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Geological and geomorphological influences on a recent debris flow event in the Ice-scoured Mountain Quaternary domain, western Scotland

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ABSTRACT

Debris flows in settings that have experienced net glacial erosion within the UK's Ice-scoured Quaternary domain are the result of a complex interaction of a range of geological and geomorphological factors. On the 11th of August 2016 a rainfall-triggered debris flow deposited 100 t of sediment onto local road and rail infrastructure blocking transport between town of Fort William and port of Mallaig in north-west Scotland. The debris flow occurred in an ice-scoured setting, where current 1:50,000-scale geological maps suggest that little or no sediment is expected on the valley slopes. In this study, we show how weathering and mass-wasting processes have interacted with bedrock structures to fill localised depressions with sediment on the upper parts of the slope. The intense rainfall event of August 2016 caused the destabilisation of this localised sediment, with eventual failure along bedrock joint surfaces resulting in two debris flows. This study demonstrates the combination of processes that can result in thick accumulations of sediment on slopes that are otherwise generally lacking in superficial sediment cover. These sediment accumulations have the potential to pose a significant landslide hazard in areas that might previously have been thought of as lower susceptibility. The research illustrates a need to improve understanding and representation of sediment thickness and distribution on hill slopes – particularly those that show an absence of superficial deposits at the scale of currently available geological maps.

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1. Introduction

Rainfall-triggered debris flows are relatively common on steep mountain slopes in the Scottish Highlands (Ballantyne and Harris, 1994; Ballantyne, 2004). Most of these occur in remote locations and do not pose a significant hazard; however, some have affected rail and road infrastructure situated at the base of slopes and have a significant negative impact on the local economy (*e.g.*, Winter, 2005, Winter et al., 2010a, 2010b; Moore et al., 2006; Milne et al., 2010; Postance et al., 2017). The distribution of debris flows across upland slopes is highly variable and is controlled by a combination of factors, including: slope angle, moisture conditions and importantly, the presence and nature of source sediment.

The landscape of Britain has been classified into a series of 'Quaternary Domains' reflecting a combination of landscape morphology, recurring assemblages of superficial sediment and the range of Quaternary geological processes that shaped it (Booth et al., 2015) (Fig. 1). In the 'Ice-scoured Montane' Quaternary domain of western Scotland, many slopes are represented on geological maps as unweathered bedrock with only a thin or patchy cover of superficial deposits (Eyles et al., 1983; Booth et al., 2015; Ballantyne, 2018). As a result, these areas have generally been interpreted as lower susceptibility regions for debris flows (Dashwood et al., 2017; Freeborough et al., 2016), due to the apparent lack of source sediments represented at the scale of geological maps. Observational data suggests that this interpretation is generally valid. For example, large parts of the Ice-scoured Montane domain across north-west Scotland lie outside the grid squares of observed debris flow activity that were mapped by Innes (1983). The UK National Landslide Database (NLD) (Foster et al., 2012) also indicates that although the 'Montane and Valley' domain is five times larger than the 'Ice-scoured Montane' domain, it contains almost 30 times more recorded debris flows events. However, disruptive debris flows have recently been recorded in the 'Ice-scoured Montane' domain, some of which have been large enough to damage local infrastructure, block transport routes, and isolate remote communities (*e.g.*, BEAR Scotland, 2016; Network Rail, 2016). Thus far there has been little documentation of the site-specific geological conditions that have contributed to debris flow activity in this domain.

In this paper, we investigate the local and *in situ* processes that have influenced the availability and distribution of thick sediment sources on the upper slopes of a valley side that is characteristic of the Ice-scoured

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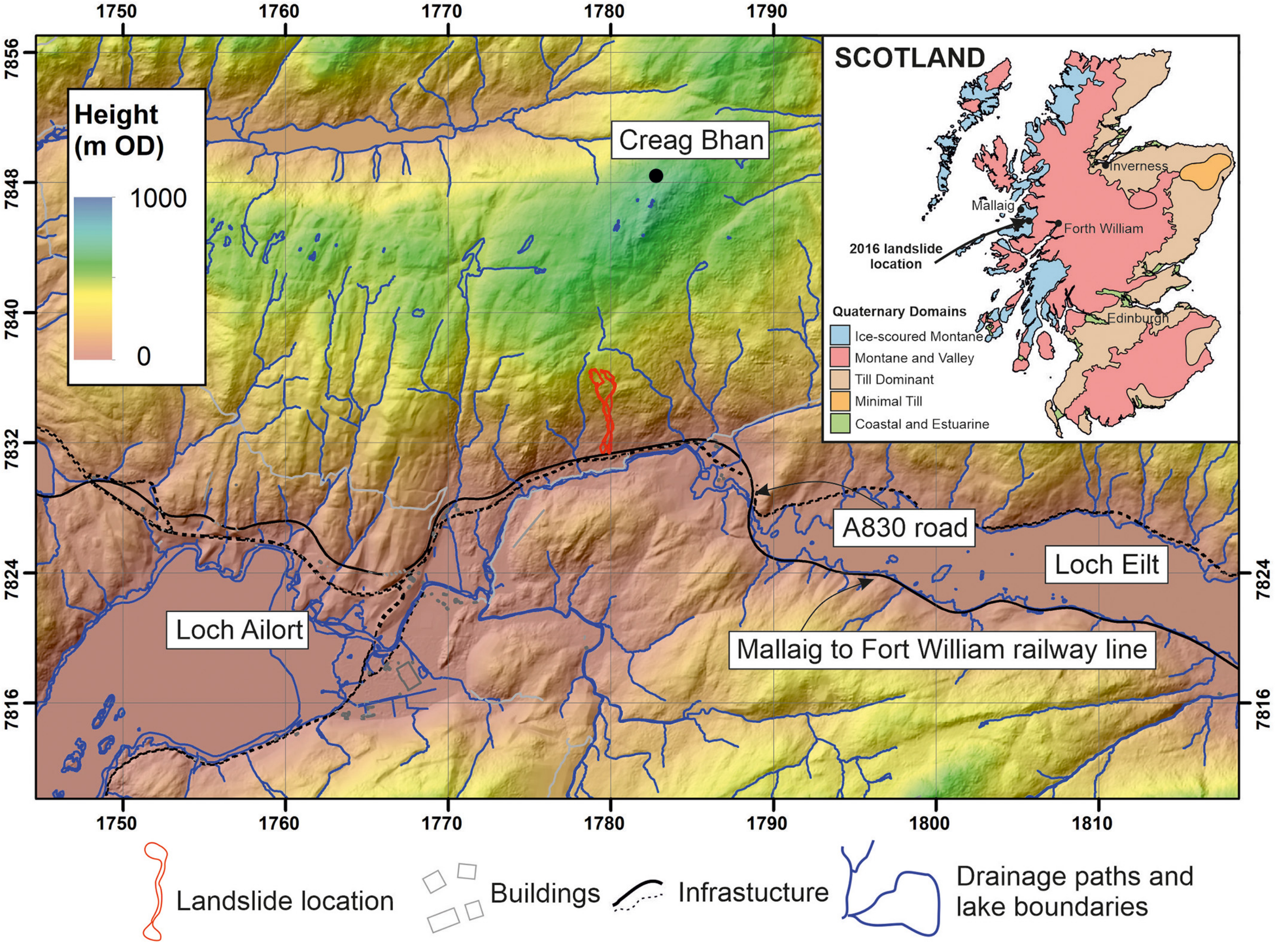


Fig. 1. Overview DEM image of the landslide site between Loch Ailort and Lock Eilit, with local roads and trainline shown. The inset map shows the Quaternary domains (Booth et al., 2015) in Scotland and the location of the lanslide.
Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited.

Mountain domain. We present a case study from Lochailort, in the Lochaber district of western Scotland, where a 450-m-long debris flow reached the base of the slope on the 11th of August 2016, blocking the Fort William to Mallaig railway line and the A830 road, causing several days of closure of the road and railway (Fig. 1). Additional costs arose from installing new debris flow mitigation for future events. New data from this landslide includes sections through the recently exposed source material, detailed descriptions of previous debris flow deposits exposed along the edges of the channel, channel dimensions, slope and infill, a sediment budget estimate and finally description of the *in situ* weathering processes occurring in the source material and across the entire system. In this study, we demonstrate the importance of understanding a broad range of geological and geomorphological controls, which can influence conditions for debris flow activity in the Ice-scoured Montane domain of western Scotland. The research illustrates a need to improve understanding and representation of sediment thickness and distribution on hill slopes – particularly those that show an absence of superficial deposits at the scale of currently available geological maps.

2. Geological setting and context for the debris flows

The case study area is along the A830 between Mallaig and Fort William (Fig. 1), between Loch Eilt and Loch Ailort. The debris flows occurred on the southern flank of Creag Bhàn between the small drainage streams of Allt na Criche and Allt Dileige. The bedrock geology across the site is the Lochailort Pelite Formation, Glenfinnan Group of the Moine Supergroup, which comprises a laterally variable sequence of pelite with subordinate bands of psammite and semipelite (BGS, 1971). These rocks form part of the Glenshian Synform, and are separated from surrounding psammites of the Morar Group by north-trending traces of the Sgurr Beag Thrust (BGS, 1971; Trewin, 2002). The BGS 1:50,000-scale superficial geology map suggests that bedrock is exposed 'at or near the surface' on the valley side slopes. This can be thought of as bedrock representing the predominant material within the top metre from the ground surface, although locally derived, thin or discontinuous superficial sediments may be present on top (McMillan and Powell, 1999). The site is thought to have been close to the limits of the western Highland ice cap, which developed during the Loch Lomond Readvance and retreated by approximately 11.5 ka BP (Lowe et al., 2019). Boulton et al. (1981) suggested that the ice margin at that time reached the mouth of Loch Ailort, whereas Dawson (1988) interpreted a more restricted ice margin farther inland to the east. Therefore, upper slopes at the site may have been exposed to periglacial conditions for at least part of the Loch Lomond Stadial. The site lies within a wider terrain zone mapped as "scoured bedrock surfaces with little drift cover" by Dearman and Eyles (1982), and within the Ice-scoured Mountain Quaternary domain, which was subsequently assigned by Booth et al. (2015) in an assessment of British Quaternary domains.

The Lochailort debris flows occurred at approximately 18:00 on the 11th August, 2016. An estimated 100 t of debris were deposited at the slope foot covering a 70-m-long section of the Fort William to Mallaig railway line and part of the A830 carriageway (BEAR Scotland, 2016; Network Rail, 2016). Initial attempts to clear the road were hampered by heavy rain continuing to wash material down; however, the road was reopened with a single lane under traffic management on the 12th August 2016 and then fully reopened on the 15th August 2016 (BEAR Scotland, 2016). The railway line was also reopened on the 15th August 2016 following clearance of the track, replacement of ballast and installation of debris flow catch fences (Network Rail, 2016).

There are no weather stations located at the site for which records cover the timing of the event; however, the HadUK-Grid (Hollis et al., 2019) provides interpolated rainfall values for the site based on data from the surrounding network of weather stations. The interpolated rainfall on the 11th August 2016 was 70 mm (Fig. 2), and this contributed to a cumulative total of >200 mm over the period from the 6th–11th of August 2016. In this area, both July and August 2016 are recorded to have experienced higher monthly rainfall than the 1981–2010 averages (Met Office, 2021). July and early August 2016 were characterised by low, but relatively continuous daily rainfall with few consecutive days of completely dry conditions. Following this, higher intensity events occurred, during which most of the total August rainfall was received over a few days from the 7th to 11th August 2016 (Fig. 2).

3. Methods

Field investigations were undertaken in June 2019 (nearly 3 years after the debris flow event) to study various aspects of the debris flow system, including the nature of the bedrock, the thickness, type and composition of the superficial sediment cover, and the geomorphology of the channel. Detailed sedimentary logs and descriptions of the sediments associated with previous debris flow events were made. Descriptions of the bedrock and measurements of key structural features such as joints and foliations were taken. Desk-based investigations were also undertaken using elevation data and derivatives from the Blue Sky digital terrain model (5 m spatial resolution), georeferenced colour aerial photographs (0.25 m pixel size), and Sentinel 2 satellite imagery (10 m spatial resolution). The flow direction and contributing drainage area for the debris flow catchments was calculated using the D-infinity algorithm (Tarboton, 1997) implemented using the TauDEM 5.0 tool (http://hydrology.usu.edu/taudem/taudem5/index.html). To assess the residual risk to debris flows, we adopted the sediment budget approach proposed by Moore et al. (2002), which involved the use of detailed site mapping of initiation, transport, storage, and deposition areas. The Eastern and Western channels were mapped along 31 and 14 transversal sections, respectively. These sections were grouped in seven terrain units, 4 for the Eastern and 3 for the Western channel. Evidence of material stored within and adjacent to the main channels was assumed to be linked to debris flow activity and measurements of deposit width, length, and depth were taken where possible along each section or inferred from photographs. The volume of material was estimated as an average volume per terrain unit and it includes only those sections where storage or deposition was observed.

4. Results

The Sentinel 2 satellite image that was taken on the 17th August 2016 (6 days after the debris flows) shows the sources and pathways of the two adjacent debris flows (Fig. 3a), which clearly coincide with zones of high flow accumulation derived from the elevation dataset (Fig. 3b). The bedrock structures, geomorphology and sediments that were observed in the source areas and the channels are described below.

4.1. Bedrock lithology and structure

Two types of bedrock were observed across the hillslope where both the debris flow channels and source areas are located. These comprise: 1) massive psammite with subordinate gneissose-layered pelite and semipelite, which form outcrops along the edges of the channel; and 2) heavily sheared and folded pelite, which is present within the channel. The psammite is quartz-rich, whereas the pelitic bands contain biotite, muscovite and quartz. The psammite outcrops form a series of small crags that are continuous across the hillside and dip downslope towards the south-east (Fig. 4). The debris flow channels descend steeply between and over the psammite crags initiating at elevations between 230 and 180 m O.D. The psammite possesses a near vertical foliation,

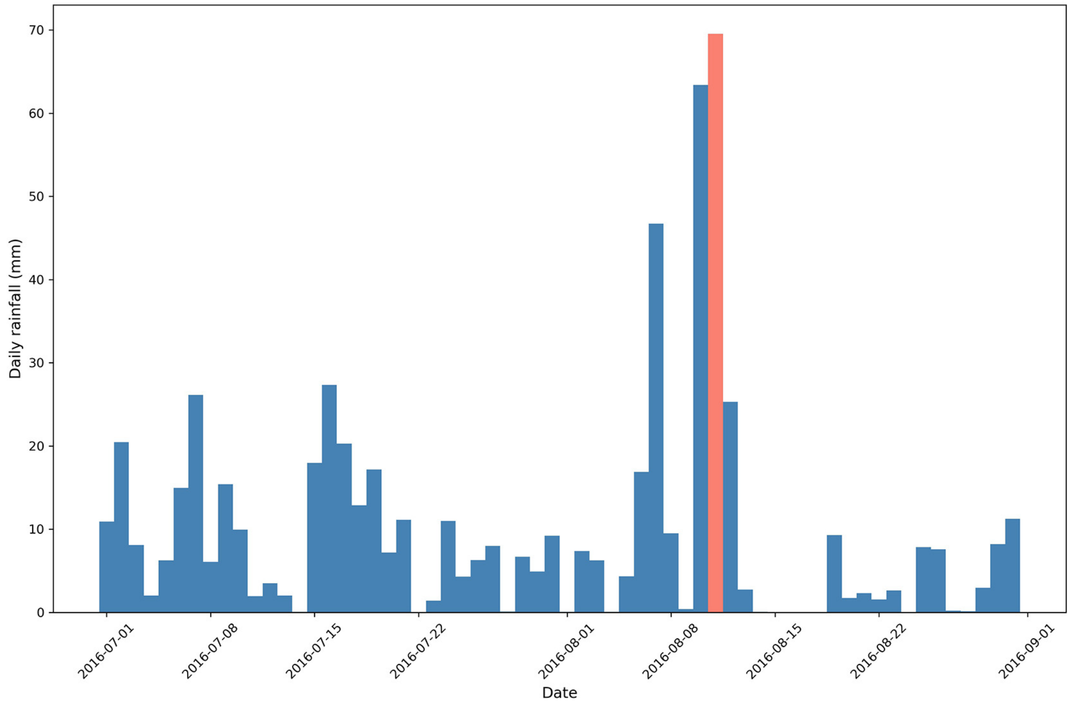


Fig. 2. Interpolated rainfall data across the Lochailort study site for the months of July and August 2016, contains HadUK-Grid, Met Office, 2019 data (Hollis et al., 2019).

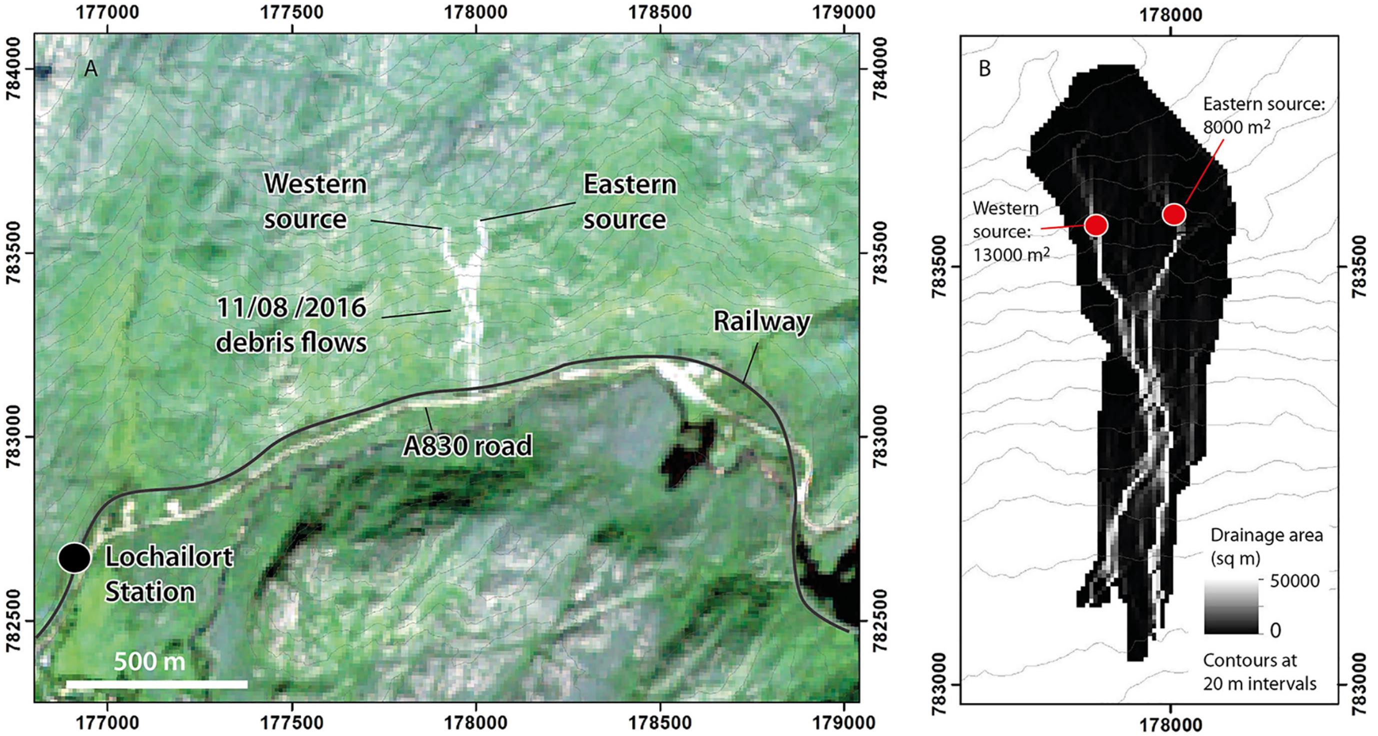


Fig. 3. a) Sentinel 2 image showing two source areas and landslides and b) drainage area for the debris flow catchments. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited.

dipping towards the south-east. Two distinct joint sets were measured in the psammite, with a major set gently dipping towards the south-east (down slope) and an oblique set dipping towards the north-east (into the slope) (Fig. 5). The exposed psammite is generally fresh and unweathered.

The gneissose-layered semipelite and pelite unit, which is locally garnetiferous, is exposed within the debris flow channels, and often forms a smooth surface that is broadly dipping down slope (Figs. 6b & 7a). The bedrock exposure within the channel is predominately the gneissose pelite whereas the psammite is found in the hillside surrounding the channel. The more quartz-rich layers remain unweathered, and the biotite-rich layers are partially weathered to a brownish red iron oxide. In several areas along the channels, this process is particularly evident with red staining of the bedrock surface by iron leached during weathering (Fig. 7a). Generally, this unit has a steep foliation that dips towards the south-east, similar to that of the surrounding psammite.

4.2. Geomorphology and sediments in the source areas

Two distinct source areas are identified for the debris flow system (Fig. 4): a western one which supplied a debris flow that terminated approximately 100 m upslope of the railway; and an eastern one which supplied the debris flow that deposited material on the railway and road. Both of the source areas form steep southward dipping topographic concavities or bowls (slope angles of 25° to 35°) at elevations between 240 m and 290 m OD, and a distance of 450 m in the upslope direction from the railway and road (Fig. 4). The bowls were bracken-covered at the time of fieldwork and are distinguished by a smooth surface texture, relative to the surrounding psammite cliffs and outcrops. The area of the western bowl is approximately 4600 m^2, and the area of the eastern bowl is approximately 2100 m^2. These source bowls are rectangular in planform and their long axes are broadly orientated north-west to south-east. The north-eastern edges of both bowls are bounded by steep and locally vertical, fracture surfaces and 5–10 m high psammite cliffs. Metre-scale cavities are present in the crag above the eastern bowl, where rock fall has been focused along a well-developed set of joints that dip at approximately 40 degrees towards the north-east. The south-western edge of the western bowl is bounded by a grassy slope with a large proportion of exposed bedrock, which forms a continuous rock surface dipping at 30–40 degrees towards the south-east (Fig. 6a–b).

The two failures initiated at the southernmost margin of each of the source bowls. The western landslide scar forms an oval shape and has an area of approximately 126 m^2. The ground surface immediately above the head scarp has a slope of 25°, and a total contributing drainage area of approximately 13,000 m^2. The eastern landslide scar is rectangular in shape and covers an area of 123 m^2. The ground surface above the eastern head scarp slopes at an angle of between 32° and 40°, and has a total contributing drainage area of approximately 8000 m^2. A series of approximately 30 cm-deep, sub-horizontally dipping surface fissures that are parallel to the head scarps were also observed on the ground surface upslope from the failure scars.

Sections exposed in the debris flow scars reveal the nature of the sediment fill of the two different source areas. In the western head scarp, a 2-m-high section revealed a dense, matrix- to clast-supported gravelly silty sand (Figs. 6c, 8a). The gravel clasts are subangular to angular in shape, and are locally concentrated in discontinuous clast-supported layers that form a poorly-developed down-slope stratification. Most of the gravel clasts are <5 cm in diameter; however occasional clasts are up to 20 cm and a 1.5 m boulders were also observed in the failure scar. Sub-horizontal fissures with a dark brown clay fill are found throughout the sequence in the head scar. The clay-filled fissures dip towards the south-east at angles of around 35° (Fig. 6c) and in places extended for over 5 m.

The sediments exposed in the eastern landslide scarp comprise a single unit of very dense, poorly-sorted, very gravelly sand, with frequent cobbles and boulders (Figs. 6d, 8b). The larger clasts are angular and composed of psammite, pelite and mafic material (Fig. 6d). The deposit is predominately clast-supported but isolated patches of matrix-supported material also occur. Short (<1 m), discontinuous, clay-filled fissures are also present in the matrix-supported sections. A number of the mafic clasts were observed to be heavily-weathered and

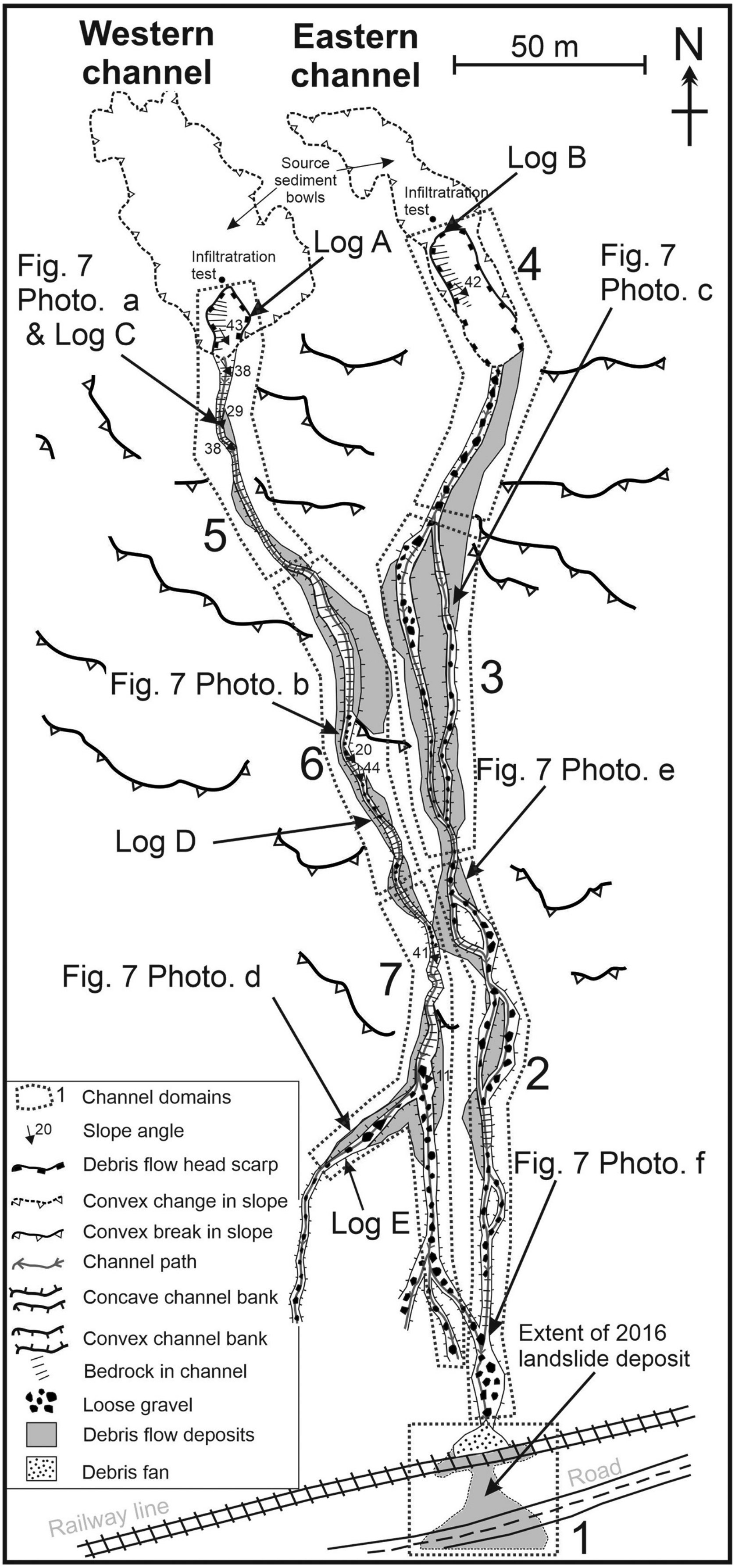


Fig. 4. Geomorphological map of the channelised debris flow system.

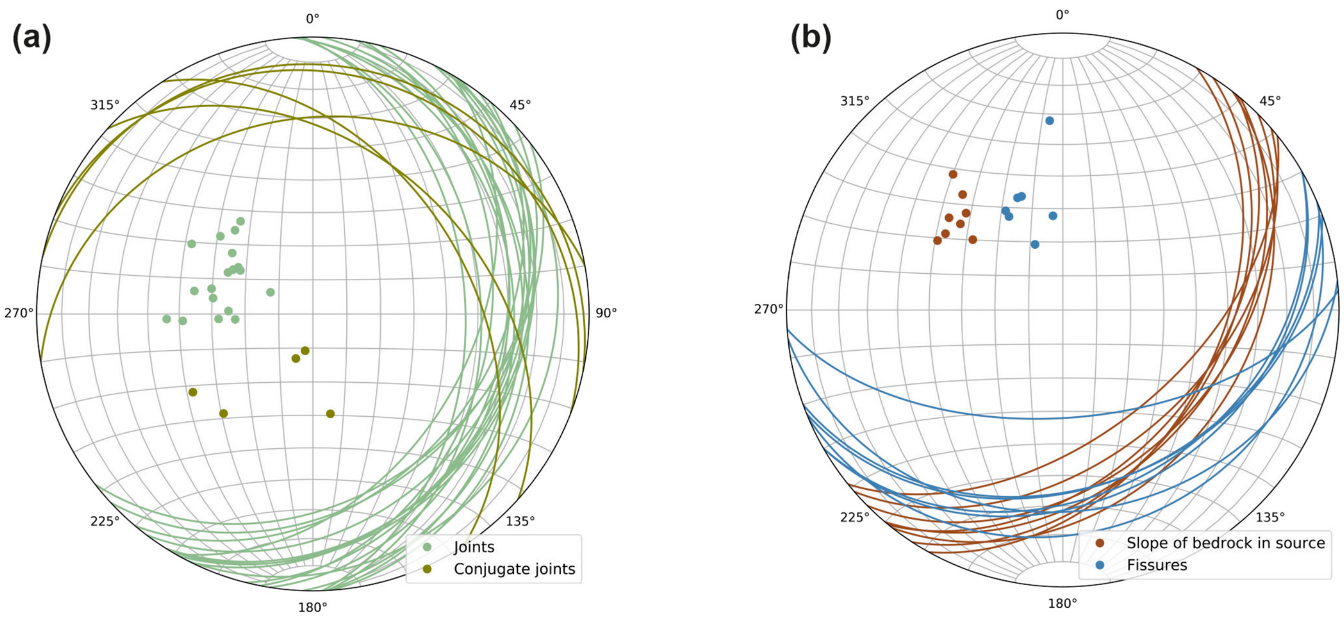


Fig. 5. Stereonets of (a) orientation data from the exposed bedrock slopes; and (b) fissures in deposits from both source areas.

disintegrated. The average thickness (n = 40) of the overlying peaty soil, which was measured over a 1000 m^2 area above the eastern failure scar, is on average 0.31 m, and ranges from 0.11 m to 0.70 m.

Vegetated rafts of peat, up to 4 m in length, are present on the floor of both the western and eastern landslide scars. The underlying bedrock is also exposed at the base of both failure scars on their western sides, and represents a plane of failure. These bedrock surfaces dip downslope towards the south-east at angles of between 30° and 40°, and are similar to the plane of the dominant joint set measured in the area (Fig. 5a, b). The recently exposed bedrock surfaces are fresh and unweathered; however, a downslope section of the failure surface in the western source has lichen growth suggesting at least one earlier stage of exposure.

Field near-saturated hydraulic conductivity for the eastern and western source areas was estimated using the double-ring infiltrometer test above each scarp. Measurements were taken at the top of the sediments underlying the peaty topsoil. Hydraulic conductivity values of 7.59×10^{-6} m/s and 8.34×10^{-6} m/s were obtained for the eastern and western deposits.

4.3. Geomorphology and sediments observed in the debris flow channels

The two source areas are located above two sub-parallel channels that run southwards downslope to the railway line and road. Deposits from the debris flows are focused around these channels, which are clearly delimited by the drainage accumulation values derived from elevation data (Fig. 9). Although the out-of-channel deposits from the two debris flows coalesce in places between elevations of approximately 160 and 100 m OD, each flow followed a distinct separate channel. In general, the upper parts of the channels immediately below the source areas are the widest (2–3 m), whereas further down the channels narrow to less than 1 m wide. In cross section, the channels vary from segments with steep banks of up to 1 m in height, to areas with gentle vegetated slopes that grade into the channel.

The angle of the slope is highly variable from the source areas at 250 m OD to the base of the hillside (Fig. 10). A series of small psammite cliffs run perpendicular to the channels and vary in height from 2 m to nearly 10 m. The cliffs are regularly spaced down slope and are intersected by the channels every 50 to 100 m (Fig. 4). The uppermost part of the western channel, immediately below the source, has bedrock exposed in the channel base for a distance of approximately 100 m through the first set of bedrock cliffs. In general, the shape of the channel in this upper section is broad and open, with rare steep bank cuts into older slope deposits. The channel slopes in this segment are generally steep at between 20° and 35°, and locally exceeding 50° at the first bedrock step between 200 m and 180 m above OD (Fig. 10). Below this section are a series channel segments with slopes that are <20°, and are characterised by a gravel channel fill in the channel bed. This pattern of steep psammite cliffs (Fig. 4), followed by gentle slope with a gravel-filled streambed is repeated four times in total down slope (Fig. 10). A similar pattern is also apparent in the eastern channel, where steep rock steps (up to 68°) separate more gently sloping sections where gravel is stored in the channel floor.

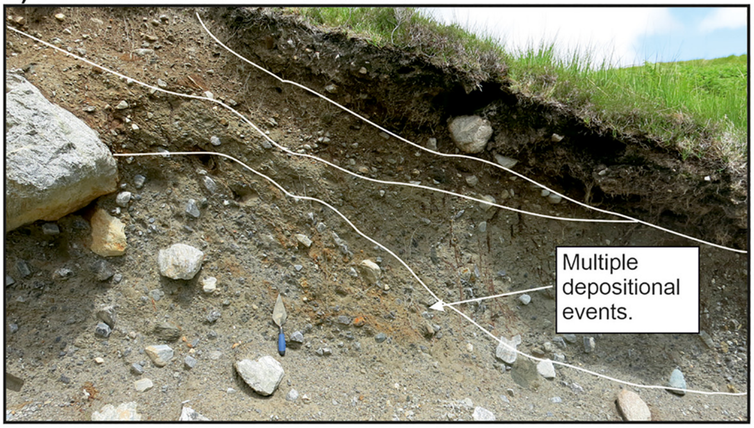
The spatial distribution of debris deposited by the 2016 debris flow is shown in the geomorphological map in Figure 4. In general, the slope is concave in shape, with the source of the debris flows on the steepest part of the slope (Fig. 9). Psammite cliffs that are orientated sub-parallel to the slope intersect the channel and cause local increases in slope angle (Figs. 4, 10). There is a distinct curve in the eastern channel immediately below the source area at 170–230 m above OD. At this location the debris flow deposits, which comprise a loose, very gravelly sand with frequent cobbles and boulders, have spilled out 12 m beyond the eastern edge of the channel and 4 m beyond the western edge.

The nature of the channel deposits, and of the adjacent slope deposits that the channels are cut into were revealed in a number of logged sections down the flow path of each channel (Fig. 8c). The various exposed sections at the margins of both channels revealed the following general sequence. The topmost deposits (laid down by the 2016 debris flows) comprise a loose, very gravelly, coarse sand with frequent cobbles and boulders. These surface deposits are generally <0.5 m in thickness. On lower gradient slopes, the 2016 debris flow deposits rest on a <0.2 m thick sandy soil, which is continuous over much of the hillslope and contains abundant roots and occasional pebble to cobble sized clasts. Below the soil is a dense sandy gravel with frequent cobbles, which varies from matrix- to clast-supported, and overlies the bedrock (Fig. 7b, c, e). The clasts are generally angular or subangular. This unit, which rarely exceeds 1.5 m in thickness, locally displays crude downslope stratification with more gravel-rich layers and some poorly-developed normal grading. Individual layers within the unit vary from 25 to 50 cm thickness with discontinuous downslope-dipping fissures also present. In places buried lenses or beds of organic soil are interbedded with the lower sandy gravel unit.

The steeper terrain is through the psammite cliffs and are characterised by much thinner sediment cover, or complete bedrock

a) Western source area overview

b) Eastern source area overview



c) Photograph of western source deposit

d) Photograph of eastern source deposit

Fig. 6. Photographs of (a–b) western and eastern source areas; and (c–d) photographs showing types of deposits in both source areas.

exposure at the ground surface. However, thicker sediment accumulations do occur in the concavities at the cliff bases (Fig. 7c, e). In contrast to lower gradient areas where the 2016 debris flow deposits rest conformably on the sandy organic soil, the bases of the cliffs are often characterised by erosional contacts between the recent deposits and the underlying sandy gravels. Sections in these localities revealed well

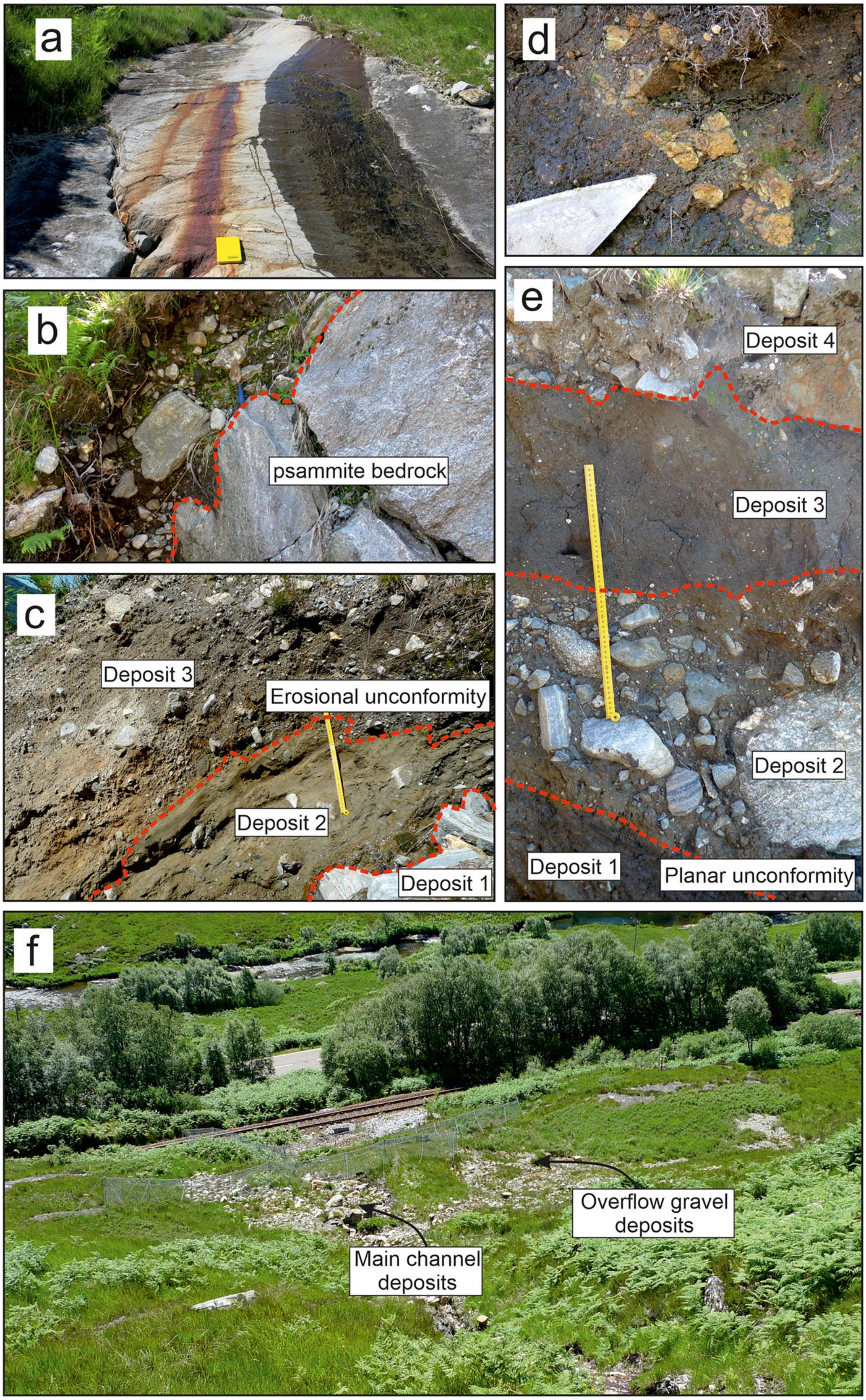
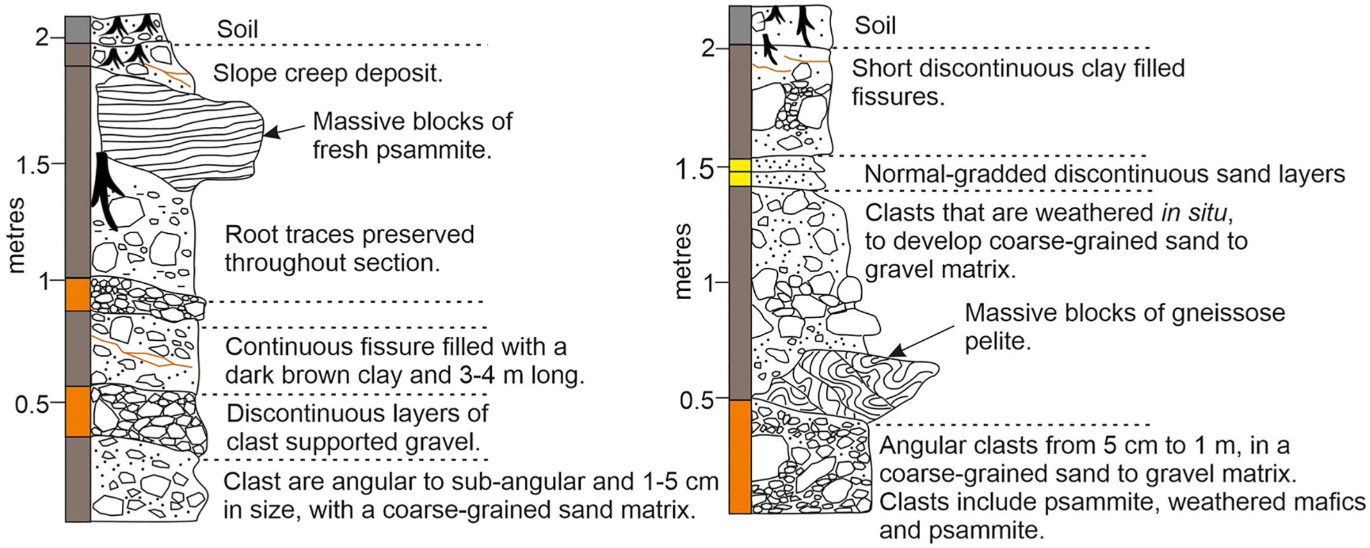
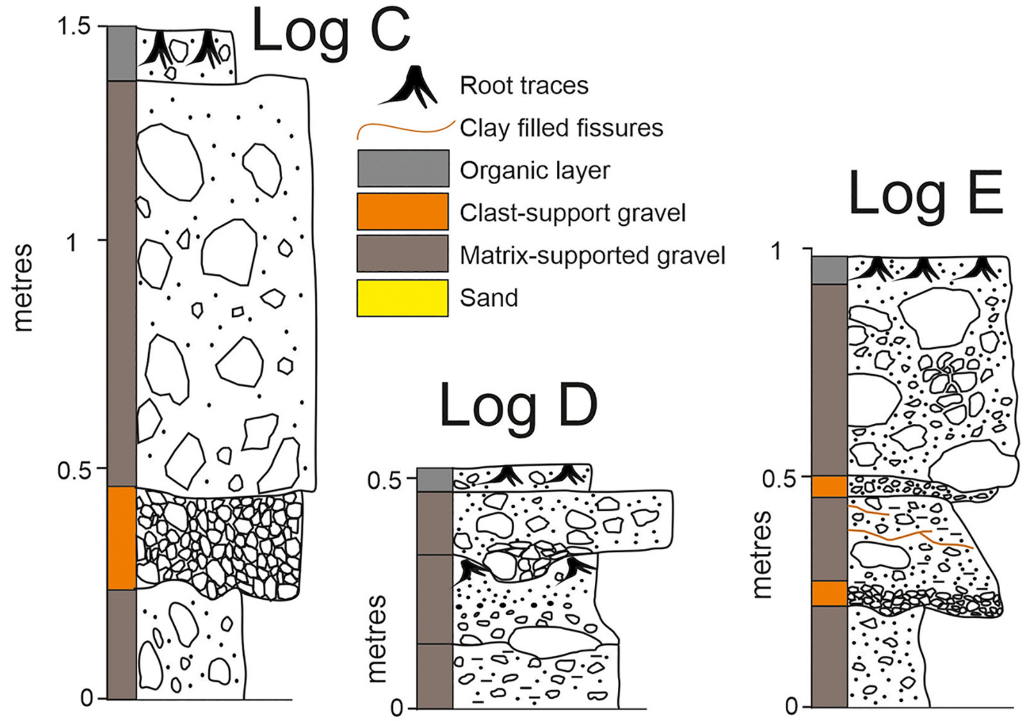


Fig. 7. Photographs from the western and eastern debris flows, (a) exposed bedrock in the upper of the western channel; (b) clast-support gravel deposited on bedrock exposed on the channel edge; (c) thick sequences of matrix-supported sediment exposed at the base of step section of the channel with the most recent debris flow deposits erosionally overlying earlier deposits; (d) ongoing chemical weathering of mafic clasts; (e) multiple gravelly (debris flow) layers with interbedded soil units; and (f) the lower channels where the debris spilled out of the channels forming a small fan that extended onto the railway line and road.



a) Log A through source material on western source area

b) Log B through source material on eastern source area



c) Logs C-E through sections exposed on the channel edges.

Fig. 8. Sedimentary logs through exposed sections in the two source areas and along the edges of the channel system.

developed shear zones and detached ‘blocks’ of the underlying dense sands.

Chemical weathering of clasts was observed in several sections down the entire length of the debris flow channel. In the eastern channel source, mafic clasts were observed to be heavily weathered forming a coarse-sand to gravel matrix. In contrast, in the same section the clasts of psammite were generally fresh and unweathered. In deposits further down the slope there are signs of chemical weathering processes but the clasts were not degraded to the same extent and generally weathering was focused along specific layers within sections. The mafic clasts appear to be most susceptible to chemical weathering and the psammite clasts appeared to be relatively unweathered (Fig. 7d).

Towards the foot of slope where gradient is < 10°, the channels split into a series of distributaries, and the recently deposited debris has spilled out forming a small fan of up to 2 m in thickness, comprising a sandy gravel with boulders. The small fan, which is now partially vegetated, extends southwards and was also deposited across the railway line and road during the failure (Fig. 7f).

The sediment budget approach results indicate a ‘best estimate’ of total sediment volume of about 6650 m^3 currently available within the catchment, out of which approximately 257.7 m^3 is located within the source area and along the channels. The breakdown per terrain units is shown in Table 1. The final deposit on the railway line and road was estimated by Network Rail to be only 50 m^3.

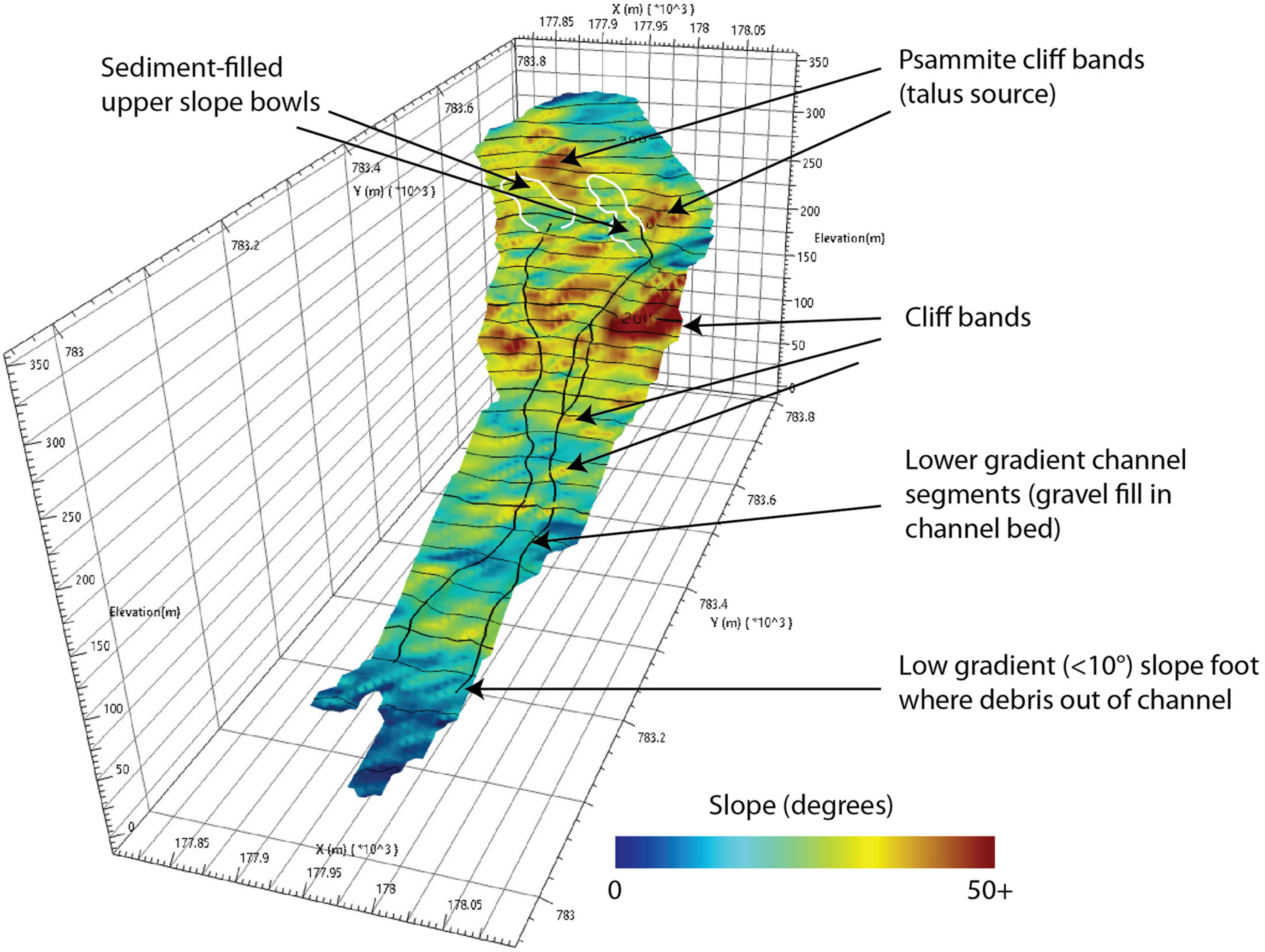


Fig. 9. 3D representation using Blue Sky DEM of the change in slope angle across the western and eastern channels.

5. Interpretation of slope conditioning and failure

Two source areas are identified for the debris flows, both feeding into two sub-parallel channels. The source areas are small asymmetrical bowl-shaped features, bound by bedrock joints, that have been locally infilled with debris. The source bowls have a shallow-dipping western side along a fracture plane and a steeper, near vertical, eastern side that forms a small cliff along edge of each bowl.

The sediment that infills the source bowls is most likely sourced from the underlying and adjacent psammite bedrock. In the eastern

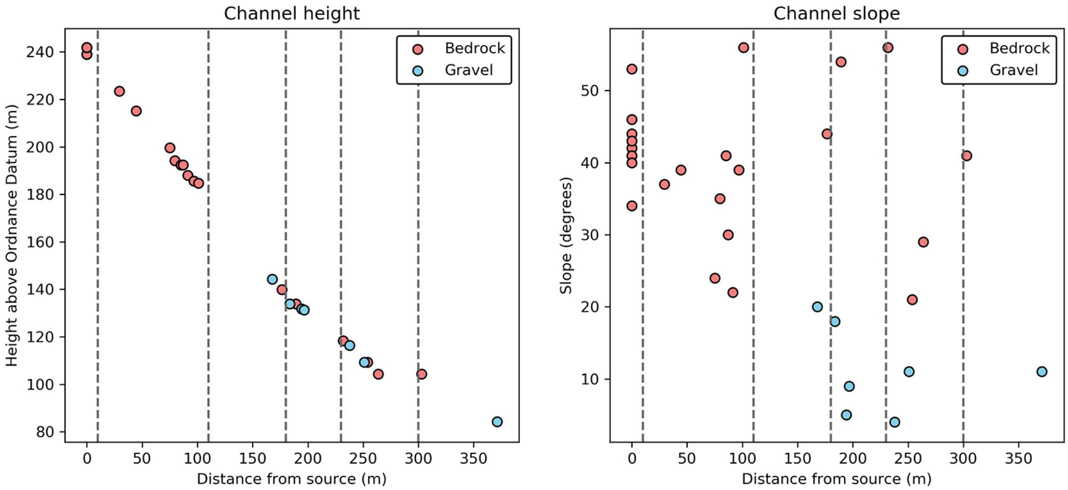


Fig. 10. Field measurements of topographic height and slope angle along the western channel. The points are coloured to show if the channel either has bedrock or gravel exposed. Dashed vertical line show the points where cliffs intersect the channel.

Table 1
Sediment budget estimate data of the western and eastern source areas, channels and the depositional fan. Channel domain locations are shown on Figure 4.

Channel domain	Description	Number of sections	Average deposit height (m)	Deposit volume (m^3)
1	Deposition area (East and West)	2	0.5	50
2	Lower middle East channel	6	0.75	41.79
3	Upper middle East channel	5	1	69.65
4	Source area East channel	3	1	27.86
5	Source area West channel	2	1	11.84
6	Lower middle West channel	4	0.3	35.52
7	Upper middle West channel	6	0.75	71.04

bowl, the exposed deposit in the head scarp is psammite-rich talus that is likely to have been sourced from the surrounding cliffs. Cavities below the cliff and above the eastern source area support the interpretation of a rockfall contribution to the talus. The fill of the western bowl includes both talus and gravel that are matrix-supported and exhibit poorly-developed clast organisation. The angular and subangular shape of the clasts in the gravel indicate relatively limited transport distances. The top most surface of the source bowls is covered in vegetation, suggesting that the source bowls underwent a previous phase of infilling that under current conditions is no longer active. In both source areas, the chemically unstable mafic clasts, have started to weather *in situ*, resulting in a reduction in the mechanical integrity of the deposit.

Exposed bedrock on the southern margin of both source areas represents the failure surface of the initial translational slide. Ongoing creep of deposits in the source areas is represented by small fissures on the top surface above the head scarps. Fissures that are sub parallel to the slope are also observed within the deposits and indicate phases of internal creep. The variation in the degree of lichen development on the exposed bedrock of the failure surfaces suggests more than one stage of exposure and therefore suggests repeated failure events. Evidence for recurring debris flow events is also present further down the channels in the form of interbedded gravelly sand and buried organic soil units (*e.g.*, Fig. 7c), and stacked sequences of sandy gravel deposits.

Overall, the evidence from the source areas suggests a joint-controlled topographic feature that has undergone infilling through talus deposition, mass-creep processes, and locally sourced debris flows. Due to the scale of the deposits observed in the source areas, they are not included on current BGS 1:50,000 superficial geology maps, which identify the area as having bedrock at or near surface. Ongoing weathering of some of the mafic and mica-rich schist clasts within the deposits has increased the clay concentration of the deposits, which likely changes the porosity, permeability and cohesivity of the deposit with time. In a similar way, progressive pedogenesis has been suggested to affect the fine-grained material content, horizon differentiation and hydraulic properties of hillslope materials at other sites in Scotland (Brooks and Richards, 1993). This may result in areas of local instability, which may contribute to future failures. Removal of material from the southern source area has resulted in fissures forming above the head scarps and within the adjacent deposit as the entire mass undergoes stress relief. It is likely that the fissures formed by a combination of processes including minor failures prior to the main landslide that were filled with weathered clay and acted as failure surfaces during the main landslide. The possible mechanism for failures in both source areas is translational sliding, where the bedrock acted as a décollement surface. Isolated peat rafts on the floor of both source areas represent remnants from the translation slides that initiated the debris flows. The first stage involved a small failure owing to pore-water pressure development at the deposit-bedrock interface, and the subsequent fluidisation of the saturated failed mass. The second stage would have involved the failure of the mass behind the failed deposit from the first stage, due to stress-redistribution (stress-relief). In the latter stage, the failed mass would have been unsaturated and therefore, not generated enough excess pore-water pressure upon failure (contractive behaviour) to initially fluidise into a debris flow.

The deposits in both source areas are rich in sand, silt and gravel material and therefore potentially have a high porosity. The hydraulic conductivity measurements from the two source areas are comparable to typical values of loamy sand and sandy loam (Clapp and Hornberger, 1978). The lower permeability of the eastern source relative to the western source could be the effect of the difference in relative density (MacDonald et al., 2012) and the presence of higher clay content owing to the weathering of mafic material sourced from the parent rock. The initiation mechanism of the shallow translational failure could be attributed to the pore-water pressure development at the interface of the deposit and relatively impermeable bedrock due to the rise in water table. The bedrock across the site is highly impermeable resulting in the majority of groundwater flow focused along fractures and across the bedrock surface. Additionally, the delayed pattern of the antecedent rainfall (Fig. 2) might have played a significant role in reducing the soil matric suction and thus, the slope stability condition (Rahimi et al., 2011).

Much of the material deposited along the channel margins by debris flows conformably overlies the pre-existing surface soil, particularly along lower gradient segment of the hillslope. This indicates parts of the channel that are dominated by deposition rather than erosion. However, at the base of the cliffs that traverse the slope, greater erosive behaviour of the flow is indicated by the evidence for scour and erosion into the underlying sediments similar to that shown in the fixed to erodible bed transition experiment by Haas et al. (2016). These localities may therefore have contributed additional sediment to the overall volume of material moved, partially replenishing the debris flows through the base of each cliff.

6. Discussion: factors influencing debris flow activity in an ice-scoured landscape

The 2016 landslide and debris flow event near Lochailort, occurred in an ice-scoured landscape where a minimal thickness of superficial cover is shown on current BGS 1:50,000-scale geological maps. As a result of the ice-scoured setting and minimal thickness of superficial sediment mapped, the area is classified as having a low landslide susceptibility. In this study, we describe and discuss the geological, hydrogeological and geomorphological factors that caused the 2016 slide and resultant debris flows.

The preconditioning of slopes in the Glenfinnan area for debris flows was controlled by the interaction of glacial erosive processes with bedrock lithology and structure. The rugged topography with large amounts of exposed bedrock is typically described as an ‘areal scour’ landscape (Rea and Evans, 1996; Bradwell, 2013) representing a setting of net glacial erosion and minimal sediment cover. In an areal scour setting, erosion is typically focused on structural weaknesses that are exploited by abrasion and plucking (Rea and Evans, 1996). At the Glenfinnan site, the bedrock is predominantly psammite with a set of south-east dipping fractures that are sub-parallel to the current slope. Joint surfaces define the base of both the western and eastern source bowls that were likely exposed during previous glaciations. The wide spacing of the fracture sets is a strong control on the depth of the source bowls enabling the potential to accommodate significant amounts of sediment. Joints in the psammite and pelitic shear-zone are continuous to the base of the slope, with ongoing erosion exploiting these structural weaknesses to form the debris flow channels.

Sediment accumulation into the source bowls appears to be dominated by physical weathering of surrounding cliffs and sediment mass wasting processes (*e.g.*, talus accumulation, mass creep and local debris flow). Both source areas are now covered in a layer of peat and vegetation. Talus and debris flow deposits are not observed above the peat layer in the source bowls suggesting that these processes are currently inactive. Sediment in the western bowl is mainly comprised of locally-derived mass-wasting deposits, and in the eastern bowl the sediment comprises a mix of talus and mass-wasting deposits. The western source area deposits are comprised of psammite clasts in a sand matrix, which are likely sourced from the surrounding cliffs and the underlying bedrock. The eastern source area sediments are predominantly composed of psammite clasts in a sand-rich matrix, with subordinate amount of mafic material sourced from the underlying shear zones.

The precise extent of the former Loch Lomond Readvance glacier in the Loch Ailort area is debated (Boulton et al., 1981; Dawson, 1988); however, it is likely that the upper slopes at the site will have been exposed to cold, periglacial conditions for some, if not all, of the Loch Lomond Stadial. We suggest, therefore, that the localised source bowls largely became infilled with sediment at that time (and possibly also during the preceding Lateglacial interstadial) through accelerated mass wasting processes (*e.g.*, talus accumulation, and the weathering and gradual downslope movement of those deposits) (*e.g.*, Ballantyne and Harris, 1994).

The long-term stability of slope material is influenced by the composition of the material, slope conditions and the climatic conditions. The source sediments are predominantly composed of quartz, which is eroded from the surrounding psammite bedrock making the deposits chemically stable. The sediments in the eastern source area contain a subordinate amount of mafic material which is chemically unstable and breaks down to clay during weathering. Generally, both source areas have a relatively high porosity and permeability, however due to slightly higher clay content the eastern source area has a slightly lower permeability. Overall the hydraulic conductivity of the two source areas is relatively low for a sand (MacDonald et al., 2012), suggesting the weathered clay has reduced the overall permeability of the sediment, and therefore reduced potential stability. Sediment budget calculations suggest that a relatively small proportion of sediment was deposited on the railway line and road relative to the original failure. A large proportion of sediment remains in the source area and channels. Under equivalent rainfall conditions there is sufficient sediment availability for the potential of future debris flows.

The talus-type sediment is likely to have accumulated in a local concavity as part of a phase of slope alteration, which may have been accelerated under periglacial conditions that accompanied the Loch Lomond Stadial. The coarse-grained and highly porous sediment became perched within structurally controlled 'bowls' on the upper parts of a steep slope within areas of focused drainage accumulation. The perched sediment is susceptible to a reduction in strength caused by an increase in water content during periods of intense rainfall, such as the events of July and August 2016 that resulted in the failure on the psammite fracture plane. The translational slide trigger could possibly be the result of effective stress reduction from a rise in water table. However, only part of the failed soil mass probably mobilised into debris flow through fluidization. The rest of the failed soil mass, as observed in field, slumped at the source area owing to dilative behaviour. The resultant failure became a channelised debris flow that deposited material blocking the railway track and road at the base of the slope. The initial failure in both source areas represents a relatively small proportion of the total source bowls; however, they still produced a relatively large amount material. The final deposit at the base of the channel that covered the road and track were estimated to have been only 100 t (BEAR Scotland, 2016; Network Rail, 2016). The calculated weight of material moved from the source areas is approximately 275 t. Therefore, it is likely that a significant amount of material was deposited in the channel and on the adjacent slope as over-spill deposits during the depositional phases of the debris flows. Indeed, more of the material appears to have been deposited on the flanks of the channel than at the base of the slope. This is in contrast to other examples such as in Glen Ogle (Milne et al., 2010) where an initial relatively small slide occurred that developed into a debris flow that gathered material from the channel edges, with the final deposit being larger than the initial slide. The Glen Ogle debris flow occurred within the Montane and Valley domain (Booth et al., 2015) where there are significantly more slope deposits available than in the ice-scoured domain.

An important control of the 2016 debris flow event was the high rainfall event that occurred prior to the landslide. In this case the preceding pattern involved a wetter than average July 2016 with very few consecutive dry days, followed by intense daily rainfall during the 2nd week August 2016. This is a familiar rainfall pattern for Scottish debris flow events, which are usually preceded both by extended periods of (antecedent) rainfall and intense storms (Winter et al., 2010a, 2010b). The UK Climate projections (UKCP18) (Lowe et al., 2018) suggest that future summer rainfall will vary from 30% drier to 6% wetter, and winter rainfall will vary from 4% drier to 9% wetter. Although there are broadly drying trends for future summer rainfall, there is likely to be an increase in intensity of heavy summer rainfall events (Lowe et al., 2018). In addition, over the last century (1914–2004) there has been an overall increase in average annual rainfall across the west of Scotland (Barnett et al., 2006). The potential future variations in both rainfall and rainfall intensity in Scotland is likely to be an important influence on the frequency of debris flow events that affect sediment loaded slopes in western Scotland.

The conditions that have generated the hazard susceptibility at Loch Ailort differ somewhat from those in the Montane and Valley Quaternary domain, which is associated with more widely reported debris flow hazard sites such as the A83 Rest and Be Thankful in Glen Croe (Finlayson, 2020) and the A85 in Glen Ogle (Winter, 2005; Milne et al., 2010). In these areas, hillslopes often support a more widespread mantle of glacially derived sediment that can provide source material for debris flows. A continuous 'sediment mantle' is far rarer in the Ice-Scoured Mountain domain; however, this research has shown how a variety of factors have combined to create local 'pockets' of sediment, which can be susceptible to failure. These pockets of thicker sediment have not been captured at the scale of current geological survey maps; and it would be a time-consuming exercise using traditional mapping approaches to capture information in sufficient detail across an entire domain or at regional scales. However, geoanalytical and geostatistcal approaches using remote sensing datasets and field-derived 'training data' provide one possible solution to improving our understanding of spatial sediment distribution on such hillslopes (*e.g.*, Scarpone et al., 2016; Williams et al., 2020). These are important local-scale features, and further demonstrate the importance of site-specific investigations when using the GeoSure Hazard map (Booth et al., 2010).

The Lochailort debris flows are an important example of how key geological, geomorphological and climatic factors have interacted to increase potential landslide susceptibility on an important infrastructure corridor in the ice-scoured Quaternary domain. The accumulation of talus deposits was influenced by bedrock structure and lithology, creating areas of thick sediment in topographic 'bowls' on the upper slopes above Lochailort. An understanding of the interaction of these processes is important for future mapping of slope sediments and hazard assessment within the Ice-scoured Montane Quaternary domain.

7. Conclusions

The 2016 debris flow event that blocked the railway line and road to Mallaig in north-west Scotland is an example of a landslide that occurred in an area of little or no mapped superficial cover on the slope. In settings of low superficial sediment cover, such as the 'Ice-scoured' Quaternary domain in north-west Scotland (Booth et al., 2015), the interaction of geological and geomorphological factors still has the potential to generate a locally significant landslide hazard. The 2016 landslide near Mallaig is an example of a disruptive landslide in an area of low superficial sediment cover that deposited 100 t of debris over transport infrastructure. The interaction of bedrock lithology and structures with erosional processes created a local setting for the accumulation of a significant thickness of sediment. Recent intense rainfall acted as the final trigger for the 2016 debris flow event.

To develop landslide hazard models for areas of minimal sediment cover an improved understanding of the nature, distribution and thickness of superficial sediment is required in upland areas of net glacial erosion. Understanding longer term slope evolution and the interaction of geomorphological processes with local bedrock structure is of value in identifying areas that may have accumulated source sediment and could, under certain conditions, be susceptible to failure. The scale of the resultant debris flows has the potential to disrupt transport networks.

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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