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Characteristics and formation of bedrock mega-grooves (BMGs) in glaciated terrain: 2 – conceptual models of BMG initiation

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A B S T R A C T

Understanding BMG formation equates to being able to explain their initiation as well as their subsequent evolution. Several scenarios of bedrock mega-groove (BMG) initiation are proposed here, which attempt to explain how such parallel fluted terrain could be incised through resistant substrates over the relatively short temporal periods associated with uni-directional fast ice flow. In cases where geological controls have been inferred from the BMG morphology or location, groove initiation was likely either structural through the exploitation of linear features, or lithological, whereby the origin of harder erodents necessary for abrading softer rocks can be explained by the succession of adjacent lithologies along former ice flow paths. Where no geological control over BMG initiation could be inferred, it is hypothesized that their initiation was due to antecedent land surface conditions, through gradual bedrock elimination or related to pre-Quaternary regolith on etchplains, which was potentially a source of erodents no longer visible in the landscape.

1. Introduction

Bedrock mega-grooves (BMGs) are relatively sparse glacial erosional landforms which occur in assemblages of straight and parallel troughs (Fig. 1), typically over 1000 m in length and up to tens of metres deep (see Newton et al., 2018, 2023; Table 1). As part of the ice-bed interface of past and present ice sheets, BMGs are an important element in the development of our understanding of ice sheet/stream dynamics, ice–bedrock interactions and bedrock landscape evolution in glaciated terrains. Since the early reports of these features (e.g., Carney, 1910; Smith, 1948; Wardlaw et al., 1969; Witkind, 1978; Funder, 1978), a number of studies have focussed on the genesis of glacially streamlined terrains that include BMGs and have highlighted the various roles of bedrock lithological control, preglacial weathering, ice abrasion and erodent layers (tribology), ice quarrying and glacifluvial meltwater in their development (cf. Bradwell, 2005; Munro-Stasiuk et al., 2005; Krabbendam and Bradwell, 2011, 2014; Krabbendam and Glasser, 2011; Eyles, 2012; Eyles et al., 2016; Krabbendam et al., 2016; Bukhari et al., 2021). Although the role of erodents in such regional scale studies has been demonstrated to be effective in bedrock striation, the scaling-up of such a process to BMG proportions, with the exception of relatively soft bedrock settings (e.g. Evans et al., 2021), has so far not been developed.

Where they have been systematically sampled, the morphological characteristics of BMGs from various substrate lithologies globally fall within well-defined ranges, and the grooves attain large dimensions through widening, deepening and possibly lengthening as erosion progresses (Newton et al., 2018, 2023; Table 1). Several general characteristics for BMGs arise from this. Firstly, BMGs in any one area tend to be confined to one lithology, despite the ice having traversed sequences of different adjacent bedrock types (Newton et al., 2023). This strongly indicates that BMG formation is underpinned by geological controls. Secondly, BMGs are large, straight and highly parallel. Groove depths in particular yield high values of between 2 and 15 m, approximately twice those for MSGL, which are soft-bedded landforms of similar shape and magnitude (Newton et al., 2023). The linear correlations between width and depth show a consistently positive trend across the analysis spectrum, whereas the length/width and length/depth correlations are also positive, but weak within individual sites (Newton et al., 2023). This means that regardless of length, any site comprises both narrow and wide BMGs, as well as deep and shallow examples. The variation of width and depth along flow is inconsistent between sites, with some showing a positive trend and others a negative one (Newton et al., 2023). It is noticeable, however, that width varies relatively little with distance down-ice flow, whereas the variation of depth is greater whether the values increase or decrease with distance down-flow.

Any genetic model for BMGs must address their characteristic

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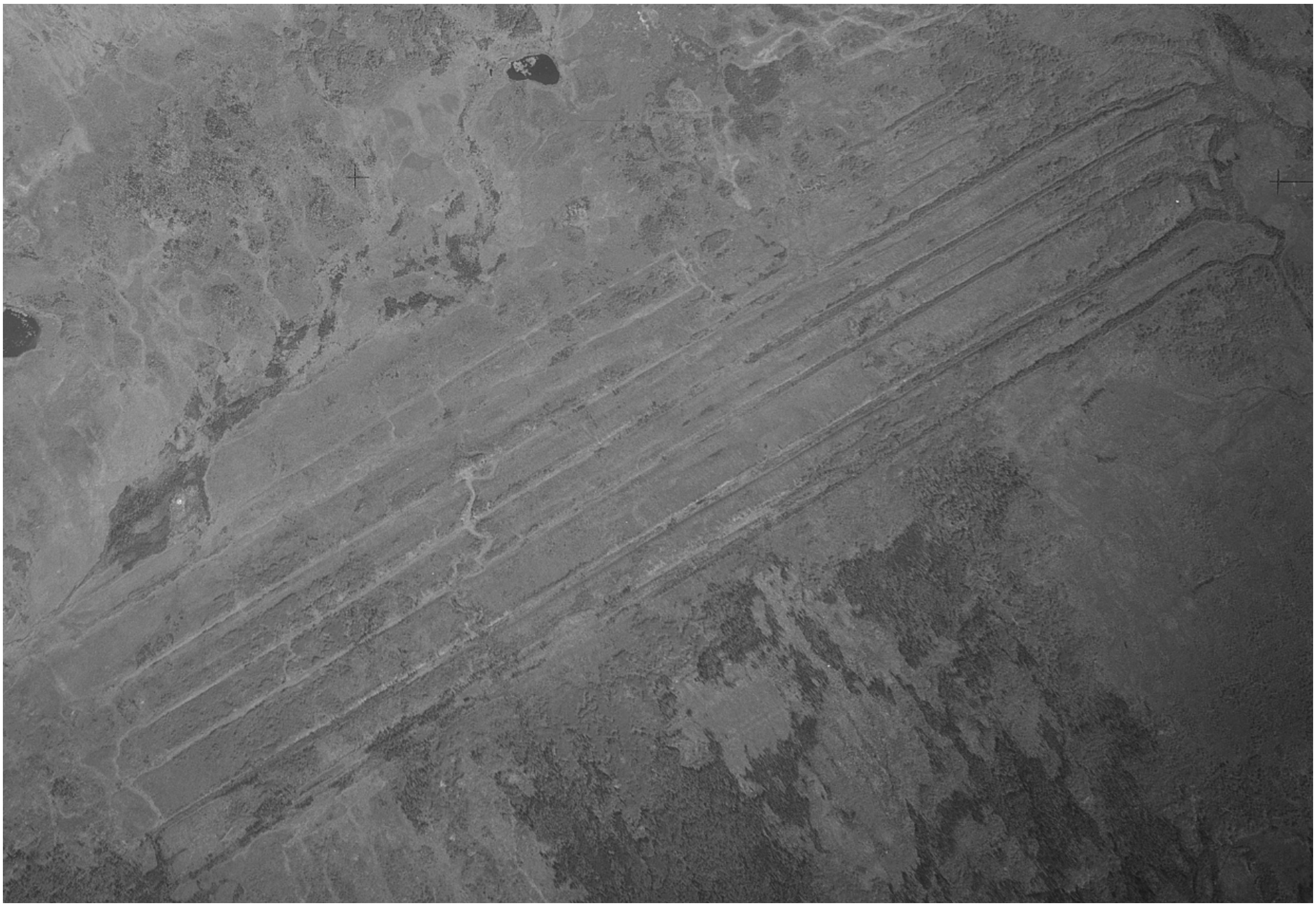

Fig. 1. Typical example of bedrock mega-grooves in the Birch Mountains area of Alberta, Canada. Extract from Government of Alberta aerial photograph AS79 5705 18. The BMGs are up to 7.5 km long and the centre of the image is located at 112° 39′ 39″ W and 57° 18′ 30″ N.

Table 1
The mean values for BMG dimensions, in meters, measured at ten sites across the world. The exact location of the ten sites are illustrated in Fig. 1 in Newton et al. (2023), which also details the protocols of BMG mapping, sampling and measuring. Abbreviations: NT = Northwest Territories; BC = British Columbia; Can = Canada; Scot = Scotland.

Metric (m)	Haarefjord (Greenland)	Elphin (Scot, UK)	Ullapool (Scot, UK)	Franklin (NT, Can)	Hanna (NT, Can)	Beavertail (NT, Can)	Iivaara (Finland)	Vikna (Norway)	Hazelton (BC, Can)	Pine Isl. (Antarctica)	All sites
Length	594	449	1039	1228	776	610	352	1350	439	1888	1018
Width	30	74	91	137	58	64	23	220	18	180	98
Spacing	45	86	82	158	72	100	35	313	37	271	134
Depth	4	7	7	5	6	6	2	8	–	18	7
Elongation (length/ width)	42	10	22	25	16	10	27	5	25	7	20

morphology and some crucial process-form relationships. Firstly, like striations, BMG production needs the provision of suitably sized and resistant striator clasts (mega-blocks) or erodent material. As BMGs are located, and therefore formed, on ice sheet beds, such blocks must be sourced from the bed relatively adjacent to the grooved site, whether through plucking (quarrying) and/or through the formation or remobilization of a deformable substrate containing erodent material (sensu Eyles et al., 2016). Secondly, in the absence of bedrock structural control, relative uniformity of parallel-aligned and straight grooves requires either fast glacier flow (Krabbendam et al., 2016) or a consistent ice flow direction over long periods of time (Roberts et al., 2010). The latter is particularly important for bedrock grooving and would conceivably imply repeat occupation of similar ice flow trajectories by erosive agents throughout multiple glaciations to ensure the length of time required for groove growth, under normal, slow-flow conditions. Thirdly, grooves must have been initiated in bedrock that was relatively weaker than the erodents; significantly if this weak rock is not represented in the grooved landscape today it must have been removed, pointing to antecedent conditions for BMG initiation, at least in some cases (e.g. at Elphin, Scotland UK; Bradwell, 2005). Fourthly, BMG fields display groove initiation either at approximately the same position, along a linear source zone, or at various points downflow (Newton et al., 2023).

A genetic model of BMG evolution must also satisfy some fundamental genetic factors that are clearly necessary for grooving bedrock. For example, the close association of BMGs with bedrock structure at some locations supports the notion that they have evolved as a result of the exploitation of geological structures by glacial erosion. Hence, BMG development could be inferred by assessing the bedrock susceptibility to erosion in conjunction with various agents of erosion expected to have

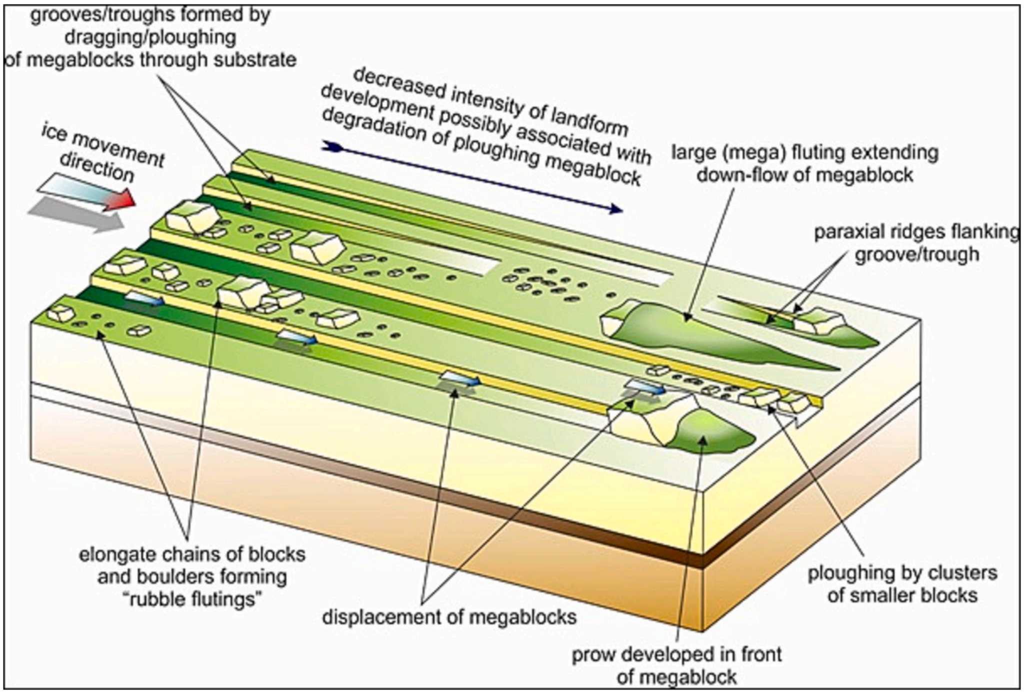

Fig. 2. Conceptual model of bedrock and/or sediment grooving through mega-block ploughing after the production of rubble terrain by bedrock plucking/rafting (from Evans et al., 2021).

acted upon the land surface throughout the Quaternary (Newton et al., 2018). In contrast to landform development, BMG *initiation* continues to be poorly understood and difficult to explore other than theoretically, likely due to its potential antiquity, especially for those grooves/landforms that are independent of bedrock structure. This is because the long-term erosion responsible for their persistence has also likely removed the physical characteristics of the land surface (i.e. the antecedent conditions) which may have triggered groove initiation (Newton et al., 2018). Also important is the fact that remarkably few examples of BMG fields exist relative to other subglacial landforms, so either the requisite conditions for their formation were rarely met or many are buried beneath glacigenic deposits and hence do indeed date to glaciations that pre-date the LGM.

Crucial questions that require addressing include: i) how is persistent, uni-directional glacier flow maintained for long enough to create straight grooves in bedrock, given the unstable nature of ice-sheet flow dynamics, especially in situations where bedrock structure has not been exploited?; and hence ii) do BMGs uncontrolled by geological structure relate to the earliest of Quaternary glaciation footprints and, thereby, result from a land surface whose characteristics were significantly different from those of today and relatively recent glaciations?

Invariably, in the absence of evidence for key factors that led to initial bedrock grooving, the construction of theoretical models of BMG initiation remain the best option. Hence, we propose here two different models of BMG initiation driven by either linear source-outcrops or by randomly distributed, *in situ* erodents contained in antecedent materials. Prior to erecting these theoretical models for further testing, we provide the details of existing genetic scenarios and critical process-form relationships related to BMG generation and formulate some underlying assumptions, all of which emerge from the compilation of BMG metrics and landscape contexts (Table 1; see Newton et al., 2023).

2. Hypotheses and scenarios of BMG formation – general considerations

The groove initiation scenarios developed here are based on two underlying assumptions. Firstly it is assumed that groove initiation took place subglacially, through erosion by glacier ice. Secondly, in order to explain how parallel fluted terrain could be incised through resistant substrates over the relatively short temporal periods associated with uni-directional fast ice flow, BMGs that are independent of bedrock structure are assumed to have been initiated on a land surface more susceptible to rapid erosion and therefore their initial incision could be of pre-Quaternary age.

2.1. *The case for BMG initiation through glacial erosion*

It has long been suggested that BMGs are the product of abrasion by glacier ice, as this is the only mechanism that can account for groove straightness and parallelism over long distances (Smith, 1948; Funder, 1978; Heikkinen and Tikkanen, 1989; Bradwell et al., 2008; Newton et al., 2018). Although it has been demonstrated that plucking is more efficient than abrasion in the glacial erosion process (Dühnforth et al., 2010), plucking has been downplayed as an eroding mechanism in BMG initiation, because it cannot incise bedrock. Moreover, the plucking mechanism operates in situations where a cavity forms between the bedrock substrate and the overriding ice due to pre-existing topographic high points (Hallet, 1996). In this context, there is some evidence that lateral plucking has been effective in BMG enlargement during the last glaciation in areas of layered, well-jointed rocks (Bradwell, 2005; Krabbendam and Bradwell, 2011; Krabbendam et al., 2016). This could indicate that overall, a higher bedrock volume may have been removed through plucking compared to abrasion in the long-term process of BMG development (Newton et al., 2023), but only *after* groove initiation or the development of primary subglacial relief. Indeed, it should be kept in mind that striations are essentially microscale grooves (i.e. Bukhari et al., 2021 refer to BMGs as “mega-striations”), the floors of which are characterised by quarrying (i.e. plucking) features such as chattermarks (Iverson, 1990, 1995; Rea, 1996). Therefore, it can be argued that both vertical and lateral plucking play a part in BMG development at an early stage and should be expected to grow in efficiency as the groove relief increases. Consequently, the role of plucking in BMG development may be reflected at sites where BMGs become deeper with distance down-ice flow, particularly in well-jointed bedrock (Newton et al., 2023), because

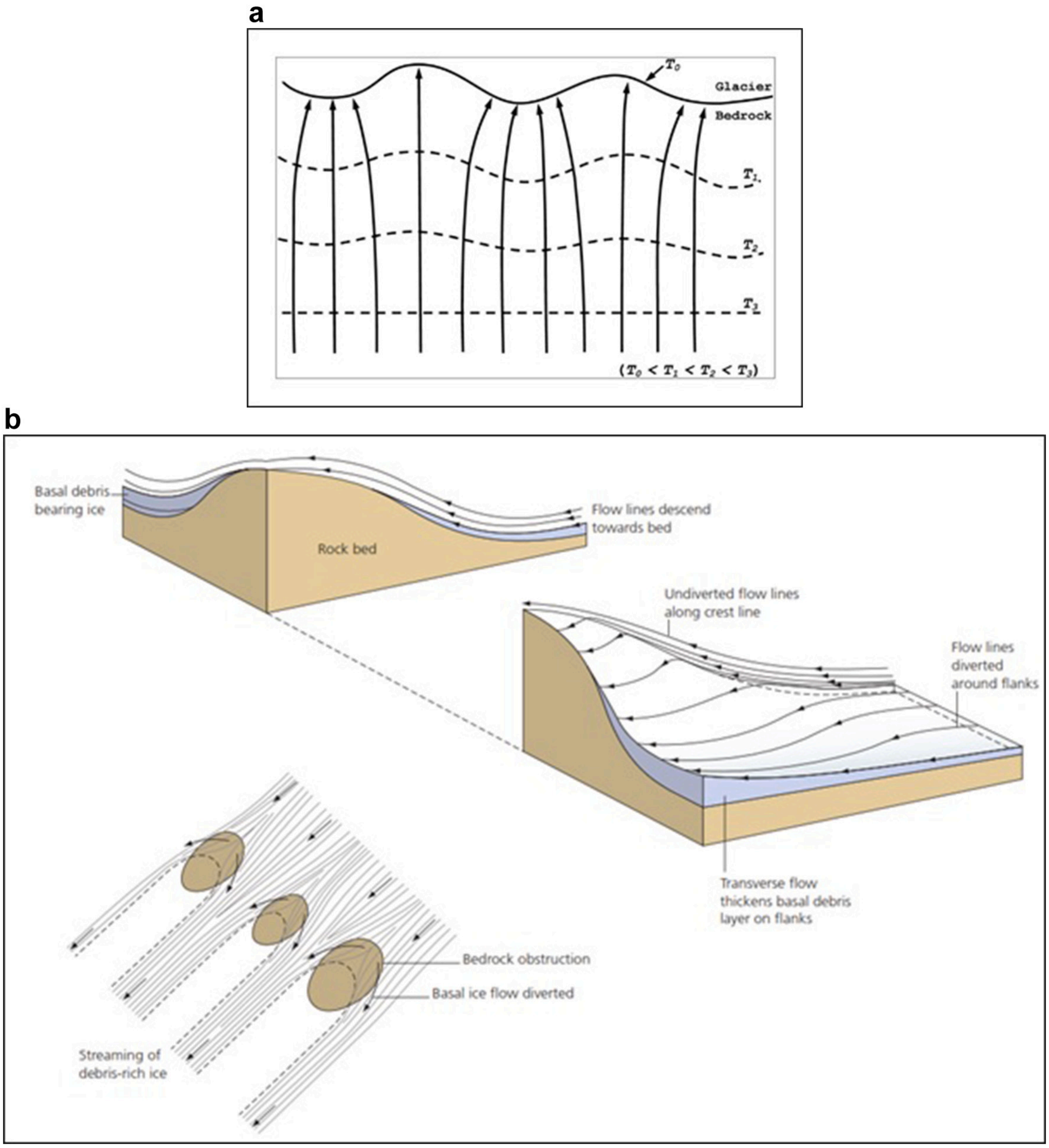

Fig. 3. Theoretical models that explain preferential till sedimentation and debris-rich ice in low areas of glacier beds: A) concentrated heat flow and elevated basal ice melt rates in depressions (Fig. 15 in Newton et al., 2018, after Nobles and Weertman, 1971); B) basal debris-rich ice thickening due to bed obstructions (after Boulton, 1975, 1979).

the rock fragments dislocated through plucking become abrading tools and increase the efficiency of groove deepening through abrasion downflow.

Striations are among the oldest recognised vestiges of glacial erosion and their occurrence is ubiquitous across glaciated terrain (e.g. Chamberlin, 1888; Geikie, 1894; Laverdière et al., 1979, 1985; Veillette et al., 1999; Rea et al., 2000). Their formation has been observed in the field (e.g. Boulton, 1979) and simulated in the laboratory (e.g. Lister et al., 1968; Iverson, 1990; Rea, 1996). Although striations and BMGs have morphological similarities and are both initiated through glacial abrasion, grooves are orders of magnitude larger than striations and, hence, potentially develop into mega-scale features (Bukhari et al., 2021) as a result of a combination of erosional mechanisms beyond that of a single striator clast impact (Krabbendam et al., 2016; Newton et al., 2018). Significantly, the dominant role of mega-blocks in mega-groove initiation in soft bedrock and Quaternary sediment has been identified recently by Evans et al. (2021) in Alberta, Canada (Fig. 2), particularly evident where groove floors contain possible mega-scale chattermarks. This remains a qualitative consideration in the absence of numerical constraints, but it is reasonable to assume that, like abraded and striated surfaces, the rate of groove deepening must be higher than the rate of ridge lowering for a BMG to develop. The availability and abundance of mega-blocks and/or bedrock rafts on former ice sheet beds, often referred to as “rubble terrain”, and their widespread association with grooves (Fenton et al., 1993; Evans et al., 2020, 2021; Bukhari et al., 2021) clearly demonstrates their crucial role as erodents or mega-striators. This scenario is supported by the small variation of groove width with distance down-ice flow (Fig. 2).

Although BMGs have been widely associated with palaeo-ice stream beds (e.g. Ó Cofaigh et al., 2002; Bradwell et al., 2008; Eyles, 2012; Krabbendam et al., 2016; Eyles et al., 2018; Bukhari et al., 2021), fast-ice flow is not in itself necessarily capable of groove initiation and it has been acknowledged that multiple glaciations with similar ice flow trajectories are similarly capable of forming grooved terrain (Livingstone et al., 2012). Critical in this respect is the availability of mega-striators capable of groove initiation and indeed their continued, or at least punctuated, availability through time. Intermittent ice stream freeze-on/shutdown (Iverson, 2000; Bougamont et al., 2003a, 2003b; Christoffersen and Tulaczyk, 2003a, 2003b; Christoffersen et al., 2006) has been proposed as a potential source of mega-striators, viable in situations where the exposure of well-jointed bedrock leads to enhanced plucking (e.g. Hall et al., 2020; Bukhari et al., 2021; Evans et al., 2021). The gradual thinning and exhaustion of subglacial deforming layers also has the potential to expose jointed bedrock and thereby refresh the supply of erodents through plucking (Evans et al., 1998; Alley, 2000; Iverson, 2010).

It follows that some form of sustained and focussed bedrock grooving is needed to initiate a BMG, which in the case of structurally controlled examples is ensured by a constant supply of abrading tools to relatively fast-flowing basal ice (i.e. warm-based thermal regimes), moving in predominantly the same direction (cf. Bradwell et al., 2008; Eyles, 2012). Early assessments of the macro-scale Kelleys Island grooves at Lake Erie by Carney (1910) inferred the importance of the localized impact of abrading tools and their constant supply to basal ice. With larger scale BMGs developed independent of bedrock structure, it is more difficult to envisage groove initiation, especially as it needs to attain sufficient size rapidly enough to concentrate the erosion processes required for enlargement and entrenchment in a stable position on the ice sheet bed. The focussing of tools, and hence erosional processes after bed perturbations have been created has been explained theoretically by Nobles and Weertman (1971) through geothermal heat flow concentrations in depressions, and by Boulton (1975, 1979) through flow diversion of debris-rich ice towards depressions (Fig. 3).

Cases have been made for the glacifluvial erosion of subglacially streamlined bedrock, especially in the development of p- or s-forms (e.g. Dahl, 1965; Shaw and Sharpe, 1987; Sharpe and Shaw, 1989; Shaw and Gilbert, 1990; Kor et al., 1991; Shaw, 2002). Even multiple, parallel-aligned and straight grooves in bedrock have been explained exclusively as the product of meltwater erosion, specifically by multiple vortices developed downflow from protuberances (Bradwell, 2005; Munro-Stasiuk et al., 2005; Shaw et al., 2008), thereby potentially explaining larger-scale grooves and ridges in fields of crag-and-tails. The limitations of an exclusive meltwater origin for such landforms has been widely demonstrated (e.g. Clarke et al., 2005; Benn and Evans, 2006; Ó Cofaigh et al., 2010a), but the pathways for subglacial meltwater are undoubtedly influenced by pre-existing topographic lows in the substrate and hence, once initiated, grooves are very likely to have been enhanced by glacifluvial erosion due to their ability to channel substantial meltwater flows (Eyles, 2006; Kirkham et al., 2019). This is entirely consistent with heat fluxes modelled by Nobles and Weertman (1971) and the concentration of debris-rich ice in grooves proposed by Boulton (1975, 1979; Fig. 3B). To elaborate further, fluctuations in subglacial effective pressures and associated meltwater production will result in switches from strong to weak ice-bed coupling. The latter initiates subglacial meltwater flows in Nye channels. In contrast, strong ice-bed coupling leads to ice creep towards such channels and freeze-on of residual meltwater and debris concentrated in channel floors. Hence, once grooves are initiated, they become the increasing focus of meltwater erosion and abrasion by flow-parallel, debris-rich basal ice stripes or bands (Boulton, 1975, 1979; Catania et al., 2005; Bradwell et al., 2008), provided that till advection to the site does not seal them off from the glacier sole. This concept of temporal switching between ice-bed interface conditions is compatible with previous theories of a hybrid genesis for p-forms, which invoke debris-rich basal ice, saturated till at the ice-bed interface, pressurised subglacial meltwater and ice-water mixtures (Gjessing, 1965; Gray, 1981). In particular, it promotes the concept of ice-debris mixtures for p-form development as advocated by Gjessing (1965). Previous models of bedrock grooving have invoked these ice-debris mixtures (Fig. 4) in terms of longitudinal, ice flow-parallel “debris streams” (Goldthwait, 1979). The relatively strong, positive correlations between depth and width in BMG populations (Newton et al., 2023) strengthen the idea that erosion progresses both laterally and vertically, keeping up with each other as the groove develops.

Fig. 4. Example of debris-rich basal ice in a sub-polar glacier, Ellesmere Island, Arctic Canada, illustrating the erosional potential of ice-debris mixtures, especially when ice-bed coupling is achieved through freeze-on and the large boulders then act as mega-striators.

In summary, BMGs are most likely to have been initiated through glacial abrasion, through the agency of large, relatively resistant bedrock blocks (erodents) dragged by the ice over relatively weaker lithologies. The contribution of plucking to BMG growth is likely to have increased as the grooves deepened. Although the role of glacifluvial erosion can be accommodated through potentially any combination of ice, water and debris slurry, such processes are difficult to envisage as *initiators* of parallel-aligned, kilometres-long BMGs. Consequently, the models of BMGs compiled below integrate these processes only in the more advanced stages of groove development, in addition to concentrated abrasion.

2.2. *The case for BMG initiation pre-dating the last glaciation*

The links between BMGs and Quaternary glaciations, in terms of ice flow direction and spatial extent, strongly suggest an early Quaternary age for groove initiation (Newton et al., 2018 and references therein), but in the absence of numerical dating it is difficult to establish how far back into the Quaternary BMGs originated. Furthermore, initiation dates may have varied both between and within sites. However, several observations indicate that, once established, BMGs have a high preservation potential, which is consistent with a significant age. We now expand upon these observations.

First, there is a lack of cross-cutting between BMGs, although smaller grooves, especially striations, can occur at an angle to the BMGs and ridges (Funder, 1978; Witkind, 1978; Bradwell, 2005). Also, in some cases BMGs are aligned at a low angle to the latest inferred ice-flow direction (Finlayson et al., 2014; Krabbendam et al., 2016). Collectively, these observations indicate that BMGs can survive changes in ice-flow direction and even continue to grow in size while maintaining their initial alignment. In contrast, MSGLs, which are glacial corrugations of similar morphology and magnitude to BMGs, can develop cross-cutting flow sets driven by changes in ice-flow direction (e.g. Clark, 1999; Ó Cofaigh et al., 2010b). This is due to the fact that MSGLs are composed of unlithified sediment and, hence, prone to subglacial reworking within a deformable substrate. This contrast in permanence of orientation between bedrock-cored BMGs and sediment-cored MSGLs highlights the relatively high preservation potential of BMGs and therefore their

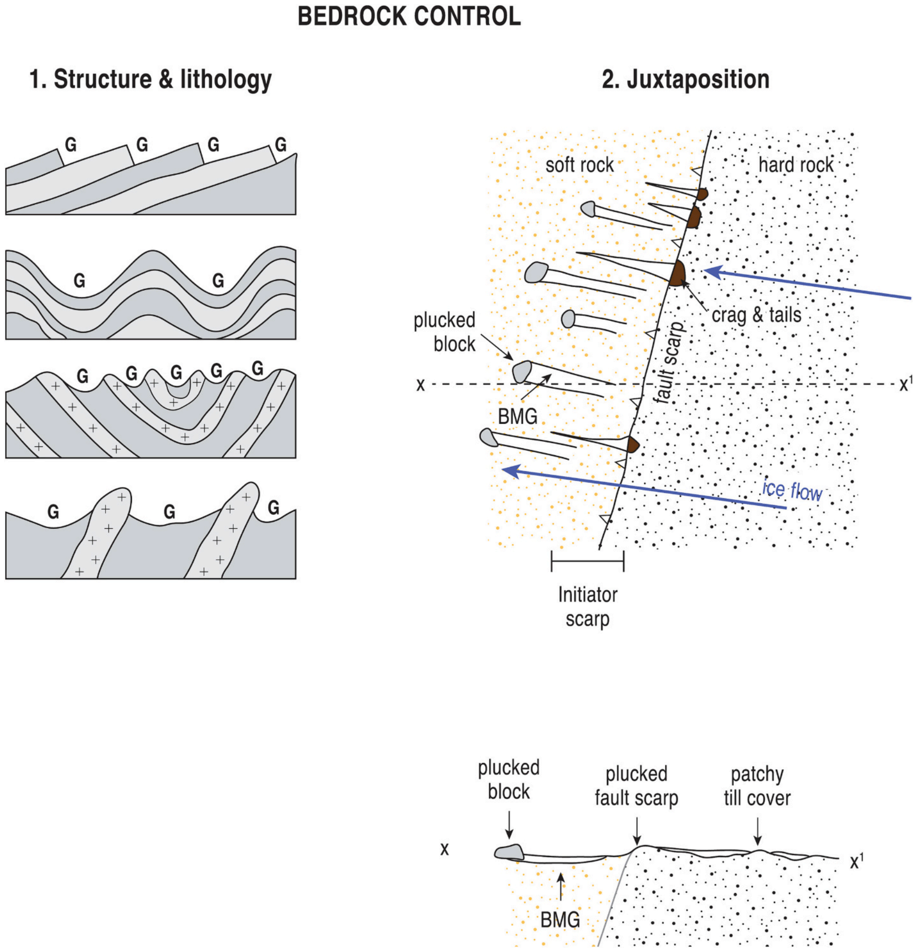

Fig. 5. Two typical scenarios for bedrock control over BMG formation: Diagram 1 - BMG development under structural control; image modified from Fig. 10 in Newton et al. (2018); Diagram 2 - BMG development under lithological control with boulders derived from hard lithology at a geological boundary (initiator scarp) subsequently dragged by the ice over softer bedrock, susceptible to abrasion. G = groove.

persistence through time as palimpsests.

Second, the typical BMG depth of 2–15 m is within the same order of magnitude as the average surface lowering through glacial erosion during the Quaternary. Overall, the latter is estimated to have been well under 100 m, for example 35–48 m in eastern Scotland (Glasser and Hall, 1997), or as little as between 9 m (±8 m) and 27 m (±11 m) in northern Sweden (Hall et al., 2013). The efficiency of glacial erosion is known to vary locally and regionally, according to the style of glaciation. Thus, deep glacial troughs underwent deepening of 100 s of meters (Sugden, 1968, 1974), whereas other areas have hardly been affected by glacial erosion (e.g. Sugden, 1968; Lidmar-Bergström et al., 1997; Phillips et al., 2006). If grooved terrains are regarded as the result of areal scouring, then the amount of surface lowering through glacial erosion is expected to lie between extreme values. Significantly, if the amount of ridge lowering is added to the BMG depth, the figure thus obtained would reflect more realistically the overall surface lowering through Quaternary glacial erosion, and it would bring the amount of erosion closer to the estimated ranges of several tens of meters, as reflected across glaciated terrains elsewhere (e.g. Glasser and Hall, 1997; Hall et al., 2013). Although this is a crude and generalised comparison, it supports an age at least older than the last glacial cycle for the BMGs and the plausibility of their initiation in the earlier stages of the Quaternary. More specifically, this conclusion is supported by the mean BMG depth of 7 m at Elphin, Scotland, developed exclusively in quartzite, which need more than 150,000 years to develop if a continuous glacial erosion rate of 0.04 mm/yr was assumed, based on the estimations of Colgan et al. (2002). This exceeds the duration of the last glacial cycle and strongly suggests BMG initiation earlier in the Quaternary.

Finally, the fact that so few BMGs appear to exist in glaciated terrain compared to other subglacial landforms may well relate to the fact that they are buried by glacigenic deposits laid down after BMG production. This is being increasingly verified by offshore seismic stratigraphies, wherein multiple ice sheet flow trajectories are recorded in mega-scale lineations in the lower/older glacigenic deposits (e.g. Rafaelsen et al., 2002; Dowdeswell et al., 2006; Graham et al., 2007; Riedel et al., 2021). It is possible, therefore, that many BMGs may have been formed during earlier Quaternary glaciations but are now obscured by the tills of subsequent ice sheets. Additionally, we have to consider that the conditions necessary for BMG initiation and indeed growth have been reduced or possibly even removed over time and, hence, there has been an overall reduction in the optimum conditions for their development. This implies that the precursor shapes and necessary erosional ingredients of some glacial landforms are inherited from older, non-glacial land surfaces such as etchplains (cf. Lindstrom, 1988; Lidmar-Bergström, 1989, 1995, 1997; Lidmar-Bergström et al., 1997; Olvmo et al., 1999, 2005; Olvmo and Johansson, 2002; Hall et al., 2013; Krabbendam and Bradwell, 2014), which strengthens the presumption of an old, pre-Quaternary age for the BMG initiation.

3. Models of BMG initiation based on case studies

In this section we present models of BMG initiation based upon the common physical characteristics of specific sites presented in Newton et al. (2023) and suggest explanations for those occurrences, working

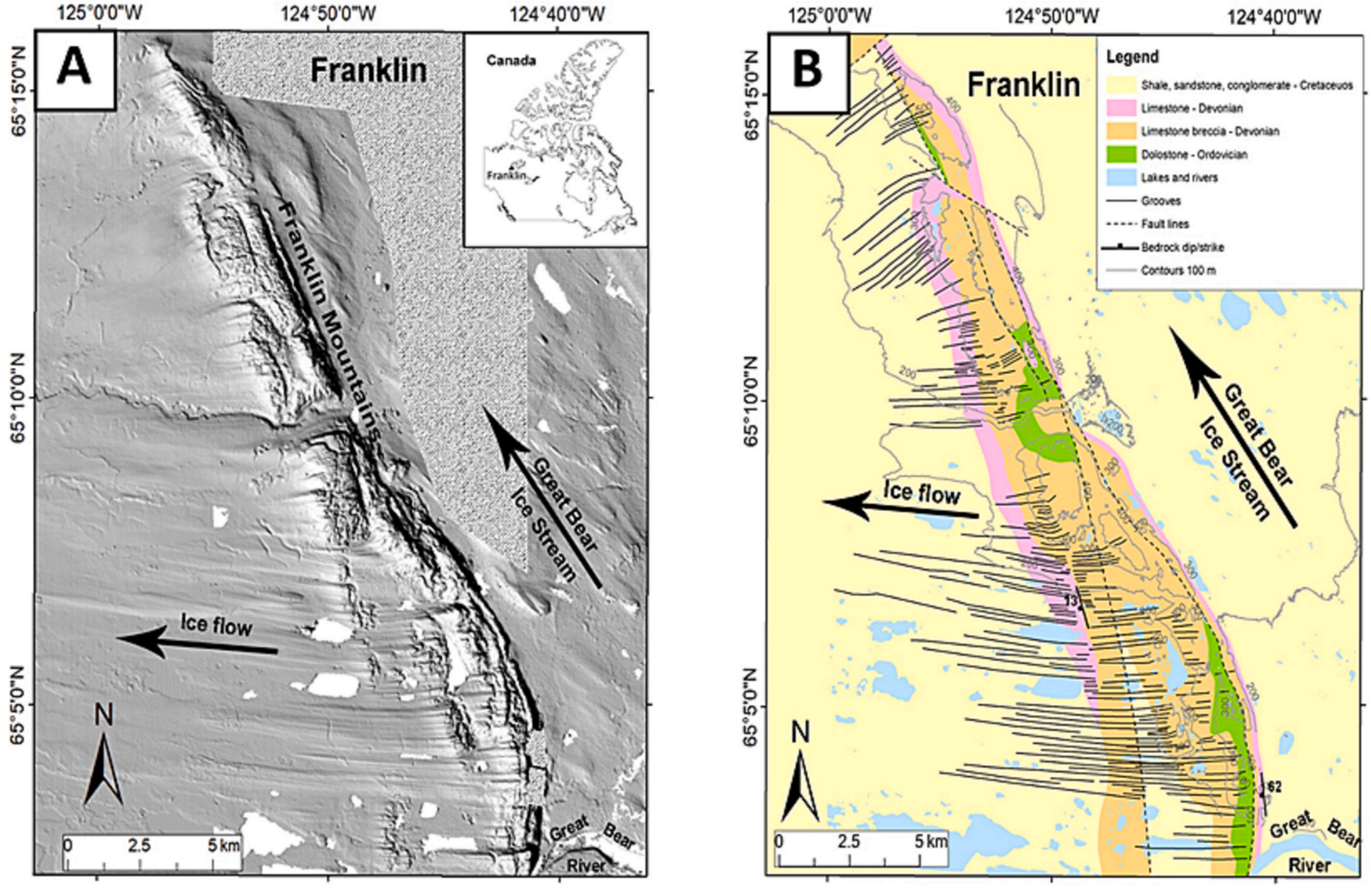

Fig. 6. Grooved terrain at the Franklin Mountains, Northwest Territories, Canada. The site lies halfway through the distance between the southwest termination of the Great Bear Lake and the Mackenzie River. The Franklin Mountains ridge is traversed by the Great Bear River. The BMGs here are the easternmost of the examples reported by Smith (1948): A) Arctic DEM extract of the area with an illumination angle at 45° from the south (textured fill represents information void and white areas are lakes or rivers). Inset map shows location of the Franklin site in the Northwest Territories; B) geology and geomorphology map showing the megagrooves and the main rock units (geology simplified from Fallas, 2013). The Devonian limestone breccia is commonly referred to as the Bear Rock Formation. Westerly ice flow resulted in the initiation of BMGs in the limestone breccia and across the Cretaceous bedrock to the west of the fault-controlled escarpment, where erodents were likely derived from the breccia and the dolostone outcrops.

with the assumptions that BMGs were formed through subglacial abrasion and may have been initiated on a land surface more susceptible to rapid erosion than the lithologies in which they currently occur. In doing so we attempt to answer our two crucial questions concerning the persistence of uni-directional glacier flow and BMG initiation on a land surface with substrate resistance/erodibility significantly different from that of today (antecedent conditions).

3.1. BMGs controlled by bedrock structure and lithology

The confinement of most BMG occurrences in specific areas to one lithology strongly indicates the susceptibility of that particular lithology to grooving, whether the original striators belonged to that specific rock type or were transported from adjacent lithologies. In this respect, it appears that primary bedrock control over BMG formation can be classified in two scenarios (Fig. 5). Firstly, structure and lithology can exert a primary control on BMG location through the occurrence of features such as steps in tilted strata, surface-parallel synclinal folds, folded strata of different resistance and multiple surface exposures of intrusive dykes (Newton et al., 2018). Secondly, the juxtaposition of lithologies of contrasting resistance, for example at fault or lithological boundaries, can result in the passage of relatively hard striator blocks plucked from fault scarps or faulted zones and then dragged across the softer bedrock located down-ice flow (Fig. 6).

In BMG case studies at Ullapool, Scotland (Bradwell et al., 2008), Isle Royale, Michigan, USA (Zumberge, 1955), Kaladar, Ontario and Cape Smith Belt, Ungava, Canada (Krabbendam and Bradwell, 2011), the host bedrock comprises layered and tilted rock strata (see Table 1 in Newton et al., 2018). The BMGs are parallel to strike and typically have a stepped, asymmetric profile. Lateral plucking during the last glaciation has been proposed as the most effective mechanism of erosion of these landforms (Zumberge, 1955; Krabbendam and Bradwell, 2011), although the age of BMG initiation is unknown. Considering the strong coincidence of linear bedrock structure and BMG alignment, it has been suggested that the grooves were initiated through differential weathering and denudation, controlled by the variable rock characteristics under subaerial conditions, presumably both preglacial and interglacial. This produced surface debris, concentrated over relatively weaker strata, which was then cleared by the later passage of ice while being used as abrading tools/erodents to further enhance groove profiles prior to fresh plucking (Krabbendam et al., 2016; Newton et al., 2018). Significantly, this type of bedrock control can be compared to the stepped, terraced profiles that occur in layered rocks in non-glaciated areas, where the debris resulting from the weathering of one layer ends up resting on the dip plane of the more resistant rock beneath (Aydin and Egeli, 2001; Nkpadobi et al., 2016). This strengthens the notion that BMGs in tilted rock strata were not so much initiated by glacial erosion as much as modified and/or enhanced by it.

The structure and lithology model depicted in Fig. 5 is particularly viable for layered rocks of varying lithology and resistance but is not

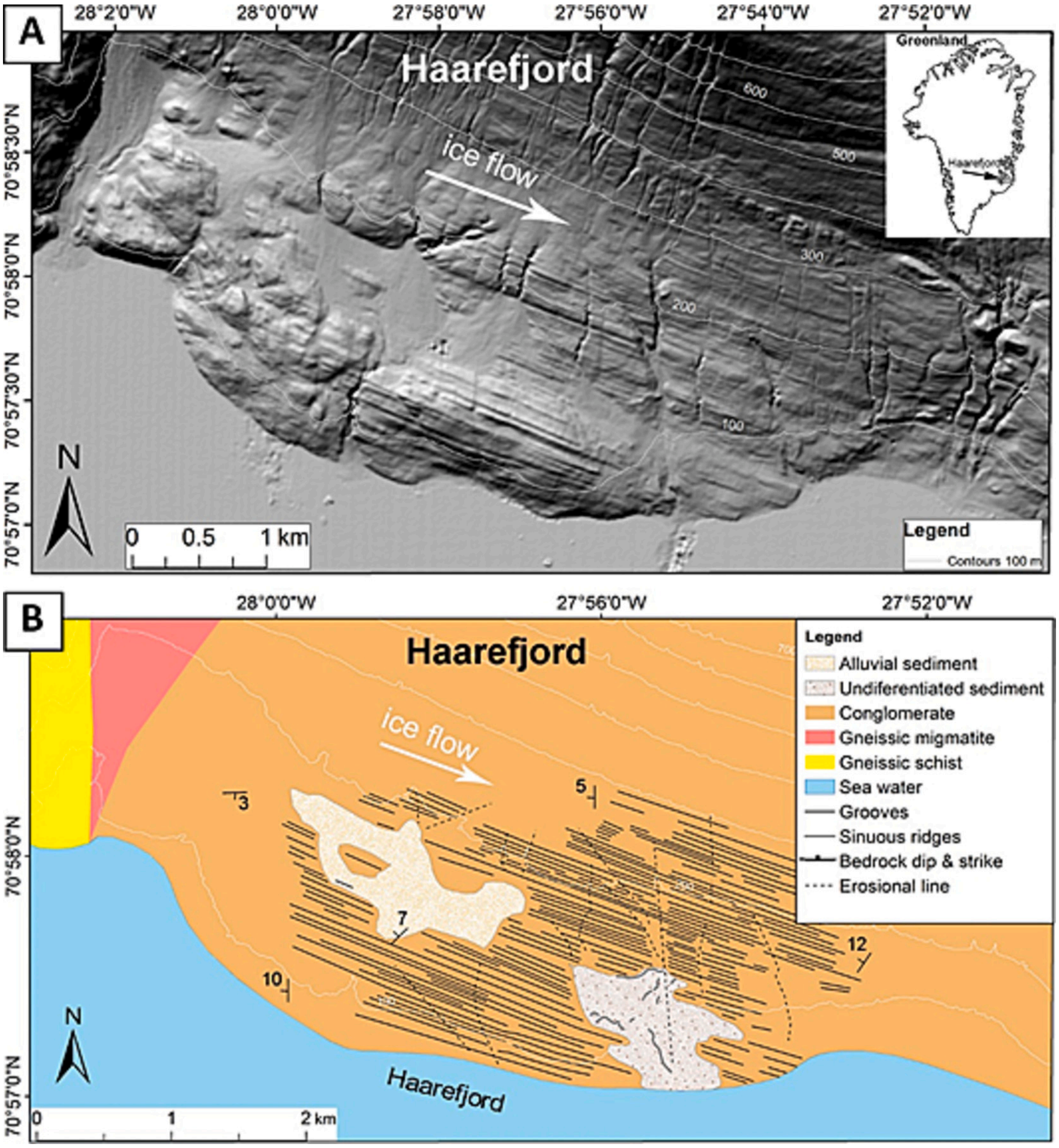

Fig. 7. Grooved terrain at Haarefjord, inner Scoresby Sund, East Greenland: A) Arctic DEM showing the BMGs with an illumination angle from the north; B) geology map of the area, compiled from Henriksen (1983) and the Geological Map of Greenland (2014).

directly applicable to settings like the Moine Schists at Ullapool, Scotland, characterised by remarkable lithological uniformity (Peach et al., 1907). The formation of stepped slope profiles prior to and/or during the Quaternary glaciations in such settings is more likely to have been conditioned by other bedrock characteristics such as joint and fracture zone spacing (Krabbendam and Glasser, 2011; Krabbendam and Bradwell, 2014). The consistency in the spacing of the Ullapool grooves (Krabbendam and Bradwell, 2011; Newton, 2022) supports this scenario in that spacing could represent a perpetuation of the structural regularities in the bedrock at initiation time, which had previously been exposed and weakened by pre-glacial weathering (cf. Turner, 1952; Wood, 1969; Fahey, 1981).

Examples of bedrock control through juxtaposition (Newton et al., 2018; Fig. 5) include the BMGs of inner Scoresby Sund, in East Greenland (Funder, 1978; Newton et al., 2018), the Vikna continental shelf off Norway (Ottesen et al., 2002) and the Franklin Mountains in NWT, Canada (Smith, 1948; Fig. 6). At Scoresby Sund and Vikna, more resistant gneissic or crystalline bedrock appears to have supplied the tools to groove the conglomerates or other sedimentary rocks, respectively, lying immediately down-ice flow, as suggested by the linear initiation zones situated a short distance down-flow from the lithological contact (Figs. 7 & 8). The BMGs at the Franklin Mountains initiate along a fault zone and are associated with crag-and-tails (Fig. 6). It is plausible that a linear outcrop of dolostone may have supplied the bedrock blocks used by the westerly-flowing ice to groove the softer limestones and Cretaceous sedimentary rocks located downflow. However, the rock outcrops that seed the crag-and-tails seem to be located on all rock types except those of Cretaceous age, suggesting that many grooves on Cretaceous lithologies might simply be the troughs between streamlined tails seeded at other lithological contacts up-flow. This complex juxtaposition of streamlined landforms is an example of an initiator scarp (Fig. 5), a feature that is common in softer bedrock and Quaternary materials in the Canadian Plains region and may relate to scarps facing either down or up ice (Evans et al., 2021; see also Bukhari et al., 2021). Clear evidence for juxtaposition at a regional scale is presented by Bukhari et al. (2021), who illustrate the impacts of crystalline Shield lithologies in erodent layers that eroded BMGs in less resistant Palaeozoic limestones located down-ice.

3.2. BMGs related to antecedent conditions

Where the role of bedrock structure in BMG production is less

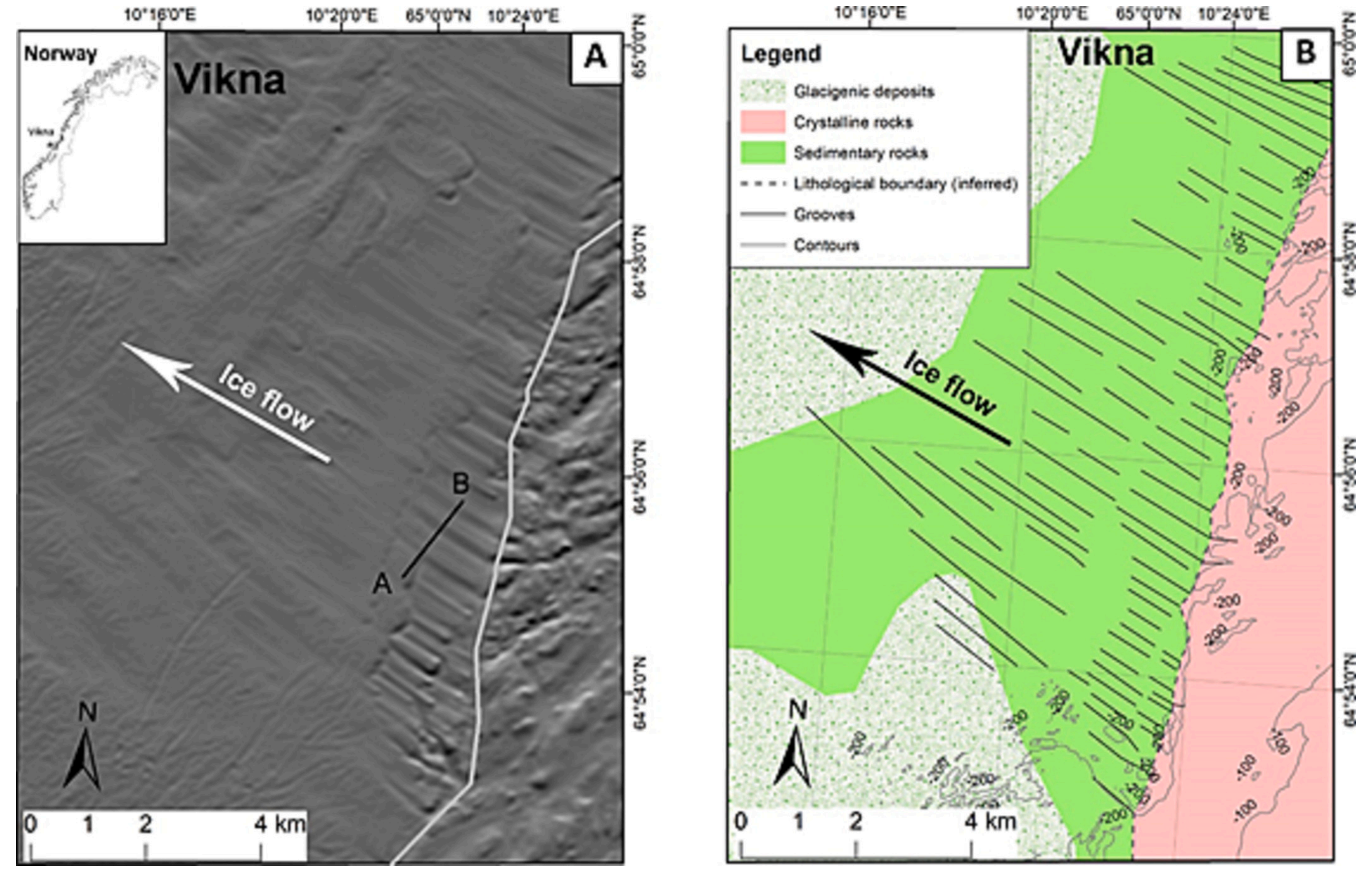

Fig. 8. The offshore BMGs of Vikna, on the west coast of Norway (after Ottesen et al., 2002): A) bathymetric DEM from the Norwegian Hydrographic Service, showing the BMGs and the lithological boundary between crystalline and sedimentary bedrock marked by grey line; B) geological map of the Vikna site.

convincing, it is likely that the pre-glacial landscape, or more precisely the antecedent conditions, are critical to explaining BMG initiation. We propose two models of antecedence that might explain BMG initiation in situations where they are likely of considerable age, namely through bedrock structure elimination, and through cannibalization and excavational deformation of regolith.

The model of bedrock structure elimination implies that BMG initiation took place in bedrock that was characterised by strong linear structures and/or the juxtaposition of strata of variable resistance to erosion, and that this bedrock was subsequently removed through repeat glaciations (Fig. 9). Our hypothetical example depicts sub-horizontally bedded strata typically observed in Carboniferous cyclothems, whereby more coherent limestones and sandstones lie over mudstones in repeat sequences. When it is near surface, the regularly spaced joints within the limestone develop into widening karst systems and dry valleys between glaciations. The exploitation of these inherent weaknesses by subglacial quarrying, aided by displacement along mudstone decollement zones, leads to the production of mega-blocks which are then dragged through the mudstone to form BMGs. The existence of such mega-blocks is well known in glacially streamlined bedrock terrain, prompting predictions that the appropriately-sized striators are consistent with the adjacent production of mega-striations (cf. Chapman and Putnam, 1951; Shulmeister, 1989; Dredge, 2000; Bukhari et al., 2021). The exploitation of linear structures, karst systems/collapsed caverns, and variably resistant strata on the preglacial land surface (stage 1; Fig. 9) led to the initiation of BMGs during early glaciations (e.g. stages 2 and 3), whereby glacial erosion, and abrasion in particular, would have been increasingly more effective in incipient grooves. This was due to Nobles and Weertman-type heat fluxes (Fig. 3A), concentrated meltwater erosion and the development of debris-rich basal ice stripes or longitudinal “debris streams” (cf. Boulton, 1975, 1979; Bradwell et al., 2008; Catania et al., 2005). Additionally, the continued exposure of resistant strata during glacial erosion over time could have resulted in punctuated replenishment of erodents (mega-blocks) and thereby ensured the continuous deepening of multiple generations of BMGs through the vertical stratigraphic sequence. Regularly spaced jointing, as might often occur in limestones for example, could conceivably control the size and shape of both erodent mega-blocks and remnant crags, thus explaining the relative regularity in groove width and spacing with distance down-ice flow. The lowering of the land surface by glacial erosion over longer timescales (stage 4) eventually removed those rocks and structures that were critical to groove initiation, superimposing BMGs onto the underlying, basement bedrock. BMG development can then continue even within rock of homogeneous character, particularly during glaciations when ice flow directions were similar to those of the BMG orientations. This situation would be best satisfied in settings where BMGs occupy prominent topographic lows but elsewhere any discordant ice flow directions might result in groove edge plucking, and hence widening, or infilling and masking by till blanket.

A similar form of bedrock structure elimination can be hypothesized to explain the BMGs at Elphin, Scotland (Fig. 10). These landforms occur in quartzite, which is a rock that is exceptionally resistant to abrasion (Krabbendam and Glasser, 2011). The rocks in the up-ice direction of the BMGs comprise mudstone, dolomite and limestone (Fig. 11) and are therefore softer than the quartzite. Consequently, any abrading tools transported by glacier flow are unlikely to have been hard enough to initiate grooves. The solution to this problem may lie in the local geological stratigraphy with quartzite being positioned below a thinner and softer layer of sandstone, commonly referred to as the Fucoid beds,

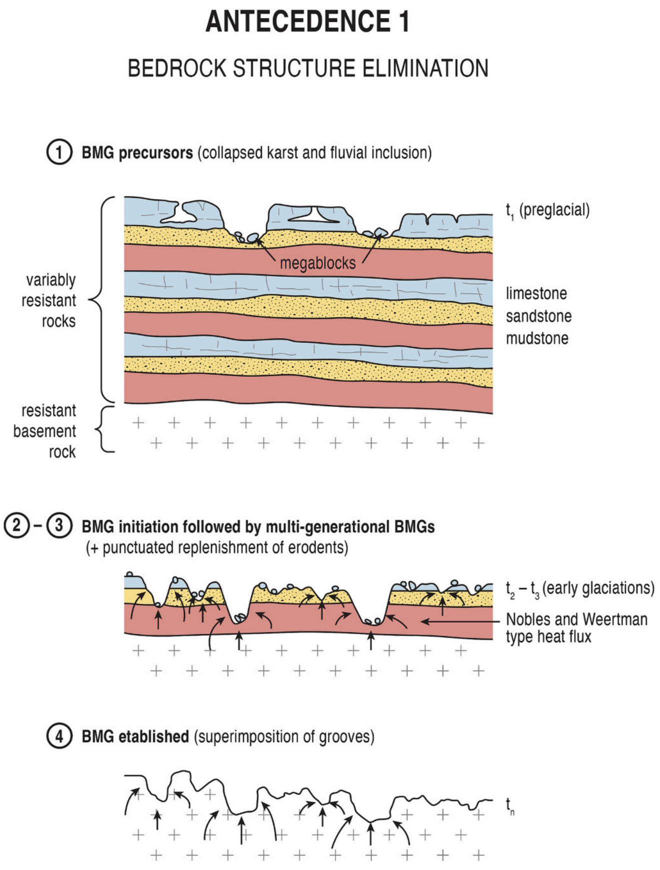

Fig. 9. Hypothetical case for bedrock structure elimination with sequential stages 1–4, based on strata with horizontally bedded sedimentary successions overlying more resistant basement rocks.

which would have originally extended westwards over the quartzite (Fig. 11). It is possible, therefore, that the BMGs, which now occur exclusively in quartzite, could have been initiated in less resistant mudstone. Once established, the grooves continued to deepen until their floors reached the lithological boundary with the quartzite, superimposing the subglacial surface and its associated linear concentrations of glacial erosional processes onto the more resistant bedrock, before the less resistant mudstone had been completely removed (Fig. 11).

3.3. *The role of pre-Quaternary regolith in bedrock grooving*

In order to appreciate the antecedent roles of cannibalization and excavational deformation of regolith, it is necessary to consider the first stages of erosion by an ice sheet advancing over a deeply weathered and regolith-covered terrain or etchplain (Hall and Sugden, 1987; Lidmar-Bergström, 1988, 1989, 1995; Nesbitt and Young, 1989; Lidmar-Bergström et al., 1997; Patterson and Boerboom, 1999; Taylor and Eggleton, 2001; Bonow, 2005; Olvmo et al., 2005; Hall et al., 2013; Sugden and Jamieson, 2018; Fig. 12). These have been summarised by Hall and Migoń (2010) as regolith stripping, tor demolition and block entrainment, and the removal of tor superstructures. Roches moutonnées then evolve from the glacial erosion and streamlining of exhumed tor stumps (Lindstrom, 1988). In areas that remained predominantly occupied by cold-based ice during the Quaternary glaciations, the remnants of the preglacial weathered regolith (saprolites) have survived (e.g. Setterholm and Morey, 1995; Hall and Sugden, 1987; Goodfellow, 2007; Fig. 13), thus providing clear and valuable illustrations of the antecedent conditions for the development of early glacial erosional landforms. The more widespread elimination of these potential early Quaternary conditions at the ice-bed interface has been demonstrated by recent re-evaluations, based on CRN dating, of the amount of glacial erosion of large areas of former ice sheet beds traditionally thought to be pre-Quaternary remnants (Andersen et al., 2018a, 2018b; Egholm et al., 2017).

The role of pre-Quaternary etchplains and their regolith/saprolite covers in subglacial processes and the dynamics of ice sheets has been demonstrated in an explanation of the mid-Pleistocene transition by Clark and Pollard (1998) and Roy et al. (2004). The mid-Pleistocene transition refers to a switch in ice sheet thicknesses at 0.8 Ma, at the time of change from 41 ka to 100 ka orbital forcing and related to the gradual stripping of saprolites and concomitant unroofing of unweathered bedrock. Applying this model of saprolite removal, Krabbendam and Bradwell (2014) propose that the regolith was stripped by early glaciations down to the preglacial weathering front, which presented an undulatory or rough subglacial surface because it was controlled by the pattern of fracture zones. This surface continued to reflect the undulatory nature of the weathering front even after numerous glaciations, because erosion was not particularly effective once the softer regolith had been removed (see also Sugden, 1976). The exception they hypothesize was in areas of fast glacier flow, where bedrock streamlining took place. Importantly, however, deep grooving would have been less likely in the more coherent bedrock than in the regolith/saprolite, so BMG initiation in the absence of bedrock structural and lithological control could conceivably have taken place in the regolith or lower saprolite (Fig. 12), which essentially acted as antecedent conditions (see Section 3.2).

This mode of BMG production is conveyed in our model (Fig. 12) in four stages, the first of which presents the likely preglacial scenario for deeply weathered pre-Quaternary land surfaces or etchplains. Depending on a combination of predominant climate, bedrock and near-surface environmental conditions, the relatively hot climates of early Tertiary (early Palaeogene) times had created various types of regolith cover. Importantly, regoliths comprise patchworks of coherent and incoherent materials characterised by either: a) relatively resistant cap rocks overlying less resistant parent soils (laterites and duricrusts); or b) saprolites developed by bedrock weathering profiles, in which relatively resistant corestones were distributed through a matrix of variably disaggregated and chemically weathered parent-rock material.

3.3.1. *Laterites and duricrusts*

Typical examples of the nature of preglacial laterites and duricrusts, both also known as cuirasse (Maignien, 1966) and plinthites, are depicted in Fig. 12 based upon modern exemplars summarised by Thomas (1974). They are lateritic soil horizons that become indurated once exposed by the stripping of soil and can occur on valley sides due to fluvial incision or over wider areas to ultimately form mesas or tablelands. Plinthites in particular can become ironstone, a hard, iron-rich rock which can generate efficient striators once entrained into glacial flow. Fluvial dissection of laterite surfaces creates specific geomorphological features that ultimately constitute the Tertiary land surface inherited by Quaternary glacial processes. Thomas (1974) summarises the most significant of these as cliffs (breakaways) that produce laterite rubble, bench or terrace-like features, and valley floor pavements of re-cemented laterite fragments. Our conceptual model in Fig. 12 highlights the importance of laterite rubble and plucked fragments of plinthite within the precursor subglacial deforming layers created out of mobilized regolith during early glaciations. The importance of rubble terrain in subglacial mega-groove formation has been clearly illustrated by Bukhari et al. (2021) in relatively hard rocks and by Evans et al. (2021) in relatively soft lithologies. A similar origin of BMGs is envisaged for situations where laterite blocks were dragged through regolith and across underlying bedrock as deforming layers thinned due to excavational deformation (Hart et al., 1990; Eyles et al., 2016). This is effectively groove-ploughing per se (sensu Baligh, 1972; Boulton, 1975, 1976, 1982; Boulton et al., 1979; Tulaczyk, 1999; Fischer et al., 2001; Evans et al., 2021), whereby the soft substratum is scored by erodent

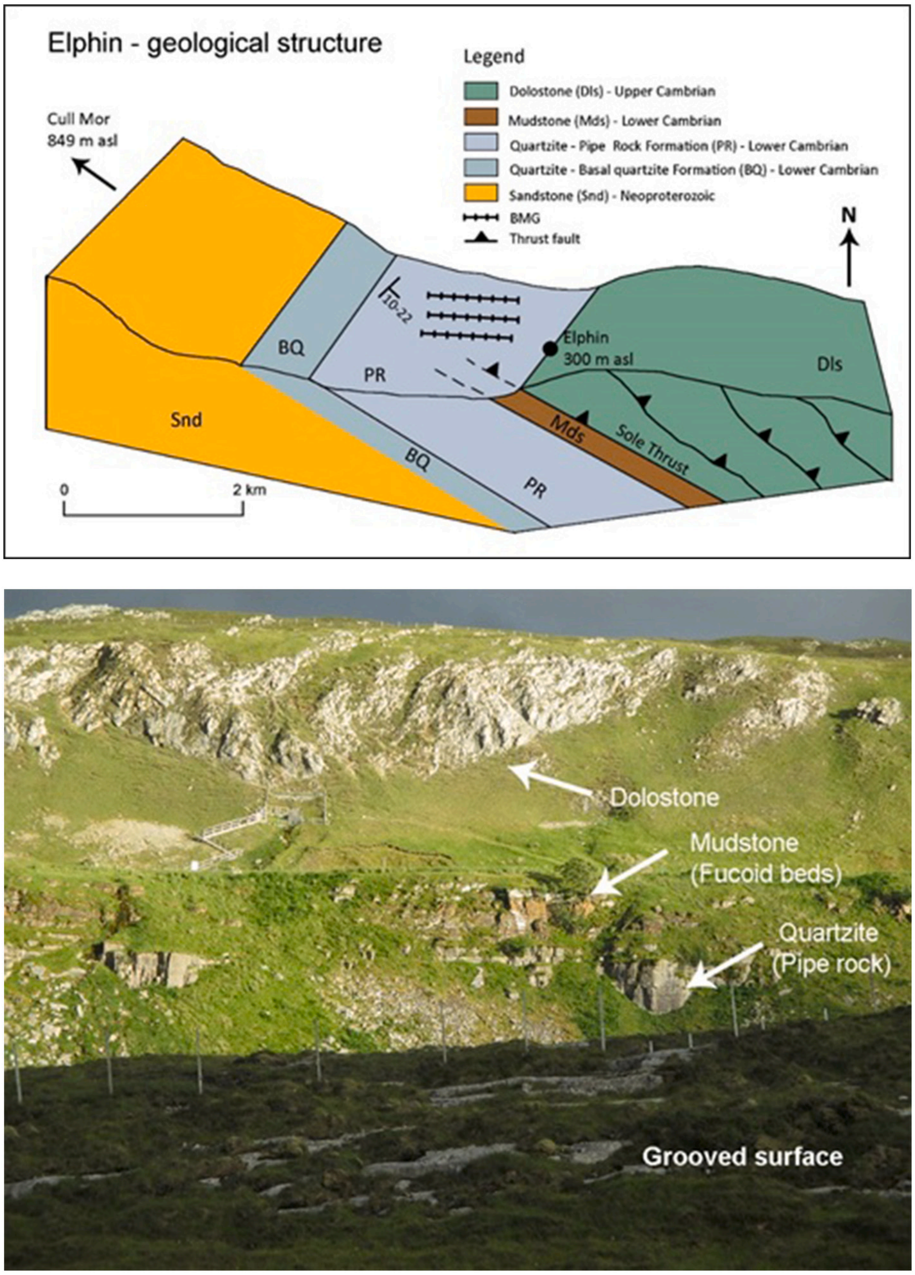

Fig. 10. The bedrock structure and lithology in the area of the grooved terrain at Elphin, Scotland, UK; the diagram was redrawn and simplified from the geological map of the British Geological Survey (2008). Note the inferred extension of the mudstone layer (dark brown) over the Pipe Rock formation (PR) in which the BMGs currently occur. The photograph shows the geological stratigraphy above the grooved terrain. Note the present-day grooved surface of quartzite lying well below the mudstone layer (Fucoid beds) in which the BMGs may have been initiated.

boulders (sensu Eyles et al., 2016). This is especially effective in settings where the parent bedrock is relatively soft, but BMGs could also be superimposed on relatively resistant substrates via a similar process to that of bedrock structure elimination outlined above (see Section 3.2). In plan view, the antecedent control of laterite landforms may be reflected in a uniform pattern of BMG emergence at a narrow initiation zone (Fig. 12). Crag-and-tail features may also persist where tablelands were formerly located.

3.3.2. *Saprolites*

Preglacial saprolites, especially in crystalline lithologies, are typically associated with inselbergs (bornhardts and tors) that represent the more coherent areas within weathered bedrock profiles (Fig. 13A). The various degrees of tor modification and preservation (Fig. 13B) in glaciated terrain is widely acknowledged, as is the removal of surrounding regolith and the liberation of upper corestones by glacier ice (e.g. Johansson et al., 2001; André, 2004; Hall and Phillips, 2006; Phillips et al., 2006; Hall and Sugden, 2007; Hall and Migoń, 2010). Our model of saprolite control on BMG initiation (Fig. 12) entertains the concept introduced above that upper regolith (saprolite) layers were mobilized by overriding ice during early glaciations to form precursor subglacial deforming layers. Importantly, we also acknowledge that Pliocene-early Pleistocene environments were cold, and hence tor and saprolite landscapes were likely subject to periglacial and permafrost processes that would have arranged surface materials into patterned features such as boulder-fronted lobes and blockstreams (e.g. Clark, 1972; Evans et al., 2017; Ballantyne, 2018). This shows scope for preglacial alignment of the future striators, which may account for the relative regularity in the spacing of BMGs.

The vertical profiles of saprolites vary in depth depending on bedrock lithology but commonly display similar zonation, as depicted in stage 1 on Fig. 12, based on the schemes of Nesbitt and Young (1989) and Setterholm and Morey (1995). Above the unaltered bedrock (Zone I), lie zones of slightly and moderately weathered bedrock (Zones II and III) or saprock. This passes upwards into highly weathered and disintegrated rock (Zone IV) and then completely weathered material

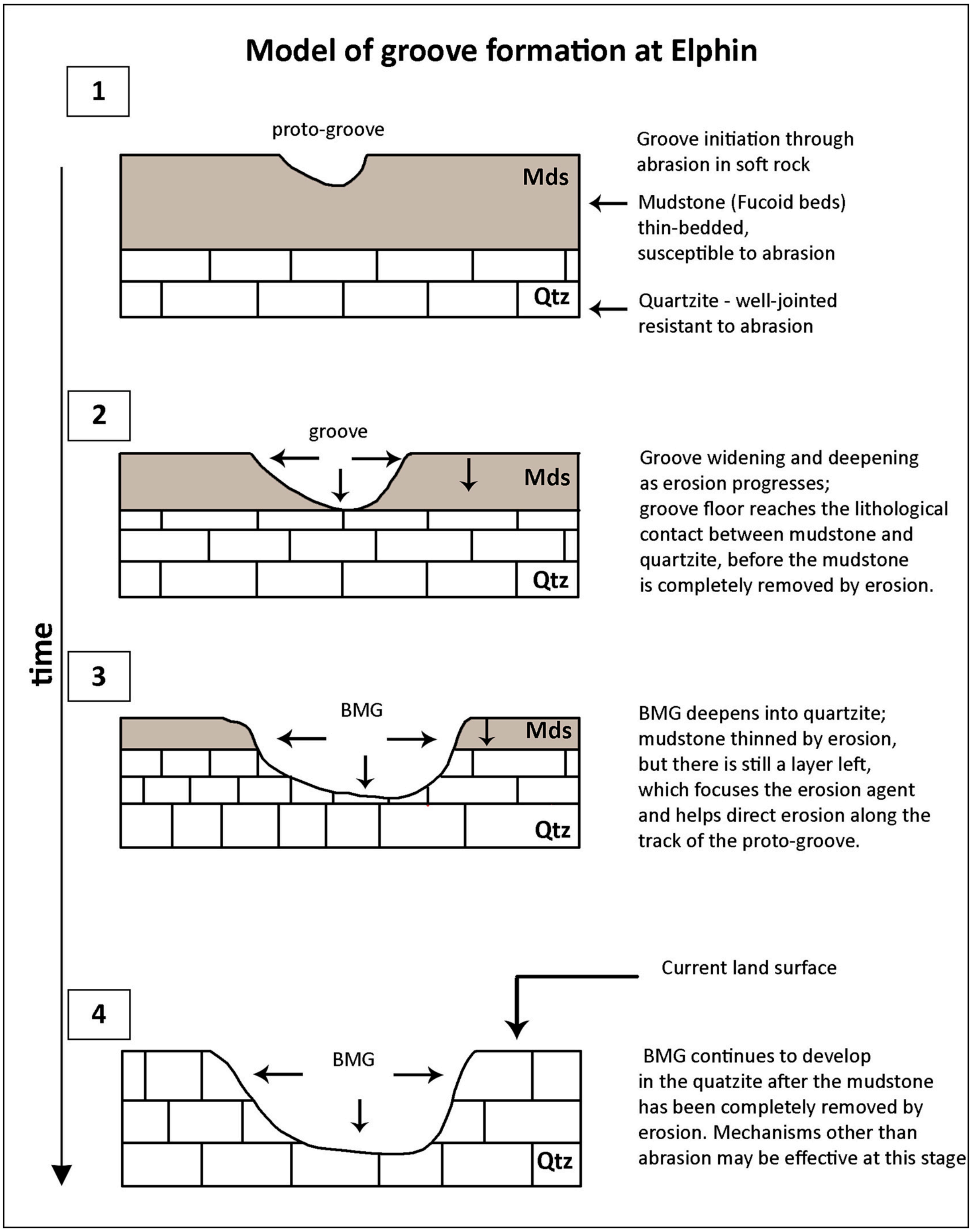

Fig. 11. Schematic diagram of the antecedence hypothesis of BMG formation at Elphin, Scotland, UK through bedrock structure elimination.

(Zone V) capped by soil (Zone VI). The terms lower and upper saprolite are also used for Zones III to V, and regardless of bedrock type, contain vertically decreasing numbers and sizes of corestones, whose characteristics are related to the structures of the unweathered rock (Fig. 13c). The soil and weathered material, and in some cases the upper saprolite, would be modified and re-arranged into periglacial and permafrost features during the onset of cold climate conditions. Later mobilization of this periglacially-altered zone as well as the upper saprolite by overriding ice would have created a subglacial deforming layer in which small corestones would act as typical till boulders, creating grooves, lodgement pavements and stoss-and-lee flutings when they arrived at the ice-bed interface. Depletion of the deforming layer by excavational deformation would then have given rise to the liberation (effectively plucking) of larger corestones in the lower saprolite, turning tors into roches moutonnées (stage 2 and 3 in Fig. 12). At this stage the large liberated corestones would plough through the lower saprolite, becoming erodents/mega-striators and thereby creating incipient BMGs. Because the erodents would be derived from tor superstructures, BMG initiation points would be relatively random in contrast to the initiator zones (scarps and bumps) created by disaggregating laterites and duricrusts (stages 3 and 4 in Fig. 12). This is consistent with descriptions of hard bed landform assemblages in areas of palaeo-ice fast flow onset, often comprising a variety of forms in which BMGs occur interspersed with both positive, glacially-modified bedrock eminences (e.g. roches moutonnées, crag-and-tails, rock drumlins, mega-ridges) as well as with negative bedrock forms (e.g. bedrock channels, canyons, p-forms and

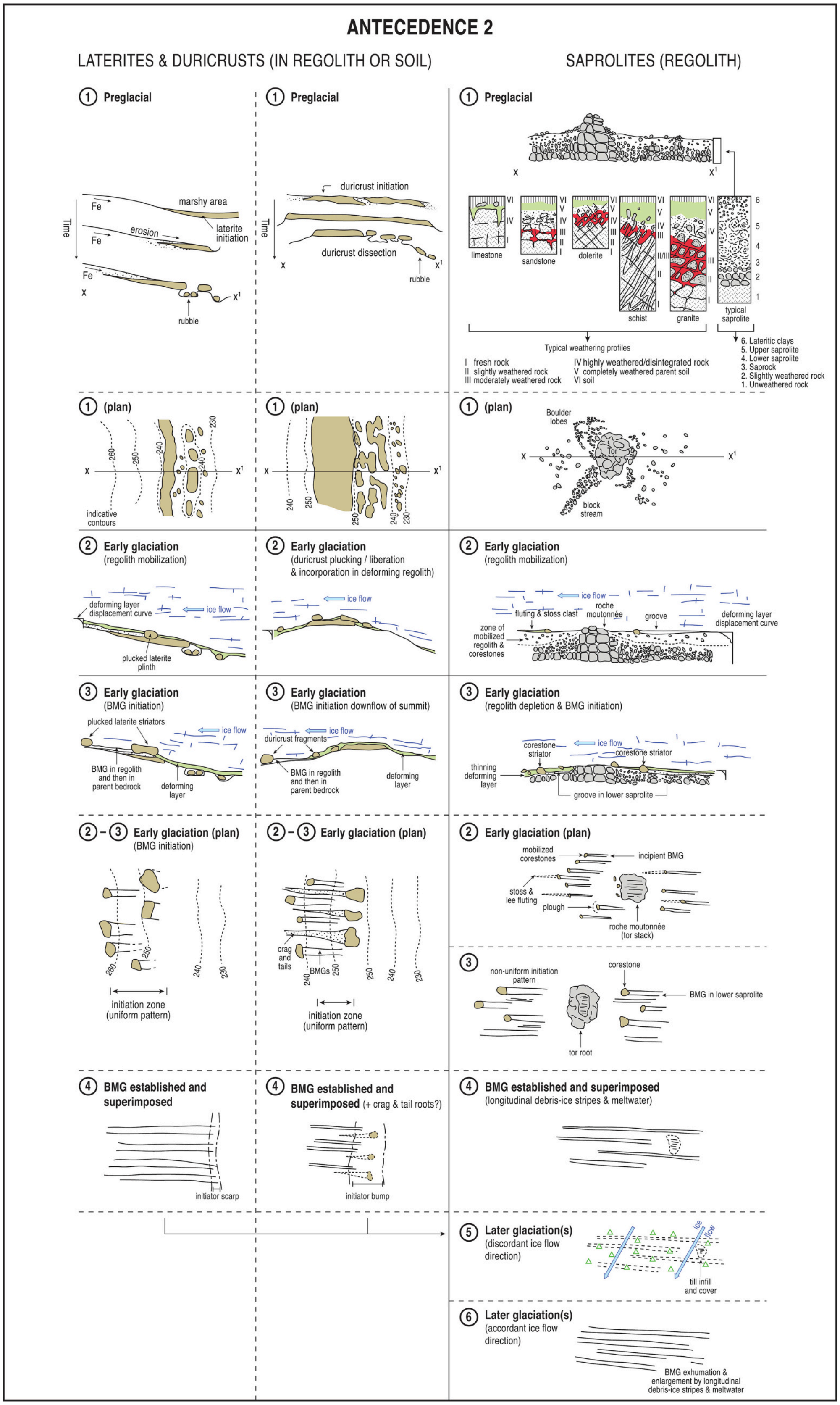

Fig. 12. Hypothetical cases of antecedence in relation to preglacial land surfaces (after Thomas, 1974; Nesbitt and Young, 1989, Setterholm and Morey, 1995).

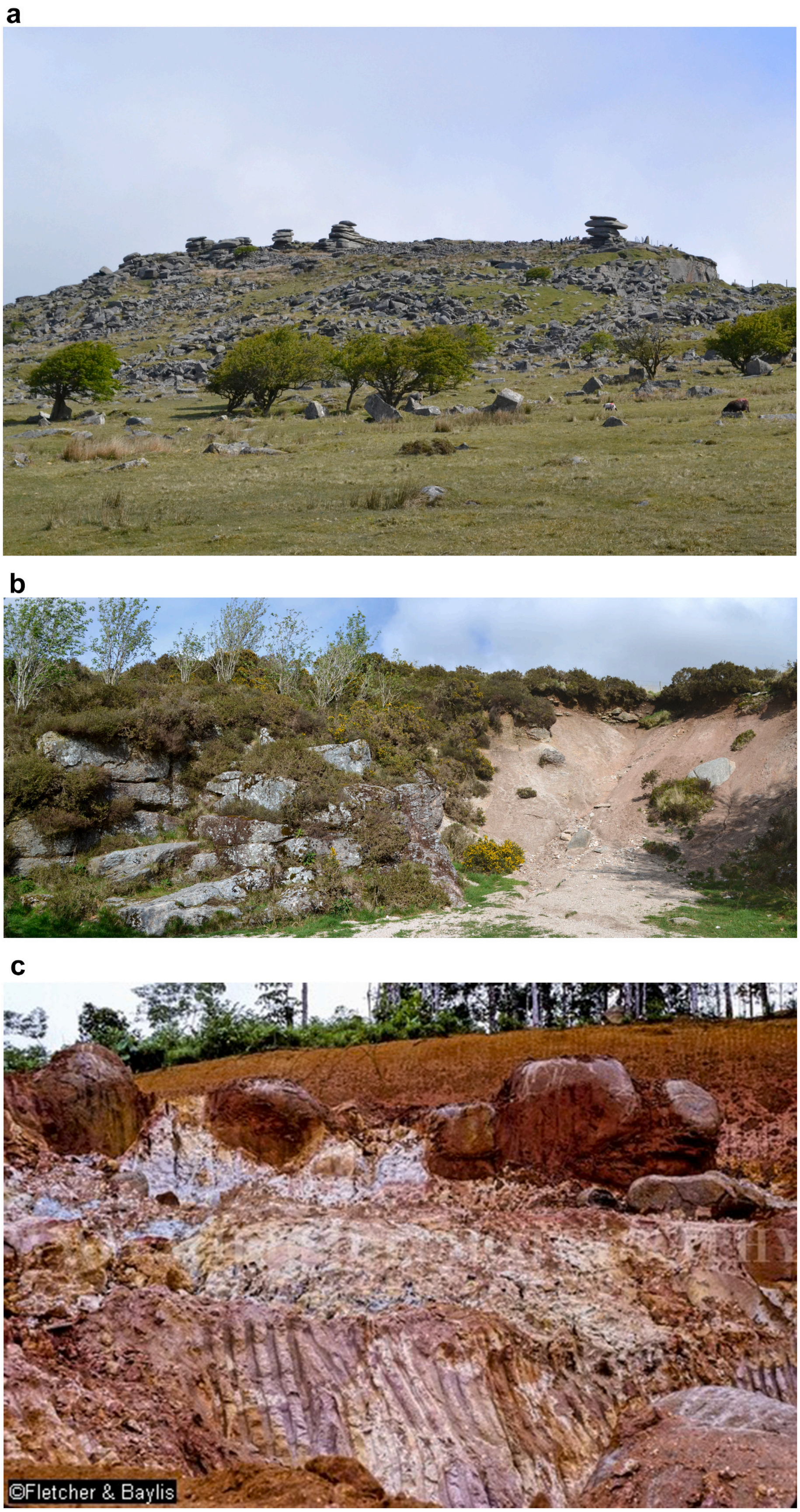

Fig. 13. Examples representative of preglacial land surfaces: A) etchplain type land surface covered by tor and blockfield, affected by Quaternary periglacial and permafrost processes, Rough Tor, Bodmin Moor, UK; B) remnant granite saprolite with corestones and tor root, with upper stratigraphy recording Quaternary periglacial slope reworking, Two Bridges, Dartmoor, UK; C) corestones in tropical saprolite, lateritic soil on granite, Malaysia (from www.wildsidephotography.ca; with permission from Fletcher and Baylis).

depressions). The lack of a coherent landsystem representative for fast-flow onset zones could be due exactly to this topographic variation derived from site-specific bedrock-weathering interactions, which remain encoded in the present-day landscape, despite general streamlining by repeat glaciations. This presumed pre-glacial surface roughness is probably also reflected in the wide scatter of data for BMG length/width and length/depth relationships as derived from individual sites (Newton et al., 2023 and Supplementary Information 1 therein). In the context of ice-stream landsystems, the often less-organised nature of hard bed assemblages is in contrast with the more consistent, well-defined, and somewhat predictable, patterns of soft bed landform assemblages of the middle and lower reaches of ice-stream landsystems, defined by long trains of MSGLs (Stokes and Clark, 2001; Spagnolo et al., 2014).

Important in the antecedent hypothesis, regardless of the exact mode of operation, is the persistence of BMGs once initiated (stages 4–6 in Fig. 12). The presumption is that BMGs become superimposed and established on more coherent or resistant substrates, effectively becoming the focus of abrasion and meltwater drainage during later glaciations, especially when ice flow direction is accordant with BMG axes. Discordant ice flow would either pluck and thereby widen BMGs in cases of till depletion (excavational deformation) or infill and seal off BMGs in cases of till advection towards the site (constructional deformation). This model of long timescale evolution of BMGs implies that they are hybrid glacial erosional features not unlike traditional p-forms.

A further long-timescale implication of the antecedent hypothesis is the likelihood that the optimum conditions for BMG initiation and development may migrate spatially over time. This concept was first introduced for the regional glaciation of North America by White (1972, 1988) as the “arc of exhumation”, or the westerly and southerly margin attained by the migration of the crystalline Shield-Palaeozoic boundary zone (S-PBz of Bukhari et al., 2021). This boundary represents the present position of repeated down-ice stripping of the Palaeozoic limestones from the crystalline basement, where over-deepened basins are presently located, as well as the location of most North American BMGs (see Fig. 2 in Newton et al., 2018). Migration of this boundary over time represents also the migration of an initiator zone for plucked mega-rafts (i.e. the limestone blocks subsequently dragged over less resistant strata), as well as the zone of increased grooving of Palaeozoic and younger rocks by crystalline blocks removed from the Shield to the north.

4. Conclusions

In explaining the diagnostic characteristics of BMGs, we propose four hypothetical scenarios for BMG initiation that are consistent with the assumptions that BMGs are formed through subglacial abrasion and, in situations where they are independent of bedrock controls, have been initiated on a land surface more susceptible to rapid erosion. Also important are working assumptions that BMG initiation requires the impact of relatively soft substrates by harder mega-striators or mega-blocks that have been derived from nearby outcrops.

Two scenarios for BMG development relate to primary bedrock control. The first simply invokes subglacial abrasion in the accentuation of pre-existing, major bedrock structure and lithological changes, whereby steps in tilted layered rocks, flow-parallel folded strata of different resistance and multiple surface occurrence of intrusive dykes control the pattern of glacial erosion. In situations where such structural alignments are ice-flow parallel it is entirely conceivable that BMGs may be generated relatively quickly. The second scenario relates to the juxtaposition of lithologies of contrasting resistance, especially at linear lithological boundaries or major faults. Here the passage of relatively hard striator blocks are plucked from fault scarps/fault zones, or derived from more resistant lithologies up-ice, and then dragged across the softer bedrock located down-ice flow. Again, BMGs may be generated relatively quickly in such settings.

For BMG initiation apparently unrelated to any structural control, we consider precursor or antecedent conditions and the recognition that BMGs are likely of considerable antiquity. For this we propose two further scenarios. Firstly, bedrock structure elimination explains how BMGs were initiated in bedrock characterised by strong linear structures and/or the juxtaposition of strata of variable resistance to erosion, followed by removal of this bedrock by repeated glacial erosion. Secondly, we envisage the cannibalization and excavational deformation of regolith, involving the mobilization of cemented cap rocks and corestones and their use as erodents in incipient and early subglacial deforming layers developed in pre-Quaternary regoliths; this is effectively groove-ploughing per se. This proposed role for pre-Quaternary regolith in BMG initiation implies that at least some BMGs may date back to the beginning of the Quaternary.

Once grooves have been initiated, their accentuation and growth is ensured because they continue to be the focus of subglacial erosion processes, providing they are not sealed off from the ice-bed interface by accreting till. These processes include meltwater erosion as well as abrasion by flow-parallel, debris-rich basal ice stripes (“debris streams”) controlled by alternating ice-bed interface conditions. Groove development could potentially be paused if the sediment infill occurs as a result of changes in ice-flow direction. This would protect a BMG from removal by erosion and ensure a resumption of development once ice-flow once again became (sub-)parallel to the groove and the sediment infill was cleared. While erosion is operational, a groove will continue to deepen as long as the lowering of the intervening ridges takes place at a slower rate. The implication is that, once established, BMGs may be difficult to erase, and also explains BMG preservation beneath ice sheets that underwent shifting flow directions.

The high preservation potential of individual BMGs is difficult to reconcile with their apparent scarcity relative to other subglacial landforms. If there was widespread scope for the existence of pre-cursor conditions necessary to BMG initiation and the BMGs are able to survive shifting ice-flow directions throughout multiple glacial cycles, then why are there so few BMGs? The answer to this question may lie in the expanding databases of geophysical evidence from the vast areas of streamlined glaciated terrain, which are typically composed of unconsolidated sediment but appear to overlie grooved bedrock.

Finally, in terms of future research directions, we must pose the question: how can antecedence be tested? Clearly in order for precursor mega-blocks/rafts, such as corestones and cemented cap rocks, to be viable as mega-striators they need to be observed in situ, preferably in positions related to stages 2 or 3 of our antecedence models. Some in situ exposures have been identified by Evans et al. (2021) in soft bedrock and sediment-cored MSGLs that have been grooved by bedrock mega-rafts, thereby demonstrating the groove-ploughing genesis of such landforms during the last glaciation. However, groove ploughing by the earliest subglacial deforming layers and erodents in pre-Quaternary regolith remains to be similarly verified and tested. An obvious starting point is the reappraisal of areas where pre-Quaternary regolith has been partly mobilized and redistributed by glaciations but the source remains identifiable in the field, for example on the Fennoscandian Shield bedrock (Olvmo et al., 2005), where Hall et al. (2013) describe fluted bedrock terrain, rectilinear depressions with typical BMG dimensions and large, locally-derived granite boulders. It is therefore not unlikely that such areas may host examples of damage trails and rectilinear-aligned erodents which represent proto-BMGs.

Declaration of competing interest

The authors have no conflicts of interest to report.

Data availability

Data will be made available on request.

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