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Glacial conditioning and paraglacial sediment reworking in Glen Croe (the Rest and be Thankful), western Scotland

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ABSTRACT

Glen Croe, located near the western edge of the Loch Lomond and Trossachs National Park, is a well-known landslide hazard site in Scotland. Debris flows have repeatedly closed the A83 Rest and be Thankful road that passes through the valley, and considerable investment has been directed towards hazard risk reduction. However, little research has focused on the former glaciation and paraglacial response that have played an important role in governing current landscape processes at the site. This paper addresses the knowledge gap by investigating the glacial processes that have shaped and conditioned Glen Croe, and pathways that have characterised subsequent paraglacial sediment transfer. The large-scale valley form results from watershed breaching and interaction between glacier erosion and paraglacial rock slope failures. The distribution of thick glacigenic sediment is conditioned by deposition at former lateral ice margins, which was influenced by topography. Sediment reworking has resulted in accumulation of debris cones and alluvial fans in the upper part of the catchment, and growth of a delta at the outlet. Spatial connectivity mapping supports an interpretation whereby upper Glen Croe is poorly connected to the valley outlet, influencing sediment storage. In contrast, slopes in the lower part of Glen Croe are well connected. Sediment distribution in Glen Croe fits within the context of glaciated valley and paraglacial landsystems, allowing an understanding of sources and transport pathways. In upland infrastructure corridors this type of information is potentially helpful for understanding how landscapes might be affected by renewed sediment reworking under altered threshold conditions.

1. Introduction

In upland landscapes erosion by temperate glaciers acts to deepen valleys and modify their catchments (Linton, 1949; Sudgen and John, 1976; Glasser and Bennett, 2004). Glacier deposition can lay down sequences of till and moraines across valleys floors and high on valley sides (Benn et al., 2003; Benn and Evans, 2010). The retreat of glacier ice, therefore, tends to expose steepened and lengthened rock slopes and metastable sediment sources, which are prone to modification by post-glacial slope and fluvial processes. In such circumstances, the subsequent redistribution of rock and sediment by these later non-glacial processes is considered to be part of a 'paraglacial response' in the sense that they are significantly conditioned by the preceding glaciation(s) and deglaciation (Church and Ryder, 1972; Ballantyne, 2002a, 2003).

Paraglacial rock slope failures (RSFs) can affect rock masses that have become progressively weakened as a result of rock stress redistribution and joint development caused by glacial erosion and loading and unloading of ice masses (McColl, 2012; Grämiger et al., 2017). Although some RSFs have accompanied or immediately followed deglaciation, substantial populations of large-scale paraglacial RSFs have been found to post-date deglaciation by more than 1000 years, and up to several millennia (McColl, 2012; Pánek, 2019). In these cases the lag time has been related to the time frame required for rock mass weakening, or triggering by extrinsic factors such as enhanced seismic activity or climatic fluctuations (e.g. Ivy-Ochs et al., 2009; Le Roux et al., 2009; Ballantyne et al., 2014). Paraglacial reworking of sediment-mantled slopes is dominated by debris flow processes, particularly where the slope angle exceeds 30° (Ballantyne, 2002a; Curry, 2000a). In contrast to the lag time associated with RSF activity, the redistribution of sediment on slopes is most active in the decades and centuries following ice retreat (Ballantyne, 2002a, b; 2003). However, some authors have noted that the transition of sediment-mantled slopes towards non-glacial conditions can also extend over millennial time scales, with later phases of delayed or

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renewed reworking (Ballantyne and Whittington, 1999; Curry, 2000b; Ballantyne, 2002b). These secondary phases of sediment transfer have been linked to the alteration of threshold conditions, influenced by processes such as vegetation change, pedogenesis, or anthropogenic activity (which can all modify slope sediment strength) as well as an increase in the frequency and/or intensity of extreme rainfall events (Innes, 1983; Brooks and Richards (1993); Brooks et al. (1995); Curry, 2000b). Consequently, the adjustment of both rock and sediment-mantled slopes that have been conditioned by glaciation can remain a potential hazard for centuries, or even millennia, after ice withdrawal (Keiler et al., 2010; Kellerer-Pirklbauer et al. (2010); Zanoner et al., 2017).

This paper investigates how past glaciation has shaped and conditioned Glen Croe, in western Scotland (Fig. 1), and identifies the processes and pathways that have characterised subsequent sediment transfer. Although Glen Croe was last deglaciated at the end of the Loch Lomond Readvance at approximately 11.5 ka BP (Lowe et al., 2019), the effects of ongoing slope adjustment by debris flow processes are well documented (Sparkes et al., 2017; Winter et al., 2017; McMillan and Holt, 2019). These have resulted in numerous closures of the A83 trunk road (Fig. 2), which provides a transport link to a population of more than 30,000 people and is used on average by 4000 vehicles each day (Jacobs, 2013). These road closures have been associated with considerable economic impacts in the area because of the large vulnerability shadow (area over which impacts are experienced) that is cast when the route is not passable (Winter et al., 2018). For example, the losses associated with a debris flow event in 2007 were estimated to be in the region of £80k per day, totalling £1.2 million over the 15 day closure (Postance et al., 2017).

Despite the widespread recognition of the slope instability hazard in Glen Croe, and the considerable investment that has been targeted at hazard risk reduction, very little research has been published on the glacial conditioning (and the paraglacial response) that has played such an important role in governing ongoing landscape processes. However, this kind of information is

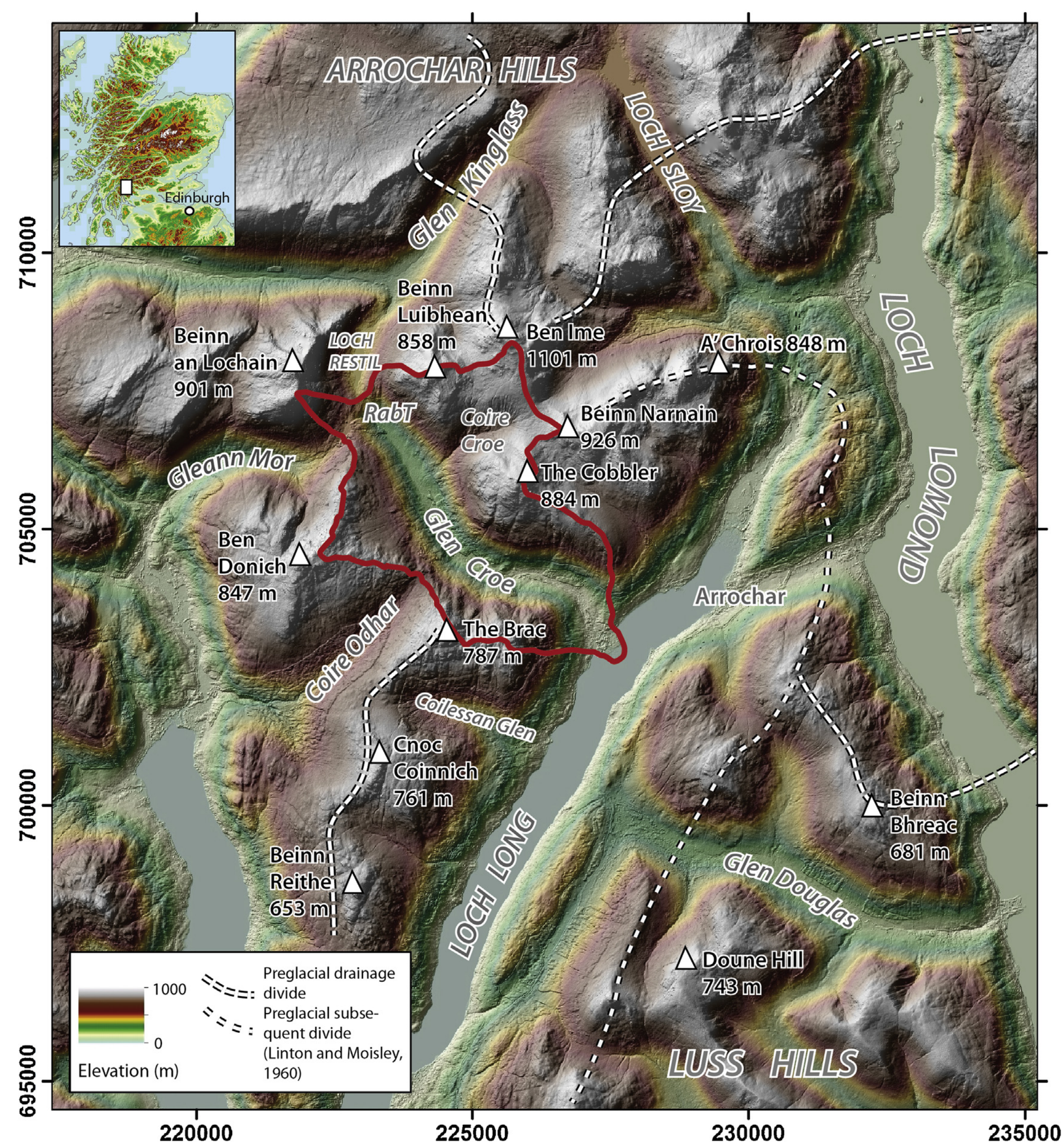

Fig. 1. Location of Glen Croe (solid red outline) in the western Scottish Highlands, and localities named in the text. RabT = the Rest and be Thankful pass. The dashed white lines mark the preglacial drainage divides that were inferred by Linton and Moisley (1960). Hill-shaded surface model built from Intermap Technologies NEXTMap Britain elevation data.

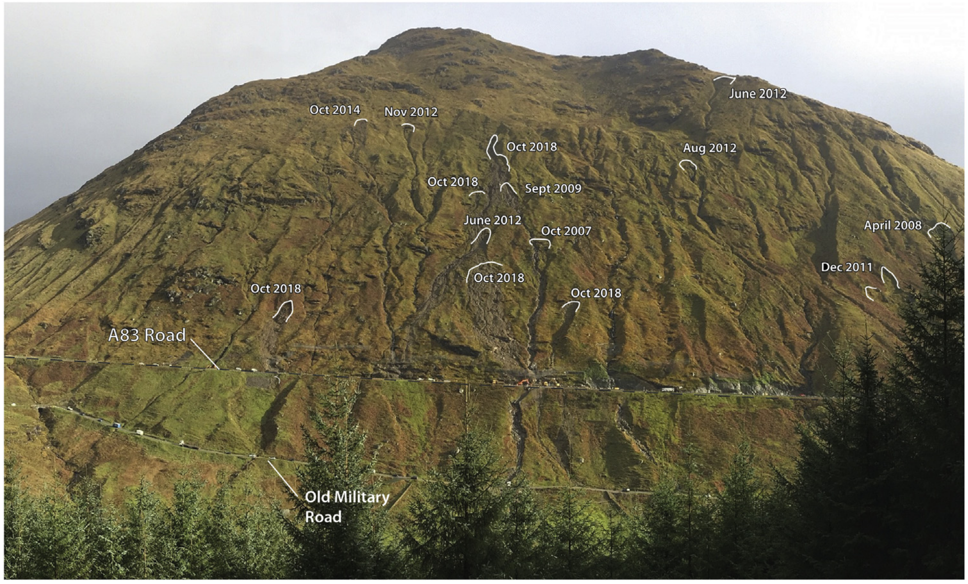

Fig. 2. Photograph taken on 17th October 2018, looking eastward across Glen Croe towards the south-western slope of Beinn Luibhean. The A83 road (which was closed at the time), and the Old Military Road below it (which can be used as a relief road) are visible. White lines indicate head scarps from recent debris flow events. A further debris flow occurred at a site to the south-east of the photograph in January 2020.

vital for understanding how the landscape has evolved, and can be beneficial for the development of conceptual ground models that are relevant for engineering investigations (Giles et al., 2017).

2. Setting and previous research

Glen Croe is located in the Arrochar Hills in the western Scottish Highlands (Fig. 1). The central axis of Glen Croe rises from sea level in the south-east, where the valley feeds into Loch Long, to 246 m above sea level (a.s.l.) at the Rest and be Thankful Pass in the north-west (Fig. 3). The catchment is flanked by several peaks that exceed 700 m in elevation, the highest of which is Beinn Ime at 1011 m a.s.l. The bedrock in the area primarily comprises Neoproterozoic schistose psammites and semipelites belonging to the Beinn Bheula Schist Formation of the Southern Highland Group (BGS, 1987). Regionally these rocks are part of the 'Flat Beds', which form the inverted limb of the Tay Nappe (Stephenson and Gould, 1995). In general, the foliation in the vicinity of Glen Croe is gently north-westward dipping or subhorizontal and undulating (Fig. 3B). Coire Croe, on the north-eastern side of Glen Croe, is formed over a Lower Devonian diorite intrusion (BGS, 1987).

The Arrochar hills are located at the junction of a network of inferred preglacial drainage divides that were mapped by Linton and Moisley (1960) (Fig. 1). These authors suggested that the preglacial catchments on the north-western side of Loch Long may have once drained through the Luss Hills towards the area that is now occupied by Loch Lomond, with Coilessan Glen forming the original headwaters of Glen Douglas (Fig. 1). Gregory (1916) and Linton and Moisley (1960) both considered that Loch Long may have formed as a fault-guided preglacial valley that captured drainage that previously flowed from the Arrochar hills towards the Luss Hills. Indeed, Gregory (1916) suggested that the preglacial

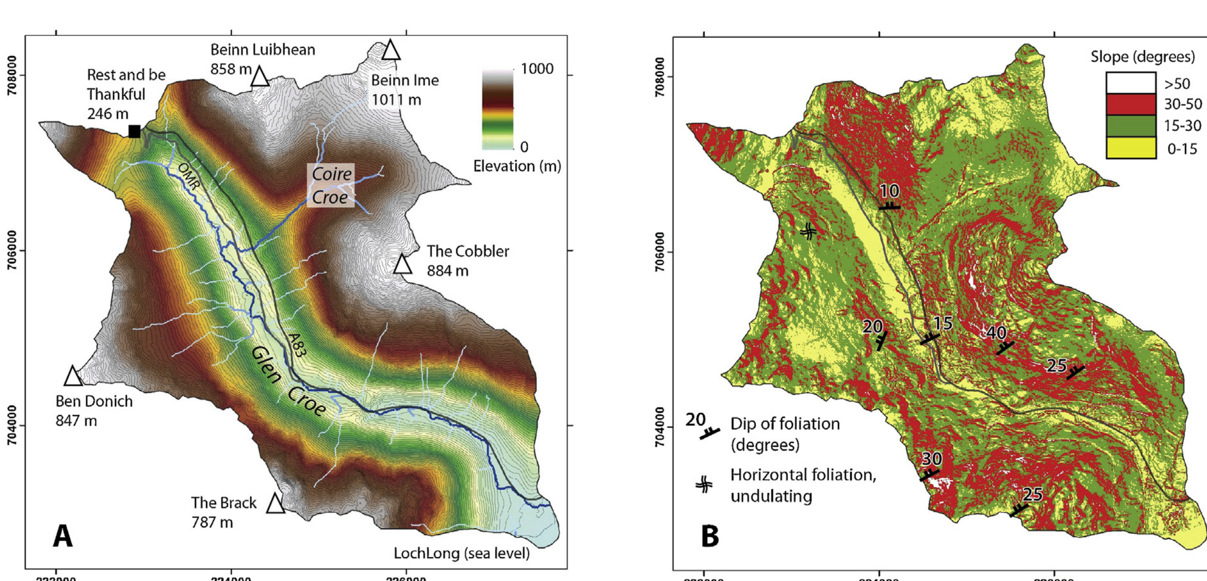

Fig. 3. A. Topography of the Glen Croe catchment. OMR = Old Military Road. B. Slope angle classes within the Glen Croe catchment. Selected structural measurements shown in B are taken from BGS (1987). The elevation model and the slope model are derived from Intermap Technologies NEXTMap Britain elevation data.

fluvial incision was so effective that Glen Croe was eroded down to sea-level at that time, citing the sinuous form of the lower valley as evidence, and that any subsequent glacial modification was limited. Linton and Moisley (1960), however, concluded that significant glacial erosion had affected the area, with the excavation of several major valley breaches. Similarly, in an analysis of valley network connections, Haynes (1977) interpreted the Arrochar area as a region that had experienced a high level of glacial modification.

Little work has been carried out thus far on former glaciation within Glen Croe. Prior to 1.1. Ma, glaciation of western Scotland is likely to have been restricted to development of small mountain ice caps with some tidewater margins (Lee et al., 2012). Valley glaciers may have developed within the Arrochar area at that time. The region is likely to have been completely submerged during the five ice-sheet scale glaciations that are thought to have periodically affected northern Britain from ~450 ka PB onwards, with the most recent being the main Late Devensian glaciation (Lee et al., 2012). Glacier ice last occupied Glen Croe during the Loch Lomond Readvance, which ended around 11.5 ka BP (Lowe et al., 2019). At that time a mountain ice cap developed over the western highlands and a valley glacier likely flowed through Glen Croe feeding a south-west-flowing tidewater glacier that reached the southern end of Loch Long (Golledge, 2010).

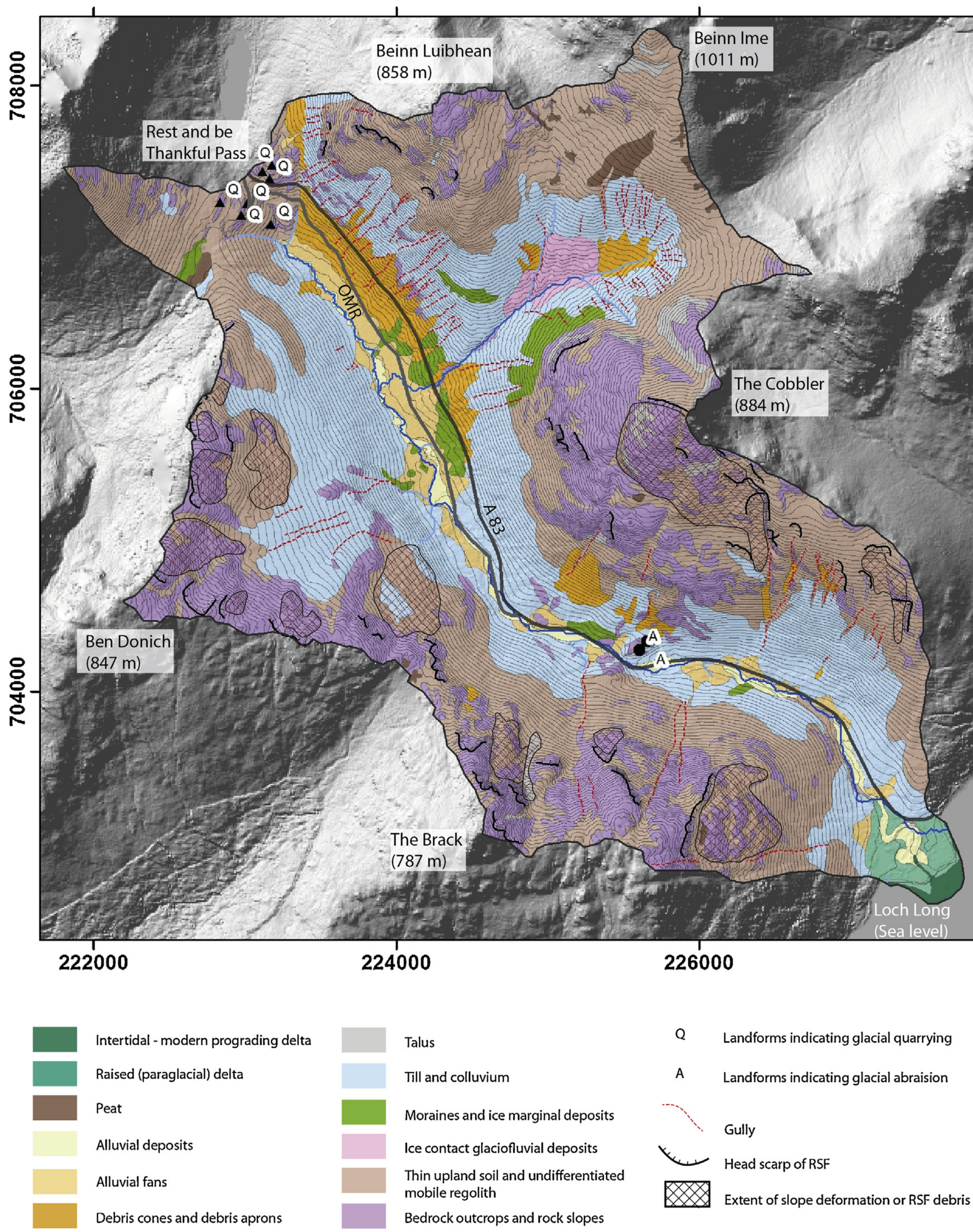

Fig. 4. Geomorphological map of the Glen Croe catchment. The background hill shaded surface model is built from Intermap Technologies NEXTMap Britain elevation data.

Jarman (2006, 2009) has suggested that the Arrochar area possesses one of the densest clusters of RSFs in Britain. This cluster incorporates a number of RSFs that have been mapped in Glen Croe itself, including a 0.84 km^2 mountain slope deformation on the Cobbler (Jarman, 2004). In a recent synthesis of British RSFs, Jarman and Harrison (2019) have proposed that the RSF clusters are predominantly paraglacial, and are associated with areas where concentrated erosion of bedrock (linked to glacial breaching of former watersheds) has caused intensified stress differentials in the vicinity of valley side slopes.

Present day geomorphic activity in Glen Croe is dominated by debris flows that have been triggered by high rainfall events. Average annual rainfall in the area exceeds 3000 mm yr^{-1} (Met Office, 2019), and debris flows in Glen Croe have recently been observed on a regular basis (Winter and Corby, 2012; Sparkes et al., 2017; McMillan and Holt, 2019). Since 2007 debris flow activity has been particularly concentrated on the steep south-western slopes of Beinn Luibhean (Figs. 2,3) above the A83 road near the Rest and be Thankful pass (Winter and Corby, 2012). Over a recent 5 year period this landslide activity resulted in an average of two road closures annually (Sparkes et al., 2017). The location is now considered to be the one of the highest ranked debris flow hazard sites in Scotland (Winter et al., 2009).

3. Methods

Geomorphological mapping (Fig. 4) was carried out in order to investigate the nature of the glacial conditioning of the landscape in Glen Croe, and the subsequent processes that have acted to redistribute and store rock and sediment. A combined field-based and remote sensing approach was used to map the presence and location of different landforms and larger-scale landscape features. Field surveys included the description of natural sections in order to aid characterisation of the internal composition of different deposits. Desk-based remote sensing investigation used derivatives generated from the NEXTMap Britain elevation dataset (e.g. hill shade, slope, and flow accumulation models), and georeferenced colour aerial photographs. The landforms and deposits that were mapped include: landforms of glacial erosion; landforms relating to RSFs and slope deformations; landforms and sediments from glacial deposition (moraines, till, ice contact deposits); and landforms and deposits related to sediment reworking and storage (e.g. gullies, debris cones and debris aprons, alluvial fans, deltas).

Spatial connectivity analysis was performed to investigate how the current topography acts to promote the evacuation or storage of sediment in Glen Croe. Borselli et al. (2008) defined the index of connectivity *(IC)* as an estimate of the relative potential for sediment converging at any point in a catchment to reach a given sink, so that:

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \tag{1}$$

where D_{up} and D_{dn} are the upslope and downslope components of connectivity, respectively. In this work the mouth of Glen Croe, where it joins Loch Long, is considered the sediment 'sink'. The component D_{up} describes the potential for sediment from an upslope source to be routed down to a reference point and is estimated from:

$$D_{up} = \overline{W}\ \overline{S}\sqrt{A} \tag{2}$$

where $\overline{W}$ and $\overline{S}$ are an average weighting factor (dimensionless) and the average slope (m/m), respectively, over the upslope contributing area, A (m^2). Borselli et al. (2008) originally used W to account for impedance to runoff resulting from vegetation type and land use. More recently, Cavalli et al. (2013) suggested that a surface roughness index *RI* is an appropriate way to objectively quantify surface characteristics that can influence runoff in alpine catchments. In this study the approach of Cavalli et al. (2013) was followed, whereby *RI* was calculated as the standard deviation of the residual topography. The residual topography was computed as the difference between the original elevation model (5 m resolution) and a smoothed version derived from averaged elevation values over a 5 × 5 moving window. The standard deviation was also taken over a 5 × 5 moving window, so that:

$$RI = \sqrt{\frac{\sum_{i=1}^{25}(x_i - x_m)^2}{25}} \tag{3}$$

where x_i is the residual topography value at a raster cell and x_m is the mean of the 25 values in the moving window. In order to weight slope and roughness equally in the connectivity map, the slope values were assigned an upper limit of 1 m/m and *RI* was converted to the weighting factor using:

$$W = 1 - \left(\frac{RI}{RI_{MAX}}\right) \tag{4}$$

The downslope component of connectivity D_{dn} describes flow path of sediment from the given reference point to a designated sink (in this case the catchment outlet):

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i} \tag{5}$$

where d_i, W_i and S_i are the length (m), the weighting factor and the slope gradient, respectively, through the *i*th cell along the flow path. In this study the D-infinity algorithm (Tarboton, 1997) was implemented using the TauDEM 5.0 tool (http://hydrology.usu.edu/taudem/taudem5/), in order to characterise flow direction.

4. Glacial erosion and valley development

4.1. Landforms of glacial erosion

4.1.1. Description

The location of Glen Croe within the context of the wider valley network around Arrochar is shown in Fig. 1. At the valley scale, Glen Croe cuts through a prominent 12-km-long SW-NE aligned ridge that connects the peaks of Beinn Reithe, Cnoc Coinnich, the Brac, the Cobbler, Beinn Narnain, and A' Chrois (Figs. 1,5). This ridge line forms the headwaters of four adjacent south-east trending valleys that are located to the north and south of Glen Croe. The hypsometry (proportion of surface area at different elevations) of Glen Croe differs markedly from these adjacent, and more V-shaped, hanging valleys that also feed into Loch Long (Fig. 5). Glen Croe possesses a hypsometric integral (area under a plot of normalised elevation against normalised cumulative area) of 0.39, which is considerably lower than the adjacent valleys and is a result its larger surface area at lower relative elevations.

The south-west trending Coire Odhar, which begins approximately half way along Glen Croe, has no headwall, and the upper reaches of that valley begin abruptly at the south-western margin of the Glen Croe catchment (Figs. 1,5). Similarly, Coire Croe on the north-eastern margin of the Glen Croe catchment has the appearance of a hanging valley, with a steep base level drop from approximately 300 m a.s.l. down to 110 m a.s.l. at the floor of Glen Croe. The head of Glen Croe itself is located at a junction where the absence of valley headwalls enables Glen Croe, Gleann Mor, and the Bealach an Easian Duibh (occupied by Loch Restil) to intersect (Figs. 1,5).

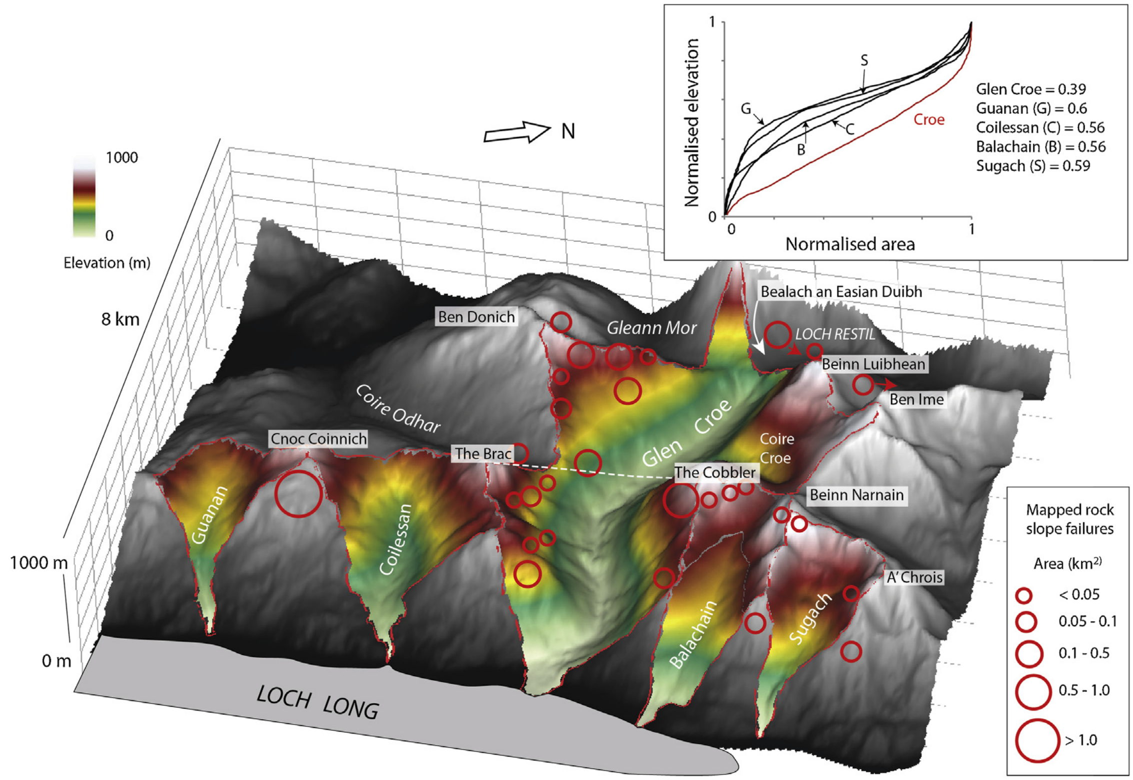

Fig. 5. Oblique view of the Glen Croe catchment and surrounding area. The dashed white line shows where the former ridge line is interpreted to have continued, prior to glacial breaching. This would connect the boundary of the pre-glacial Loch Long watershed suggested by Linton and Moisley (1960). Mapped rock slope failures are shown by the red circles. The inset plot shows the hypsometry of Glen Croe (red line) and the neighbouring catchments (black lines). The elevation model is derived from NEXTMap Britain elevation data.

At the head of Glen Croe, a prominent 50-m-high bedrock outcrop possesses a moderately dipping (~20 degrees) north-western-side, which approximately follows the foliation within the schistose bedrock (Fig. 6A). The steeper south-eastern-side has a stepped appearance where the height of steps (1–3 m) corresponds to the spacing of well-developed north-west dipping discontinuity planes in the bedrock. The south-eastern-side of the outcrop forms a convexity in the down-valley profile and leads into steeply sloping ground that descends more than 150 m down to the valley floor (Fig. 6B). Numerous rock exposures on this south-east facing slope again reveal a stepped appearance where cavities with sharp-edged steps have formed along the discontinuity planes (Fig. 6C).

These bedrock exposures contrast with a cross valley bedrock ridge located 3 km further down Glen Croe between the Brac and the Cobbler, where the south-east facing sides are much smoother suggesting that it has been affected by different processes (Fig. 7). Here scalloped surfaces (0.5–1.5 m in diameter) and rounded open linear depressions are present on the down-valley facing slopes (Fig. 7A). Although steps (approximately 3–5 m high) are evident (Fig. 7B), these are less obvious and have more rounded edges than at the head of the valley.

4.1.2. Interpretation

Prolonged erosion by valley glaciers can skew hypsometric curves towards lower elevations, leading to smaller hypsometric integrals (Brocklehurst and Whipple, 2004). The hypsometry of Glen Croe is consistent with enhanced erosion by valley glaciers and contrasts with the adjacent south-east trending valleys, which possess higher hypsometric integrals (Fig. 5). The valley pattern suggests that Glen Croe is a glacially breached valley, which has cut through a ridge line that once connected the Cobbler and the Brack (Figs.1,5). The following lines of evidence support this interpretation. First, the former head wall and headwaters of Coire Odhar, which must previously have been located to the north-east, have been removed indicating a substantial amount of erosion in the vicinity of the interpreted breach. Similarly, the ~200 m base level drop from Coire Croe down to the floor of Glen Croe suggests that deep erosion has occurred up valley from the breach. Indeed one possible scenario might be that Coire Croe once fed into Coire Odhar prior to the glacial deepening of Glen Croe and breaching of the ridge line (Fig. 1,5). Second, the breached section of Glen Croe is narrower and flanked by steeper and rougher slopes (Figs. 3B and 4), which is consistent with characteristics observed from other breached watersheds in the area (Linton and Moisley, 1960). Third, the valley floor at this location is divided by a cross valley bedrock ridge which is characterised by landforms of glacial erosion (Fig. 7, discussed below). This cross valley ridge may represent an eroded remnant of the ridge line that once connected the Brack and the Cobbler. A breach through the centre of Glen Croe itself is not depicted in the recent maps of Jarman and Harrison (2019), but is consistent with the general cluster of glacially breached valleys identified in that study and in earlier work (Haynes, 1977; Jarman, 2006).

Headward expansion of glaciated valleys is recognised as a mechanism of watershed breaching (Hall and Jarman, 2004), and can propagate through enhanced erosion rates that occur over steeper valley head slopes (Shuster et al., 2011). This process is likely to have affected Glen Croe, extending the valley head back to the Rest and be Thankful pass (Fig. 3). Under the current valley configuration, ice flow into the head of Glen Croe is likely to have been derived from locally accumulated ice below Beinn an Lochain, and also ice directed southward through the fault-guided Glen Kinglass, which would at times have drained over the Bealach an

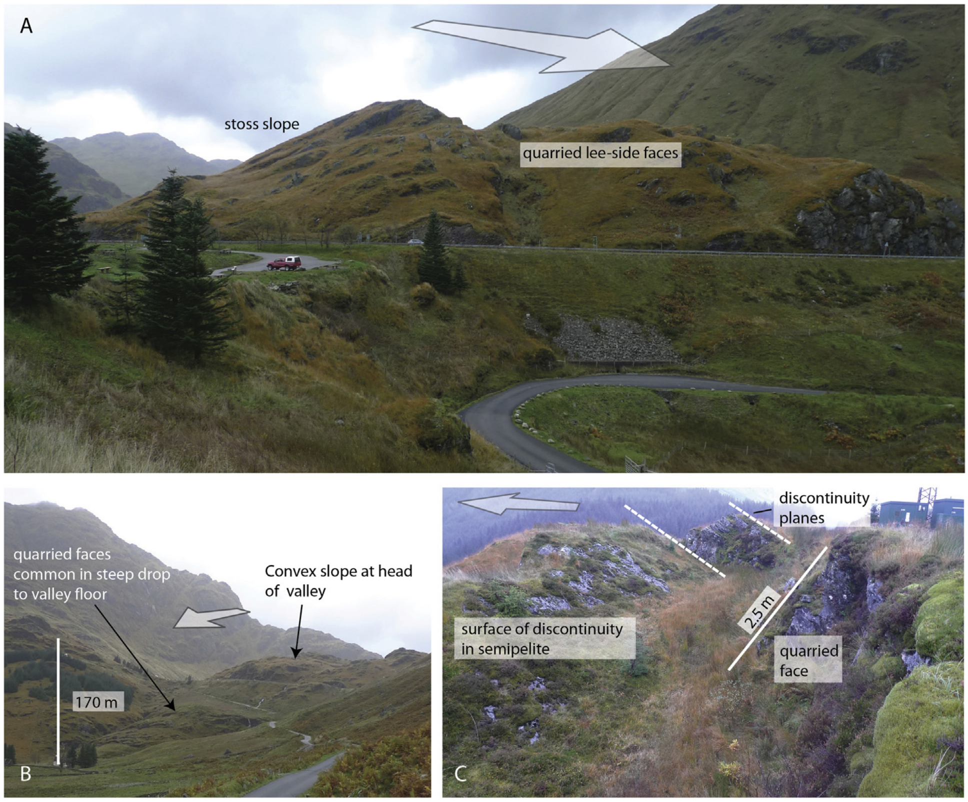

Fig. 6. A. View looking north-east showing smoothed stoss and quarried lee faces on an ice moulded bedrock outcrop at the Rest and be Thankful car park at the head of Glen Croe. B. View from the Old Military Road looking up the valley towards the drop from the head of Glen Croe to the valley floor. C. Cavity formation within dipping semipelites at the head of Glen Croe. White arrows show the interpreted former ice flow direction.

Fig. 7. A. Scalloped rock surfaces on the lee side of an outcrop which forms part of the bedrock ridge close to the valley floor of Glen Croe, between the Brac and the Cobbler. B. View looking south-west across the ridge. White arrows show the interpreted former ice flow direction.

Easian Duibh (Loch Restil) (Figs. 1,5). Numerical simulations suggest that basal sliding could have contributed considerably to ice velocity in this area under glacier configurations similar in nature to the Loch Lomond Readvance (Golledge et al., 2009). Therefore, basal ice velocity is likely to have been relatively rapid as it accelerated over the steep terrain at the valley head, while the more elevated position of Rest and be Thankful pass would have resulted in a thinner cover of glacier ice with low effective basal stresses. These conditions favour glacial quarrying, which is an efficient erosional process whereby cavities form over irregular surfaces concentrating stresses where the ice contacts bedrock ledges and promoting fracturing (Hallet, 1996). The bedrock structure at the Rest and be Thankful pass, with north-westward dipping psammites and semipelites, would have formed an optimum 'stepped' surface over which quarrying operates (Hallet, 1996), and facilitated the formation of cavities beneath the ice (Fig. 6C). The existing discontinuities in the bedrock would have significantly aided fracture propagation, which has been identified as the rate-limiting process in glacial quarrying (Hallet, 1996). Blocks could then have been efficiently removed and transported within the ice, contributing to the headward expansion of Glen Croe.

Rapid variation in water pressure may have enhanced the process of quarrying by causing fluctuations in the pressure being exerted on rock ledges, and by contributing to fracture propagation (hydrofracturing) in rock (e.g. Hooke, 1991, 2005). Hooke (2005) has suggested that a positive feedback mechanism can act on convex topography, such as that at the Rest and be Thankful Pass (Fig. 6B). In this process, crevassing occurs over the convexity that leads into the slope, enabling localised water input to the glacier bed, and in turn enhancing quarrying on the down-side of the convexity. This has the effect of amplifying the convex feature causing further crevassing and reinforcing the process.

In contrast to the quarried surfaces at the valley head, smooth and scalloped surfaces (p-forms) are present on the down-valley facing side of the bedrock ridge in lower Glen Croe (Fig. 7A). Higher effective basal stresses caused by increased thickness of ice in the lower valley would have restricted cavity formation, maintaining greater ice-rock contact over the lee side of obstacles. In this way, erosion by abrasion or by sediment-charged subglacial meltwater (Glasser and Bennett, 2004), would have played a greater role at this location during latter phases of the last glaciation. However, the smooth stepped profile on the proximal side of the ridge suggests that quarrying could also have operated at some earlier stage.

Overall, the present-day valley configuration and the interpreted glacial erosional history (including the potential breaching of a former ridge connecting the Brac and the Cobbler) suggests that up to ~700 m of rock may have been removed from parts of Glen Croe relative to adjacent locations. Glacial erosion rates on bedrock have been estimated and modelled to be in the order of 0.1 mm – 10 mm yr^{-1} (Hallet, 1996; Shuster et al., 2011). Therefore, even with the favourable conditions for quarrying (described above), prolonged phases of glacial erosion over several glacial cycles, or additional processes of rock removal (see section 4.2 on RFSs), would have been required for Glen Croe to take its current form. It is likely that active valley glaciers have occupied Glen Croe for much of the 'average glacial conditions' during the Quaternary (Porter, 1989), which in the western Highlands have been suggested to be broadly similar to the Loch Lomond Readvance glacier configuration (Golledge et al., 2009). This could contribute to the time frame required for these erosion rates to shape the valley.

4.2. Rock slope failures and deformation

4.2.1. Description

Rock slope processes that have shaped the summit of the Cobbler have already been described in detail by Jarman (2004) and published inventories by Jarman (2006) and Jarman and Harrison (2019) include numerous other RSFs in the vicinity of Glen Croe. Examples of some of the key features associated with RSFs that were observed in this work are described below.

Some of the most common landforms associated with RSF around Glen Croe are very steep head scarps that exceed 50° in angle. Good examples include a head scarp up to 150 m in height on the north-eastern slope of the Brac, and a ~50-m-high head scarp on the north-eastern ridge of Ben Donich (Fig. 8A,B). In both of these examples, the head scarp marks the top of broad, 300−500 m wide cavities in the slope. The foot of these head scarps is marked by relatively sharp breaks in slope onto more planar surfaces that slope at angles of between 30° and 40° down into the valley. Relatively smooth grassy slopes characterise much of the ground below the head scarp on the Brac (although a 400 m long train of boulders extends downslope from the south-eastern end). In contrast, a more widespread, densely spaced accumulation of angular boulders extends for approximately 250 m below the head scarp on Ben Donich. Other smaller head scarps, such as those at the col between Glen Croe and the Coire Odhar, occur above slopes that have little or no boulder debris (Fig. 8A).

Tension cracks are particularly well-developed on the north-east ridge of Ben Donich (Fig. 8B) and also occur behind head scarps on the mountain's south-east ridge. These are oriented NNW-SSE and WSW-ENE and correspond to major joints sets on the mountain, which are visible on aerial photographs. Tension cracks or fissures, up to 10 m in depth, have also been described by Jarman (2004) on the western slopes of the Cobbler, as well as prominent antiscarps that reach up to 6 m in height.

A head scarp that is up to 50 m high (slope of approximately 20–50 degrees) is located above a 0.25 km^2 block of deformed mountain slope on the east facing side of the Brack, which looks over Loch Long at the mouth of Glen Croe (Fig. 8 C,D). In places the surface of the block slopes gently back into the hillside, and it is characterised by prominent antiscarps and a toe bulge (Cross section X-X' in Fig. 8C,D). A drainage channel that follows a fracture line down the hillside is clearly offset, by up to 20 m, along the distance of the block (Fig. 8C).

4.2.2. Interpretation

Processes of rock fall or rock avalanche, and mountain slope deformation are all evident in Glen Croe. Where steep head scarps sit above accumulations of boulders, a rock fall or rock avalanche interpretation can be made. However, in some cases the size of cavity at the head scarp far exceeds the volume of debris on the slopes below (Fig. 8B), and elsewhere there is no boulder debris present (Fig. 8A). In these cases, much of the failed mass has probably been transported from the site. This could have occurred either supraglacially if failure took place when the valley was occupied by ice or by incorporation subglacially if the failure occurred during an ice free period prior to the last glacial advance (e.g. Ballantyne, 2013; Carter, 2015). In this way, many of the failures conform to the morphologies described by Ballantyne (2013) for Lateglacial RSFs in Scotland, suggesting that they were active following main Late Devensian ice sheet retreat, but prior to the Loch Lomond Readvance. Indeed the size and height of some of the failure zones suggests that multiple episodes of failure (including pre-main Late Devensian) may be evident in the landscape. Whether these former failures involved rock falls moving as individual fragments, or larger scale rock avalanches is difficult to ascertain, and discrimination between the two modes can sometimes be challenging (Hungr et al., 2014). However, the large scale of some of the head scarps and cavities in Glen Croe suggests that rock avalanches may have occurred (e.g. Fig. 8B).

The rock slope overlooking Loch Long, which is characterised by a 50 m high head scarp, anti scarps and a toe bulge is interpreted as a mountain slope deformation (Fig. 8C, D). Features resembling the early stages of rotational sliding are evident; however, a defined rupture surface is not fully evident (Hungr et al., 2014). Elsewhere in Glen Croe, other sections of rock slopes that have become weakened, but have not failed, are evident from tension cracks (Fig. 8B) and networks of scarps and antiscarps (e.g. the western side of the Cobbler as described by Jarman, 2004).

Overall, RSFs and slope deformations show varying degrees of evolution in Glen Croe. These includes RSFs with subsequent debris removal by ice, failures with debris still present (i.e. post glacial failure), and rock slope deformations and weakening but without failure. Jarman (2009) has highlighted the role of RSFs in the glacial-paraglacial cycle of valley development whereby failed or weakened rock slopes provide material that is readily eroded and entrained in the next glacial cycle, providing a positive feedback in valley widening. In particular, the process has been suggested to be most effective in zones of watershed breaching, where changes in slope stresses associated with the removal of 10^1 – 10^2 m of rock contribute to further susceptibility for failure (Jarman and Harrison, 2019). Results from modelling work also suggest that increased depths of erosion lead to increased rock damage relative to intitial conditions (Grämiger et al., 2017). The spatial distribution of RSFs in Glen Croe, and their concentration near areas of interpreted glacial breaching (e.g. between the Brac and the Cobbler) support this suggestion (Fig. 5). An important implication of the past RSF activity in Glen Croe is that it would have

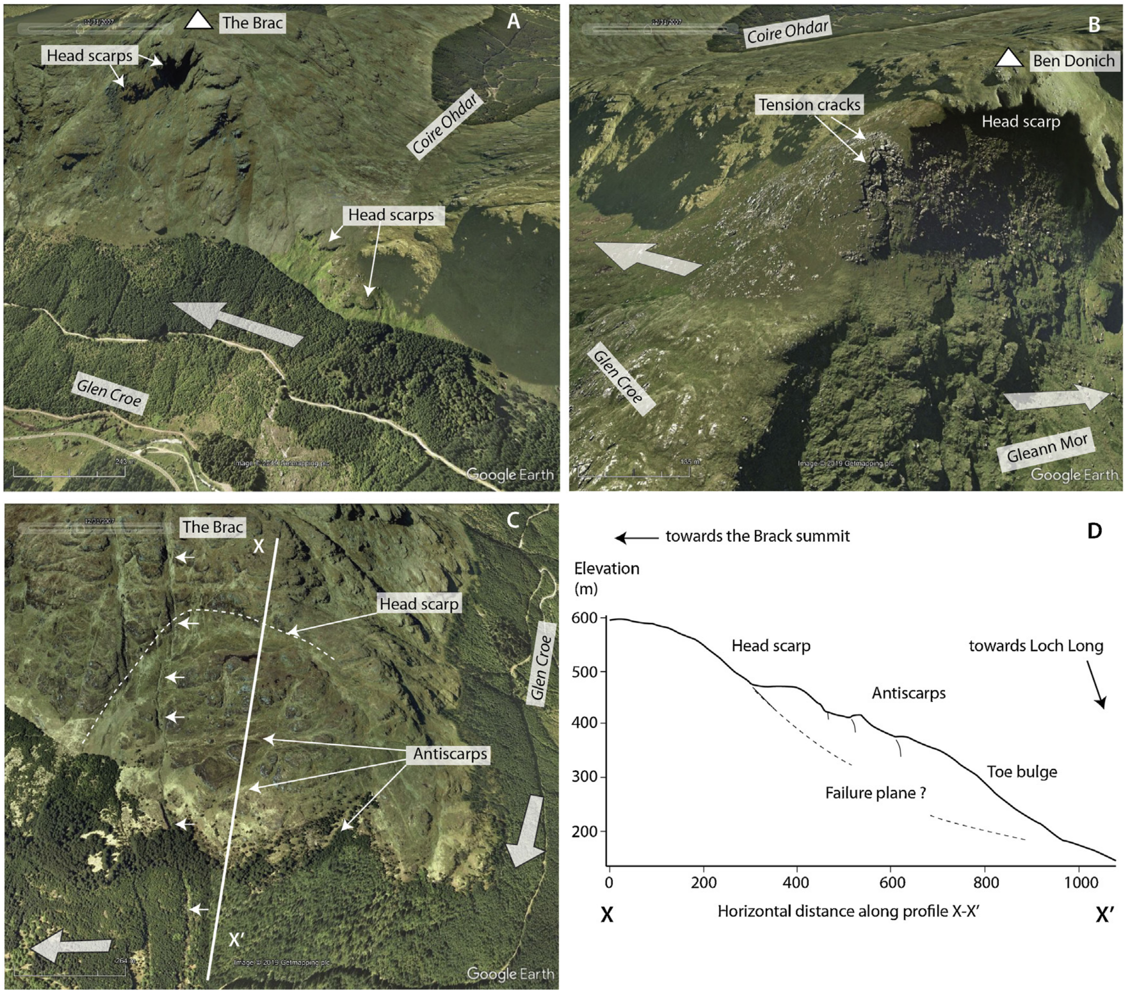

Fig. 8. Examples of landforms associated with rock slope failure and rock slope deformation around Glen Croe. A. View looking south showing a head scarp and cavity on the Brac, and head scarps below the col between Glen Croe and Coire Odhar. B. View looking south towards the head scarp and cavity on Ben Donich, with boulder debris and tension cracks clearly visible. C. View looking west onto the rock slope deformation on the eastern side of the Brac. The small white arrows show the line of a fracture-controlled drainage channel, which is offset across the deformed block. The thick white line marks the line of the topographic section, X-X', shown in D. D. Topographic section through the rock slope deformation in shown in C. All images in A,B and C © 2020 Getmapping plc, Source: Google Earth.

accelerated the overall bedrock erosion rates in the valley in excess of those attributable to glacial erosion alone.

5. Glacial sediments, paraglacial reworking and connectivity

5.1. Landforms of glacial deposition

5.1.1. Description

Some of the clearest features relating to glacier deposition occur in the vicinity of Coire Croe, which joins Glen Croe on its north-eastern side (Figs. 1, 3A). Well-defined benches between 480 and 370 m a.s.l. trend across the southern slope of Coire Croe and extend into Glen Croe (Fig. 9A). The benches can be traced continuously for a distance of ~500 m and have a down valley surface gradient of approximately 0.1 m/m. Small sediment exposures near the surface of the benches revealed medium dense, poorly sorted gravelly sand, with isolated angular and sub-angular cobbles. Locally, weathered diorite boulders were also observed within the matrix. The head of a prominent debris flow scar clearly corresponds with the uppermost bench on the north-western flank of the Cobbler (Fig. 9A). Within Coire Croe, the benches can be traced eastwards where they merge with a distinct upslope limit of densely spaced gullies (at approximately 600 m a.s.l.), which are incised into sediment (Fig. 9B).

Elsewhere in Glen Croe, small cuttings, gully development and scars left by shallow translational debris slides show that a sediment cover exists on the mid-slopes of the valley sides in many places. In particular, the slopes on the south-western-side of Beinn Luibhean and in Coire Croe have intensive gully development within a considerable sediment mantle. Many of these gullies exceed 1 m in depth and in places some reach depths of 5 m or more. Natural exposures in these sediments are rare and limited observations of the mid-slope material have ranged from poorly sorted gravelly sand with boulders, to more cohesive clayey and silty sand. On Beinn Luibhean, above the A83 road, there appears to be a defined upper limit of gullied sediment at approximately 500 m elevation (Fig. 2), which can tentatively be traced in a down valley direction to the upper sediment bench at the southern side of the entrance to Coire Croe (although no prominent bench feature is visible on Beinn Luibhean). Due to ongoing engineering work, the slopes directly above the A83 road were not visited in this investigation. However, previous observations at this location described the mid-slope material as thin and patchy cohesive sediments variably overlain by loose morainic debris and gravelly colluvium (BGS, 2007).

Towards the base of Coire Croe, the lower slopes are occupied by accumulations of sediment that reach 10–12 m in thickness. These features have a planar upper surface that dips very gently toward

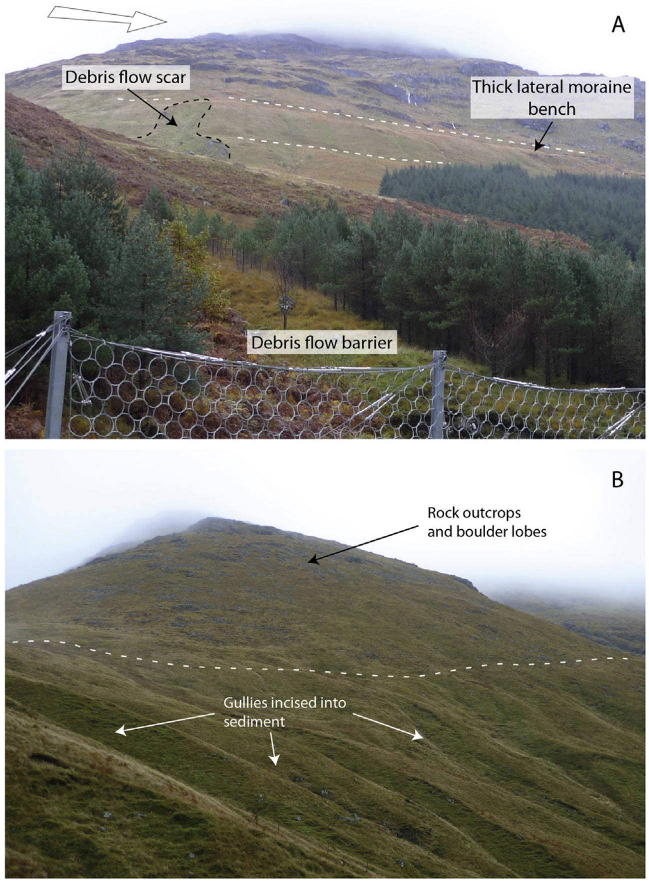

Fig. 9. A. View looking eastward up to the sediment benches, interpreted as lateral moraines, on the north-western slope of the Cobbler. White arrows show the interpreted former ice flow direction when the Loch Lomond Readvance glacier was near its maximum thickness. B. View towards the south-east in Coire Croe showing the contrast between upper slopes with rock outcrops and boulders lobes, and the lower gullied slopes.

the east, into the valley (Fig. 10A). A small 1.5 m high exposure in these sediments revealed dense laminated sands at the base, which are overlain by bedded gravels (Fig. 10B). A wedge of massive clast-supported diamicton, which thickens towards the west, rests on top of the gravels, and is in turn overlain by a lens of laminated sand. These sediments form an open fold, which verges towards the east. The top of the sequence comprises a clast-supported diamicton and peat.

Finally, at the floor of Glen Croe rare isolated ridges and mounds (2–5 m high) are present in some locations, occasionally with scattered boulders on their surfaces. Few exposures are available in these features. In some areas they align with the local strike of the bedrock. However, in locations near the tributary of Coire Croe some of these features have a subtle diagonal down valley alignment.

5.1.2. Interpretation

The benches on the southern side of Coire Croe and eastern side of Glen Croe (Fig. 9A) are interpreted as lateral moraines – the slight down valley gradient giving an approximation for the former glacier surface gradients at this location in the valley. The upper limit of the higher lateral moraine can be tentatively traced further up the valley and eastwards into Coire Croe, where a clear boundary is evident on the hill slopes separating the gullied sediment below and the talus slopes and boulder lobes above (Fig. 9B). This type of contrast has been used elsewhere to infer former lateral ice marginal positions of Loch Lomond Readvance glaciers (e.g. Ballantyne, 2002c; Lukas, 2006), and suggests that the sediment on the slopes is of glacial origin. The configuration of landforms indicates that ice flowed out of Coire Croe as a tributary and joined the glacier in Glen Croe when the ice was close to its maximum thickness during the Loch Lomond Readvance (Fig. 11A). The lateral moraines in this location are relatively large and similar features are not well defined in other parts of Glen Croe. There are two possible reasons for this. First, the diorite bedrock that crops out in Coire Croe may be have been more susceptible to erosion, and therefore could have led to a greater debris supply (via subglacial or supraglacial pathways) to the lateral margin. Secondly, pre-existing sediment could have accumulated in Coire Croe during episodes of ice marginal ponding in Coire Croe, associated with an earlier retreat phase (see below, Fig. 11B). During the Loch Lomond Readvance, this material could have been pushed against the valley side and transported in a down glacier direction along the ice margin. Both these mechanisms are consistent with causes of within valley moraine asymmetry identified in glaciated valley landsystems elsewhere (Benn et al., 2003).

The intense gullying on the south-western slopes of Beinn Luibhean suggests that considerable glacial sediment deposition had also once been focused in that location (Fig. 2). This may be partly due to the steep slope above the ice (Fig. 3B) focusing

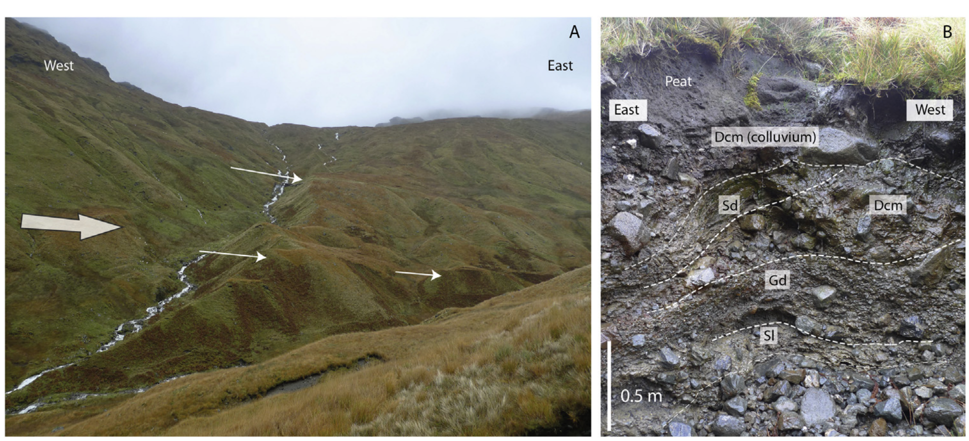

Fig. 10. View looking north towards the thick sediment accumulations in the floor of Coire Croe. Thin white arrows show the planar surfaces that dip gently eastwards into Coire Croe. The thick white arrow shows the interpreted local ice flow direction during glacier retreat when the sediments were deposited. B. Natural section exposed in these sediments. Sl laminated sands; Gd gravels with deformed bedding; Dcm clast supported massive diamicton; Sd sands with deformed bedding.

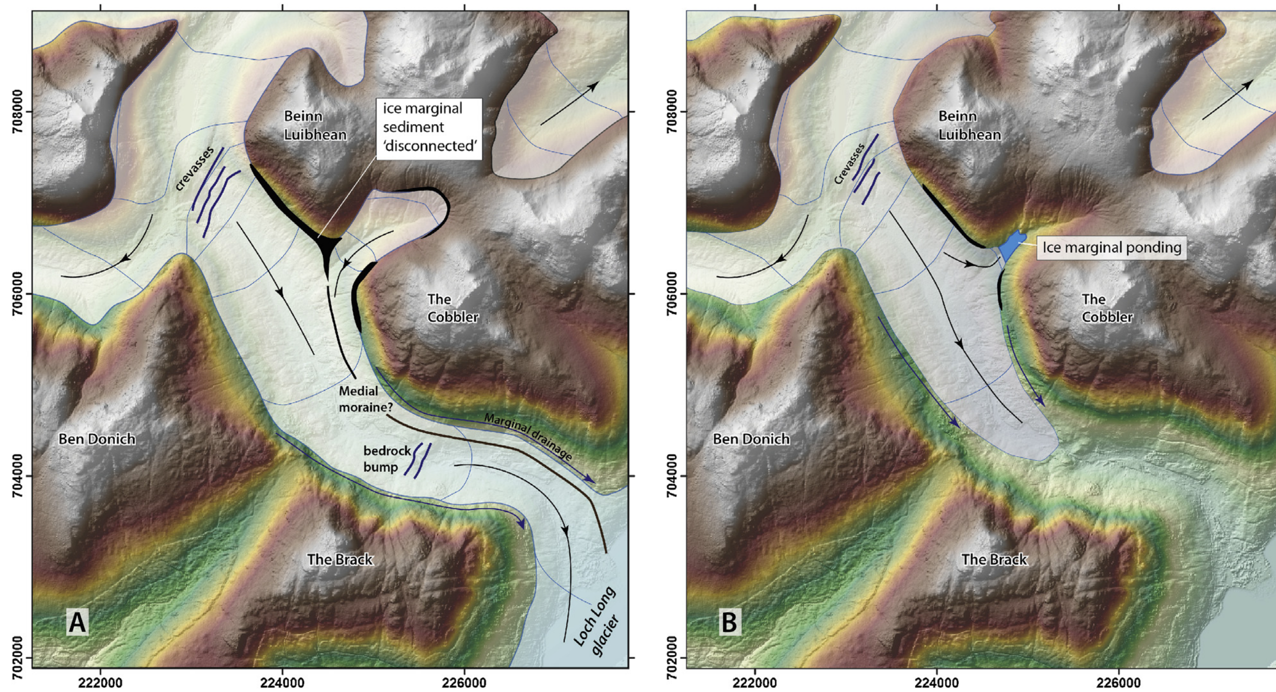

Fig. 11. Reconstructed glacier configurations in Glen Croe during: (A) a period close to the maximum stage of the Loch Lomond Readvance; and (B) a later stage of overall retreat of ice from Glen Croe. This latter configuration could also represent retreat at the end of the main Late Devensian glaciation, prior to expansion during the Loch Lomond Readvance. The background hill shaded surface models are built from Intermap Technologies NEXTMap Britain elevation data.

sediment delivery to the lateral ice margin by mass wasting processes. Previous work has linked focused sediment accumulation along lateral margins to the location of steep faces in former glacier catchments (Benn, 1989; Benn et al., 2003). Additional sediment sources may have included debris that had been removed by quarrying farther up the glacier and transported towards the ice margin, or debris that had been elevated by possible serac fall over steep rock sections at the valley head (Fig. 6B). However, it is uncertain whether these latter mechanisms could have elevated debris to the upper limit of gullied sediment that is now visible on Beinn Luibhean.

A possible effect of the former glacier configuration in this area is that redistribution of sediment from the western slopes of Beinn Luibhean by marginal streams was restricted due to the confining ice slopes of the Coire Croe tributary glacier at southern end of the hillslope (Fig. 11A). In this way, sediment that had accumulated on the slopes of Beinn Luibhean was disconnected from ice marginal drainage systems farther down the valley, and therefore remained in place. Some of the sediment at the margin of the confluence with the Coire Croe tributary could have been transported supraglacially as a medial moraine; however, these features generally contain relatively small amounts of debris and have a low preservation potential upon deglaciation (Benn et al., 2003).

The planar-topped, gently eastward sloping morphology that is present on parts of the sediment mass in the floor of Coire Croe suggests that these sediments were sourced from an ice margin that flowed into the corrie, during a stage of deglaciation (Figs. 10A, 11B). The laminated sands and bedded gravels that are revealed in the exposure in these sediments indicates that they were locally deposited by water. The wedge of clast-supported diamicton within these bedded sediments is interpreted as a mass flow deposit; the thickening of the wedge towards the west suggests a possible source area. The eastward (upslope) verging weakly developed open fold suggests that these sediments may have been pushed by ice from the west (Fig. 10B). Together, the landform and sediment assemblage in the base of Coire Croe suggest that during overall glacier retreat, ice flowed from Glen Croe into Coire Croe. At this stage Coire Croe would have no longer had a sustainable source area, thereby allowing the local ice flow direction reversal. The flow of ice into Coire Croe from Glen Croe would have temporarily blocked drainage and resulted in water ponding leading to the deposition of thick accumulations of sediment that slope gently into the corrie. The sediment may have periodically been pushed by small ice margin oscillations during overall retreat out of Coire Croe. This configuration would also have occurred during ice retreat prior to the Loch Lomond Readvance, providing a source of sediment that could be reworked during subsequent glacier growth (e.g. Ballantyne, 2002c) and a source of material required for the construction of the large lateral moraines (Fig. 9A).

The nature of the sediment that creates a general cover over the mid-slopes more widely in Glen Croe is more difficult to distinguish. Ballantyne (2003) has noted that differentiation between *in situ* glacigenic deposits and material that has been reworked by slope processes is not always clear and this is especially true where exposures are not available, and characteristic landforms are absent (or obscured by forestry). The slope sediments that can be directly linked with the clear lateral moraines are certainly glacigenic in origin. Elsewhere, landforms such as small failures scarps and terracettes indicate mobilisation by ongoing slope movement processes. Much of the mid slope material in Fig. 4 is classified collectively as till and colluvium, in recognition that although the sediment may be glacial in origin, it has probably been mobilised to varying degrees, by semi-continuous slope processes such as soil creep.

Finally, the valley floor mounds that have a diagonal down-valley alignment are interpreted as remnants of lateral-frontal moraines. These landforms do not have any exposed bedrock on their surface suggesting that they are depositional. Sediment transported from Coire Croe by fluvial and slope processes would have provided material that could be worked into ice marginal moraines on the floor of Glen Croe as the ice front actively retreated past this point (Fig. 4).

5.2. Sediment reworking and storage

5.2.1. Description

Areas lying below the densely gullied slopes on Beinn Luibhean and in Coire Croe are characterised by debris lobes and cones, which in many places coalesce to form laterally continuous sediment aprons along the slope foot. On Beinn Luibhean, the A83 road and the lower lying Old Military Road run along the top of these deposits (Fig. 12A). The surfaces of the debris cones generally rest at angles of between 15° and 35°, and in places head scarps mark where more recent shallow debris slides have occurred on top these features.

A natural section in a ~20° debris cone on the lower slopes of Beinn Luibhean revealed that the upper 2 m comprised dense, poorly sorted, slightly silty and very sandy gravel, with numerous angular and sub-angular cobbles and occasional isolated boulders (Fig. 13A). The exposed deposits were predominantly clast supported, but matrix dominated areas were also observed. The sediments were generally massive in appearance; however, some weak downslope stratification was apparent in the form of concentrated layers of cobble sized clasts with weak downslope alignment. Rare 5–10 cm thick lenses of sand were also observed, though these were only continuous for 1–2 m. Another section within a slightly lower angle (15°) debris apron in Coire Croe revealed that the upper 2.5 m included stacked sequences comprising 0.2-0.5 m thick units of dense matrix- and clast-supported gravelly sand with frequent sub-angular cobbles, overlain by semi-continuous, 5–20 cm thick layers of dense, thinly bedded silty sand (Fig. 13B).

At the foot of the sediment apron below Beinn Luibhean, small peaty alluviual fans extend across the valley floor and confine the river Croe to a narrow 20–100 m wide alluvial plain at the western edge (Fig. 4). These fans have slope angles of 5-12°, and are characterised by relatively smoother surfaces than the debris cones and lobes, which in places partly extend across the fan surfaces. A more prominent and relatively large (0.1 km^2) alluvial fan spills out from Coire Croe onto the floor of Glen Croe further diverting the river at that location (Fig. 12B). The surface of the present river channel on this fan is almost entirely dominated by large sub-angular and sub-rounded boulders, many of which exceed 1 m in diameter (Fig. 12C).

The mouth of Glen Croe is marked by 0.19 km^2 raised delta which extends out into Loch Long (Fig. 4). The flat-topped surface of this delta lies at ~ 9 m a.s.l. and is now incised by the modern river which feeds an active delta (~0.06 km^2) that is graded to current sea level and extends farther into the loch. Based on the current bathymetry of Loch Long (approximately 80 m water depth at the toe of the delta) and assuming the floor of the delta grades up in elevation towards the apex, the total volume of the delta can be estimated as 0.012 km^2. This is a minimum estimate because sedimentation on the loch floor will mask the true depth of the deltaic deposits.

5.2.2. Interpretation

The formation of debris cones (also referred to as colluvial fans), which coalesce to form continuous aprons of sediment is widely observed in formerly glaciated environments where dense gully networks develop on sediment covered slopes (Blikra and Nemec, 1998; Ballantyne, 2003, 2008). The massive and poorly sorted nature of the exposed sections in the sediment aprons at the foot of Beinn Luibhean and in Coire Croe, together with crude downslope stratification is consistent with accumulation by debris flows. The greater degree of stacking and occurrence of thinly bedded sand layers in the lower angle Coire Croe sediment apron section indicates that flows at that location had a greater water content and were less viscous, with sheet flow conditions likely following the preceding debris flows.

Sediment reworking by debris flows is evident in several areas in Glen Croe, but is most prominent on Beinn Luibhean and in Coire Croe (Figs. 2,4,9). The spatial focus is partly related to the initial sediment availability, which may have been influenced by the former glacier configuration limiting the removal of ice marginal sediments by meltwater (discussed above, Fig. 11). Furthermore, the west side of Beinn Luibhean represents the longest continuous slope in the catchment (Fig. 3B). A positive relationship has been demonstrated at other sites in Scotland and elsewhere between

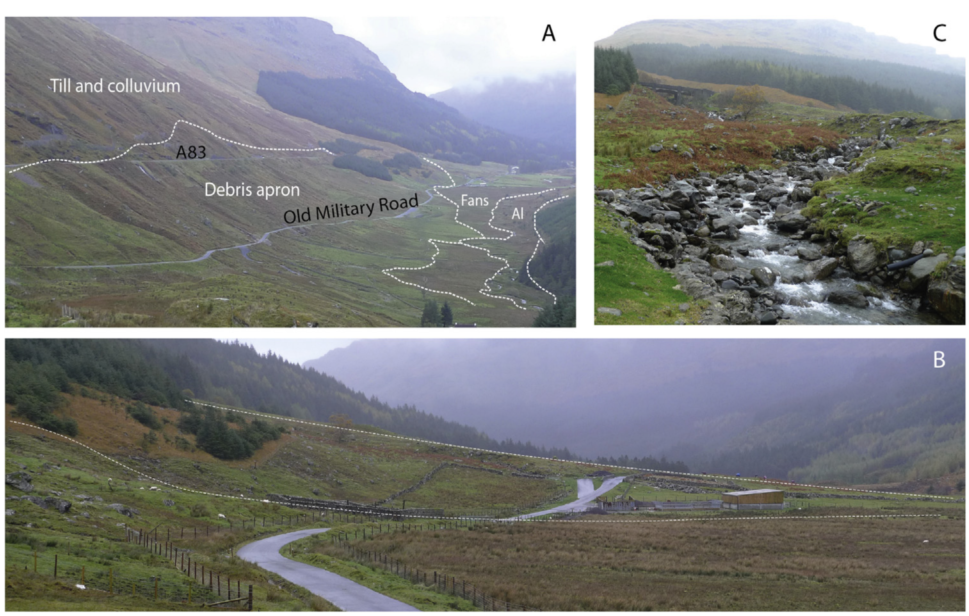

Fig. 12. Landforms associated with sediment reworking. A. Debris cones have coalesced to form a debris apron at the slope foot of Beinn Luibhean. Small alluvial fans spill out across the valley floor so that the river and narrow alluvial channel (Al) are confined to the south-western edge. B. View looking south towards the relatively large alluvial fan deposit that spills out from Coire Croe, and crosses the floor of Glen Croe. C. The river channel on the alluvial fan surface is almost entirely dominated by boulders.

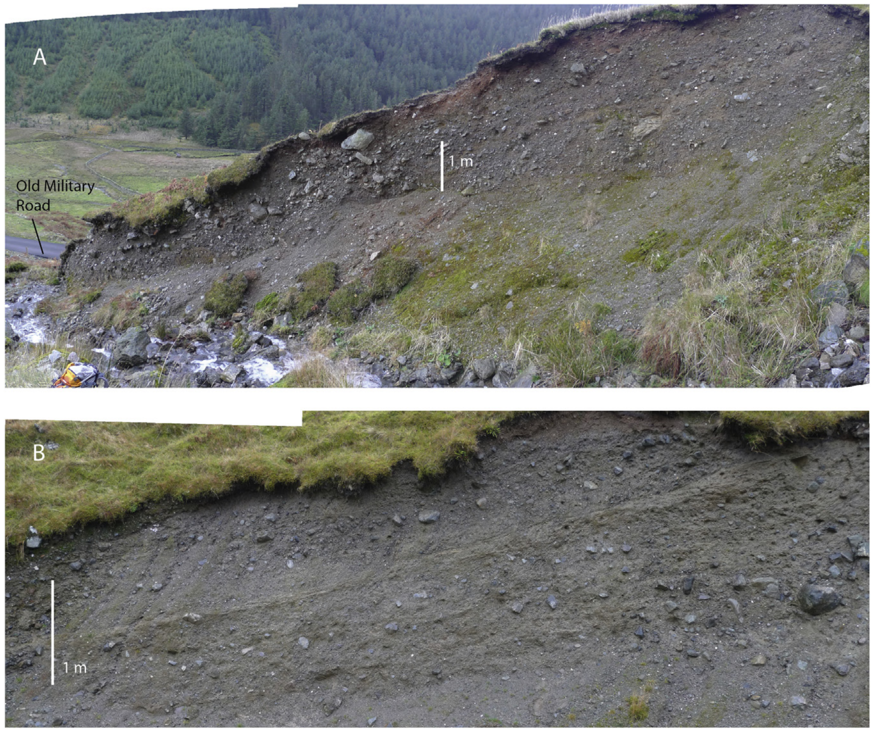

Fig. 13. Sediment exposures through debris flow deposits that form debris aprons on (A) the south-western slope of Beinn Luibhean above the Old Military Road, and (B) a south-facing slope in upper Coire Croe.

slope length and debris flow magnitude (Hungr et al., 2008; Milne et al., 2015), and it is likely that this characteristic has also influenced debris flow volume in Glen Croe.

The large alluvial fan deposit that spills out from Coire Croe is likely to have been sourced by sediments that had previously accumulated in Coire Croe when its drainage was blocked by a valley glacier in Glen Croe. The size of the boulders exposed in the current river channel on the fan surface demonstrate that the deposition of this feature occurred during a substantial discharge event(s) from Coire Croe (Fig. 12B, C).

There are not yet any published dates to constrain the timing of the bulk of debris cone and debris apron accumulation in Glen Croe. Published radiocarbon ages from organic horizons in a selection of debris cones in elsewhere in Scotland indicate that the top 1–3 metres of the deposits have accumulated during the past 7000 years (Curry, 2000b; Reid and Thomas, 2006). However, many debris cones typically exceed 10 m in thickness, and therefore a substantial amount of the sediment accumulation must have occurred earlier. This is likely also to be the case in Glen Croe, where boreholes along the Old Military Road near the foot of the sediment apron on Beinn Luibhean have recorded 10–15 m of sand and gravel (borehole records viewable in Geology of Britain viewer: http://mapapps.bgs.ac.uk/geologyofbritain/home.html). A rapid initial phase of debris cone and debris apron accumulation would be consistent with observations other deglaciated environments. For example, dating evidence from the Guttannen Basin in Switzerland has shown that most of a valley floor fan had accumulated by the early Holocene, within one to two millennia of the site becoming ice free (Kober et al., 2019). Similarly, investigation of slopes following Little Ice Age glacier indicates a phase of considerable sediment reworking (source sediment erosion rates of 50–100 mm yr^{-1}) within decades of deglaciation (Ballantyne and Benn, 1994; Curry et al., 2006). Rapid initial slope response is also described by the paraglacial exhaustion model (Ballantyne, 2002b), with later Holocene episodes of renewed debris cone accumulation being linked to changing threshold conditions, such as patterns of extreme rainfall events (Curry, 2000b; Ballantyne, 2008). In Glen Croe, recent debris flow activity is well documented because of its impact on the A83 road (Fig. 2). The potential for these 'recent' events to mobilise substantial volumes of sediment is demonstrated by a debris flow in lower Glen Croe in 1913, which blocked the river and caused flooding of a nearby house (Fig. 14).

Together, the debris flow and alluvial fan deposits are likely to represent a substantial proportion of the total volume of valley fill storage in upper Glen Croe. The upper river Croe is a low order stream above the confluence with Coire Croe, and has no substantial valley head (due to removal by glacial erosion). As a result fluvial sediment sources and river reworking are likely to have been less important for accumulation of the valley fill than material derived from the valley sides through growth of debris cones and alluvial fans. This is also evident from the confined position occupied by the river on the south-western side of the valley floor, where it has been pushed to the opposite side from the main sediment source slopes (Fig. 4).

The cross-valley bedrock ridge (Fig. 7B) and associated valley narrowing that is located approximately half way down Glen Croe is likely to mark the distal end of an overdeepening of the valley. As a result, much of the valley fill sediments in the upper part of Glen Croe, thought to be primarily derived from debris flows and alluvial fans, are disconnected from the lower part of the valley. In this sense the ridge acts as a barrier within the sediment connectivity system (e.g. Fryirs et al., 2007) maintaining a higher local base level in the upper half of the valley.

Approximately 80 % of the surface area of the delta at the mouth of Glen Croe is graded to ~9 m a.s.l. This is the height of the Main Postglacial Shoreline in the area, which was developed around 7 ka BP (Shennan et al., 2006; Smith et al., 2012). Therefore, a substantial proportion of sediment delivery to the delta must have occurred by that stage in the early Holocene, in the same way that large parts of debris cones elsewhere in Scotland had accumulated prior to 7 ka BP (Curry, 2000b; Ballantyne, 2008).

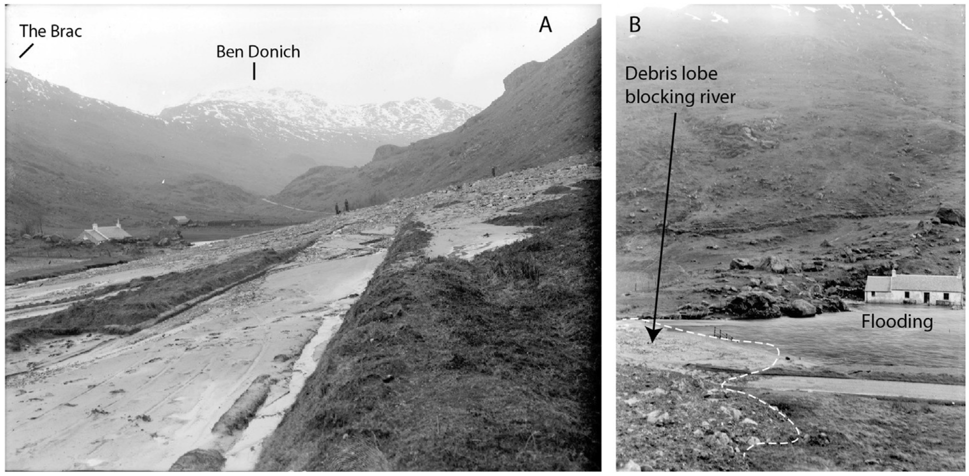

Fig. 14. A. Photograph taken in 1913 looking towards the north-west at a debris flow deposit in lower Glen Croe (BGS photograph number P002174). B. Photograph of the same debris flow showing that sediments temporarily blocked the river, causing localised flooding (BGS photograph number P002176).

Based on a timeframe of 4500 years to build ~80 % of the delta (timing of deglaciation at ~11.5 ka BP to the sea level high stand at 7 ka BP), an average delta growth rate of approximately 2700 m^3 yr^{-1} is estimated for the deglacial and early Holocene period. If the bulk of the delta had built up prior to 7 ka BP, the true rate may have been higher. Nonetheless, this average accumulation rate is comparable (though at the lower end) to calculated sediment export rates for the similar sized Haut Glacier d'Arolla catchment, Switzerland, which is currently undergoing rapid glacier recession and exposure of paraglacial sediment sources (Lane et al., 2017).

5.3. Sediment connectivity

An overview of the relative likelihood that sediment from any given source area will reach the catchment outlet (be delivered to the delta) is given by the spatial connectivity index map in Fig. 15. The map indicates that slopes in the lower half of Glen Croe are relatively strongly connected to the outlet. This part of the catchment is characterised by strong hillslope-channel coupling with a short and steep river flow path to the outlet. Hillslope connection to the channel is demonstrated by debris entering the river in the 1913 debris flow event (Fig. 14), where a considerable proportion of the material deposited on the valley floor (and blocking the river) was subsequently transported downstream. This coupling and efficient transfer of material from the lower part of Glen Croe is likely to be an effect of the valley being narrower and steeper in the vicinity of the interpreted glacial breach through the ridge line that once connected the Brac and the Cobbler (Figs. 3B,5). An implication of this is that much of the record of past debris flow activity in this lower part of the catchment is likely to have been removed. Therefore, the absence of thick sequences of debris flow deposits is not an indication that they have not occurred there.

In contrast, the upper half of Glen Croe is poorly connected to the catchment outlet. Here, the wider valley floor (which likely conceals a bedrock overdeepening) reduces the likelihood of debris flows entering the river channel. As a result larger debris cones, slope foot aprons, and alluvial fans have been able to build up across the valley floor, and now act as buffers in the sediment connectivity system (e.g. Fryirs et al., 2007). These low connectivity features (highlighted by the wide corridor at the slope foot shown in blue in Fig. 15) form important sediment stores, where boreholes indicate thicknesses of 10–15 m. In addition, the cross-valley bedrock ridge that has led to a locally raised base level means that the main channel gradient in the upper part of Glen Croe is relatively gentle, reducing transport capability. As a result, the valley floor in this area has the potential to hold a long-term record of post-glacial slope activity and landscape processes (e.g. Sletten and Blikra, 2007; Matthews et al. (2009)).

An implication of the low connectivity in sediment routing between the upper valley and the outlet is that the volume of sediment accumulated in the delta (0.012 km^3) is likely to be primarily derived from slopes in the lower part of Glen Croe (particularly the coarser sediments). It is therefore feasible that a substantial volume of material remains held in storage in the valley floor and the foot of the slopes in the upper part of Glen Croe. Indeed, given that the upper part of Glen Croe drains a larger proportion of the catchment, the valley fill storage is likely to exceed that held in the delta.

6. Discussion

The interpretations above are consistent with an overall concept that the topography of Glen Croe is the result of long-term landscape evolution over several glaciations. The bulk of the large-scale landscape shaping processes must have occurred in relation to valley glacier configurations, as the periodic continental scale ice sheet glaciations were likely to have been characterised by a relatively stable ice divide over the western highlands, associated with more limited erosion (Finlayson et al., 2014). In this sense, erosion under 'average Quaternary glacial conditions' (Porter, 1989), which in Scotland have been likened to the extent of the Loch Lomond Readvance, would have been important (Golledge et al., 2009). The interaction of glacial erosion and paraglacial RSFs over Quaternary time scales is likely to have played an important role in removing the volume of material that was necessary to breach parts of the catchment (locally ~700 m relative lowering has been interpreted) and generate the modern topography. The mapped distribution of RSFs in Glen Croe is consistent with the suggestion whereby changes in slope stresses associated with watershed breaching contribute to susceptibility for further failure (Jarman and Harrison, 2019). This kind of conceptual understanding of overall topographic evolution, from which zones of possible stress redistribution can be inferred, provides potential insights for evaluating rock slope stability for engineering purposes (Griffiths and Giles, 2017).

The observed sediment distribution in Glen Croe can be placed in the context of a glacial debris cascade (Benn and Evans, 2010; Evans, 2017). Subglacial debris entrainment from bedrock was sourced by quarrying at the head of Glen Croe (Fig. 6) and by

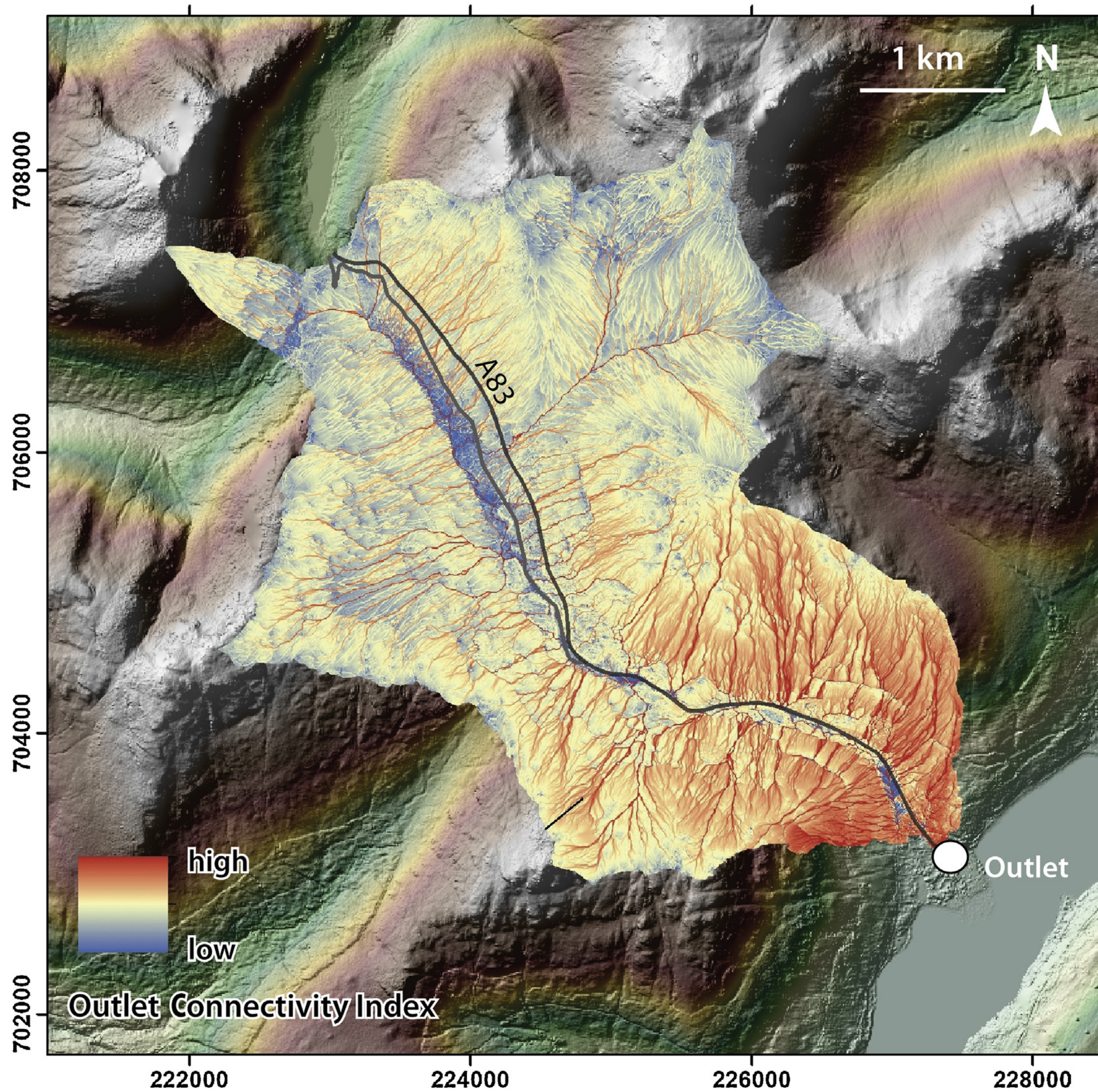

Fig. 15. Map of spatial sediment connectivity to the catchment outlet in Glen Croe, computed following the approach of Borselli et al. (2008) and Cavalli et al. (2013).

abrasion lower in the valley (Fig. 7). Surpraglacial entrainment was sourced by mass wasting on valley sides above the ice surface, and particularly in the vicinity of steep slopes (Fig. 3). There is also a strong likelihood that material from lateglacial (or earlier) RSFs (Fig. 8) could have been entrained both supraglacially through rock fall or avalanche onto the ice surface, or by incorporation from valley sides subglacially (e.g. Ballantyne, 2013; Carter, 2015). McColl and Davies (2013) have also suggested that some large RSFs that have reached failure may deform the adjacent glacier ice, with material potentially moving into the flow and becoming entrained in transport, prior to glacier recession. Both active and passive transport paths are likely to have operated, and subaerial and sub-marginal deposition at lateral margins was important for the accumulation of sediment stores on valley sides (e.g. Fig. 9), setting up conditions for subsequent slope reworking. Sediment accumulation on the western side of Beinn Luibhean may have been more focused due to disconnection with ice marginal fluvial transport paths farther down the glacier (Fig. 11A). A theme from the observations in Glen Croe is the influence that topography had on glacier configuration, sediment pathways and zones of focused deposition (e.g. Fig. 11B). These are consistently recognised in glaciated valley landsystems (Benn et al., 2003).

The landforms and sediments relating to slope reworking in Glen Croe are widely recognised in paraglacial landsystems and can be described within a sediment cascade (Blikra and Nemec, 1998; Ballantyne, 2002a, 2003). Steepened rock slopes (e.g. Fig. 8), valley side moraines, and debris from a ponded ice margin have provided source material for reworking (e.g. Figs. 2,9). Sediment has been redistributed into debris cones, alluvial fans and a delta (Fig. 4). The spatial sediment connectivity analysis used in this study provides an additional way to help map the paraglacial sediment cascade (Fig. 15), and is in agreement with field observations of relatively connected and disconnected zones, in terms of sediment transfer to the outlet of Glen Croe.

7. Conclusions

This article has described how past glaciation(s) have shaped and conditioned Glen Croe, and identified processes and pathways that have characterised subsequent paraglacial sediment reworking. Many aspects of sediment distribution and landscape processes in Glen Croe are predictable through evaluation in the context of glaciated valley and paraglacial landsystems. This highlights the potential offered by these kinds of conceptual models when considering the wider landscape in glaciated terrains that present engineering challenges (Evans, 2017). Assessing the landscape in this way can help identify source areas (produced by focused glacier deposition) and likely transport pathways, which may be susceptible to 'renewed' sediment reworking under altered threshold conditions. Future changes to the amount, distribution and intensity of rainfall is likely to affect the distribution, intensity and frequency of sediment reworking by debris flow events in Scotland (Winter et al., 2010). Given projected future increases in average winter rainfall and summer precipitation extremes (UKCP, 2018), an understanding of paraglacial sediment sources and pathways in formerly glaciated high-relief landscapes that form infrastructure corridors could therefore be of value.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pgeola.2020.02.007.

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