscured by glacifluvial deposits in the west and north. **Multiple glaciations**	Some lithological control is suggested based on the close association between the flutings and the Røde Ø Conglomerate; possible secondary flow of ice and/or meltwater at glacier sole suggested to account for spacing regularity. **N/M**
West Greenland Roberts et al. (2010)	5,000	200	30-50	Ca 100 km northeast of Sisimiut, close to the ice sheet margin. Closely-spaced and elongated bedrock ridges separated by grooves and	Precambrian Archean gneissic rocks, heavily foliated and intruded by swarms of ultramafic dykes trending ENE-WSW. The	The grooves and ridges follow the grain of the land.	Quaternary ice sheets advanced repeatedly over the area; general flow to the west.	Selective and prolonged abrasion throughout multiple cycles of erosion rather than fast flowing ice.

				elongated depressions aligned ENE-WSW. **Arctic lowland**	mega-grooves eroded in gneiss; harder dykes form the ridges. **Gneiss and dykes**	**Concordant**	**Multiple glaciations**	**Glacial abrasion**
North-east Alberta, Canada Gravenor & Meneley (1958)	Several 1,000s	N/M	3 - 8	Pure bedrock landforms only north-east of Andrew Lake, other sites contain fluted till. Consistent spacing regularity at 90-120 m and 180-215 m. Flutings occur in various topographic settings. **Spacing regularity**	Precambrian shield rocks in Andrew Lake area. Hard rocks (pegmatite dykes) eroded to the same depth as adjacent softer metasediments across grooved areas. **Canadian shield rocks**	Perpendicular to strike. Groove spacing independent of bedrock characteristics and topographic control. **Discordant**	General flow of regional ice, from the Keewatin ice centre; striae parallel to the grooves. The ridges at Andrew Lake are grade into drumlins, and are similar in size, shape and spacing to till ridges. **Continental glaciation**	Intrinsic properties of ice lead to alternating low & high pressure parallel bands at the glacier sole. Groove formed in the high-pressure areas through erosion. Water-logged sediments deposited on top of ridges; assumes pre-existing glacial deposits. **Focused glacial abrasion**
Isle Royale, Michigan, US Zumberge (1955)	2,000-20,000 (65,000)	N/M	N/M	North-east of Lake Superior. Parallel ridges and valleys aligned northeast-southwest. The valley floors are occupied by over 50 lakes at 30-60 m above local base level of Lake Superior. **Lowland**	Lower sequence formed of lava flows intercalated within beds of conglomerate and flow breccia, and upper sequence formed of conglomerate and sandstone. **Intercalated lavas and sedimentary layers**	North flank of the Lake Superior syncline; dips 10-30° to the south-east. Some lava flows are massive, others thin and hexagonally jointed; grooves follow bedrock strike; cross profile asymmetric: shallower slopes along the dipping plane. **Concordant**	The present stepped topography is formed subaerially through fluvial denudation during the Tertiary when Isle Royale was part of the wider Superior Basin drainage system. Assumed multiple glaciations with ice flowing parallel to bedrock strike. **Multiple glaciations**	Quaternary glaciers enhanced Tertiary topography through plucking rather than abrasion, aided by the geological structure with well jointed rocks. Lateral plucking also suggested by Krabbendam & Bradwell (2011). **Lateral plucking**
Assynt, NW Scotland, UK Bradwell (2005)	500-1,500 (4,300)	20-30	5-20 (27)	Well defined grooves west of Elphin village; linear, aligned east-west, slightly divergent pattern in planform; discontinuous and less well-defined grooves in adjacent areas. Lowland at ca 300 m a.s.l. surrounded by fragmented highlands. **Lowland**	Cambrian quartzite dipping 7-20° to the east; mega-grooves can be traced across the landscape to the west, in Torridonian sandstone. The longest groove crosses 3 lithologies. Cavernous limestone bedrock to the east. **Quartzite**	Cut across strike; generally unrelated to faults and joints; two grooves follow local fault lines. Long profile: deepen upslope; five end abruptly mid-slope, against steep cliffs; gorge-like aspect. Cross profile: asymmetric; steeper northern slope with signs of plucking; inferred U-shape. **Discordant**	Small-scale erosional features: depressions and undulation surfaces, transverse scours; striae and chatter marks; plucked surfaces; longitudinal channels. Last ice sheet moved from east to west. **Multiple glaciations**	Erosion by subglacial meltwater. Pressurised subglacial jets emerged at the down-glacier end of limestone bedrock and hydrofractured the impermeable but jointed quartzite bedrock. The grooves underwent subsequent fluvial and glacial erosion. **Meltwater erosion**

Ullapool, Scotland Bradwell et al. (2008); Krabbendam & Bradwell, (2011)	500-3,000 (3,500)	50-120 (200)	10-20	Large breach in local watershed; low ground at 300 m a.s.l. flanked by mountains. Area ca 600 km$^{2.}$. Numerous grooves, closely spaced (100-500 m) and rectilinear; overall convergent pattern; cross all slopes; maximum density on the steeper, north-facing slopes. **Lowland**	Neoproterozoic rocks: coarse and relatively massive Torridonian sandstone (west); Morar metasandstone (east), well bedded and jointed, with thin mica beds. Closely-spaced mega-grooves are more common in sandstone. **Metasandstone**	Where bedrock strike parallels ice flow, grooves have an asymmetric cross profile: steep side cuts across strata ends and shallow side follow bedding plane. Others have a parabolic or a V-shaped profile. **Parallel to strike**	Westwards general ice-flow direction with abundant off-shore evidence for former ice streaming. Grooved area interpreted as onset zone for fast ice flow. Thin and patchy glacial deposits. **Ice streaming**	Focused glacial erosion during the last glaciation in ice-stream onset zone (Bradwell et al, 2008). Krabbendam & Bradwell (2011) propose lateral plucking, whereby the low-pressure cavity forms in the *vertical* lee-side of the rock, so that the loosened block undergoes a rotation around its own vertical axis before complete dislocation. **Lateral plucking**
Ungava Peninsula, Canada Krabbendam & Bradwell, (2011)	10,000-40,000	N/M	N/M	Ca 5,000 km^{2} of elongated bedrock ridges separated by grooves; closed basins containing lakes. The area was surveyed through remote sensing. **Arctic lowland**	(Meta)sedimentary strata, forming the Cape Smith Belt, include: sandstone, carbonates, conglomerate, pelite and semipelite, with igneous intrusions. The strata strike WSW-ENE dip 10-40°north. **(meta)sedimentary and igneous intrusions**	Grooves and ridges follow the strike swings. grooves spacing is 300-700 m dictated by strata thickness. Classic cnoc-and-lochan topography is obvious either side of the Cape Smith Belt, on shield rocks. **Concordant**	Repeated Quaternary glaciations, recorded multiple shifts in the ice flow direction; at some stages the flow paralleled grooves. **Multiple glaciations**	Initiation of ridge-and-groove topography possibly due to pre-glacial differential erosion was further enhanced through lateral plucking (see row above for Ullapool, Scotland). **Lateral plucking**
Kaladar, E Ontario, Canada Krabbendam et al. (2015)	10,000s	300 – 2,000	10-30	Mega-groove field of 100 km^{2} **Lowland clode to sea level**	Strongly layered succession of metasedimentary rocks. Well developed in softer and more fractured lithologies. Adjacent tonalite and granite areas are not grooved. **Metasedimentary rocks**	Grooves follow lineaments of bedrock strike. Undetermined shape of cross profile; grooves are partly occupied by lakes and post-glacial debris. **Parallel to strike**	Area occupied by the Laurentide ice sheet, and possibly affected by ice streaming. **Ice sheet & ice streaming**	Differential glacial erosion according to lithology; lateral plucking suggested as the dominant mechanism. **Lateral plucking**
Tyne Gap, England, UK Livingstone et al. (2008); Krabbendam & Bradwell,	1,000-4,000	N/M	5-20	Topographic breach in the watershed bounded to the north and south by plateau areas, up to 300 m higher. Alternating grooves and ridges spaced 100-400 m.	Carboniferous limestone and mudstone alternates with coal bed; the Whin Sill dolerite intrusion; well developed joints define cuboid rock blocks.	The grooves and ridges follow the bedrock lineaments and have an asymmetric cross-profile, flanked by steep slopes to the south, and shallow, bench-like slopes to the north.	Ice flowed eastwards during most of the last, Late Devensian glaciation. Patchy till cover in some grooves.	Initiation of ridge-and-groove topography may be due to pre-glacial differential erosion, and further enhanced through lateral plucking.

(2011);				**Watershed lowland**	**Sedimentary**	**Concordant**	**Regional glaciation**	**Lateral plucking**
Lapland, Finland Heikkinen & Tikkanen, (1989)	N/M	5-20 (50)	2-4 (0.5-8)	Area of fairly pronounced relief with relative heights of 100-300 m, south of river Kielajoki. Grooves cut across the fjell summits at 400-600 m a.s.l. and become shallower or disappear over lower ground; extensions of grooves continue in till. **Lowland**	Precambrian bedrock, with various types of gneiss and granite. The grooves are littered with loose blocks removed by postglacial weathering and slope processes. **Gneiss and granite**	Cross profile is U-shaped in structureless bedrock and asymmetric in schistose bedrock where grooves parallel strike; uneven long profile, with bedrock knolls and small ridges. **Concordant where bedrock structure is obvious**	Abundant glacial and glacifluvial deposits (e.g. fluted ridges, Rogen moraines, drumlins and eskers), accounting for shifting direction in ice flow during deglaciation. **Regional glaciation**	Implied glacial erosion for groove formation, especially plucking for the asymmetric grooves. The grooves are inferred to have formed early in the stadial, due to alignment at an angle to that of deglaciation landforms. **Implies glacial erosion**
Manitoulin Island Ontario Canada Eyles (2012)	>1,000	10s	N/M	Area of intense bedrock erosion with sparse glacial deposits. Bedrock forms: drumlins, mega-grooves and ridges. Numerous striae parallel to long axis of grooves; some post glacial modifications of striae by micro-karst. Mega-grooves continue off-shore. **Lowland**	Best developed on dip slope of the Amabel dolostone, a relatively soft lagoon carbonate rock formation of Palaeozoic age, with bioherms; Mega-grooves flank bedrock ridges containing harder core of fossil remnants at their higher, up-glacier end. **Limestone with bioherms**	Stacks of Palaeozoic carbonate rocks dipping south-westwards from the periphery of the Canadian Shield. Grooves incise dip planes and are perpendicular to strike. Cross profile: symmetrical, with smooth floors and side-cliffs; long profile: straight or slightly sinuous; elongated and drumlinised ridges. **Perpendicular to strike & parallel to dip**	Multiple continental glaciations with ice flowing to the south-west, from the domed shield area, gradually stripping off the Palaeozoic strata. Saginaw-Huron Ice stream thought to have eroded these forms during the last (Wisconsin) glaciation. **Ice streaming**	Split flow of sediment-laden basal mini ice-streams around bioherms led to enhanced erosion and groove formation; possible persistence of such landforms through several cycles of glaciation. The author objects to meltwater erosion as the main mechanism of groove formation. **Glacial abrasion**
Key Harbour Georgian Bay, Ontario Canada Krabbendam et al. (2015)	10-100s	N/M	1-3	Coastal lowland. Well-developed streamlined bedforms; abundant P-forms and straitions; minor post-glacial modification. **Coastal lowland**	Relatively homogeneous granulite gneiss of the Canadian shield. **Granulite gneiss**	Fairly structureless with some layering recognisable. U-shaped cross profile. Rounded intervening ridges, many drumlinised. **Irrespective of structure**	Integral parth of the Huron-Saginaw palaeo ice-stream lansystem which affected wider area. **Ice streaming**	Focussed subglacial abrasion along parallel ice flow-lines. Shorter, sinuous channels and other P-forms attributed to meltwater erosion. **Glacial abrasion**
Interlake, Manitoba – Canada Wardlaw et al. (1969)	1,000-2,000	1-152 (up to a few kms)	12-30	Bedrock partly mantled by till, but the ridge-and-groove topography mirrors bedrock topography. The grooves continue along the lakes' floor.	Silurian and Devonian carbonate rocks: limestone, dolomite and red shale; granitic "islands" north of Lake St. Martin also grooved. Abundant and well	In folded strata, the grooves correspond to synclines and the ridges to anticlines. No preferred joint orientation has been found in relation to the grooves.	Grooves aligned north-south parallel to former ice flow direction. Striations parallel to grooves; mega-grooves are cross-cut by smaller grooves. Larger grooves	Glacial origin based on relationship with striae. Authors discuss and reject a number of previously proposed hypotheses of formation. It is suggested that the basins of lakes Winnipeg,

				Lowland	preserved striations indicate little post-glacial chemical weathering. **Carbonate rocks**	**Concordant to folds**	contain smaller grooves and strations. **Regional glaciations**	Winnipegosis and Manitoba are more mature grooves. **Glacial origin**
Montana, US Witkind (1978)	500-3,000	50-275	10-60	Mega-grooves can be straight or broadly curved, beginning and ending at valley-floor level; some merge lengthwise. Marked contrast between grooved topography in the northern half of the Mission Range and the dendritic pattern, typical of fluvial incision in the southern half. **Local highland**	Slightly metamorphosed fine-grained rocks (argillite, saltire, dolomite and quartzite) belonging to Precambrian Y Belt Supergroup; locally interrupted by thin dykes and diorite sills. Mission Range is a fault block tilted eastwards. **Metamorphic**	Width varies among grooves, but remains constant within the same groove; inferred U-shaped cross profile; variable depth. Rock beds dip eastwards and faults disturb rocks in places. Grooves follow neither strike nor dip, but reflect some joint control. **Pre-glacial joint control**	Direction of ice flow is uncertain and complex: the Cordilleran glacier likely flowed southwards (straight grooves), the continental glacier flowing northwards and deflected westwards around the spur (curved grooves) **LIS and Cordilleran ice**	Focussed glacial abrasion. Erosion by meltwater under hydrostatic pressure is dismissed, as it fails to explain straightness. Multiple cycles of glacial erosion suggested and groove evolution from an initial stage. **Glacial abrasion**
Pine Island Bay, West Antarctica Lowe & Anderson, (2003)	1,000 - 5,500	<50-300	20-50	Submerged West Antarctic continental shelf. In places same-magnitude singular bedrock channels cross-cut mega-grooves. Mega-grooves on top of bedrock highs. Size and spacing decreases downstream. **Antarctic continental shelf**	Crystalline bedrock overlain by a 30-450 cm clay deposit with dropstones. **Crystalline**	N/M	Onset zone of former ice streaming. Also present: bedrock drumlins and large P-forms, plus a variety of bedrock channels; **Ice streaming**	It is proposed that glacial abrasion formed the mega-grooves where ice was in contact with bedrock, while subglacial meltwater shaped other landform, indicative of flow separation. **Glacial abrasion**

Size range	**Length (m)**	**Width (m)**	**Depth (m)**	**Typical occurrence**	**Hypotheses of formation & references**
Micro-grooves (striae) (Figure16 A&B)	0.01 – 1; Up to 2-3	< 0.01	< 0.01	Series of straight and parallel individuals on stoss side of other glacial bedforms, and also on flat bedrock.	**Glacial abrasion** :(laboratory and field simulation): Boulton, 1974; Sugden and John, 1976; Iverson, 1990 & 1991; Rea, 1994.
Meso-grooves (medium-scale grooves) (Figure16 C&D)	1-10/20	0.01 - 1	0.01-1	Within fields of P-forms, occasionally straight, but more often sinuous; sometimes occur in series of parallel individuals;	**Glacial abrasion:** Boulton, 1974; Sugden and John, 1976. **Abrasion by soaked till:** Gjessing, 1965; Gray, 1981. **Meltwater erosion:** Dahl, 1965; Sharpe & Shaw, 1989.
Macro-grooves (furrows) (Figure16E)	10 - 100s	ca 10	<10	Straight in planform, but sinuous in detail. Smaller grooves and P-forms abundantly present inside macro-grooves.	**Glacial abrasion:** Chamberlin , 1888, Carney, 2010, Ver Steeg & Yunck, 1935, Goldthwait, 1979. **Meltwater erosion:** Kor et al., 1991; Tinkler and Stenson, 1992; Tinkler, 1993; Munro-Stasiuk et al., 2005.
Mega-grooves (giant grooves) (Figure16F)	100s - over 1000	20-50	> 10	Series of straight and parallel individuals and not in conjunction with P-forms, but often cross-cut by striae;	**Glacial erosion:** Smith, 1948; Gravenor & Meneley, 1958; Wardlaw et al., 1969; Witkind, 1978; Lowe and Anderson, 2003; Bradwell, et al., 2008; Roberts et al., 2010; Krabbendam and Bradwell, 2011; Eyles, 2012.

Table 2 Classification of bedrock grooves according to size, based on data from published studies.

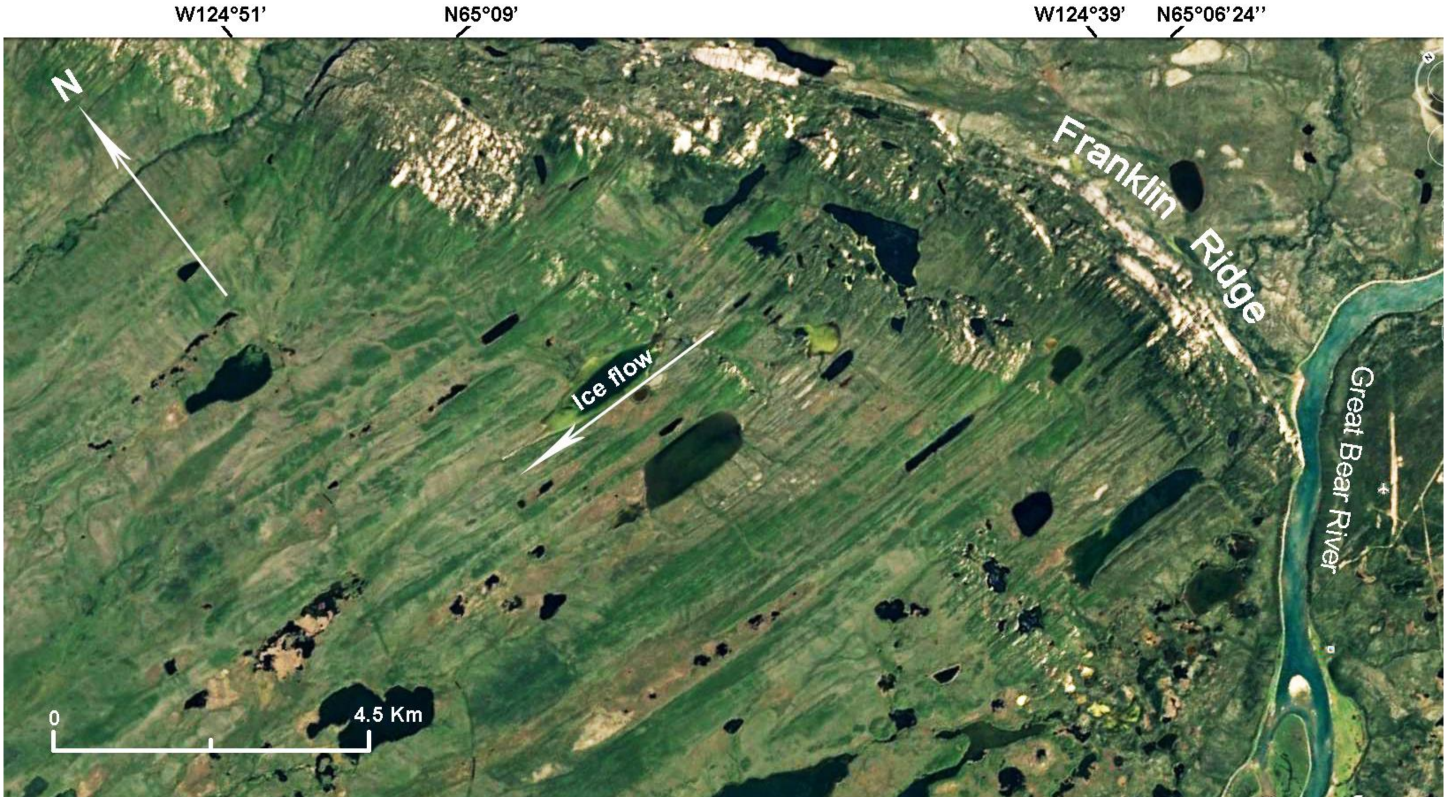

Figure 1 Landsat image of mega-grooves in Palaeozoic carbonate bedrock on the western slope of the Franklin Mountains in NT Canada. The mega-grooves formed on the lee side of the ridge relative to palaeo ice-flow direction and represent one of the ten sites described by Smith (1948). The grooves and ridges are straight in planform; their slightly curved appearance towards the top of the Franklin Ridge is given by the 3D-angle of the image. Source of Landsat image - Google Earth © 2016 Google; Image © 2016 DigitalGlobe; #1 on Figure 2.

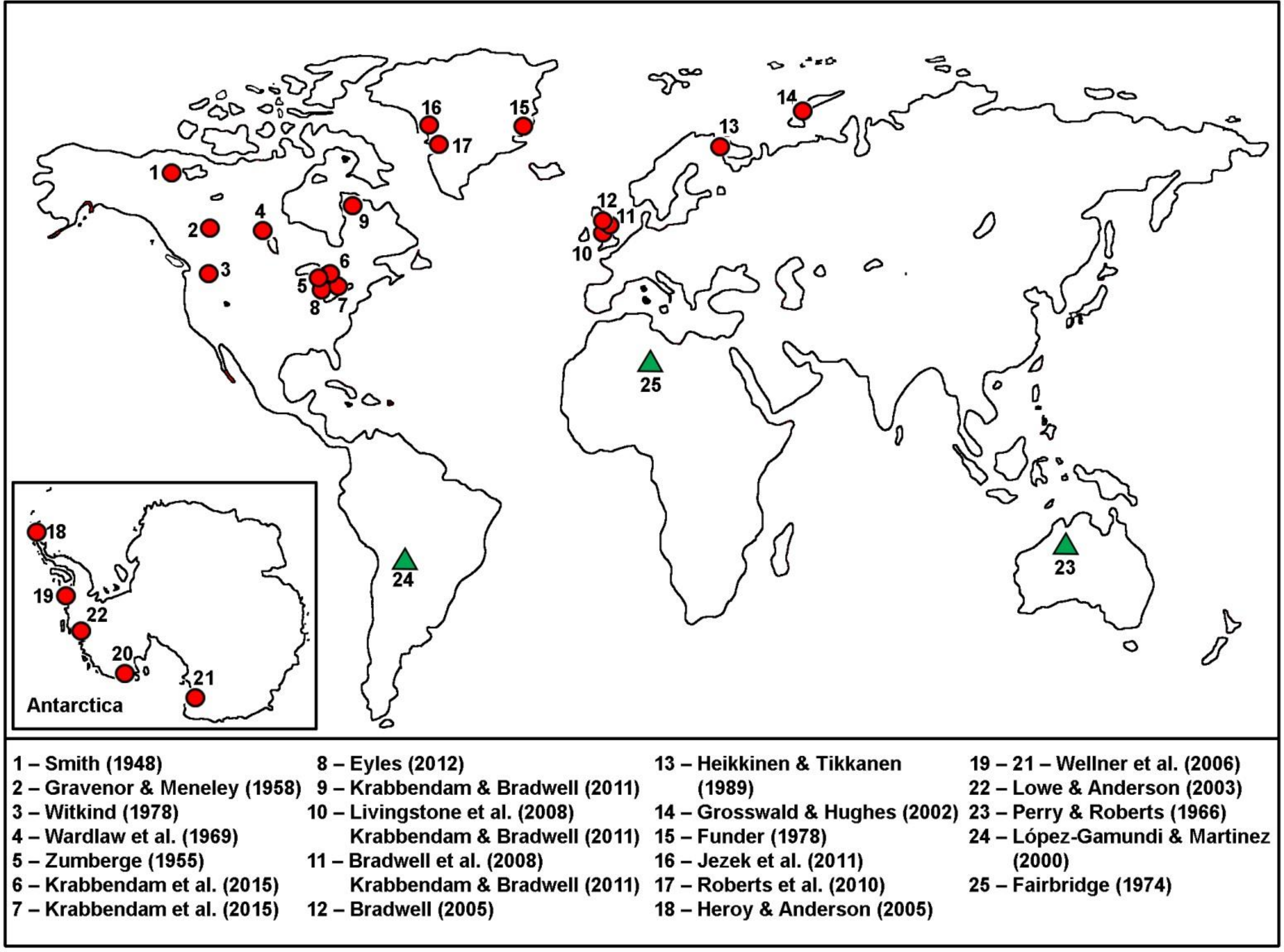

Figure 2 Location of bedrock mega-groove sites described in the literature. Circles represent sites within the maximum extent of glaciers during the last, Marine Isotope Stage 2 (MIS2) glaciation, and triangles represent mega-groove sites at locations affected by ancient, pre-Quaternary glaciations.

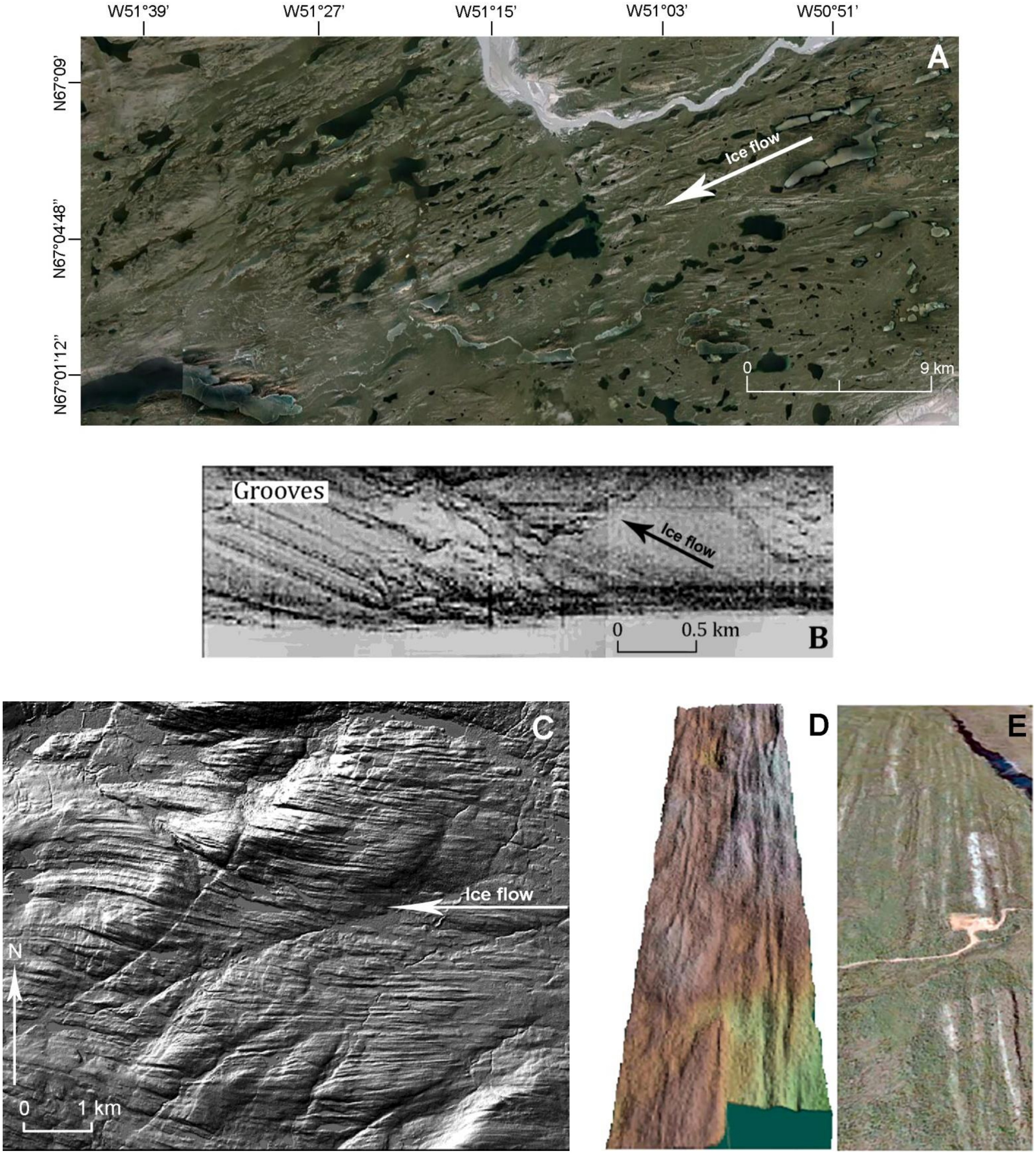

Figure 3 Images of mega-grooves obtained through various methods of remote sensing. (A) Mega-grooves and ridges in west Greenland, ca 100 km north-east of Sisimiut, described by Roberts et al. (2010). The grooves are eroded in gneissic bedrock and the ridges consist of mafic dykes relatively more resistant to erosion. Source of Landsat image - Google Earth © 2015 Google; © 2015 DigitalGlobe; # 17 on Figure 2. (B) Series of straight and parallel mega-grooves at Pine Island Bay, West Antarctica. The image was obtained through a compilation of swath bathymetry data and is modified from Lowe and Anderson (2003). Ice flow was in a NNW direction. Base image reproduced with permission from IGSOC; #22 on Figure 2.(C) Digital surface model (NEXTMap Britain) of large mega-groove field north of Ullapool,

Scotland, UK, with 1m resolution in the vertical plane and 2 m in the horizontal plane, illuminated from the north-west. The image is centred on N 57°56’45’’ and W 5°02’26’’. Image modified from Bradwell et al (2008) and reproduced with permission from Elsevier; #11 on Figure 2. (D&E): Comparison between mega-grooves under the Greenland ice sheet (D), located at approximately N 69°06’ and W 48°, and mega-grooves at Norman Wells, NT Canada (E), located at N 65°18’ and W 126°42’. The bedrock topography beneath the ice sheet was reconstructed using radar tomography algorithms (Jezek et al., 2011). Close similarity in morphology and size between mega-grooves at the two sites suggests subglacial formation primarily through differential erosion of the bedrock by glacier ice (Jezek et al, 2011). The grooves and ridges measure around 2,000 m in length. Base image modified from Jezek et al. (2011) and reproduced with permission from John Wiley & Sons; (D) corresponds to #16 and (E) to #1 on Figure 2.

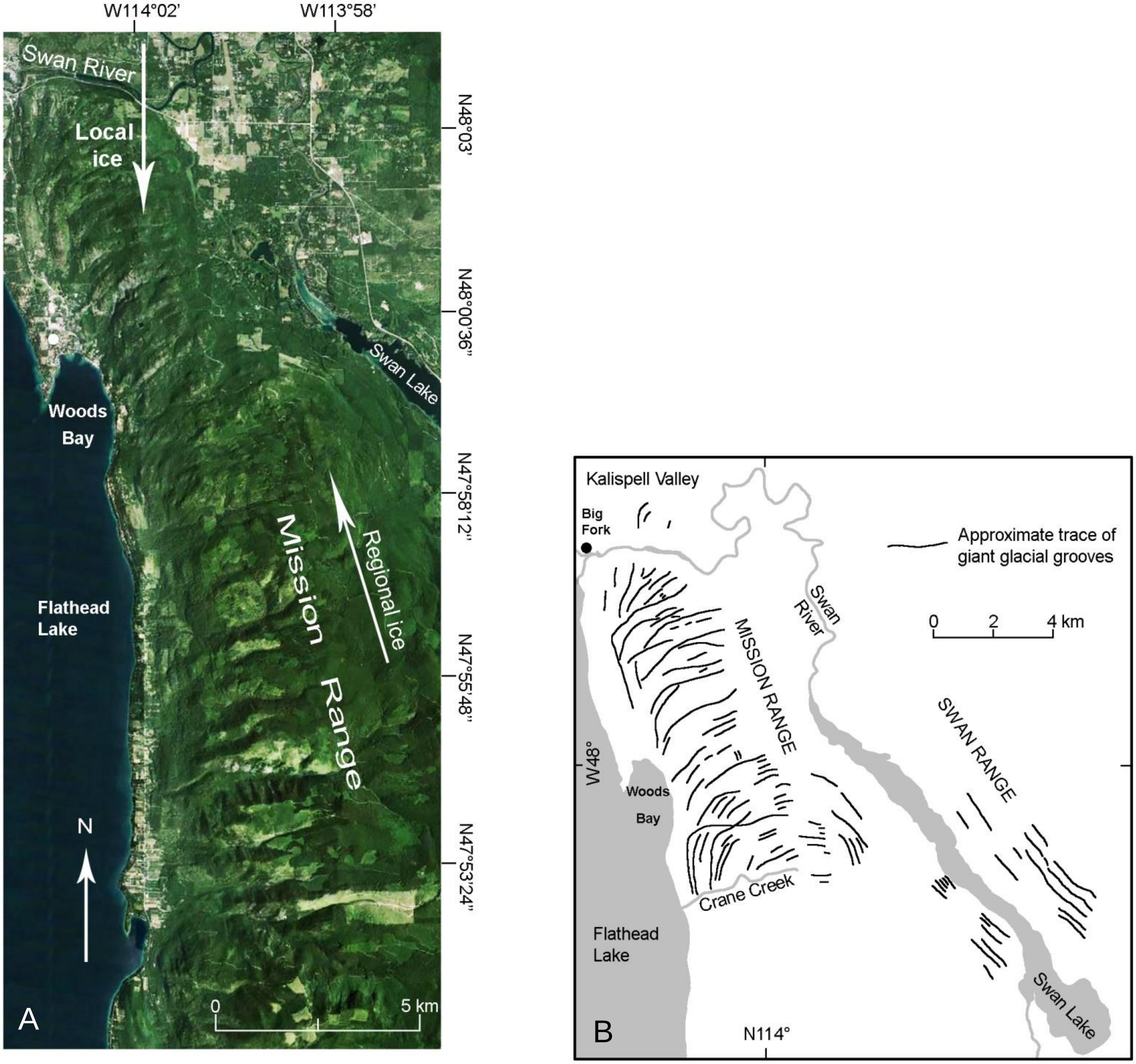

Figure 4 (A) Crescentic mega-grooves curving round the northern spur of the Mission Range, Montana, US. The grooves immediately south of the Swan River are thought to have been formed by the local, Cordilleran mountain glacier advancing southwards (Witkind, 1978). Source of satellite image - Google Earth © 2015 Google; #3 on Figure 2. (B) Map modified from Witkind (1978). South of the Crane Creek the overall drainage pattern is described as dendritic, typical of fluvial erosion (Witkind, 1978).

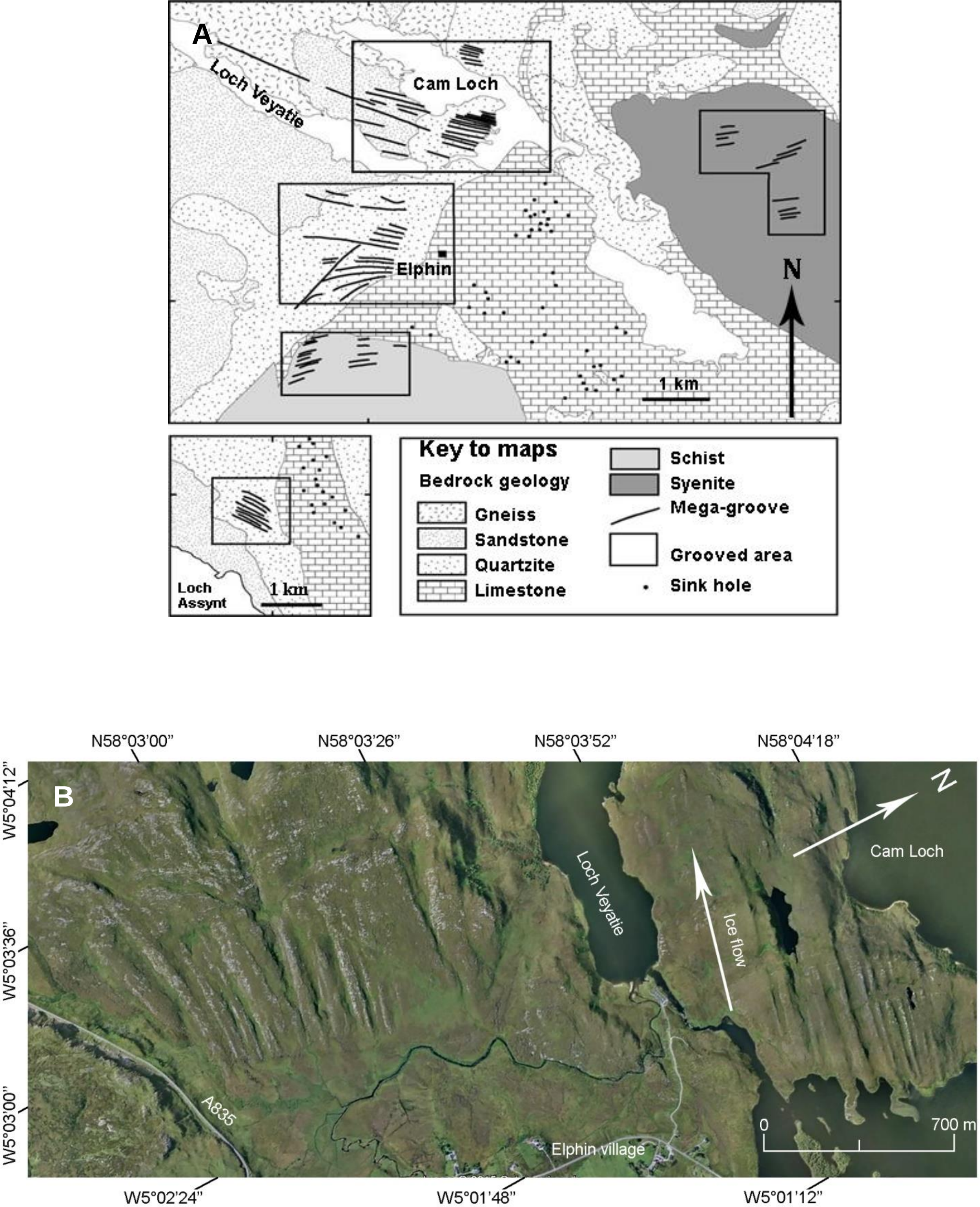

Figure 5 Mega-grooves in Assynt, NW Scotland. (A) mega-grooves in relation to the bedrock lithology showing their preferential occurrence in Cambrian quartzite. Image modified from Bradwell (2005), reproduced with permission from Elsevier. (B) Satellite image of mega-grooves west and north-west of Elphin village, Assynt, NW Scotland. Note the slightly divergent pattern of the mega-groove south of Loch Veyatie. Source of satellite image - Google Earth © 2015 Google; Image Landsat; image © DigitalGlobe; image © 2015 Getmapping plc; #12 on Figure 2

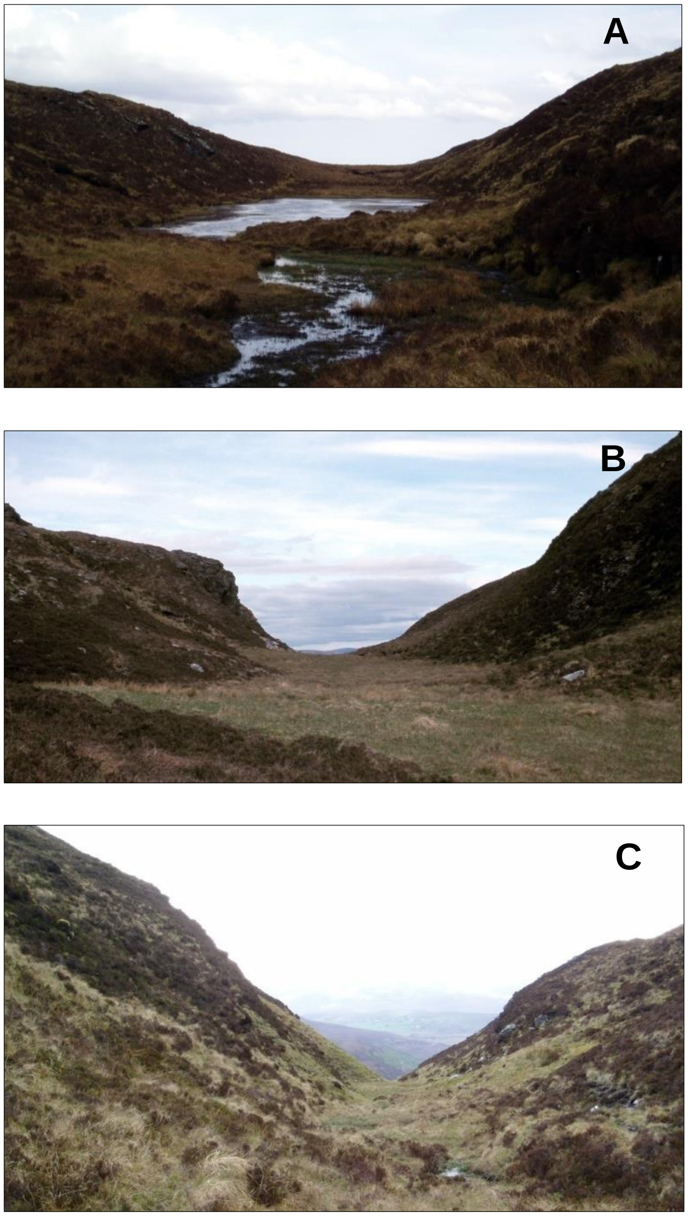

Figure 6 Cross profiles of mega-grooves north of Ullapool, Scotland: (A) parabolic, (B) U-shaped, (C) V-shaped. Photographer Maarten Krabbendam (A and C) and Tom Bradwell (B); Images © NERC UK

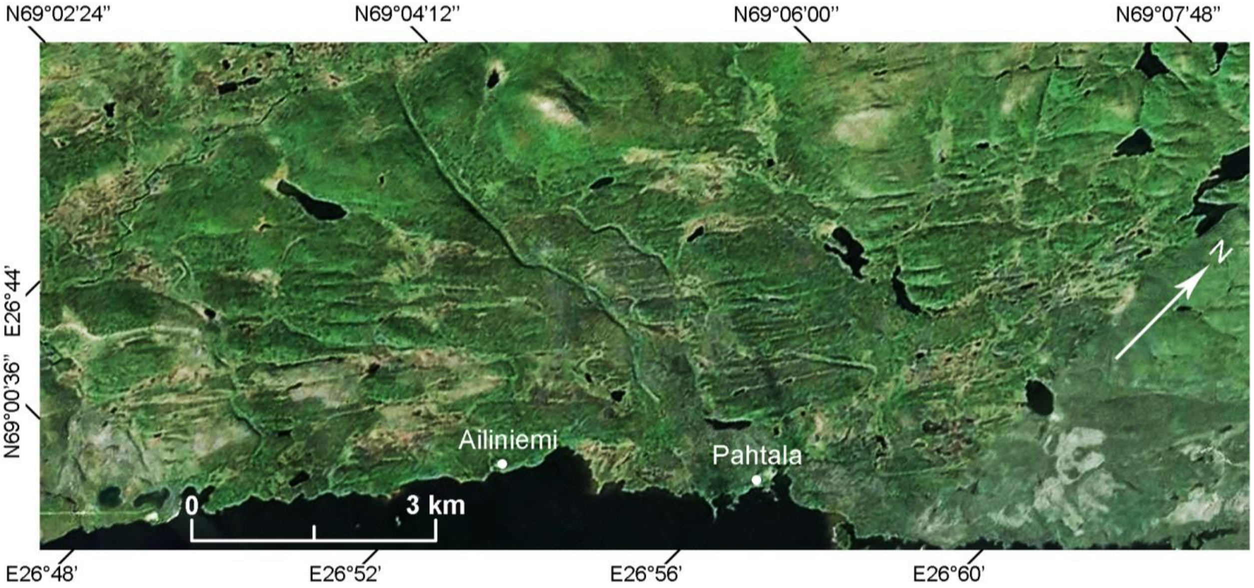

Figure 7 Mega-grooves eroded in the Precambrian shield rocks of Finnish Lapland. Note how seemingly discontinuous and quasi-parallel individuals give a general impression of continuity over the landscape (Heikkinen and Tikkanen, 1989). Satellite image from Google Earth © 2015 Google; Image Landsat; © 2015 DigitalGlobe; #13 on Figure 2.

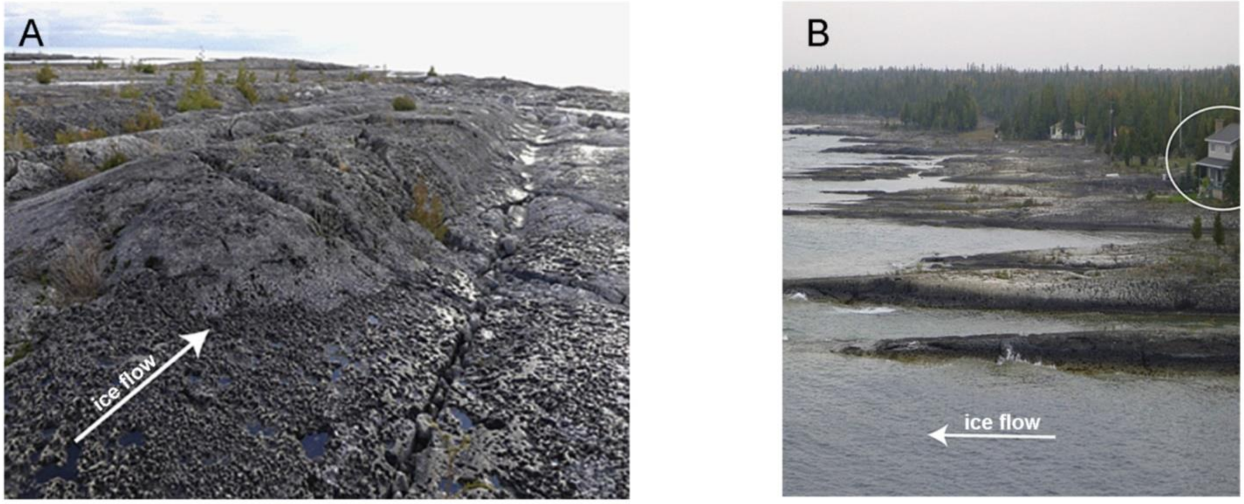

Figure 8 (A) Bioherm mound more resistant to erosion than the surrounding carbonate bedrock, standing high at the up-glacier end of bedrock ridge, Manitoulin Island, Georgian Bay, Canada. U-shaped Bedrock grooves flank the ridges. (B) The grooved bedrock topography at the south-eastern end of Manitoulin Island, Georgian Bay, Canada Images (A) and (B) are reprinted from Eyles (2012), with permission from Elsevier; #8 on Figure 2.

Figure 9 Aerial photograph of grooved terrain on the northern shore of Harefjord, inner Scoresby Sund, east Greenland. Note the discordant alignment of mega-grooves to the dip and strike of the bedrock. The thick dashed line (top left) marks the lithological boundary between gneissic bedrock to the west and the Røde Ø conglomerate to the east (Funder, 1978). Note confinement of grooves and ridges to the area of Røde Ø conglomerate. 'A' on the image marks the presence of till flutings, 'B' shows sites with well preserved glacial striations, and the thin dashed/dotted line mark kame terraces (Funder, 1978). Centre of image is at approximately N 70°57'41'' and W 27°56'25''. Image reprinted from Funder (1978), with permission from Danish Geodata Agency. #15 on Figure 2.

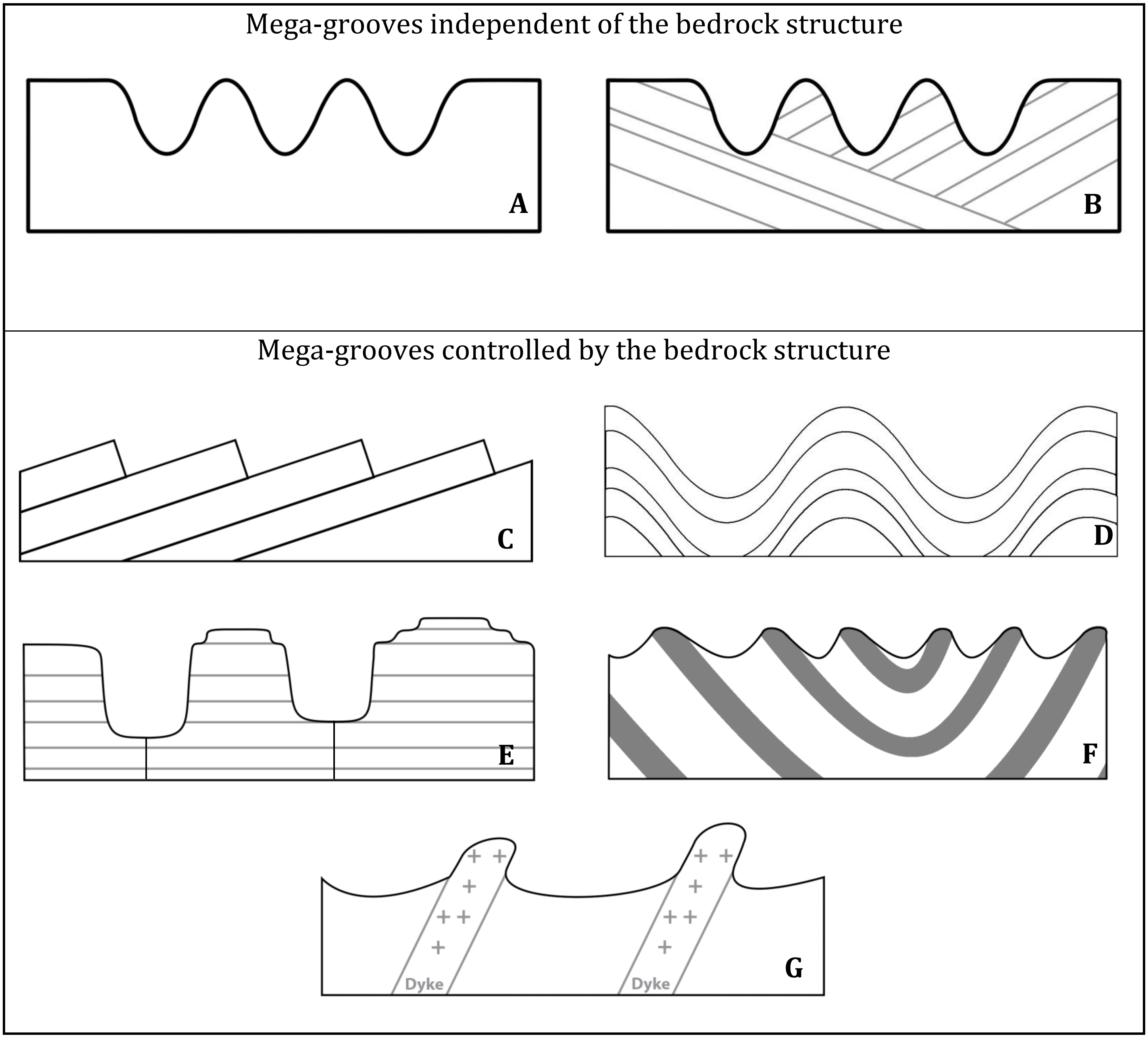

Figure 10 Schematic diagrams of different types of bedrock mega-grooves in relation to bedrock structure; ice-flow direction is into the page. A & B illustrate mega-grooves independent of the bedrock structure and C-G illustrate mega-grooves controlled by the bedrock structure. (A) Mega-grooves in homogeneous rock, unrelated to bedrock structure. Locations: Elphin, Scotland (Bradwell, 2005); NT, Canada – most sites (Smith, 1948); Lapland, Finland – some sites (Heikkinen and Tikkanen, 1989); Kelleys Island (Goldthwait, 1979; Munro-Stasiuk et al, 2005); Ontario, Canada (Eyles, 2012; Krabbendam et al., 2015); (B) Mega-grooves which cut through lithological and structural lines. No structural control has been reported at these sites. Locations: Elphin, Scotland (Bradwell, 2005); NT, Canada (Smith, 1948); Harefjord, East Greenland (Funder, 1978); Lapland, Finland (Heikkinen and Tikkanen, 1989). (C) Typical asymmetric profile of mega-grooves which mould on to the strata ends in areas where ice flow was parallel to the bedrock strike. Locations: Ullapool, Scotland (Bradwell et al., 2008); Northern England (Livingston et al., 2008; Krabbendam and Bradwell, 2011); Isle Royale, Michigan, US (Zumberge, 1955); Cape Smith Belt, Ungava Peninsula, Canada (Krabbendam and Bradwell, 2011); NT, Canada – site E and F (Smith, 1948). (D) Relatively soft carbonate rocks, where ridges correspond to anticlines and grooves to synclines (Wardlaw et al., 1969). Locations: Interlake Region,

Manitoba, Canada (Wardlaw et al., 1969). (E) Mega-grooves thought to have been formed subglacially along fault lines or joints. Locations: Manitoulin Island and Bruce Peninsula in Georgian Bay, Ontario, Canada (Bell, 1867; Eyles, 2012); Mission Range, Montana, US (Witkind, 1978). (F) Eroded syncline with mega-grooves corresponding to softer rocks, and ridges to harder rocks. Locations: Kaladar, Ontario, Canada (Krabbendam et al., 2015). (G) The fluted landscape with grooves and ridges formed through differential erosion throughout prolonged glacial conditions (Roberts et al., 2010). Locations: West Greenland, north-east of Sisimiut (Roberts et al., 2010).

Figure 11 Large-scale bedrock grooves and ridges at Key Harbour, Ontario, Canada. The grooves were eroded in highly metamorphosed gneissic bedrock of the Canadian shield and are described in detail by Krabbendam et al. (2015). Source of satellite image - Google Earth © 2016 Google; Image © 2016 DigitalGlobe; #6 on Figure 2.

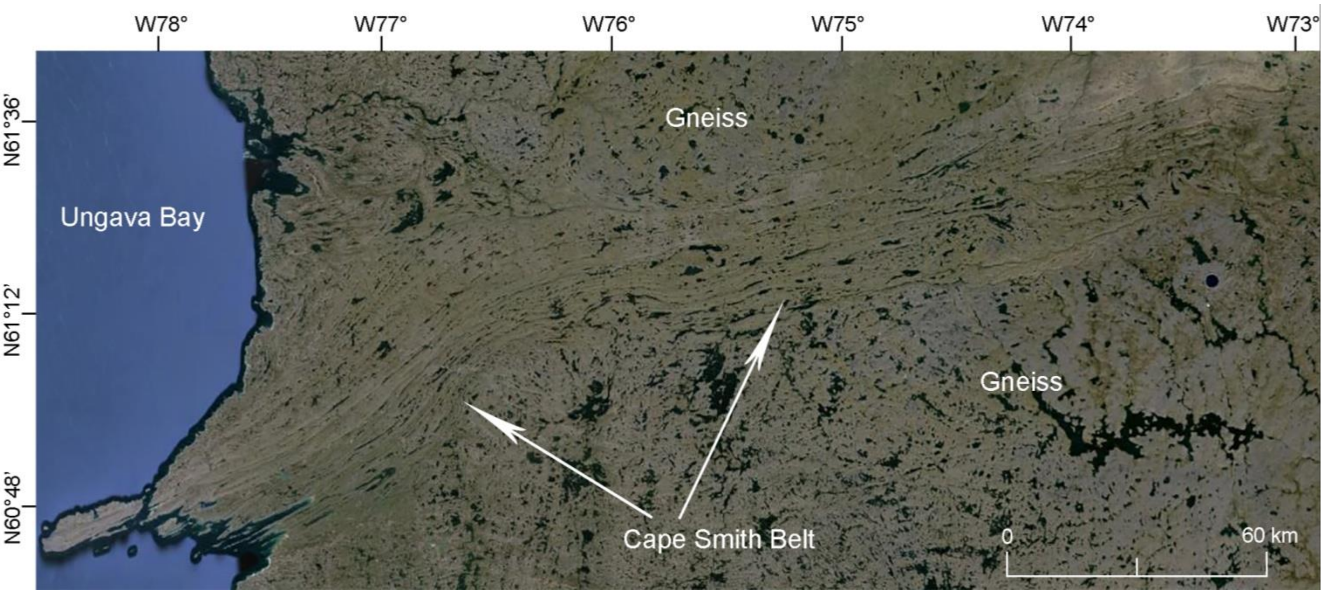

Figure 12 Mega-grooves following the SW-NE strike of rock strata in the Cape Smith Belt, Ungava Peninsula, Canada. The area was subjected to multiple glaciations during the Quaternary and the ice flow is inferred to have been on a general west-east direction at least on several occasions (Krabbendam and Bradwell, 2011). Note the contrast between the grooved appearance of the metasedimentary Cape Smith Belt, formed of tilted rock layers of different lithologies, and the cnoc-and-lochan appearance of the gneissic shield, either side of the belt. Source of satellite image - Google Earth © 2015 Google; Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat; #9 on Figure 2

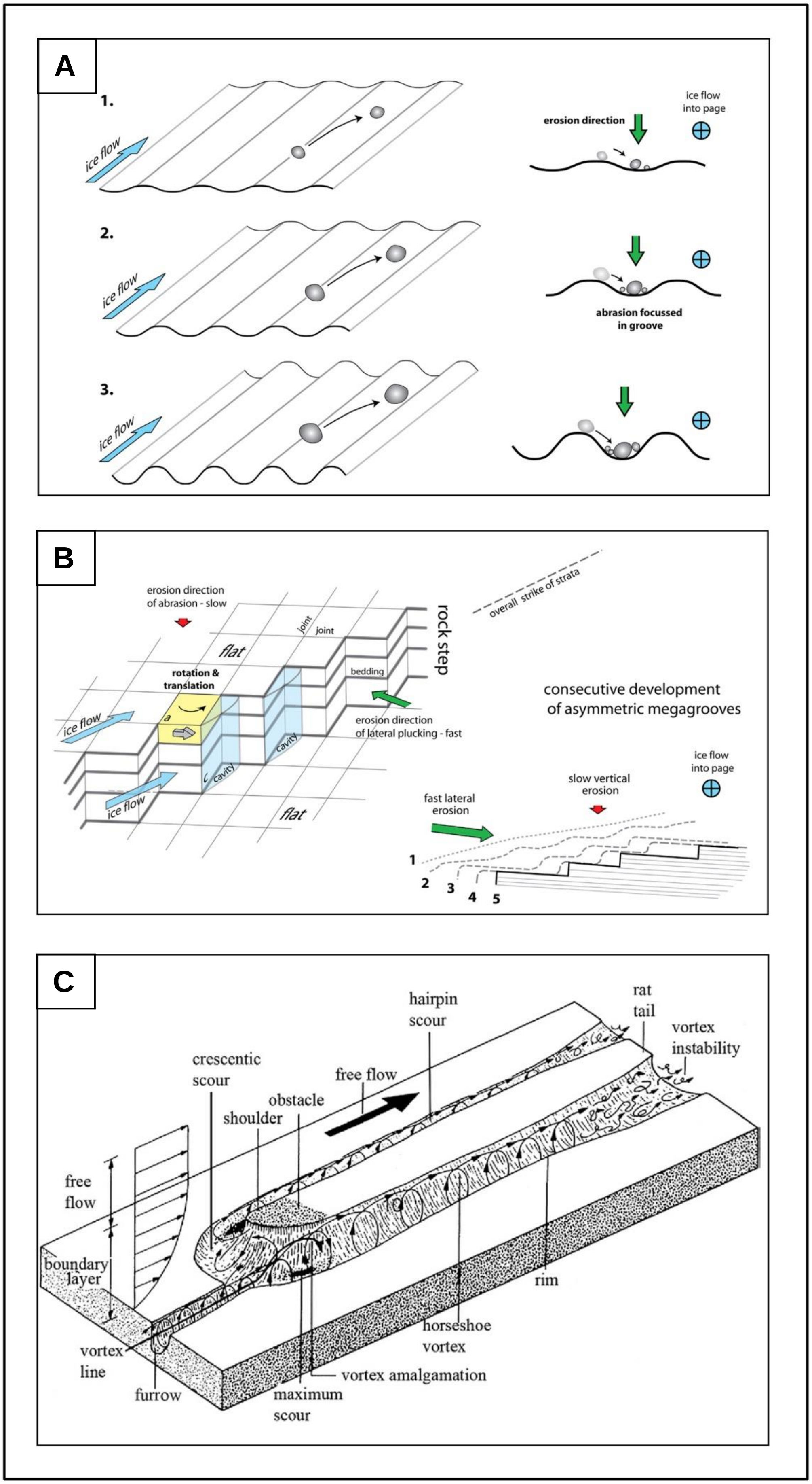
A
1.
ice flow
erosion direction
ice flow into page
2.
ice flow
abrasion focussed in groove
3.
ice flow
B
erosion direction of abrasion - slow
overall strike of strata
rock step
joint
joint
flat
rotation & translation
bedding
a
c
cavity
cavity
ice flow
ice flow
flat
erosion direction of lateral plucking - fast
consecutive development of asymmetric megagrooves
ice flow into page
slow vertical erosion
fast lateral erosion
1
2
3
4
5
C
hairpin scour
rat tail
vortex instability
crescentic scour
free flow
obstacle
shoulder
free flow
boundary layer
rim
horseshoe vortex
vortex line
vortex amalgamation
furrow
maximum scour

Figure 13 Diagram illustrating erosion mechanisms proposed for bedrock groove formation. (A) Focussed abrasion, whereby subglacial debris tends to accumulate in bedrock troughs and contribute to abrasion, thus enlarging the initial troughs and eventually modifying them into mega-grooves (Boulton, 1974; Krabbendam et al., 2015). (B) Lateral plucking proposed as the main mechanism of bedrock erosion in tilted layered strata (Zumberge, 1955; Krabbendam et al., 2015). Figures A and B are modified from Krabbendam et al. (2015) with permission from Elsevier. (C) Meltwater vortex erosion proposed as the main mechanism of groove formation at Kelleys Island (Munro-Stasiuk et al., 2005). Image reproduced from Shaw et al. (2008) with permission from Elsevier.

Figure 14 Stacked lava layers in west Mull, Scotland where differential erosion has rendered the topography a terraced aspect. The rocks are of Palaeogene age and a common occurrence on the island (Williamson and Bell, 2012). Note the similarity between the hill profile and the schematic diagram of mega-groves in layered strata from Figure 10C. The talus at the slope base is likely post-glacial.

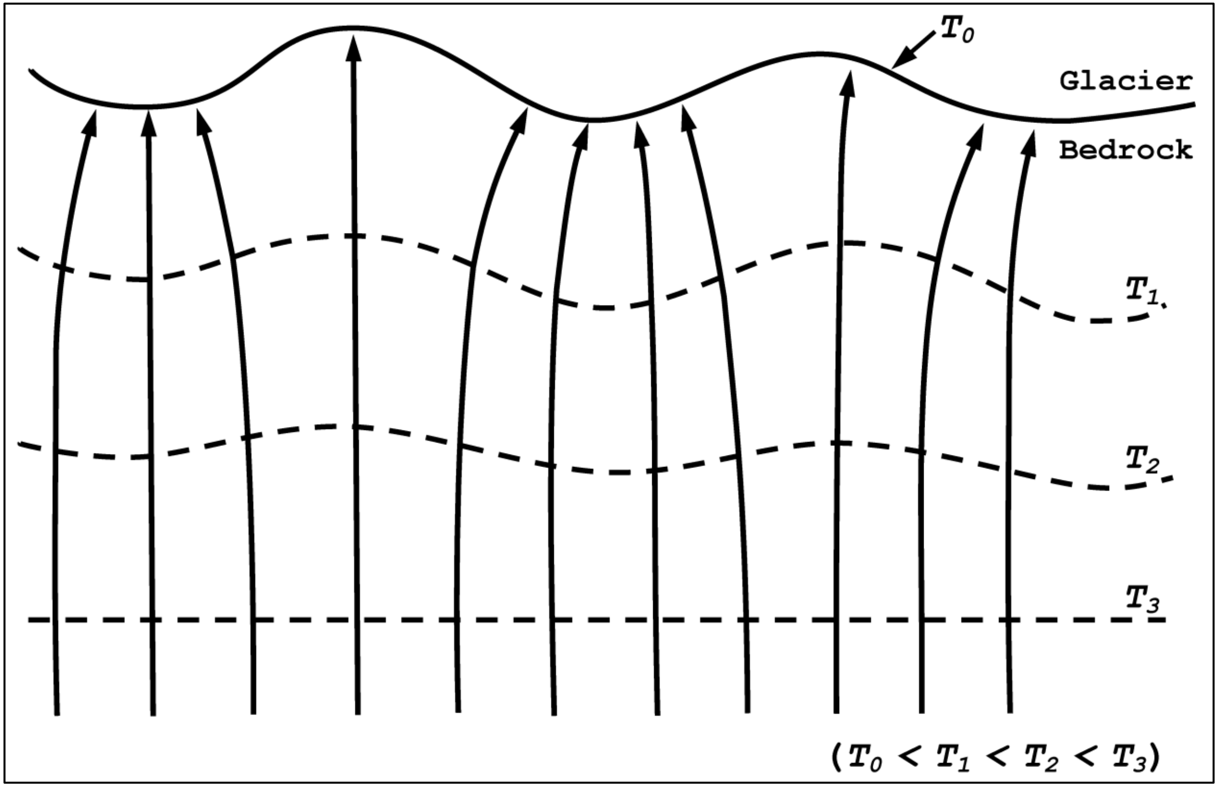

Figure 15 Diagram showing the paths of geothermal heat flow intercepting the isotherms (T_0 – T_3) at right angles, thus leading to more heat being delivered into the bedrock depressions than the topographic highs. Image modified from Nobles and Weertman (1972).

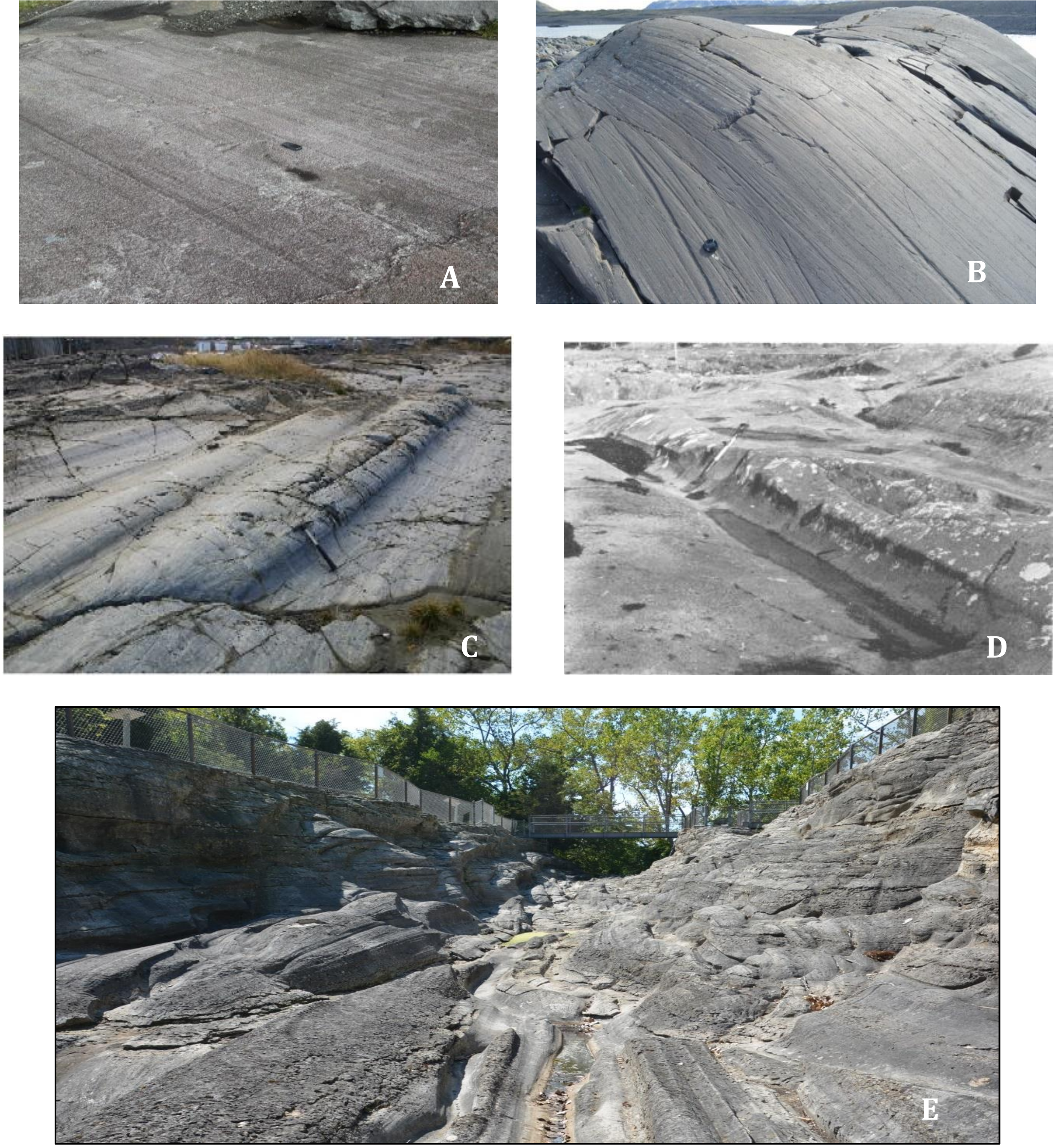
A
B
C
D
E

Figure 16 Size ranges of bedrock grooves ranging from striations through to mega-grooves. (A) striated gabbro on the Isle of Skye, Scotland. (B) striated stoss side of a roche moutoneé in Iceland, photo DJA Evans. (C) meso-grooves in Sudbury, Ontario; image reproduced from Eyles (2006) with permission from Elsevier. (D) meso-grooves on the Isle of Mull, Scotland; image was reproduced from Gray (1981), image © SJG. (E) macro-groove in Palaeozoic limestone at Kelleys Island, Michigan, US; image © Bianca Kallenberg. (F) mega-grooves in Torridonian sandstone, Northwest Highlands, Scotland; author of base image Tom Bradwell, image © BGS – NERC UK, #12 on Figure 2.

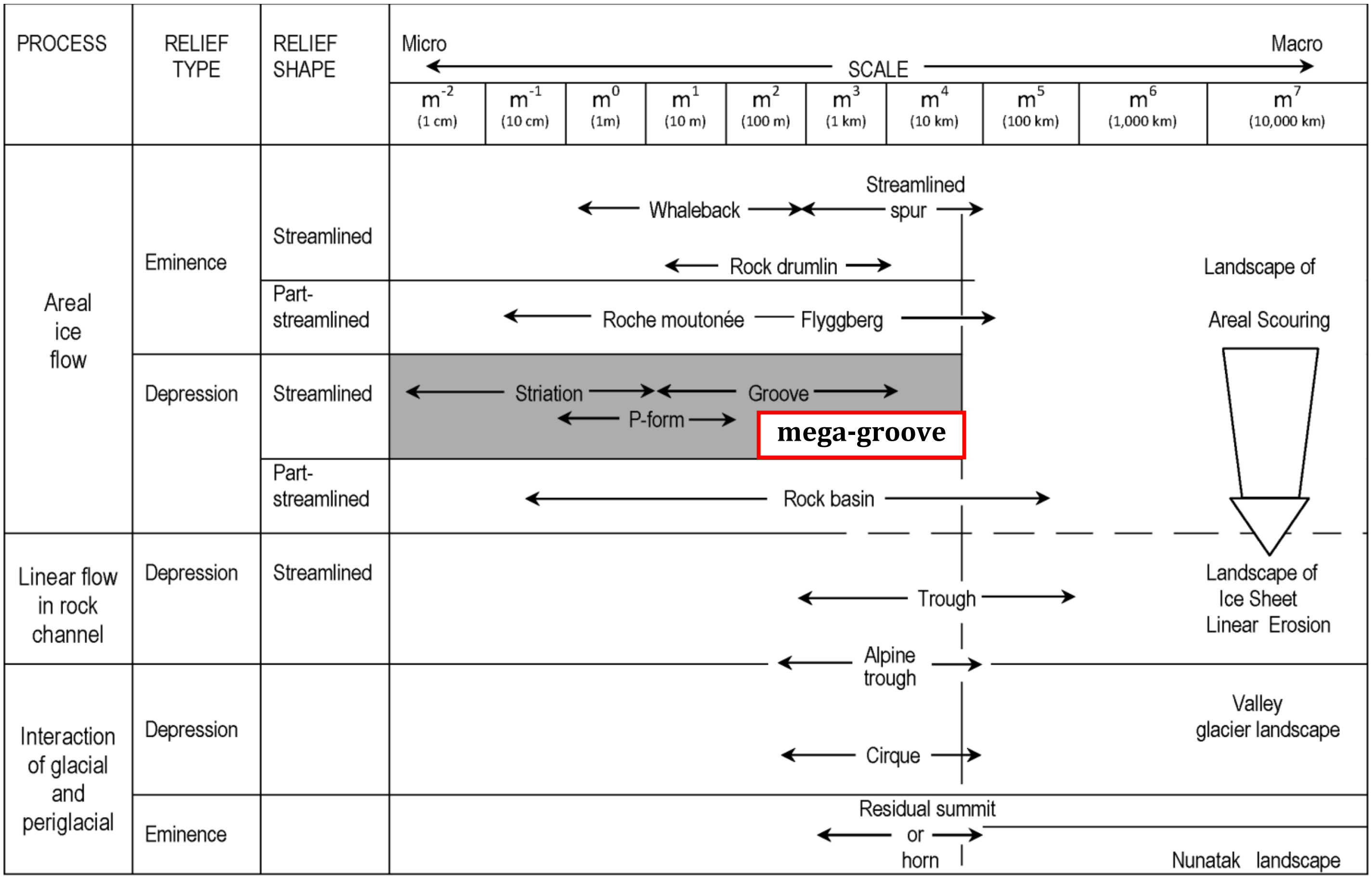

Figure 17 Table comprising landforms of glacial erosion, re-drawn from Sugden and John (1976); annotation 'mega-groove' corresponds to bedrock grooves of 100s – 1,000s meters in length. The bedrock grooves highlighted grey span the same size range as those compiled in Table 2 from the published literature. Please note the discrepancy in the meaning of 'macro' between Sugden and John (1976), at the top of the table, and this study (see Table 2), where macro-grooves refer to grooves in the length-range of 10s – 100s meters. Sugden and John (1976) also mention the prevailing glacial signal in the formation of striations and large-scale grooves, as opposed to meltwater erosion in P-forms.