**Late Quaternary solifluction sheets in the British uplands**

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**Abstract**

Solifluction sheets are large-scale and extensive valley floor and valley side landforms developed widely in the British Isles from mass wasting of glacial and periglacial sediments during lateglacial times. We describe their geographical distribution and review the processes that have lead to their development. We use data from the Cheviot Hills, the one site in the British Isles where sedimentology and OSL dating have been combined, to assess their age and nature of deposition. We also present data from central Wales where new mapping and resistivity survey has reconstructed the nature of valley-side solifluction sheets. We explore the relative lack of recent research on these landforms and argue that solifluction sheets represent a clear example of how upland geomorphological systems have responded to late-glacial climate change. We end by identifying a number of areas where research on these enigmatic features could be focussed, including better understanding of their distribution, sedimentology and age.

**Introduction**

Solifluction sheets are large valley fill drift landforms developed on the lower parts of hillsides in areas of upland Britain that underwent Devensian glaciation. They should be differentiated from other solifluction landforms in the British Isles (eg lobes and terraces) as the latter are generally smaller, and associated with Holocene periglacial processes (see Mottershead and White 1969; Sugden 1971; Ryder and McCann 1972; Ballantyne and Harris 1994).

The solifliuction sheets described here are the most widespread drift landforms in these upland valleys and form distinctive long rectilinear smoothed benches underlain by resedimented deposits whose thickness increases towards valley bottoms. Their fronts are often trimmed by fluvial erosion producing their terraced form. They have been termed 'solifluction sheets' and 'valley floor solifluction terraces' (Ballantyne and Harris 1994)and have been described from a number of upland valleys in Britain (Figure 1) including in central and south Wales ( e.g. Watson 1970, Harris 1981); the Isle of Man (Thomas 1971, 1976; Chiverrell *et al.* 2001); the Southern Uplands (e.g .Tivy 1962) and the Cheviot Hills (Douglas and Harrison 1987) (Figure 1). The processes responsible for their emplacement has been discussed in a number of publications (e.g. Harris and Wright, 1980; Harrison, 1996; Harris, 1998).

These solifluction sheets have a distinctive morphology and are variable in size and form. Valley width appears to be an important control on sheet form. In wide, open valleys these landforms are often present on both valley sides and display treads up to 300m wide set at low angles (often between 3° and 10°). In more incised valleys solifluction sheets are less well developed, often form on only one side of the valley and display narrower treads (rarely more than 100m wide) set at angles up to 31°. In all cases sheet fronts are less than 15m high (Figure 1 inset and Figure 2 a, b).

Marked asymmetry is common in many valleys with solifluction sheets deposited only on one side of the valley. The reasons for this are varied, reflecting the sites of deposition of glacial till and possible localised changes in microclimate, and these are discussed below. The drifts underlying these sheets are usually mass-wasted tills and/or gelifractates although in some places the underlying stratigraphy is more complex (Harrison 2002; Mitchell 2008). *In situ* tills and bedrock are often present at the base of sections.

While valley floor solifluction sheets are widespread in many upland regions, they are also absent in others. For instance, almost none have been identified in the Scottish Highland and Islands, although they are widespread in the Southern Uplands. In addition, in central Wales (and perhaps more widely) such solifluction sheets have been preserved as mid-slope rather than valley floor landforms and these are discussed below.

As a result, this paper aims to assess the past research on these landforms; to provide a current state of the science review; to identify gaps in knowledge, which are numerous, and finally to rejuvenate research into these landforms.

**Importance**

Their importance rests on 3 assertions.

First, solifluction sheets form the largest drift landforms in many upland valleys in Britain and, therefore, for purely intrinsic reasons, understanding their development and geomorphology is of great interest. Despite this, there is a pronounced absence of recent research on these features. We can illustrate this by a simple comparison between the number of papers published on these landforms compared with those on moraines. A *Web of Science* search conducted in October 2020 using the search terms 'moraine' and 'Scotland' returns 107 papers since 2000. The term 'solifluction sheet' returns only 3 papers (Harrison 2002; Harrison 2010; Mitchell 2008)for the whole British Isles, although the term 'solifluction terrace' produces some additional references (eg

Chiverrell et al 2001). While reviews on Holocene and lateglacial upland landforms have discussed solifluction sheets (eg Ballantyne 2008; 2019) no empirical work on these large and extensive landforms has been published for a decade in the British Isles.

Second, solifluction sheets represent a clear geomorphological response to climate change at a time of rapid deglaciation. They may therefore provide a useful analogue for understanding geomorphological responses to current climate change in some similar upland settings, especially as ice sheets, ice caps and large valley glaciers undergo future recession and eventual deglaciation.

Third, it is important to understand sediment fluxes from solifluction sheets since late-glacial times as they provide, and have provided, much of the sediment for upland rivers that is reworked to form floodplains.

**Distribution**

Several recent review papers have assessed the role of solifluction in modifying landscapes in the British Isles (eg Ballantyne 2019, Wilson 2017) but there has been no review of the solifluction sheets discussed here.

Solifluction sheets are widely developed in many upland regions of the British Isles, but perplexingly absent in many others. Table 1 lists the main authors who have described solifluction sheets in The British Isles. What is clear is that solifluction sheets appear to be absent in Ireland (or, more likely, no research has identified these; Wilson 2017) despite decades of periglacial studies (eg Colhoun 1971; Warren 1987). They have also not been described from large parts of western Scotland and the Islands (Galloway 1961a,b), although see Figure 2a. In addition, while there has been considerable research interest in these solifluction sediments and landforms from the late 1950s to the early years of the 2000s, after this, no fundamental research has been carried out on these landforms and their sediments.

**Evolution**

The nature of solifluction sheets has been the focus of considerable debate and this has concentrated on the processes which emplaced the drifts, the timing of these processes and thus their climatic and geomorphological significance. As a result, a number of different hypotheses have been put forward to explain the sedimentology and geomorphology of these landforms. These hypotheses can be broadly grouped into three.

*The periglacial hypothesis.* This argues that these features are the result of prolonged weathering of bedrock and mass-wasting of the debris under periglacial conditions, and was championed by workers such as Crampton and Taylor (1967), Watson (1970), Potts (1971), Tivy (1962), Common (1954), Galloway (1961a,b) and Humphries (1979). These authors worked in the valleys of central and south Wales and the Southern Uplands of Scotland and the periglacial hypothesis was based upon an interpretation for the presence of reworked frost-shattered bedrock fragments underlying the solifluction sheet surfaces. Watson (1970) used the presence of these landforms as an argument for the absence of glacial ice in large parts of central Wales during much of the Devensian. If we assess the nature of contemporary solifluction in periglacial environments this has demonstrated the slow nature of solifluction (in the order of cm per year) and the fact that solifluction only operates on the top metre or so of regolith. Based on this, the thick sequences of sedimentary deposits must therefore represent a long time period of periglacial, rather than glacial, conditions.

*The Younger Dryas (Loch Lomond Stadial) solifluction hypothesis.* This is similar to the periglacial hypothesis but argues that the landforms are the result of solifluction operating on glacial and periglacial drifts following glaciation largely during the periglacial episodes of the Younger Dryas (Loch Lomond) Stadial and follows from research by authors such as Potts (1971) and Harris and Wright (1980) in Wales who identified glacially-modified clasts within the deposits. This hypothesis was developed in the Cheviot Hills by Douglas and Harrison (1985; 1987). Here, resedimented tills and gelifractates were identified overlying *in situ* tills which, on chronostratigraphic grounds, were taken to have been deposited by Dimlington Stadial glaciers. It was argued that the period of resedimentation of drifts occurred during the short-lived Loch Lomond Stadial by solifluction processes.

*The paraglacial hypothesis.* This hypothesis was developed by Wright (1991) working in south Wales and by Harrison (1991; 1996) in the Cheviot Hills. They argued that the nature of contemporary solifluction (see the periglacial arguments above) and the short length of the Loch Lomond Stadial makes a solifluction origin of the drifts unlikely and that rapid deposition of glacially-derived sediments occurred shortly after deglaciation by paraglacial debris flow processes.

The debates between these contrasting hypotheses have never been satisfactorily resolved, despite the 60 years that have elapsed since the first papers on these enigmatic landforms were produced. As a result, this paper attempts to show the variability of solifluction sheets in parts of the UK and addresses their significance. We examine solifluction sheets as valley fill deposits with examples from the Cheviot Hills, and also as terrace features which are widely developed on hillsides from central Wales, where we argue they represent the fossilised position of individual sheets.

**Sedimentology, geomorphology and age**

The complexity of the stratigraphy underlying solifluction sheets has been described by Harrison (2002) and Mitchell (2008). A number of different facies exist beneath sheet surfaces and this variability reflects differences in bedrock lithology, the angle of the sheet surface (controlling slopewash and therefore clast:fines ratios) and the varied distribution of available sediments on hillsides. Despite this variability, the stratigraphy tends to be of a lower diamict (usually interpreted as an in situ glacial till overlain by a thick sedimentary unit interpreted as a resedimented till, but also containing weathered bedrock fragments where available. In turn this tends to be overlain by a thin sedimentary unit consisting of frost shattered clasts in a weakly consolidated matrix; this is interpreted as a true solifluctate emplaced during cold periglacial conditions.

A classic location where this stratigraphy is exposed is in the Breamish Valley in the Cheviot Hills at Linhope (Figure 3) and this was described by Harrison et al (2010). This is a stream cut section in a solifluction sheet 200m upstream of Linhope Spout waterfall in the valley. The section represents the type site for this sedimentary landform, which has been termed the Linhope sedimentary deposit (Harrison, 2002). The section consists of 8m of sediment that can be differentiated into 5 distinct depositional units on the basis of lithology, clast form and roundness and macrofabric analysis (Figure 4). The basal Unit A is a stiff, matrix supported diamict with predominately angular to sub rounded clasts. The clasts display a strong fabric orientated parallel to the valley axis. Work by Douglas and Harrison (1985; 1987) and Harrison (2002) considered this unit to be a deformation till deposited by a warm based glacier during the maximum of the LGM (around 26– 13 ka BP) flowing eastwards along the Breamish Valley. Units B, C and D were originally interpreted as soliflucted till deposits created under sustained Younger Dryas periglacial conditions (Douglas & Harrison, 1985; 1987), but Harrison (1991; 2002) later speculated that they could have been formed by the rapid resedimentation of till sheets by debris flow processes shortly after the retreat of LGM Ice. More detailed assessment of the sedimentology of the section discussed in Harrison et al (2010) suggests that periglacial active detachment slides might also have emplaced some of these sediments.

Unit B is a matrix supported diamict, which contains a relatively high proportion of subangular and sub-rounded clasts, all showing a pronounced fabric that is orientated obliquely to the direction of max slope gradient (Figure 3). A distinctive feature is the increasing numbers of sand lenses and discontinuous layers of sand towards the downslope end of this unit. These range in thickness from 3 to 5 cm and are composed of medium and coarse sand with varying amounts of gravel and display lamination and trough cross lamination structures. Unit C is a matrix supported diamict with strong downslope fabric. This unit contains a higher proportion of angular clasts and a small percentage of very angular clasts. Unit D is a matrix supported diamict with a strong downslope fabric and a relatively high proportion of very angular to sub angular clasts (Figure 3). A distinctive feature in Unit D is an irregular discontinuity, with a zone of brecciated clasts of diamict directly above. Similar to Unit B, Unit D also displays increasing numbers of cross cutting sand lenses and discontinuous layers of laminated sand towards the downslope end of the unit. At the top of the section, Unit E is a matrix supported diamict with predominantly angular and sub angular clasts and abundant thin layers and lenses of medium to coarse sand. This unit also displays a strong downslope clast fabric (1668) (Figure 3).

Overall, the basal Unit A is interpreted as an in situ till deposited by a valley glacier moving west to east and units B-E as the result of mass-wasting of weathered granite and tills from the hillsides with the addition of gelifracted clasts in Unit E. Clast lithological analysis between units A, B and E shows no significant differences between them at $p= 0.05$.

Harrison et al (2010) used OSL to date six samples from the exposed sediments at Linhope and these represent the only dates from these landforms yet obtained in the British Isles. Details of the sampling and analysis are reported in Harrison et al (2010). Overall, the dates demonstrated that unit A was formed before 12.7 ka and therefore suggests strongly that it is an LGM age till as the sedimentology suggests. Units B, C and D were dated to between 12.70 to 10.29 ka. The timing of the retreat of the LGM ice sheet in Northern Britain is, in part, poorly constrained, but it is probable that this area became ice free around 15 ka. The lengthy gap between the timing of deglaciation in the Cheviots and the age of units B, C and D suggests that their origin is not related to the rapid paraglacial reworking of the Devensian till as speculated by Harrison (1991; 2002). Instead, since the period 12.70 to 10.29 ka broadly coincides with the timing of the Younger Dryas cold climate conditions, it is more likely that Units B, C and D are soliflucted till deposits as concluded by Douglas and Harrison (1985; 1987). The date for the sand lens near the top of Unit E of 2.33 ka BP is taken to represent a phase of late Holocene colluviation.

This stratigraphic pattern of in situ tills at the base of stream cut sections overlain by resedimented tills and a periglacial solifluction layer at the top of sections is repeated, with small variations, throughout the Cheviot Hills and elsewhere (eg Mitchell 2008). However, the spatial pattern of solifluction sheet development varies considerably. In wide, open valleys where ice-flow was predominantly controlled by the underlying topography and was down-valley, solifluction sheets are found on both valley sides (see Figure 4a and 4b from the Harthope Valley). Where ice-flow was not controlled by the underlying topography and was therefore across (mainly tributary) valleys, solifluction sheets are largely developed on down-ice facing valley sides, with up-ice facing valley sides being eroded and free of soliflucted sediments. Examples of thus are shown in Figure 4c and 4d from the Bowmont Valley.

While solifluction sheets of the type discussed in the Cheviot Hills are widely found in many other regions of upland Britain, in parts of central Wales solifluction sheets have developed on valley-sides and have not always accumulated to reach the valley floors as seen in the Cheviot Hills.

These features located in mid Wales are in an area centred around the village of Carno (SN 959 969) and across the Dinas Mawddwy and Llanidloes 1:50,000 geological maps (sheets 150 and 164) which lie in the central part of Wales between Dolgellau and Newtown (Figure 5a and 5b). The districts were most recently geologically surveyed in 2008 with some parts mapped in the preceding years. The area includes part of the Cambrian Mountains, a sparsely populated moorland landscape. The topography is hilly with the Cambrian mountain range in the west of the region rising to over 700m at the highest point. The bedrock geology of the region is predominantly of Silurian (Lower Palaeozoic) age, comprising medium-coarse mudstones and turbidite sandstones with beds of coarse sandstones. The area of interest is located on the Llandovery and Penstrowed formations. These are heavily deformed by faults which strike in a SW-NE direction. The dominant drainage mirrors the bedrock structure draining into the valley of the Afon Banwy in the north east.

Much of the area is covered by superficial (Quaternary) deposits. Alluvium underlies the floodplains of the Severn and Carno rivers as well as sand and gravel river terrace deposits. Diamict is found in many of the lower lying areas and comprises glacial till deposited during the Late Devensian glaciation (Patton 2013).

From a remote sensing survey, over 1500 features were identified and digitised at the convex break in slope and a number of them were mapped in the field (Figures 5a and 5b). The features are located on superficial geology and on east facing hillsides. Six trial pits were excavated in a lobate feature at SN 29470, 96291 to a depth of 1.8m using a mechanical digger (Figure 6). A weathered track section was also freshly excavated which provided a cross sectional view. The diamict examined is highly-consolidated, consisting of matrix supported clay, silt, sand, gravel, cobble and boulders with clasts comprising of heavily striated local bedrock. In Carno, (Grid Reference SN943957) this diamict has been drilled to a depth of over 30m for wind turbine foundations. The features do not appear to occur on steep slopes (>30°) or shallow slopes below 5°. An upland environment with a slope angle of around 10° seems to be the optimum location for formation. The features have been recorded from the tops of the slopes down into the valleys where they have become obscured by agricultural activity and other slope processes and often form valley floor solifluction sheets. The main concentration of these features is within a 50km square but there are some outliers such as a few to the NW of Newtown which are also on rocks of a Silurian age. Some of the features recorded do not follow the contours of the hill slope, they instead seem to cross cut it lying at an angle oblique to the horizontal. This removes the possibility that they are some kind of relict shoreline.

At one site excavations were made to assess the sedimentology. Upon excavation, the composition of the feature was divided into three separate deposits. The very top layer of about 30-50 cm thickness featured a saturated dark brown organic soil with rare sub-rounded clasts. The next 40-80 cm comprised a pale orange-brown soft silty clay with occasional sub-rounded pebbles up to 3cm in size (and interpreted as a resedimented slope deposit). Beneath this lies a very stiff blue grey clay, silt, sand, sub-angular gravel, striated cobbles and boulders up to 1.5 m in size. Frost shattering of the boulders and cobbles occurs towards the surface of that deposit and this unit is interpreted as a glacially emplaced diamict.

To better understand the sub-surface architecture of the solifluction sheets we carried out a geophysical survey at Carno using 2D Electrical Resistivity Tomography (ERT). Full details of the methodology are discussed in textbooks (Binley and Slater, 2020) and the review by Loke et al. (2013). We used a linear array of 64 stainless steel electrodes along a transect with a maximum length of 315 m, crossing two separate solifluction fronts in the presumed direction of flow. The full transect had regular inter-electrode spacings of 5 m (profile CAR-A), whereas the shorter profile (CAR-B) used 1 m spacings. The aim was to achieve higher spatial resolution at shallower depth and shorter profile length, and greater lateral coverage and greater depth of penetration at longer transect length, respectively. Profile CAR-B was therefore nested within profile CAR-A between the profile distances of $x$=44 m and $x$=107 m, focussing on the upper of the two features.

Measurements of the electrical resistance were made across multiple combinations of four electrodes at a time, in order to determine the spatial distribution of electrical properties (here: resistivity) of the rocks and sediments beneath the surface. Data were collected using a dipole-dipole array configuration with the characteristics $n$=1...8 and $a$=1...6 (Loke et al., 2013), which yielded 1,980 resistance measurements each for CAR-A and CAR-B. Reciprocal data were also collected to facilitate the assessment of measurement errors and constrain the inverse model appropriately. Smoothness-constrained least-squares inversion with topographic corrections was then applied to both transects, resulting in 2D cross-sectional models of subsurface electrical resistivity $\rho$ (measured in Ωm = Ohm.metres, the inverse of conductivity $\sigma$ measured in S/m). The method maps and differentiates between regions of higher and lower ability of the ground to conduct electrical current. Resistivity in Quaternary sediments (and rocks more generally) is strongly dependent on (1) clay content, (2) grain size, (3) porosity and (4) the moisture content and degree of saturation of the material. Temperature and salinity influence resistivity, but are not thought to play a significant role at this site.

The results are shown in Figure 7 for profile CAR-A CAR-B. The red end of the colour range represents more resistive material, whereas the blue is more conductive. We interpret regions of high resistivity as material that is less well consolidated, better drained and is likely to exhibit lower clay content and have a higher proportion of clasts and pebbles in the matrix. The top of the sequence varies gently in thickness (typically 1.0-2.0 m), and likely corresponds to the combined Units A and B discovered during excavation nearby. The layer is fairly uniformly resistive ($\rho > 150$ Ωm), except for a more conductive region at the crest of the hill, and a more resistive region to the base of the slope at 90 m, where $\rho$ exceeds 1,000 Ωm. Excavation showed the material at the base of the slope to be much softer and looser than the material in the section cleared through the track, which corresponds to the deposits lower down in the feature. These observations would suggest that the sediment within the top ~2 m of the feature has been re-mobilised, which will have improved drainage and accelerated weathering and soil formation, thus in turn increasing the resistivity. We therefore interpret this as an unconsolidated periglacial solifluction layer.

Material beneath this layer displays a broadly uniform low resistivity ($\rho < 100$ Ωm), likely driven by greater clay content and a higher degree of consolidation. This corresponds to our observations from excavations in the deposits (Figure 6), which show a stiff diamict containing an abundance of striated clasts. The uniformity in electrical properties of this unit mean that we interpret this deposit as an in-situ glacial till, of probable Late Devensian age.

## Discussion

In this discussion we focus on eight main issues.

1. Terminology and classification

This has bedevilled studies on solifluction processes and landforms for decades. There is general agreement that solifluction describes the slow downhill movement of saturated materials, often affected by frost creep and usually occurring in a periglacial environment (e.g. Harris 1981). Matsuoka (2001) further classifies solifluction by including needle ice creep and gelifluction; the latter being associated mainly with seasonal thawing. Benedict (1970) and Washburn (1979) originally classified solifluction landforms as stone-banked and turf-banked lobes and terraces, although Ballantyne (1984) argued that "such distinctions are misleading, ambiguous, vary in usage and do not distinguish features of different structure, development or age". He thus classified solifluction sheets and lobes according to their internal composition. However, absent from this classification are the large-scale 'solifluction sheets' described here. While similar landforms to those discussed in this paper are found in many contemporary periglacial environments (Smith 1956; Everett 1967; French 1976) they are much smaller than the features described in the British Isles, with sheet fronts (risers) commonly only a few tens of cm high. Finally, the IPA Glossary (IPA 1988 p. 78) describes solifluction sheets as "a broad deposit of nonsorted, water-saturated, locally derived materials that is moving or has moved downslope". This partly describes the landforms described here, although, as has been discussed in this paper, much of the constituent material is glacially transported and not locally-derived.

2. Why has there been so little interest in solifluction sheets in recent years? They form major elements of the landform-sediments associations in large areas of upland Britain and clearly represent a large amount of sediment mobilisation during late glacial times. In addition, there are also obvious gaps in our knowledge of these features. For instance, we have almost no information on the age of sediment emplacement, and only limited understanding of the processes involved. Only Harrison et al (2010) provided any information on these questions, and only from one site in the Cheviot Hills. Is there therefore a case to be argued that this is an example of how fads exist in geomorphology and Quaternary science, with research on solifluction sheets having fallen out of favour? There is an enormous literature on fads and fashion in science (see Abrahamson 2009 for some examples) and it may be that geomorphology and Quaternary science is also prone to this (for instance, how many papers have been recently published on erosion surfaces in the British Isles, compared to the number published in the 1950s-1980s?). The reason why some subjects become fashionable, and others lose this is open to debate, but it may be that once subjects have been studied to some level, it may take a methodological and/or conceptual change before that subject becomes fashionable again. We would argue that we are on the cusp of such a reinvestigation of

solifluction sheets given improved dating and mapping techniques. We hope so, and hope that this paper stimulates more research.

3. Do these features represent a case of equifinality in upland deglacial and periglacial systems? Equifinality occurs where significantly different initial states evolve to indistinguishable final states through many potential trajectories. This is opposed to the mathematical notion of chaos where the system trajectory is sensitively dependent upon initial conditions. Equifinality is also called 'convergence' and is a characteristic of system behaviour in many complex sciences (see Harrison 2011).

Defining an equifinal system is a major practical and philosophical problem in most earth and environmental sciences, and in attempts to reconstruct past changes (also see Phillips 1999). If we argue that a landform or sediment can be seen as the product of a range of processes, then we can suggest the presence of equifinality. However, this might merely reflect the coarse-graining of our classification system, how careful we have been in discriminating between the two products and the preservation of evidence in the geological record. If we were to increase the fine-graining of our classification attempts, then the characteristic of equifinality might disappear. At this point we are left with further differentiated products within which equifinality again becomes obvious. Clearly, this process becomes essentially reductionist and leads eventually to an infinite regress. A more practical consideration is the temporal domains within which equifinality can be expected to apply. For example, the impact of human disturbance throughout the Holocene may mean that equifinality has not developed within landscapes fashioned in this period and equifinality may require a degree of environmental stability over some defined time. It is not clear whether the late-glacial in the British Isles was stable enough climatically to allow equifinality to occur (although see the palaeoclimate discussion below).

It is clear that similar solifluction sheets are underlain by a wide range of deposits. For instance, Harrison (2002) identified four different sedimentary sequences underlying solifluction sheet surfaces, representing the resedimentation of glacial tills, weathered bedrock and gelifracted bedrock. As a result, identification of sediment signatures in response to mass wasting is not possible based only on their surface morphology.

The features identified in central Wales also represent solifluction sheets deposited by mass wasting processes, yet these are essentially valley-side landforms, although valley floor solifluction sheets also exist in central Wales (see Crampton and Taylor 1967; Watson 1970; Humphries 1979).

As a result, we argue that solifluction sheets represent a diverse set of landform/sediment associations and show the variable response of valley side sediments to climate warming, even as the end-point of these processes is a uniform and widely distributed sheet surface.

4. New techniques can now be brought to bear in helping assess their development. This includes new dating techniques (eg single grain OSL); improved geophysical techniques; new models of landscape evolution (including analogues from high latitude regions and comparative studies from other parts of the world). Perhaps the most important has been the recognition of the rapidity of slope readjustments to deglaciation from rapidly deglaciating regions (eg Patagonia (Harrison et al 2005) and the European Alps (Jäger and Winkler 2010; Embleton-hamann and Slaymaker 2012) which has given us insight into how upland valleys might have responded to deglaciation at the end of the Pleistocene.

5. The solifluction sheets of the British Isles have an intriguing distribution. They are all developed within Last Glacial Maximum limits (except perhaps some features described by Galoway (1961a) in northeast Scotland, and all are found outside Younger Dryas limits. They are widely formed in south (see Figure 2b), west and central Wales, and further west on the Isle of Man (Chiverell et al 2001) but absent in large areas of the western Scottish Highlands (although this might just represent a lack of research; see Figure 2a). They are also developed in the eastern side of England and Scotland (eg Cheviot Hills, Kale Water region and Southern Uplands). Given the sharp climatic contrasts in temperature and precipitation that existed over Britain during the late-glacial period, it is clear that palaeoclimate played only a minor role in their development. In addition, lithology appears not to be a controlling factor, and solifluction sheets are widely formed on the Silurian shales and sandstones of central Wales, the Isle of Man and the Southern Uplands, but also on the granite and andesites of the Cheviot Hills.

6. International comparisons

Similar landforms are widespread in many other regions (see Matsuoka 2001). They have been described from central Asia (eg Gorbunov and Severskiy 1999); Scandinavia (eg Rideflet et al 2010) and central Europe (eg Migoń et al 2020). Despite this, no attempts at a synthesis of these landforms has been published.

7. How did these features form?

Earlier we proposed three hypotheses to explain the development of solifluction sheets (the long-term periglacial hypothesis; the Loch Lomond periglacial hypothesis and the paraglacial hypothesis).

All three have had their own proponents. We discard the long-term periglacial hypothesis as it argues for prolonged ice-free conditions in central Wales (and presumably elsewhere) during late Pleistocene times and is at odds with current understanding of ice extents in the region at this time (see Jansson and Glasser 2005; Glasser et al 2012). The Younger Dryas (Loch Lomond Stadial) periglacial hypothesis is also discarded given the short length of the Stadial and the slow nature of contemporary solifluction processes. In effect, such large landforms could not have been produced by slow mass movement processes during the Stadial alone. The third hypothesis identified by researchers (the paraglacial hypothesis) is also problematic for two reasons. First, in areas undergoing contemporary glacier retreat, paraglacial debris fan and cone deposition dominates (e.g. Owen, 1991; Ballantyne & Benn, 1994; Harrison & Winchester, 1997) and these features differ morphologically from the planar sheets observed in the British uplands, although considerable infilling of undulating surfaces may have occurred by slopewash processes during the Holocene. Second, why is no soil development or weathering surface observed at the junction between the 'paraglacial' sediments (generally Unit B in the Cheviot Hills) and the overlying periglacial deposit (generally Unit C), especially as there is probably a considerable hiatus between these two phases of deposition?

So, we argue here for a synthesis of the Younger Dryas solifluction and paraglacial hypotheses. We think it likely that mass wasting of tills on hillsides occurred shortly after deglaciation, and that the processes involved included debris flows and slumps on steep hillsides along with other processes including active detachment slides over permafrost, and some solifluction on low angled slopes. During the cold but non-glacial phases during the late-glacial, solifluction *sensu stricto* would have produced a covering layer of weakly-consolidated debris comprising angular clasts, and this is seen almost everywhere in the Cheviot Hills and central Wales immediately underlying sheet surfaces.

8. Finally, the role of solifluction sheets in providing material for floodplain development in upland regions has been almost totally overlooked. As a result, we cannot yet gauge their importance in this regard.

*Conclusions*

We have shown that solifluction sheets are major landforms found in valley bottoms and valley sides in many upland areas of the British Isles. Despite this, little recent research has been published on these landforms. Although solifluction sheets are widely distributed in several upland regions of the British Isles, they are also notably absent in other areas (eg Ireland and western Scotland). This uneven distribution may simply reflect the lack of research on these landforms rather than their real absence. We argue that solifluction sheets represent a clear example of how upland geomorphological systems have responded to late-glacial climate change, and we suggest that deposition of sediments occurred by a range of periglacial and paraglacial processes after deglaciation, with most sediment deposition ceasing at the start of the Holocene. Finally, we have identified a number of areas where research on these enigmatic features could be focussed, including better understanding of their distribution, sedimentology and age.

**Acknowledgements**

SH would like to acknowledge the help and support of Dr Terry Douglas over a number of years. He would also like to thank the contribution of Dr Ian Evans and Dr Angus Lunn during the fieldwork in the Cheviot Hills. We also thank the two reviewers and the editor, Professor Neil Roberts, whose incisive and helpful comments significantly improved the paper.

**Supplementary Information File**

The geophysics is an Electrical Resistive Tomography survey (ERT) which involves making a large number of four-point electrical resistance measurements (consisting of a current and a potential dipole) using computer-controlled automated measurement systems and multi-electrode arrays. On the ground these consist of metal spikes pushed into the soil and connected with a clip to a wire along which current is passed. The spacing of these spikes and the combination in which you send/detect current gives the overall picture of the electrical resistance properties of the ground. Ground which is saturated, highly consolidated or contains metal ore is more conductive than dry, loose material. These data from these surveys are used to produce 2D and 3D models of subsurface electrical property distributions, from which subsurface structure and property variations can be identified. ERT surveys are entirely scalable, and can be used to cover areas ranging from a few square meters to a kilometer. In order to generate images from the field measurements, data inversion is undertaken, where the aim is to calculate a resistivity model that satisfies the observed data. A starting model is produced, e.g. a homogeneous half-space, for which a response is calculated and compared to the measured data. The starting model is then modified in such a way as to reduce the differences between the model response and the measured data. This process continues iteratively until acceptable convergence between the modelled and measured data is achieved, which implies that the goodness of fit between model and observations falls below a pre-set threshold or the change calculated for consecutive iterations becomes insignificant.

**Figures**

Figure 1. Distribution of solifluction sheet research in the British Isles. Inset: solifluction sheet in the Harthope Valley (Cheviot Hills). Note the fluvially incised front of the sheet and smoothed rectilinear upper surface. This is typical of all such valley-floor features. (Photo by Lily Harrison).

Figure 2 (a) Solifluction sheets in the Auchengaich Burn, Glen Fruin, Luss Hills, Argyll, western Highlands of Scotland. Photo by Jane Meek. (b) Solifluction sheets in the Blaen y Glyn valley, Brecon Beacons showing solifluction sheet asymmetry with extensive sheet development on east-facing slope, and limited development on west-facing slope. Upper and lower limits of solifluction sheet are shown as red and yellow lines respectively. Photo by Florence Harrison.

Figure 3. Sedimentology of the Linhope section, Breamish Valley, Cheviot Hills.

Figure 4 (a) Location map of the Cheviot Hills showing locations described in the text. Map provided by NEXTmap. (b) Solifluction sheets occupying both valley sides in the Harthope Valley, Cheviot Hills. Map provided by NEXTmap. (c) Solifluction sheets developed near Mowhaugh, Bowmont Valley, Cheviot Hills. This shows solifluction sheets developed in the lee of a drift tail reflecting resedimentation of glacial tills formed by northwards-flowing glacial ice. Map provided by NEXTmap. (d) Solifluction sheets showing marked asymmetry in the Sourhope Burn, Bowmont Valley, Cheviot Hills. Down-ice facing slopes (those on the South-easter side of the Burn) have well developed solifluction sheets, and up-ice facing slopes show glacial erosion and poorly developed solifluction sheets , Bowmont Valley. Map provided by NEXTmap.

Figure 5 (a). Map showing the distribution of mid-slope solifluction sheets in the Carno region of mid-Wales. Sheet fronts are marked in red. Map provided by NEXTmap. (b) Detailed map of the Carno solifluction sheets. The location of the Geophysical survey is also shown (blue line is CAR-A in Figure 7 and green line is CAR-B in Figure 7). The survey runs from higher to lower elevations (left to right) as in Figure 7. Map provided by NEXTmap. (c) photo of front of solifluction sheet. The front is around 6m high.

Figure 6. Trial pits at Carno showing resedimented tills overlying in situ till.

Figure 7. Electrical Resistive Tomography transect through features at Carno, Mid-Wales. The location of this is shown in Figure 5b (blue line is CAR-A and green line is CAR-B).

Table 1. Summary of solifluction sheet research in the British Isles.

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