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Glacial geomorphology of the Tweedsmuir Hills, Central Southern Uplands, Scotland

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The Quaternary glacial history of the Tweedsmuir Hills, Central Southern Uplands, Scotland, has received little attention since the 1980s, with earlier studies focussing on single lines of geomorphic evidence in isolated valleys. This study presents the first systematic glacial geomorphological assessment of the region, covering approximately 300 km^2 with the map designed to be presented at A0. Mapping from remotely sensed imagery and field investigation reveal a large number of moraines and meltwater channels, both within valleys and occasionally extending to the plateau, alongside a range of peri- and para-glacial features, including solifluction lobes, alluvial fans, debris cones, river terraces and rock slope failures. Aspects of the mapped geomorphology are consistent with plateau icefield landsystems mapped elsewhere in Britain and this will hopefully form the basis for palaeoglaciological reconstructions which will improve our understanding of the extent and dynamics of former ice masses in the region.

Keywords: glacial geomorphology; plateau icefield; Tweedsmuir Hills; Scotland

1. Introduction

The Tweedsmuir Hills, form the most easterly upland region in the Southern Uplands (55°46′N, 03°34′ W; Figure 1), reaching an altitude of 840 m. The valleys contain suites of glacial landforms, thought to be associated with a separate, later stage of glaciation (Younger Dryas; c. 12.9–11.7 ka b2 k (before 2000); Rasmussen et al., 2006) subsequent to the Last Glacial Maximum in Britain (LGM; c. 27 ka BP; Clark et al., 2012; Geikie, 1863; May, 1981; Young, 1864). Glacial landforms in the area were initially documented by Chambers (1855) with subsequent research predominantly focussed on the southern sector (Brown, 1868; Geikie, 1863; Lewis, 1905; May, 1981; Price, 1961, 1963, 1983; Sissons, 1979; Young, 1864). However, published research is inconsistent and contradictory, with Price (1963) reconstructing a plateau icefield, whilst May (1981) infers a restricted glaciation with only three valley glaciers occupying the area. Such discrepancies leave our understanding of glaciation style, dynamics and the

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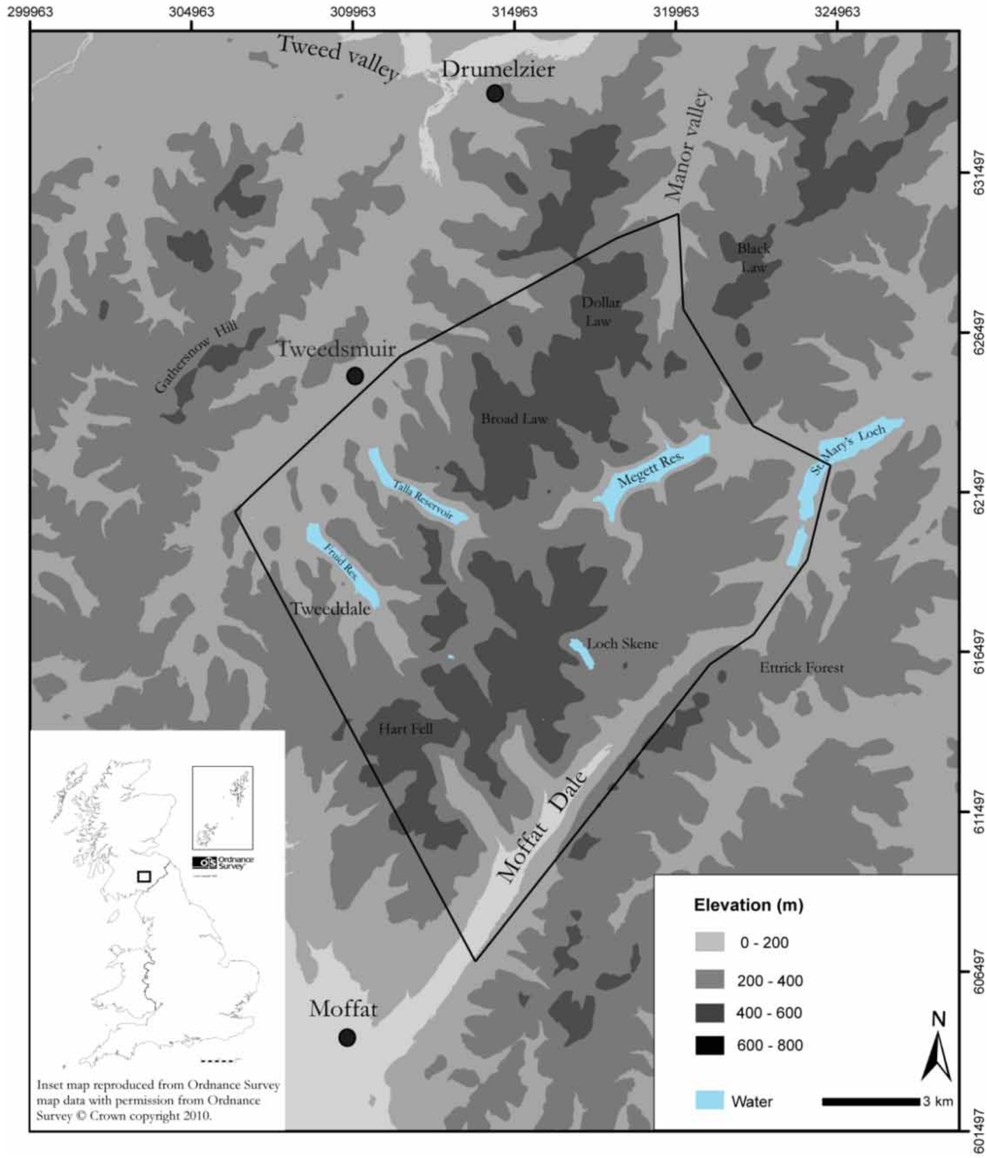

Figure 1. Topographic map to show the location of the Tweedsmuir Hills in central Southern Scotland. The study area is denoted by the black line. Elevation data were derived from the NEXTMap Britain DSM UK Outline Reproduced from Ordnance Survey map data by permission of Ordnance Survey© Crown copyright 2013.

relationship to climate incomplete. Importantly, comprehensive numerical modelling experiments for the period 38–10.4 ka BP (Hubbard et al., 2009) predict a significant body of ice over the Tweedsmuir Hills, at the onset, and throughout the Younger Dryas (cf. model runs E109B8 and E102b2). Such models require validating against field data which, at present, are unavailable for the Tweedsmuir Hills. This paper addresses this gap and presents the first systematic glacial geomorphological map for the area.

2. Methods

Glacial landforms were mapped using two forms of remotely sensed data, the NEXTMap Britain (NEXTMap) dataset and one set of colour aerial photographs, alongside 10 weeks of ground truthing divided over two field seasons in 2010 and 2011. Google Earth was used for 3D landform visualisation and virtual reconnaissance of valleys prior to field work.

The NEXTMap dataset was obtained by Intermap Technologies between 2002 and 2003 using airborne Interferometric Synthetic Aperture Radar (IFSAR). The digital surface model (DSM) has a vertical accuracy of c. 1.2 m and a horizontal resolution of c. 5 m, which enabled rapid assessment of the geomorphology and was provided by the Natural Environment Research Council (NERC) via the British Geological Survey (BGS). The DSM was used as it represents the first surface that the radar strikes. As a result, it includes forested areas but this was only problematic for valleys between Fruid and Talla Reservoirs. Despite these forested area in the Tweedsmuir valley, large-scale erosional features (e.g. meltwater channels) remained identifiable.

The DSM data were converted into a hillshaded relief model using the Spatial Analyst function in ESRI ArcGIS 10, for meaningful graphical and analytical purposes (Paine & Kiser, 2012). Under this rendition the model provided a visually realistic representation and enabled mapping onto the dataset in ArcMap 10. To avoid azimuth biasing, two images with the sun placed in orthogonal positions of 45° (NE) and 315° (NW) were generated for each valley with an illumination angle of 30° (Figure 2(a and b)). These settings have been used in extensive glacial mapping programmes and are suggested to be optimal for visualisation (Boston, 2012; Hughes, Clark, & Jorden, 2010; Smith & Clark, 2005). This simple manipulation within the model permitted features to be viewed under different lighting conditions, which can increase the visibility of subtle landforms (e.g. small meltwater channels). Features mapped when

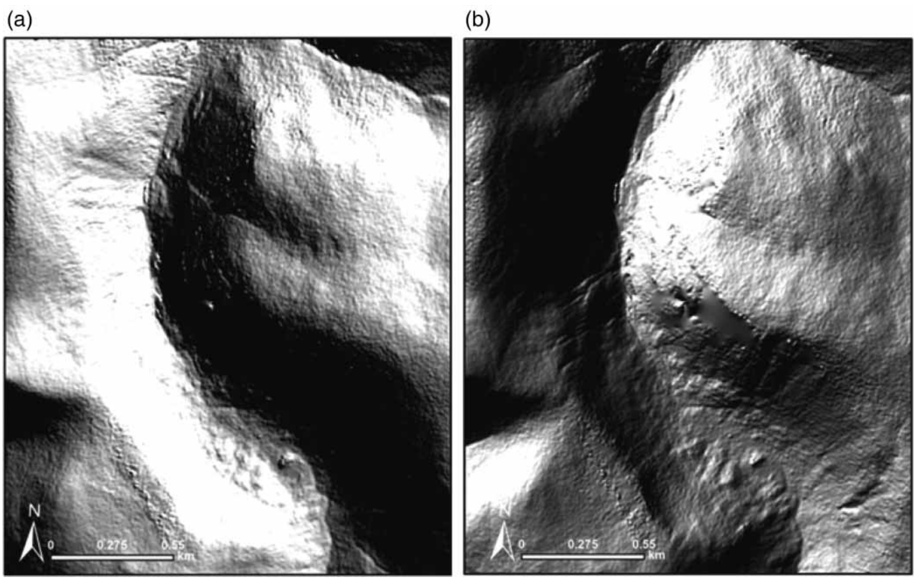

Figure 2. Hillshaded relief models derived from NEXTMap DSM of Gameshope valley in the central area of the Tweedsmuir Hills. (a) is using an azimuth of 45° and (b) 315° with both having an angle of illumination of 30°. The different appearance of the landforms between the two illumination angles is apparent, although not every valley mapped encountered the same level of difference, dependent on the orientation of the features. Scale 1:15,000. NEXTMap from Intermap Technologies Inc. provided by NERC via the British Geological Survey.

artificially illuminating the dataset from different angles were carefully checked against other data sources, such as aerial photographs or field observations, before final interpretations were decided upon (Smith & Wise, 2007).

Remotely-sensed mapping was also undertaken using one set of orthorectified seamless vertical digital colour aerial photographs with a resolution of 0.25 m GSD (Ground Sampled Distance) per pixel for display at 1:2500 (courtesy of Getmapping/UKP, and licensed to the BGS, Edinburgh).

Glacial landforms were also digitally mapped in the field using a ruggedised Tablet PC with built-in global positioning system (GPS) and installed ArcGIS 10 software. Use of this dataset on the Tablet PC in the field enabled the identification of landforms, in particular features with clear break of slopes (such as fluvial terraces and alluvial fans). Landforms identified in the field which were unclear on the aerial photographs were recorded using a handheld GPS with a vertical accuracy of 6 m and of horizontal 15 m and transferred into ArcMap 10.

3. Map production

The production of the final geomorphological map (see Main Map) utilised all three techniques discussed above. Google Earth and NEXTMap were used in reconnaissance surveying prior to mapping and field work. NEXTMap was also valuable where the resolution was sufficient to depict landforms (Figure 3(a)) but did not permit the recognition of smaller or more subtle landforms, such as subdued moraines and meltwater channels (Hughes et al., 2010). Consequently, the aerial photographs provided the highest spatial resolution best suited for the mapping of smaller or subtle features (Figure 3(b)). They were subsequently overlaid onto the DSM hillshade with a transparency of c. 30–60%, since many landforms and breaks-of-slope become clearer when overlain by the DSM (Figure 3(c)). An iterative process involving several consultations of NEXTMap, aerial photographs and field mapping was important in the creation of the geomorphological map (Figure 3(c)). The final map was produced in ArcMap 10 and a contour layer calculated at 50 m intervals using Spatial Analyst and the NEXTMap DSM to derive the elevation data (Figure 3(d)). The map was exported in PDF format.

4. Landforms

4.1. *Moraines*

Moraines are found predominantly in and around the valley floors and lower slopes. The approach used by Boston (2012) was followed, where moraines are subdivided based on morphological ‘types’. Type 1 moraines are located in the upper parts of the valleys (c. 350 to 550 m.), closer to the plateau summits. Typically they are smaller in all dimensions (2 m to 7 m high) and exhibit a closely spaced pattern with defined crestlines. Aerial photos and field observations show that the moraines are spatially aligned forming oblique down-valley chains, often curving arcuately towards the valley centre line. This spatial configuration has been documented in other areas of Scotland and indicates that the moraines represent former ice-marginal positions of actively retreating glaciers (Benn, 1992; Benn & Ballantyne, 2005; Bennett & Boulton, 1993; Boston, 2012; Finlayson, Golledge, Bradwell, & Fabel, 2011; Lukas & Benn, 2006; Lukas & Bradwell, 2010; McDougall, 2001). Type 2 moraines are sporadic, typically found at lower altitudes (150 to 350 m.), and range in morphology from very subtle (c. 1 m in height) to large isolated moraines reaching a maximum c. 7 m in height and possess rounded crestlines with no clear orientation when viewed in the field (e.g. Tweedsmuir valley).

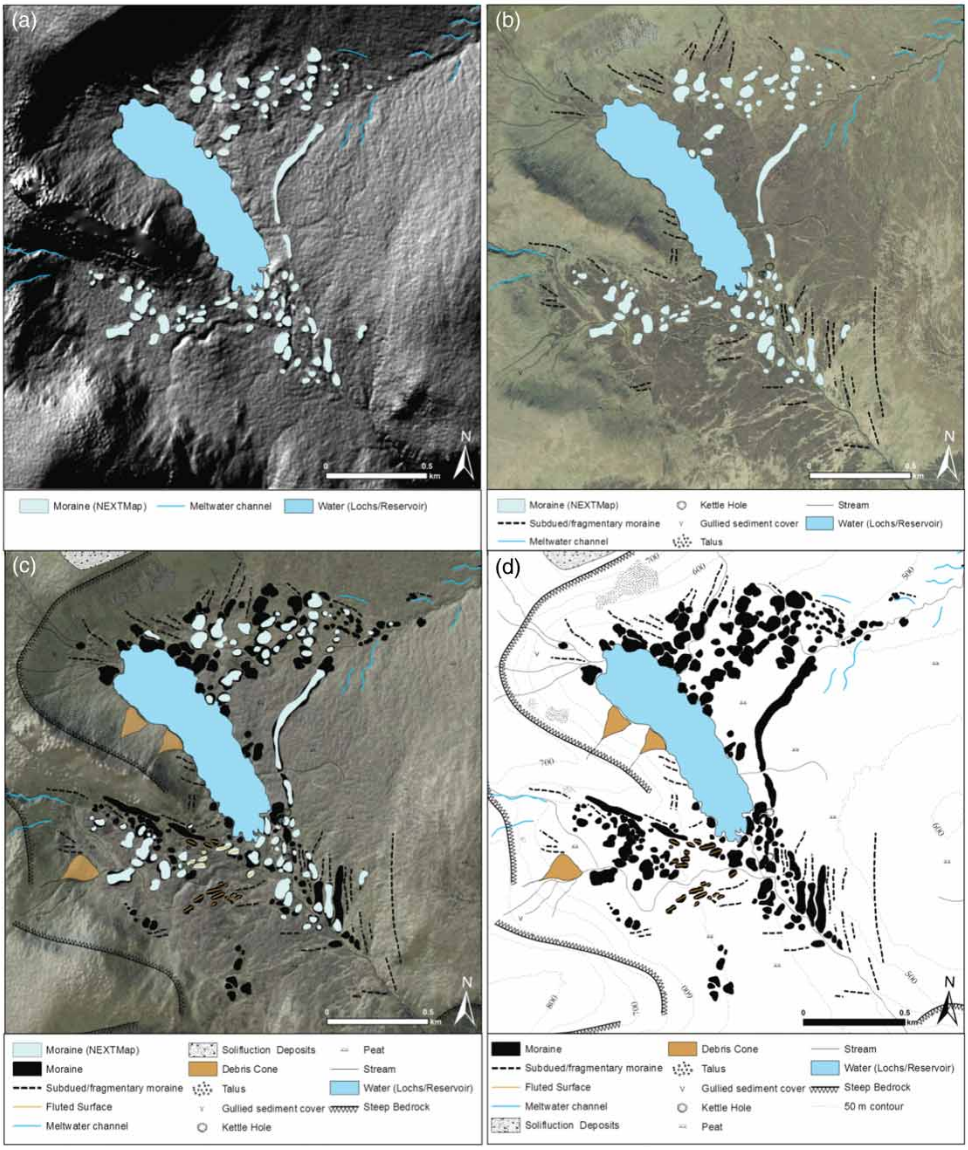

Figure 3. Example of the mapping process for Loch Skene. (a) NEXTMap (b) aerial photographs (c) NEXTMap features mapped using aerial photographs overlaid (∼30% transparency) and field mapping and (d) final map production using all three methods. Keys for the respective mapping are below A–D. Hill-shade models in A and C were produced using the NEXTMap DSM and contours in D were derived from the NEXTMap DTM (Intermap Technologies Inc. provided by NERC via the British Geological Survey).

Many of the valleys lack distinct backwalls separating the valley from the plateau (e.g. Games Hope, Donalds Cleugh, Winter Hope, Wylies, Cramalt, Ling Hope and Talla). The term ‘plateau’ requires clarification because it implies an area of topographically level high-ground, whereas ‘plateau’ in the Tweedsmuir Hills, is defined by undulating interconnected summits from c. ≤700 m.

Evidence to suggest these valleys were fed by plateau ice in the Tweedsmuir Hills is found in Fruid valley, in which closely spaced moraines, oblique to the valley axis, continue to c. 50 m below the plateau (and altitude of c. 600 m). In a few isolated valley floor locations the moraines are interspersed with kettle holes with no clear spatial pattern and are therefore interpreted as the product of localised ice stagnation (e.g. Benn, 1992). Streamlined, or fluted topography, is only visible in one valley, Mid Law (to the west of Loch Skene), where the moraines have a more elongate morphology when viewed in the field, most likely due to a localised valley readvance since no other valley exhibits similar morphology.

4.2. *Meltwater channels*

Numerous lateral meltwater channels have been identified at lower altitudes (c. 250 to 450 m) following the criteria of Greenwood, Clark, and Hughes (2007). They possess oblique down-slope profiles parallel to the valley sides and their overall pattern formed flights of discontinuous, lateral channels, noticeable on NEXTMap from the successive negative features on the valley sides. In the upper parts of the valleys and at higher altitudes (c. 450–570 m) meltwater channels are occasionally found extending onto the plateau. The only valley with numerous lateral meltwater channels is Fruid valley, where they extend from c. 507 to 570 m, marking the likely position of a former ice margin and supporting the recognition of a plateau icefield landsystem.

4.3. *Fluvial landforms*

Alluvial fans are present in the lower parts of the region (c. 150 m), with particularly impressive examples in the Tweedsmuir valley. They coincide with the lower altitude lateral meltwater channels (see section 4.2) but the channels do not lead towards the fans. Paired and unpaired river terraces are present in most valleys, though generally limited to the lower parts. They are identifiable as a relatively level strip of land above the present river. Flood plains and river terrace breaks-of-slope have been mapped because they are prominent features within the larger valleys of Tweedsmuir and Moffat Dale, whereas they diminish towards the valley heads.

4.4. *Periglacial features*

Solifluction features are widespread, particularly in the Tweedsmuir valley, where solifluction sheets partially cover the alluvial fans. On the high ground around Broad Law, Dollar Law, and Molls Cleugh, impressive solifluction lobes interconnect to form lobate solifluction sheets. The predominant bedrock lithology is greywacke, which on most of the higher summits has weathered into a sandy regolith comprising small blocks set in a matrix of granules (where exposed). In a few valleys thick talus slopes extend to the valley floor (e.g. Manor valley to the north of the Tweedsmuir Hills) and are identifiable from the loose debris at the foot of a cliff comprising angular boulders. Scree was mapped based on minor accumulations of smaller angular clasts on the valley sides, with the majority present towards the valley heads (e.g. Talla valley and the south-facing slopes of Loch Skene).

4.5. *Paraglacial features*

Paraglacial features are prominent in the valleys with steeper slope morphology, such as Carrifran and Black Hope, which have debris cones emanating from small gullies on the valley sides. Accumulations of sediment are frequently documented on the valley sides (e.g. Winter Hope), the majority of which, exhibit a hummocky micro-topography due to intensive gullying.

4.6. *Rock slope failures*

Notable rock slope failures (RSF) are recognised in the region, the majority of which are around the fault-guided Moffat Dale valley. These were originally mapped by May (1981) and interpreted as lateral meltwater channels associated with Devensian ice sheet deglaciation but have since been reinterpreted as successive rotational failures (by D. Jarman (personal communication, 2012)).

4.7. *Cirques*

Cirques are uncommon in the Tweedsmuir Hills and are only located where the greywacke contains a more resistant quartzite. Documented to the south of the site, Loch Skene (c. 520–705 m) and Mid Law (c. 575–700 m) form adjacent cirques, although they are atypical since they flank the open Winter Hope valley and have poorly defined down-valley limits. Two separate subsidiary east facing cirques occupy Black Hope from c. 375–695 m. A further three pseudo cirques are clustered to the south of Mid Law and form depressions from c. 550–805 m.

4.7. *Peat cover*

Extensive peat accumulation (previously noted by Geikie, 1863; May, 1981; Young, 1864) dominates the area. The valleys of Loch Skene and Winter Hope have deposits extending to c. 3.5 m depth in the valleys and c. 2.5 m on the summits, which frequently conceals the geomorphology. Careful mapping was required, with frequent comparisons between NEXTMap and the aerial photographs.

5. Map quality and completeness

The mapped region has been thoroughly examined for glacial landforms using NEXTMap DSM, aerial photos and Google Earth. The resolution of NEXTMap limits the size of detectable landforms so that those smaller than c. 5 m could only mapped with the aid of the aerial photos. Field mapping and validation confirmed the mapped geomorphology. The area also depicts, where possible, periglacial and paraglacial landforms which have been mapped with the intention of aiding further work in understanding former glaciation in the Tweedsmuir Hills.

6. Conclusions

The mapped landforms in the Tweedsmuir Hills include a large number of moraines and meltwater channels, both within valleys and occasionally extending to the plateau, alongside a range of peri- and para-glacial features, including solifluction lobes, alluvial fans, debris cones, river terraces and rock slope failures. Many aspects of the mapped glacial geomorphology in the Tweedsmuir Hills are consistent with a plateau icefield glacial landsystem. The lack of defined back walls, closely spaced moraines and lateral meltwater channels which extend onto the plateau are a key indication of a plateau icefield draining into the surrounding valleys. Similarly, the moraine assemblage in the valleys below Broad Law and Cramalt, in conjunction with no backwall separating them from the plateau, requires a high-level source of ice, i.e. plateau.

The map presented here provides the first regional assessment of glacial geomorphology in the Tweedsmuir Hills. The map provides a framework for further work, including dating, glacier reconstruction and the implications for former climate.

Software

ESRI ArcGIS10 was used to view and undertake mapping from the NEXTMap DSM and aerial photographs. ArcMap was used to produce the final map.

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