Landscape evolution of the granitic Criffel-Dalbeattie hills, south-west Scotland

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ABSTRACT

This paper examines the geomorphological evolution of the Criffel-Dalbeattie granitic pluton (CDGP). Research is based on data from Shuttle Radar Topography Mission, Google Earth, Ordnance Survey maps and field measurements. Granitic emplacement into Southern Uplands terrain along Caledonian structural trends took place during the mid-late Devonian. Faulting and subsidence during the late Palaeozoic and Mesozoic preceded assumed differential uplift of the pluton during the early Palaeocene. This led to the development of bidirectional palaeo-surfaces. Structural rather than lithological controls formed the dominant bases for subsequent weathering during the Palaeogene and Neogene. Shallow surface weathering over the CDGP and absence of saprolite imply that weathering episodes may have been relatively short-lived. However, joint enlargement and in situ eroded corestones indicate that earlier weathered features were substantially modified by glacial agencies. Pleistocene glacial events included ice streaming from the NNW which took place over moulded hills. Thinner late-stage ice scoured irregular hill long profiles while divergent ice contributed to basin erosion. Localised resurgent ice streaming was short lived. After early uplift and palaeo-surface formation, the CDGP hills evolved through phases of granitic weathering and glacial erosion likely over the past 65 Ma since the early Palaeocene.

Key Words

Faulted structures, Palaeo-slopes, Granitic weathering, Glacial modifications

1.Introduction

This paper examines the geomorphic evolution of hills derived from a Devonian granitic pluton intruded into the western Southern Uplands in south-central Galloway. These under-researched hills form the Criffel-Dalbeattie granitic pluton (CDGP) which is one of the largest such plutons in the area. Particular research questions driving this paper include: a) how the CDGP may have evolved during Late Palaeozoic, Mesozoic and Cenozoic tectonic events (Hall 1993, Johansson et al. 2001a, Stone et al. 2012 and Cogne et al. 2016), b) whether the pre-Pleistocene internal relief is structurally or lithologically controlled and how range configuration, slope and granitic weathering contributed to landscape development (Godard, 1969, Hall, 1991, Thomas, 1994 and Hall and Gillespie, 2017) and c) how the CDGP were modified during Pleistocene glacial events, particularly ice streaming (Boulton and Clark 1990a, 1990b, Kleman and Glasser 2007, Krabbendam and Bradwell 2011 and McMillan et al. 2011). The overall aim is to provide new data for the evolution of granitic topography in a south-west Scotland context. This work is also intended to stimulate interest in granitic landscape development in western Scotland while helping to clarify inputs into regional models of glaciation.

2. Study area background

2.1 Regional Geomorphology

The CDGP lies on the southern edge of the western Southern Uplands adjacent to the Solway Firth north of the Lake District (Figure 1). Topographic variation within the western Southern Uplands stems from the underlying Ordovician-Silurian accretionary complex with its NE-SW Caledonian grain. The landscape comprises interior mountain-hill ranges and coastal lowlands which are often sub-divided into northern, central and southern belts (Salt 2001). Topographic decline from the interior mountains (700-800 m asl) to the Solway Firth coast has previously been described as a NW-SE erosion surface (Sissons 1960). The main river systems flow down this regional surface which lies orthogonal to the underlying Ordovician-Silurian grain (Figure 1). The Southern Upland mountain hinterland of the CDGP occurs between the Nith and Dee rivers and rises to 797 m asl at Cairnsmore of Carsphain. Between the Nith and Dee rivers the much shorter Urr Water flows southwards through the western edge of the CDGP. An Urr tributary, Kirkgunzeon Lane flows approximately NE-SW along the NW flank of the CDGP parallel to the Ordovician-Silurian grain (Figure 1).

2.2 Regional Geology and CDGP intrusion

Ordovician and Silurian turbidites underlie most of the western Southern Uplands. These formed an accretionary thrust complex at the Laurentian continental margin during the subduction of the Iapetus Ocean (Stone et al. 2012). The beds developed as a series of southward-propagating thrust faults in a structurally repeated oceanic sequence (Figure 2). In the north older fault-defined tracts consist of a thin basal assemblage of graptolitic mudstone (Moffat Shale Group) overlain by thicker turbiditic sandstones. The younger more southern turbidites do not contain a basal mudstone unit (Stone et al. 2012). The accretionary thrusts now appear as near-vertical, major strike faults running NE to SW on Caledonian trends. The age of the turbidite successions becomes younger southwards with the northern Caradoc and Ashgill beds extending southwards into Llandovery (and early Wenlock locally) beds which include the Gala, Ettrick and Hawick groups (Figure 2). The CDGP is intruded predominantly into Hawick group calcareous greywackes.

Regional magmatism in the western Southern Uplands is expressed as three major plutons (Loch Doon, Cairnsmore of Fleet and Criffel-Dalbeattie) and a minor pluton (Cairnsmore of Carsphain) which were all emplaced during late Caledonian tectonic events (Figure 2). The CDGP closely follows Caledonian (NE-SW) structures. Doleritic Palaeogene dykes cross the Uplands from NW-SE (Dagley et al. 2008). Phillips et al. (1981)

suggest that the Criffel-Dalbeattie granodiorite-granite pluton developed from the convectional circulation of granitic magma which partially consolidated as an outer granodiorite shell. Magmatic convection initially rose along the north-west margin and across the roof where it recrystallised prior to sinking along the opposite margin. Following water release, unsaturated magma incrementally formed the outer granodioritic shell which later descended along the opposite walls (Phillips, 1956, Phillips et al. 1981). Hence foliated granodiorite is evident along most margins of the pluton forming a peripheral zone 2.5-3 km wide (Figure 3a). Porphyritic granite is mainly exposed across the pluton interior and along the north-west margin. In addition, the entire pluton is intermittently crossed by small NW-SE and E-W trending aplitic dykes (Piper et al. 2007) and smaller veins some of which are mineral-rich (Leake and Brown, 1978). Whole rock ages suggest a late Early or early Middle Devonian emplacement for the CDGP confirmed by an Rb–Sr isochron age of 397 ± 2 Ma (Halliday et al. 1980).

Details of regional Late Palaeozoic and Mesozoic tectonic events are found in Stone et al. (2012). These events have largely contributed to faulting throughout the CDGP as described in Phillips et al. (1981), Ord et al.(1988), BGS (1993), Piper et al. (2007) and Stone et al. (2012) (Figure3a). External faults largely define the oval shape of the pluton and include: a) the NE-SW North Solway Fault and b) the NW-SE Nith and Urr Valley faults. Internal faults including NW-SE tear faults date from the Jurassic (Miller and Taylor, 1966) and extend from the vicinity of the North Solway Fault towards the centre of the pluton (BGS 1993). Magmatic cooling and the consequent development of tensional joints (Figure 3b) are considered significant here as the basis for structural control in relation to ice directional analysis over CDGP hill summits (c.f. Bankwitz et al. 2004).

2.3 Glacial History

Recent in depth glacial studies are limited to the eastern boundary (McMillan et al. 2011) of the CDGP while work by Salt (2001) and Salt and Evans (2004) lies to the west of the study area mainly over the Machars and Rhins of Galloway (Figure 1). Ice flow over south-west Scotland including the Solway coastal plains has been considered by Charlesworth (1926a, 1926b), Sissons (1967 and 1974), Roberts et al. (2007) and Livingstone et al. (2008). Morainic deposits on the north-west side of the CDGP hills were previously regarded as an end-point for the Loch Lomond Re-advance (Charlesworth 1926b, Sissons 1974 and Cornish 1981). However it is now clear that this last ice advance extended no further south than the higher Galloway Hills (Ballantyne et al. 2013) which lie 45 km to the NW of the study area. Following multiple glacial episodes during the Pleistocene, the last ice flow to over-ride the CDGP was the Main Late Devensian or British Irish Ice Sheet (BIIS) (Roberts et al. 2007, Livingstone et al. 2008 and Clark et al. 2018). Glacial events have provided considerable geomorphic evidence for ice streaming mostly in adjacent areas (Salt and Evans 2004 and Phillips et al. 2010). McMillan et al. (2011) mention possible ice streaming over the CDGP hills as a later stage resurgent event in the Urr valley. This was followed by a lengthy period of deglaciation which gave way to extensive periods of warmer and cooler Arctic and periglacial conditions (McMillan et al. 2011).

3. Study Area and Methods

The CDGP is approximately 14 km long and 8 km wide and is fringed on the north-west side by the A711 and on the south-east side by the A710 and Solway Firth. A small-scale digital elevation model (DEM) overview of the western Southern Uplands (> 4000 km^2) was initially captured by NASA’s Shuttle Radar Topography Mission (SRTM). The SRTM Version 3.0 data are available at 1 arc-second resolution, with four scenes required to cover the regional area (NASA 2015). The digital elevation data was imported as a GeoTIFF file. SRTM data for more detailed analysis (>100 km^2) over the CDGP entailed clipping one scene to a generalised pluton outline area using a .kml project file generated from Google Earth. This was used to help identify lithological and structural controls over the hill ranges and intervening valleys and basins. Morphological analyses were undertaken using a range of sources including Google Earth images, the Ordnance Survey (Dumfries and Dalbeattie 313, 1:25 000) map, Solid geology (BGS 1993) and Drift maps (BGS 1981 Sheet 5E) augmented by data from 53 field sites and aerial photography. Ordnance Survey map based long axis orientations of 40 hill summits were used to assess directions of ice streaming as part of discordant analysis (Phillips et al. 2010). Long axis orientation was based on identifying the lowest encircling contour (5 m interval). Where necessary two adjacent summits were linked and a combined direction measured. Lines drawn through the long axes were projected through space with the actual bearing and nearest inter-ordinal direction noted using a multi-graduated desk-top Douglas compass protractor. A total of 815 joint directional compass measurements were taken in the field from 28 sites (c.f. Johansson et al. 2001b). Care was taken to remove adhering moss and the bearings of only the steepest joints were noted. Both summit orientation measurements and joint direction readings were entered into a spreadsheet. The joint data were subject to frequency analysis to establish dominant and secondary bearings (E or W of north) per inter-ordinal space. The degree of angular discordance was calculated as the difference between streamlined summit orientation and dominant joint structure (Phillips et al. 2010). The relative speed of ice streaming was assessed using the length/width ratio of hill summits and is termed the elongation ratio (Livingstone et al. 2008 and Phillips et al. 2010).

4. Results

4.1 Palaeo-surfaces in the western Southern Uplands

A Digital Elevation Model (DEM) of the western Southern Uplands illustrates the importance of regional surfaces and the peripheral location of CDGP relative to the other regional granitic intrusions (Figure 4a). A profile through the Loch Doon and Cairnsmore of Fleet plutons and host Ordo-Silurian lithologies shows a gently sloping surface to the Solway coast (Profile 1 Figure 4b). However, a similar profile through the Cairnsmore of Carsphain pluton to the coast intersects the base of the CDGP (Profile 2 Figure 4c). The topography of the CDGP is characterised by a surface (Profile 3) which drops in the opposite direction to the regional trend and requires further explanation. To provide more detail, the overall surfaces which underscore the basic topography of the CDGP were analysed using SRTM contouring at a 20 m interval (Figure 5). Results depict height variation across the exposed pluton. Importantly these show decreases in overall elevation along the long axis of the pluton from north-east to south-west (c.f. Figure 6a). This provides a primary surface over the main granitic outcrop area, excluding the apical part to the extreme north-east. In addition, contour data show that the hills are mainly higher along the south-east margin and lower along the north-west margin of the pluton thereby indicating a secondary south-east to north-west surface across the outcrop area (Figures 6b, 7a and 7b).

4.2. Lithology and structure

The granitoid types which comprise the CDGP and major structures result from inherent intrusive mechanisms (Phillips et al., 1981) and post intrusive faulting (Stone et al., 2012) (Figure 3a). The most elevated south-east margin of the pluton (Figure 6a) is underlain by foliated granodiorite (Figure 3a). This transitions after 2-3 km further north-west through the pluton to porphyritic granite (Figure 6b). Hence the pluton is almost encircled by a foliated granodiorite fringe while mostly porphyritic granite prevails across the centre and north-west. The highest summit, Criffel is underlain by granodiorite. SRTM morphological data over the pluton provide a basis for delineating intersecting structural trends (Figure 8) which compare well with mapped faults (Figure 3a). External structures which define the CDGP on three sides, follow faults which are aligned to either NE-SW (Southern Uplands) or orthogonal trends. Most of the internal structures also follow orthogonal NW-SE trends. The main expression of the NE-SW trend occurs along the North Solway fault along the entire SE margin of the pluton (Figure 9a). In addition SRTM morphological data indicate other structures along WNW-ESE trends in the NE part of the pluton and along NNW – SSE trends in the western part of the pluton (Figure 8). While largely unexplained these appear to be related to cooling patterns or metasomatism towards the pluton periphery. The internal structures currently depict valleys, basins and minor depressions. Interestingly the deeper valleys or basins have developed along structural lines with a mainly NW or WNW orientation. Shallow valleys and high-level cols follow the more orthogonal NE-SW oriented structures.

4.3. Range Configuration and Slopes

In terms of overall morphology, the hill ranges are segmented mainly by the NW-SE structural valleys and basins (Figures 8 and 10). Within this segmented pattern, the CDGP comprises four main ranges and an outlier group of hills to the south-west. The main ranges and outlier hills comprise 40 summits or compound summits (Figure 10) which lie en echelon across the NE to SW palaeo-surface. Table 1 lists height, shape and lithology data for the individual hill-summits in detail. These start with the Range I hills which occur on the north-eastern metasomatic fringe of the CDGP followed by the Range II hills which form the highest backbone ridges (from 560-200 m asl, Figure 6b). Ranges III and IV decrease in elevation south-westwards down to the Urr valley (from 150-55m asl, Figures 7a and 7b). The almost linear ranges decline in elevation along the palaeo-surfaces down towards the SW and the NW. These elevation trends emphasise the significance of the palaeo-surfaces in providing a backdrop to later topographic evolution.

Further examination shows that the incised CDGP hills developed steep convex slopes which were quantified in the SRTM data. The steeper slopes face mainly N or NE or alternatively S or SW (Figure 11) as these define the NW-SE valleys and basins. Maximum slope angles lie at 40-41º (facing N to NE) and 38-40º (facing S to SW). The higher, steeper hills are frequently rounded in profile (Figure 9b, Table 1). Most show evidence of summit convexities with lower linear or concave slopes terminating in basins or burns, typical of granitic terrain (e.g. Migon 2006). Lower, less steep hills are more angular and often composed of multiple linear ridges with ridge heights decreasing to the valleys below.

4.4. Granitic weathering

Whereas evidence of granitic weathering was observed on rock exposures throughout the CDGP, larger more definitive features tend to be more localised (Figure 12). Most hill summits show examples of enlarged joints and in situ corestones which are partially formed between converging joints (Figure 13a). The Range III area contains most examples of granitic weathering including localised tor-like crags on the southern and south-eastern slopes of Drumstichnall-Auchenlosh (Figure 13b) and weathered granite enclosing a spheroidally weathered corestone on Bainloch-Laggan (Figure 14a). Evidence of granitic weathering was also found on Dalbeattie rock drumlin EDI (location on Figure 12). On EDI, 23 mostly ENE oriented enlarged joint cavities were mapped and measured (Figure 15). The deepest joints range in depth from 14-19 cm with widths up to 22 cm (Table 2). Most of the enlarged joints have a width/depth ratio >1 suggesting secondary enlargement. This may be explained in terms of glacial erosion widening earlier weathered joint apertures. The overall joint patterns which range from weathered overhangs, exfoliation sheets, central troughs and enlarged lateral joints (Figure 14b) strongly testify to the efficacy of a pre-glacial phase of granitic weathering on the pluton despite the apparent absence of deep saprolite formation.

4.5. Pleistocene Modifications

4.5.1 Pluton wide Pleistocene ice streaming

The original incised CDGP palaeo-surfaces which were later modified during a phase of granitic weathering were again transformed during Pleistocene glacial events. Cumulatively glacial episodes are assumed to have largely eroded the valleys and basins where assumed deep weathering had previously taken place along lines of weakness. The rounded, elongated hill shapes suggest that glacial episodes also led to the orientation of summits as a result of ice streaming (McMillan et al. 2011). Summit orientation in relation to field based joint measurements provide an assessment of ice flow direction (Table 1). The overall frequency of hill summit axes and joint directional trends show a degree of similarity (Figures 16a and 16b). Discordance analysis (difference between joint trends and summit orientation) was intended to help validate ice flow direction. Results derived from comparing the two metrics showed three categories: a) when the summit orientation and joint data were parallel, ice flow direction was considered to be unclear so additional evidence (such as abrasional microforms) was used for clarification, b) when summit orientation and joint data are slightly discordant (±11.5º) sub-glacial modification is considered likely to have taken place, and c) when summit orientation and joint data are highly discordant, major sub-glacial summit re-orientation is highly probable (c.f. Phillips et al. 2010).

Results over three summits in Range I show major components of ice streaming took place from the NNW, NW and WNW (Table 1). Evidence on the ground includes the highly discordant Auchengrey roche moutonnee where joints are oriented ENE while summit long axes show ice flow from the NNW (Figure 17a). Generally ice streaming over the four summits in Range II was indicated by slight discordance. Ice from the NNW and N is confirmed mainly by crescentic gouges on Lotus Hill, Long Fell and Round Fell (Figure 10). Slight angular discordance is also recorded over the four summits in Range III which, in addition to high discordance over Bainloch-Laggan (Figure 10), suggests ice flow from the NNW and NW. Slight angular discordance over the four summits in Range IV suggests ice flow from the NNW, NW and N. Finally, the Outlier area shows four summits with slight discordance inferring ice flow from the N and NW.

The results of ice flow directional analysis suggest that over the duration of the Pleistocene, the CDGP hill summits were slightly modified (streamlined) several times by ice flow mainly from the NNW with ancillary flow extending from the NW or N. Elongation ratios provide a possible basis for assessing the relative speed of ice flow (Stokes and Clark 2001, 2002 and Livingstone et al. 2008). Results show that higher elongation ratios are found over the highest hills (Range II, with ratios between 1.3-6) and over the Range IV and Outlier hills (2-4). This rapid flowing ice likely contributed to the denudation of the landscape. Lower ratios are found over the Range III hills suggesting relatively slow flowing ice with aspects of landscape preservation.

4.5.2 Late stage ice streaming

A localised glacial event is represented by relatively small erosional features within the northern Range IV hills (Figure 10). The >15 small rock drumlins and wedge-shaped whalebacks found in north Dalbeattie are exemplified by a compound rock drumlin (EDI and II) which lies at ~33 m above the lower Urr valley (Figure 18). The drumlin comprises two oblong shaped crests with a predominant ENE joint orientation and combined elongation ratio of 4.3. In cross section the southern crest of EDII forms a heavily fractured asymmetric half dome (~84 cm high) with a steeply jointed eastern side (e.g. Figure 14b) and more gradually dipping (30º from horizontal) western side. The western side is covered by rock-cut erosion channels with intervening ridges. The asymmetry implies the possible effects of two erosional agencies. Sub-glacial scouring appears to have moulded the rock drumlin. Erosion and elongation later gave way to meltwater release down south-west oriented channels towards the Urr valley below. In contrast the northern crest (EDI) forms a low, striated bench (~80 cm high) crossed by a series of joint set cavities some of which although originally weathered, show varying degrees of enlargement orthogonal to the direction of ice movement (Figure 18). The results of detailed measurements on ENE trending joints indicate two categories based on their differing width/depth ratios (Table 2). Some wider joints appear to have resulted from exfoliation sheet erosion with the initially weathered sheets being removed by fast flowing ice (Figure 17b). While often linear some of these are arcuate in cross section and so may comprise crescentic scars (e.g. Krabbendam et al. 2017). Other narrower joints appear to represent sub-glacial drainage conduit which are mostly oriented up-ice (sub-parallel to the joint directions) draining towards a near central trough. This trough is longitudinally located and rectangularly enlarged in cross section. The trough is infilled by compacted peaty soil, root material, grus particles, granitic rock fragments and compacted, exogenous pebbles (Figure 18). The pebbles are small (2-5 cm long), angular and of Southern Upland (Hawick greywacke) provenance, suggesting that basal ice scoured the trough and deposited debris down into the pre-existing depression. This close juxtaposition of sub-glacial erosional features with later channels indicative of meltwater activity implies a relatively rapid change of environmental conditions.

5. Discussion

Examination of the geomorphic landscape of the CDGP hills and environs provides new information on the development of granitic terrain within south-western Scotland.

5.1 Pluton emergence and palaeo-slope development

Gravity anomalies detected over the CDGP (Bott and Masson-Smith 1960) and the Cairnsmore of Fleet pluton (Parslow and Randall 1973) indicate considerable density deficits. These has been explained by erosion of the upper granitic roof to the extent of 1-1.5 km in the Cairnsmore of Fleet example. A similar erosion pattern appears to have occurred over the CDGP suggesting long term roof stripping over the past ~500 Ma. Initial stripping is shown by the accumulation of granitic detritus of CDGP provenance in the local Upper

Old Red Sandstone, indicating early unroofing during Late Devonian times (Piper et al. 2007). Since then, the CDGP and immediate environs have been subject to a series of tectonic events involving basin development and uplift during the Variscan (Ord et al. 1988), Permo-Triassic and Jurassic (Stone et al. 2012). Peripheral basin development took place during the Permo-Triassic when movement along the Nith and North Solway faults may have led to early upheaval along the northern and eastern margin of the pluton, particularly in the vicinity of Criffel-Drumburn (e.g. Ord et al. 1988 and Hounslow et al. 2012). Later events on orthogonal trends during the Jurassic led to the development of NW-SE tear faulting (Miller and Taylor 1966). Tectonic activity in particular along the North Solway fault was re-current throughout the Late Palaeozoic and Mesozoic and provided a structural framework for later uplift.

Evidence suggests that uplift may have been particularly significant during the Late Cretaceous-early Palaeocene over both sides of the Solway Basin. Green (2002) describes results from Apatite Fission Track (AFT) data over the northern Lake District (Figure 1). AFT data combined with the known removal of thicknesses of overlying rock, demonstrates that Early Tertiary exhumation took place. This may have been related to enhanced mantle plume activity associated with the opening of the North Atlantic Ocean. Later Conge et al. (2016) considered exhumation events around the Irish Sea basin using a combination of AFT and (U-Th-Sm)/He (AHe) dates. Thermal history models indicate that a rapid exhumation pulse probably related to mantle plume activity was focussed below the northern Irish Sea Basin during the Early Palaeocene. Interestingly, measurements indicating the highest level of exhumation are located on the CDGP (Cogne et al. 2016, Sct-1) which is portrayed as sustaining overburden losses of between 1-2.5 km. This exhumation level decreases both to the south-west over the Solway Firth and north-west over the SW Southern Uplands. While the amount of uplift is unknown, a possible exhumation profile based on the work of Cogne et al. (2016) is shown as Figure 4c, Profile 3. While tentative it appears possible that CDGP uplift may have been particularly influenced by mantle plume activity (causing exhumation) during the early Palaeocene. We speculate that this uplift took place as a result of differential movement on the pre-existing faults peripheral to the pluton (Figure 3a). If this uplift event led to the development of the CDGP bidirectional palaeo-surfaces then it was particularly effective along the North Solway fault in the vicinity of Criffel (c.f. Figure 6b). Evidence elsewhere in Scotland indicates that possibly similar uplift events intermittently persisted throughout the Palaeogene and Neogene (c.f. Hall and Bishop 2002).

5.2 Effects of structure and lithology on landscape development

Once uplifted exposed granitic bedrock forming the CDGP became susceptible to weathering and erosion especially along fractures which presented zones of weakness (c.f. Hall and Gillespie, 2017). These zones indicated as faults (Figure 3a) or structural trends (Figure 8) likely provided loci for preferential transformation into deeply weathered saprolite similar to the weathered beds currently found exposed in granitic terrain in SW England (Tierney and Glass 2016). However while fracture induced weathering appears plausible as an explanation for the incised valleys and basins on the CDGP, deeply weathered profiles were not observed during this work. Both probable deep weathering and observed surficial weathering on summits nonetheless indicate widespread granitic disintegration. This may have taken place intermittently during warm-moist periods in the Palaeogene-Neogene (c.f. Hall and Bishop 2002). Interestingly structural trends (Figure 8) with a north or west component (WNW, NW and N) have been preferentially excavated into deeper (up to 250 m) incised valleys and basins. The deeper valleys, once preferentially enlarged and infilled with weathered saprolite are oriented so as to take advantage of major excavation resulting from later glacial erosion.

The different lithologies across the pluton are indicated on Figure 3a. In relation to elevation changes, granodiorite occurs beneath the higher summits along the SE margin whereas the lower NW and SW margins are generally underlain by porphyritic granite (Figures 6 and 7). Elsewhere granites rich in quartz and K-felspars tend to underlie higher ground supporting inselbergs for instance, while granodiorites tend to form undulating countryside often with basins (e.g. Godard, 1969 and Migon 2006). The CDGP presents the opposite case suggesting that in terms of topographic development, inherent rock resistance appears less significant than structural controls.

5.3 Granitic Weathering

Topographically the CDGP can be described as a dissected, weathered granitic landscape with hill-side exposures characterised for instance by shallow joints and remnant corestones (Figures 12, 13 and 14). Similar features are recorded in the north-east of Scotland as indicated in the work of Hall (1986), Merritt et al. (2003), Hall et al. (2015) and in the Cheviot hills (Mitchell 2008). The timing and duration of weathering events may be questionable. Positive field relationships on the pluton which infer that granitic weathering took place prior to Pleistocene glacial activity include instances of: a) weathered granite lying beneath till units and b) glacial modification of weathered forms, particularly joints (Figure 17b). The age of the weathered granite which often occurs towards the top of the exposed palaeo-surface is unknown at this time. Granitic weathering may have been initiated post uplift during the Palaeocene and continued whenever favourable conditions permitted, through the Neogene. This infers possible parallels with the work of Hall and Bishop (2002) who suggest that differential weathering and erosion under the warm to temperate humid climates of the Neogene contributed to the development of granitic landscape features in north-east Scotland.

Types of granitic weathering examined at 51 sites across the pluton revealed particularly widespread examples of widened joints and eroded relict corestones (e.g. Figures 13 and 14). Examples of the extensive type of granitic weathering were revealed by joint pattern analysis on rock drumlins EDI and EDII. These indicate several enlarged joints showing exfoliation control, weathered overhangs and corestones (Table 2, Figure 15). Exfoliation is taken here to mean near surface parallel rock detachment and in the CDGP the layers of detached rock occur between near surface joints (Migon, 2006). The rock sheets are 15-30 cm across and often dip into the surface joint above (Figure 17a). The enlarged joint above appears to owe its size to the removal of an intermediate (exfoliated) granitic sheet by erosion. This leaves a wide joint aperture with an overhanging sheet above. Erosive corestones are also widespread. These have remained often at the intersection of two or more joints despite erosion on the adjacent rock face (Figure 13a). The widespread extent of these features is indicative of the pervasiveness of granitic weathering across the pluton.

More localised weathering was found in Range III and included a single corestone and tor-like crags. The single corestone is the product of spheroidal weathering and lies within a degraded matrix on Bainloch-Laggan hill (Figure 14a). Tor-like crags were found located on Drumstichnall-Auchenlosh resemble piles of boulders up to 9 m high (Figure 13b). Although presently localised these kinds of more definitive weathering features may have extended over the CDGP before the Pleistocene. Their absence probably testifies to the effectiveness of glacial erosion.

5.4 Glacial events

Glacial advance periods during the Pleistocene have mainly impacted the CDGP by summit ice streamlining and by possibly removing extensive remnants of granitic weathering. Inferences drawn from different glacial features have enabled the recognition of three main phases of glacial activity which comprise: a) Complete ice cover during successive glacial advance episodes including ice streaming, b) Partial cover during thinner ice streaming when inherent topographic control prevailed and c) Localised ice streaming down the Urr valley.

5.4.1 Complete ice cover during successive glacial advance episodes

During the Pleistocene the CDGP hill summits were moulded by ice flow mainly from the NNW with ancillary flow extending from the NW or N (Figure 19a) (c.f. McMillan et al. 2011). Ice streaming probably took place multiple times during the Pleistocene including during the last Devensian (BIIS) episode (Clark et al. 2018 and McMillan et al. 2011). Discordance and related data indicate NNW-NW-N ice stream directions from different locations over the pluton (Table 1 and Figure 19a). Numerous (40) streamlined summits developed at the sub-glacial interface of wet-based ice by the moulding and/or grooving of subglacial materials (Benn and Evans 1999, 2014 and Clark 1994). Moulding likely involved both erosional and depositional components (Boulton and Clark 1990a, 1990b, Clark 1993, 1999, Evans et al. 2006 and Benn and Evans 2014). Roche moutonnees formed where the discordance angle was high (Figure 17a). Other re-oriented summits formed as a result of lower discordance angles over the pluton.

Summit streamlining appears to have taken place at different relative speeds of ice flow (Stokes and Clark 2001, 2002 and Livingstone et al. 2008). It appears that more rapid ice streaming took place over CDGP Ranges I, II, IV and the Outlier hills (Table 1) where effective erosion obliterated the more transient granitic weathering landforms and evacuated the major valleys. Interestingly localised features (Figure 12) such as tor-like crags and spheroidally weathered corestones were preserved in Range III. The preservation of tors in granitic areas in NE Scotland, has challenged notions regarding the effectiveness of glacial erosion. For instance cold-based ice may afford a degree of protection on exposed granitic slopes (Hall and Sugden 1987, Hall and Glasser 2003, Hall and Phillips, 2006, Phillips et al. 2006 and Atkins 2013). However ice streaming effects on CDGP summits suggests intermittent cover by wet-based ice, with evident erosive properties (Eyles and Marshall McCabe 1989, Salt and Evans 2004 and Roberts et al. 2007). The frequency of wet-based ice and its streamlining impact suggests that most exposed granitic weathering forms would be eroded. However some granitic features including tor-like crags and weathered sediment remain in the landscape (Figures 13b and 14a). Interestingly these features are restricted to a sheltered area within the Range III hills (Figures 12 and 7a). The sheltered area is relatively unique as it forms a col between two successive hills aligned in the direction of ice flow with low elongation ratios, between 1.2-2.4 (Table 1). In this case it appears that slow flowing wet based ice failed to totally remove remnant granitic features when these occurred in specific sheltered locations over the CDGP.

5.4.2 Thinner Ice Streaming and Topographic Controls

Ice thinned over the CDGP during later glacial stages including the waning stages of the BIIS as it further transitioned into the Irish Sea Ice Stream (Roberts et al. 2007, Phillips et al. 2010) (Figure 19b). The transverse nature of the CDGP relative to the main directions of streaming ice flow meant that flow adjustments were required. Specifically the thinner streaming ice came up against: a) the north-west marginal hill slopes which face directly into the direction of ice advance (Figure 4c) and b) the irregular north-west to south east uphill gradients over the main hill ranges (Figure 6b). In both cases ice flow likely adjusted by decelerating over high ‘sticky spots’ but continued moving by shearing and rotational scouring similar to processes described in Kleman and Hattestrand (1999), Stokes et al. (2007) and Phillips et al. (2010). Rotational scouring along the exposed NW margin of the pluton may have led to the formation of the eroded re-entrants and the related scoured depressions of Lochaber, Loch Arthur and Kirkgunzeon (Figure 10). Uphill ice streaming over hill ranges which increased in elevation down-ice may ultimately lead to lateral ice divergence off the highest threshold point and differential erosion as the ice descended from the topographic highs (Figure 19b). This form of divergence down through cols is described in the uphill seaward margin of Norwegian fjords (Sugden and John 1976 and John 2017). Hence elevation differences brought about by the CDGP palaeo-surfaces (Figure 8) provided substantial elevation increases which not only caused erosion at the base of the higher hills (Figure 6b) but may also have induced flow divergence downslope into the Southwick and Fairgirth basins (Figure 19b). Hence drawdown probably contributed to the erosion of pluton basins.

5.4.3 Localised ice streaming

The northern Dalbeattie drumlins and whalebacks appear to represent erosion resulting from the last late Devensian resurgence which involved ice streaming from the north down through the lower Urr valley (McMillan et al. 2011 and Clark et al. 2018) (Figure 10). This resurgence probably occurred as small ice-caps occupied the higher hill summits and meltwater activity became widespread elsewhere on the pluton (Figure 19c). The rock drumlins are streamlined in the direction of ice flow from the NNW down the Urr valley (Figure 18). Whereas a number of erosion glacial features are evident these are juxtaposed compound forms ranging from a sub-glacial to meltwater origin. The complex landforms may suggest that ice streaming relatively quickly gave way to meltwater flow implying that the resurgence event was short-lived.

6. Conclusions

Mostly new data provide a preliminary explanation for the evolutionary geomorphology of the CDGP in south-west Scotland. Following emplacement along Caledonian structural trends during the mid-late Devonian the CDGP subsequently underwent faulting and subsidence during the late Palaeozoic and Mesozoic. Importantly the early tectonic events defined the pluton in terms of both interior and marginal faults. Marginal faults, especially the SE North Solway fault appears to have provided the basis for later differential uplift. Differential uplift during the early Palaeocene (based on Conge et al., 2016) led to the formation of bidirectional palaeo-surfaces which provide the backdrop for later geomorphic evolution. Important aspects include the following:

- Structural rather than lithological controls formed the dominant bases for subsequent granitic weathering during the remaining Palaeogene and possibly during the Neogene
- The numerous shallow small scale granitic weathering landforms suggest pervasive weathering over the pluton
- Cumulative advances of frequently wet based ice led to the streamlining of summits from which ice flow directions mainly from the NNW are deduced. Glacial erosion substantially impacted the pluton by excavating valleys and scouring summits throughout the Pleistocene.
- Elongation ratios suggest slower ice flow over specific lower hills partly protected granitic tor-like landforms. More rapid flow over the remaining higher hills left a relatively denuded landscape in terms of well-formed granitic weathering features
- Localised resurgent ice streaming formed juxtaposed glacial erosional features of sub-glacial and meltwater origins implying that the resurgence was temporary in nature.

After early uplift and palaeo-surface formation, the CDGP hills evolved through significant phases of granitic weathering and glacial erosion over the past 65 Ma since the Palaeocene.

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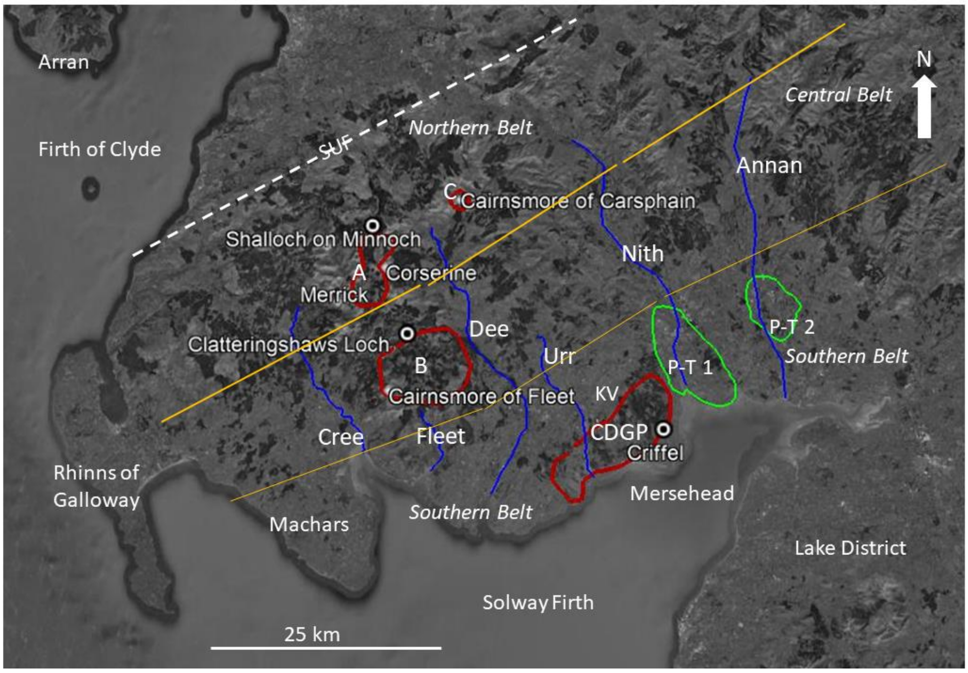


Figure 1. Location of the Criffel-Dalbeattie granitic pluton (CDGP) within the western part of the Southern Uplands, Scotland covering most of Dumfries and Galloway. Northern, Central and Southern Upland Belts after Salt 2002. Main mountains include Shalloch on Minnoch at 775 m, Corserine at 814 m, Merrick at 843 m, Cairnsmore of Carsphain at 797 m, Cairnsmore of Fleet at 711 m and Criffel at 570 m. Main southerly flowing rivers comprise the Annan, Nith, Urr Water, Water of Fleet and Cree. KV = tributary valley of Kirgunzeon Lane, D=Loch Doon pluton, F=Cairnsmore of Fleet pluton, C=Cairnsmore of Carsphain pluton, CDGP=Criffel-Dalbeattie pluton. P-T 1 = Permo-Triassic Dumfries basin, P-T 2 = Permo-Triassic Loch Maben basin. SUF = Southern Upland Fault.

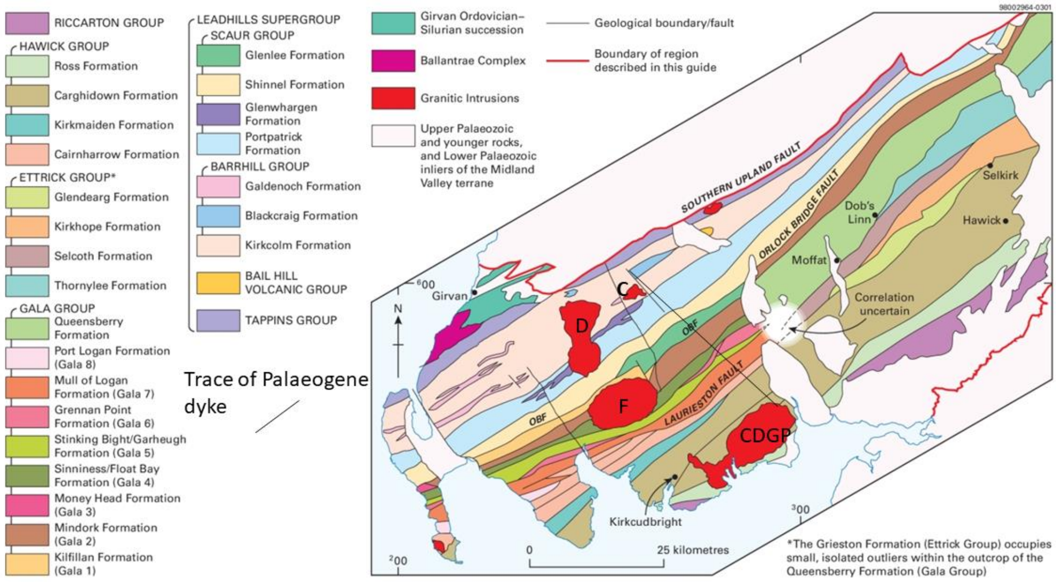
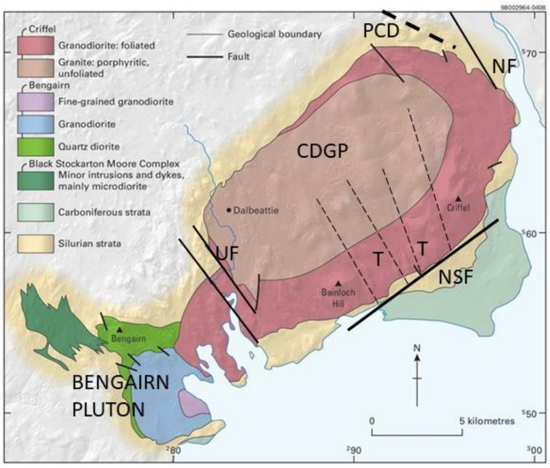


Figure 2. Ordovician and Silurian geology of the Southern Uplands (P912325) after Stone et al. (2012). Granitic plutons include: CDGP=Criffel-Dalbeattie,
C=Carsphain of Fleet, D=Loch Doon, F=Cairnsmore of Fleet. Trace of Palaeogene dyke after Dagley et al. (2008)

a.



b.

Figure 3a. Main lithologies within the Criffel-Dalbeattie granitic pluton (CDGP) and adjacent Bengairn pluton modified after Earthwise.bgs.ac.uk (P912343) with additional faults added from Miller and Taylor (1966), BGS (1993) and Ord et al. (1988). Palaeogene Cleveland Dyke (PCD) from Dagley et al. (2008)
Figure 3b. Surface expression of near vertical joints in the Dalbeattie Forest (NX847608) Person for scale 1.8 m

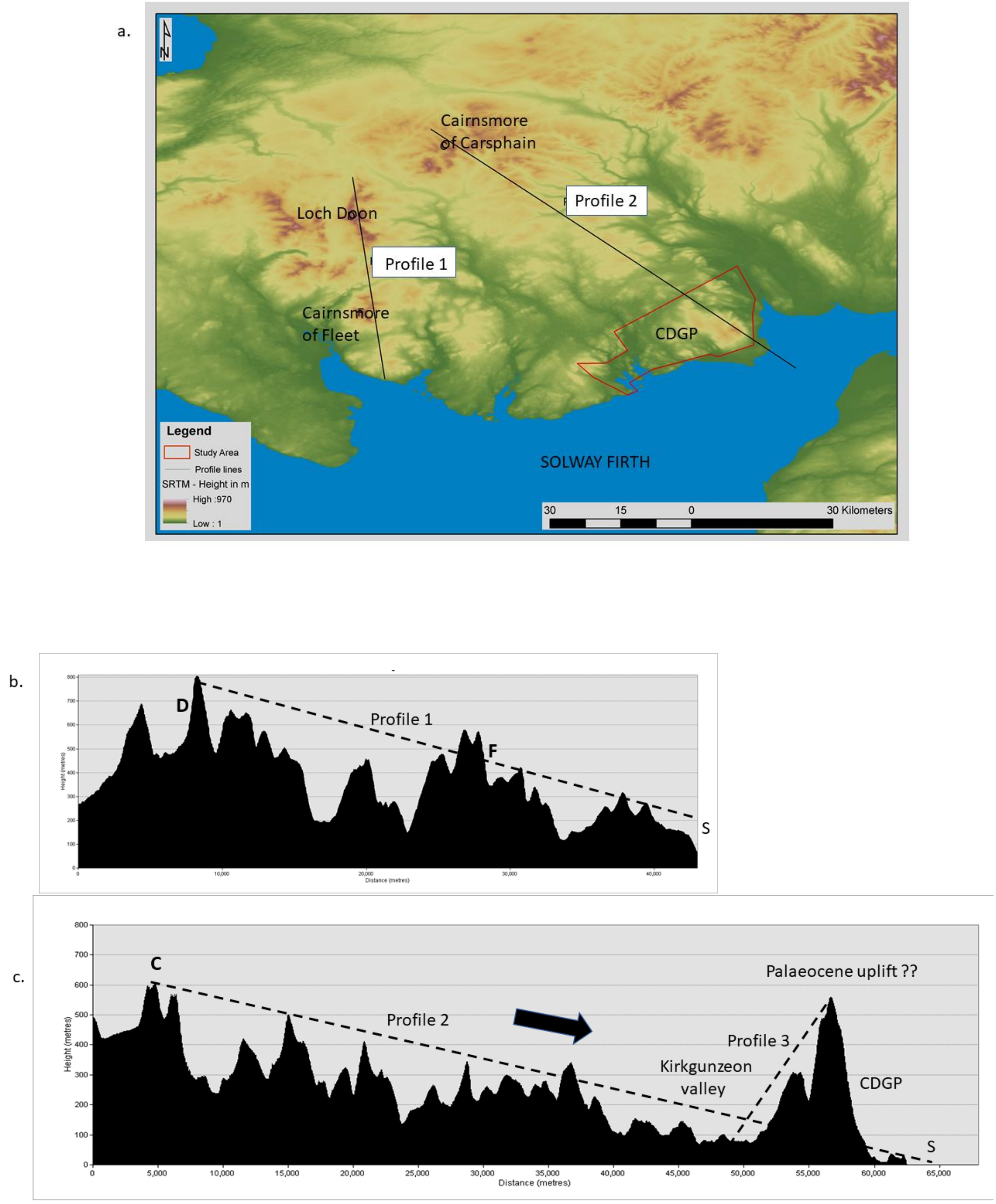


Figure 4a. SRTM derived outline map showing location of Profiles 1 and 2 across part of the western Southern Uplands (Locations on Figure 1)
Figure 4b. Profile 1 from Loch Doon pluton (D) and Cairnsmore of Fleet (F) pluton to the Solway Firth (S) VE=17x
Figure 4c. Profile 2 from Cairnsmore of Carsphain pluton (C) to CDGP along Southern Uplands surface intercepted by CDGP. Profile 3 indicates the direction of NW facing palaeo-surface possibly resulting from Palaeocene uplift of CDGP
Arrow indicates the direction of ice-flow during thinner Pleistocene ice flow VE=23x

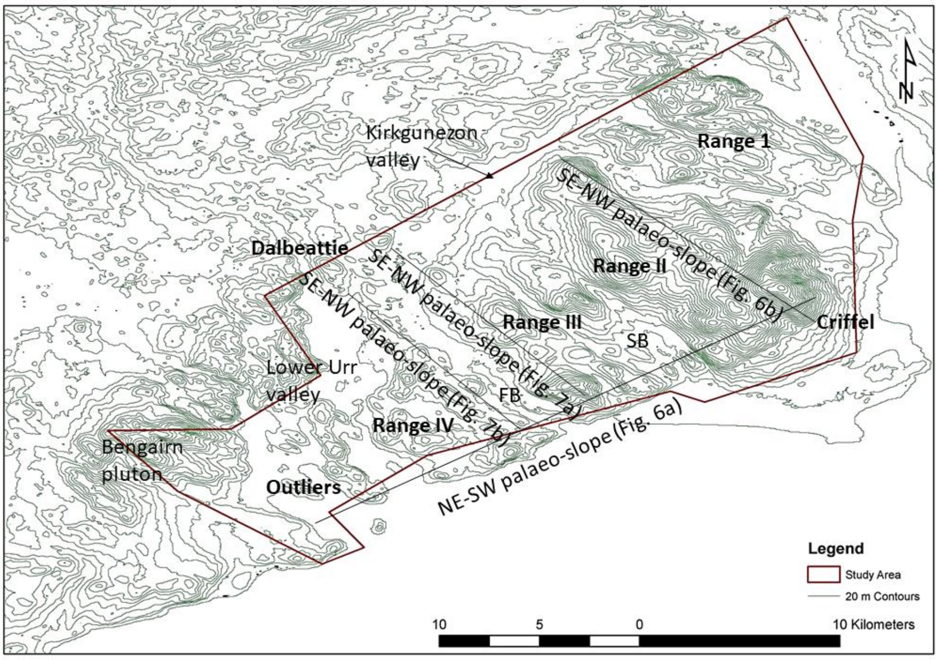


Figure 5. Major features of the CDGP depicted using SRTM derived contours showing the highest point at Criffel (570 m) down to Dalbeattie (ca. 50 m). The major NE-SW palaeo-surface trend is shown along the south-east margin of pluton (also on Figure 6a) Three additional lines depict trend of orthogonal palaeo-surface extending SE-NW down to Kirkgunzeon valley. Profiles of the SE-NW palaeo-surface are also shown on Figures 6b, 7a and 7b. NB the spatial distribution of the four hill Ranges and Outlier hills (Roman numerals) described in the text

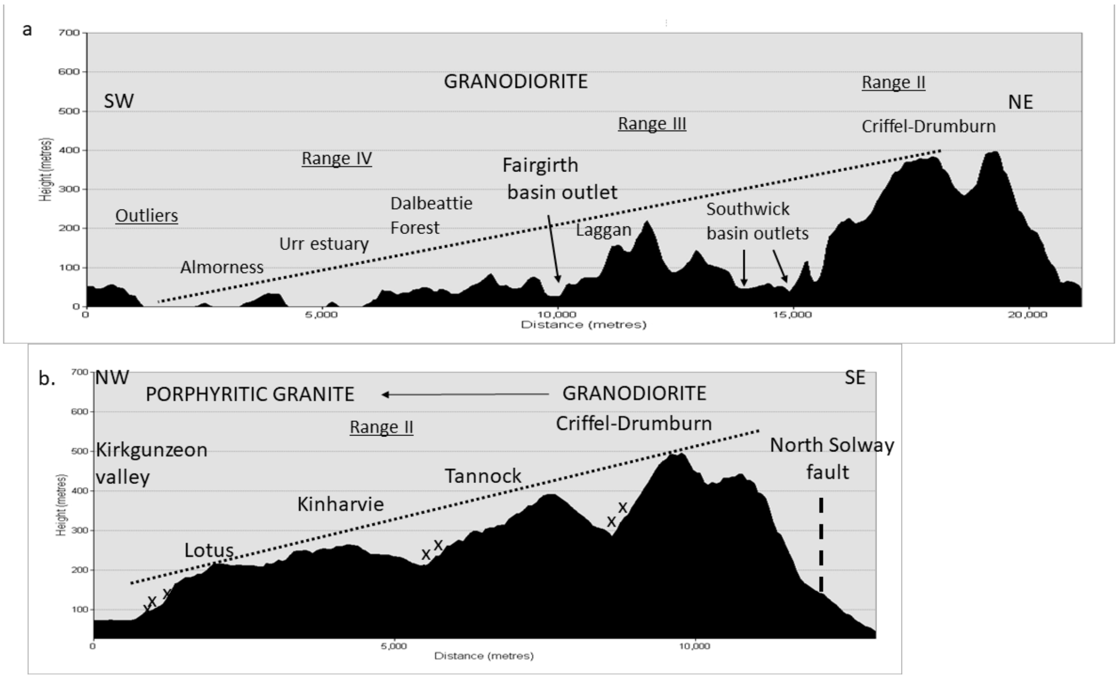


Figure 6a. SRTM profile along the south-east (granodiorite) margin of pluton abutting against the North Solway Fault. Dashed line is an expression of the NE-SW palaeo-surface. Southwick and Fairgirth Lane basin outlets indicate erosion through the otherwise prominent south-east marginal hills. Hill summit locations given on Table 1. V.E.=8.3x
Figure 6b. SRTM profile along Range II showing orthogonal palaeo-surface running from SE to NW (dashed line) initially across marginal granodiorite then changing into porphyritic granite. xxx marks 'sticky spot' climb locations of thinner ice flow from Lotus to Criffel-Drumburn. Approximate location of North Solway fault shown along the south-east margin of Criffel. Hill summit locations given on Table 1. V.E.=6.0x

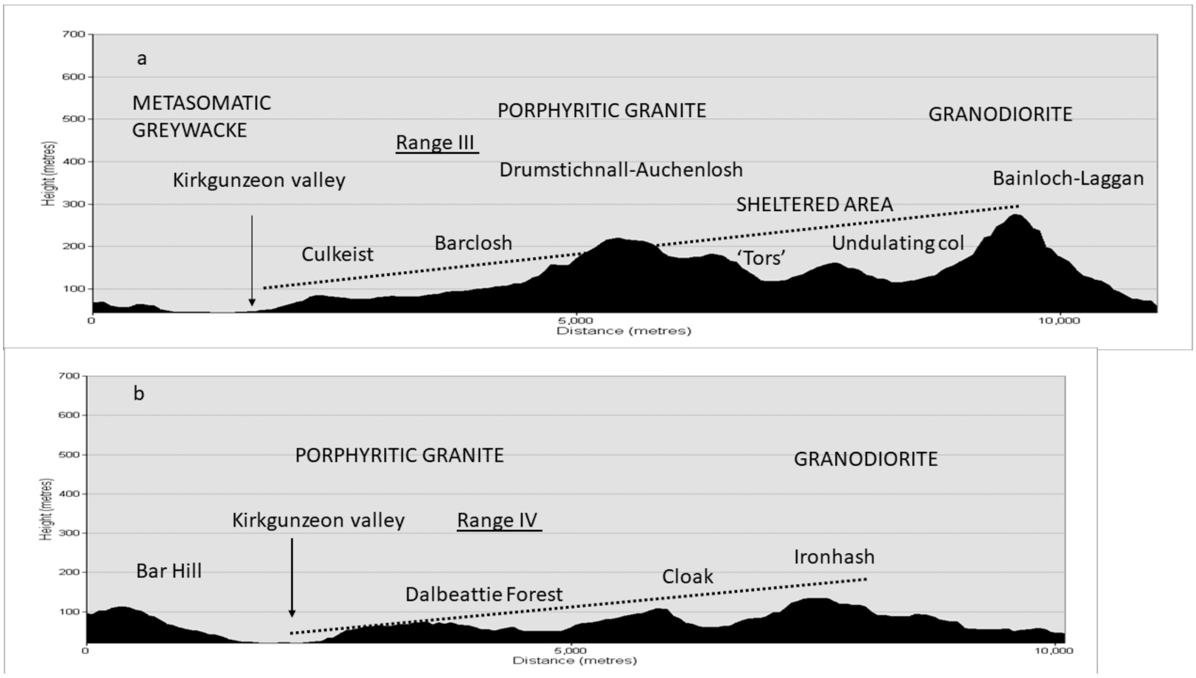


Figure 7a. SRTM profile along Range III showing orthogonal palaeo-surface running from SE to NW (dashed line) initially across marginal granodiorite then changing into porphyritic granite. Summit locations given on Table 1. V.E.=3.6x

Figure 7b. SRTM profile along Range IV showing orthogonal palaeo-surface running from SE to NW (dashed line) initially across marginal granodiorite then changing into porphyritic granite. Summit locations given on Table 1. V.E.=3.0x

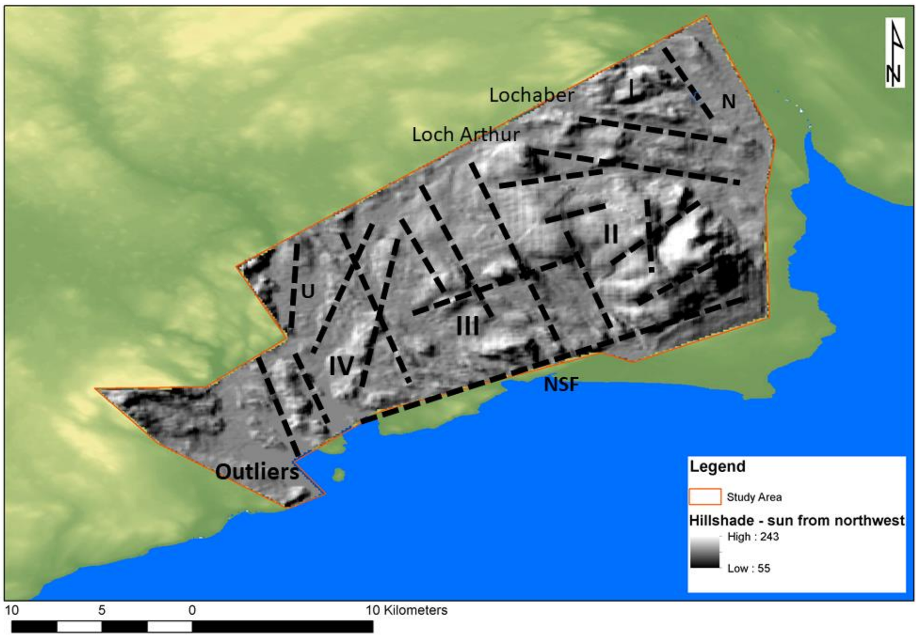


Figure 8. SRTM topographic map showing assumed structural (mainly fault) controlled valleys and basins crossing CDGP on either pre-existing NE-SW (Caledonian) or dominantly later NW-SE orthogonal trends. WNW-ESE and NNE-SSW trends which control valleys towards the periphery of the pluton are considered to be associated with metasomatic activity. The structural trends mostly depict the main zones along which weathering and erosion occurred into the original granite surface

a

b

Figure 9a. Part of the south-east margin of CDGP showing 20-30 m cliffs along the line of the North Solway fault facing NW from Mersehead (Figure 1). Laggan-Bainloch hill (Range III) visible to west.
Figure 9b. Upper convex slopes of Round Fell (to 272 m) facing east with other Range II hills in background

Figure 10. Depiction of main hill ranges and basins (c.f. Table 1). Names of individual summits viz: 1=Woodhead 2=Marthrown 3=Troston 4=Craigbill 5=Lochbank/Craigend 6=Auchengrey 7=Lotus 8=Breconside 9=Longfell 10=Kinharvie 11=Cuil 12=Tannock 13=Miekle Hard 14=Boreland 15 Criffel/Drumburn 16=Redbank 17=Drumcrow 18=Round Fell 19=Clawbelly 20=Drumstinchall/Auchenbay 21=Auchenlosh 22=Barclosh/Culkeist 23=Bainloch/Laggan 24=Hawthorn-Clifton Crags 25=Doon 26=Bareness Craig 27=Barr and eastern Urr 28=Cloak 29=Youngs 30=Moyle 31=Ironhash 32=Mark 33=Almorness 34=Tor 36=Munches 37=Barskeoch 38=Barlochan 39=Blackbellie
Basins: A=Lochaber B=Glensone C=Southwick Basin D=Fairgirth Basin
Other features: E=Clonyard Lochs F=Lower Urr valley. Main NW slope re-entrants=Lochaber Loch, Loch Arthur and Kirkgunzeon.
White bars=Dalbeattie rock drumlins and whalebacks (Hill grid references on Table 1)

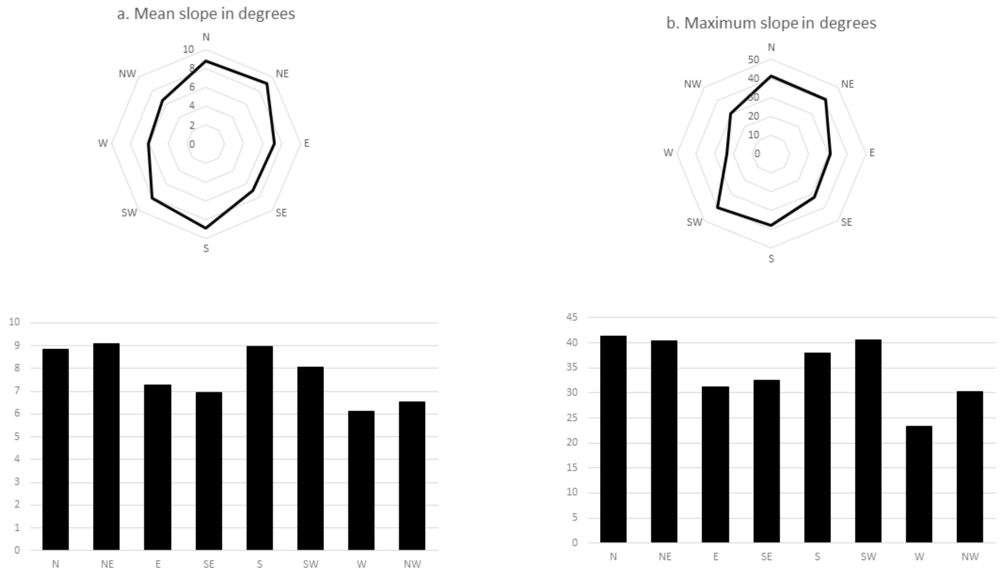


Figure 11. SRTM slope aspect data showing high proportion of steep slopes in the CDGP. a) Steepest mean slopes facing north - north east and south – south west b) Steepest maximum slopes

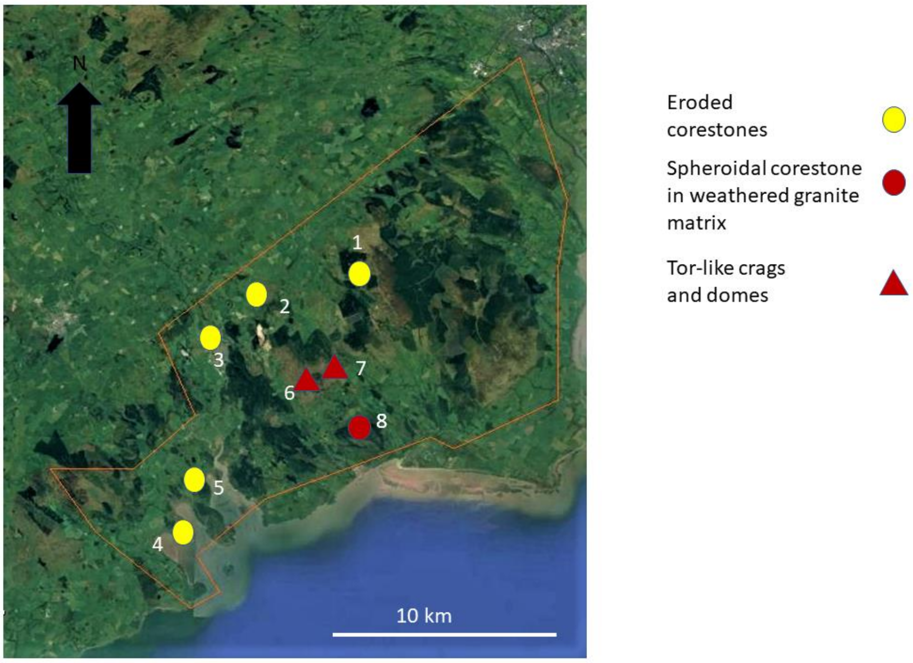
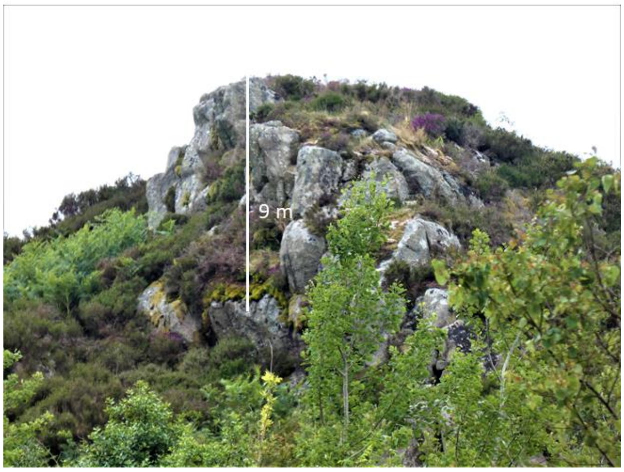


Figure 12. Schematic map showing location of most granitic weathering landforms. 1=Long Fell 2=Gilkeist 3=Dalbeattie drumlins (EDI and EDII) 4=Torr peninsula 5=Almorness 6=Drumstinchall 7=Auchenlosh 8=Bainloch/Laggan spheroidally weathered clast in degraded saprolitic matrix (Locations on Table 1)

a



b

Figure 13a. Remnant corestones retained between joints on eroded hill slope, Long Fell (Penknife= 8.5cm) (Location on Table 1)
Figure 13b. Tor-like crag on southern summit of Auchenlosh hill (Location on Table 1)

a

b

Figure 14a. Spheroidal weathering around granodiorite clast encased in degraded saprolitic matrix on Bainloch/Laggan hill (NX 898585) GPS=5cm
Figure 14b Shallow but wide joints on steep slopes peripheral to rock drumlin EDII (NX 828619) (Hammer = 30 cm)

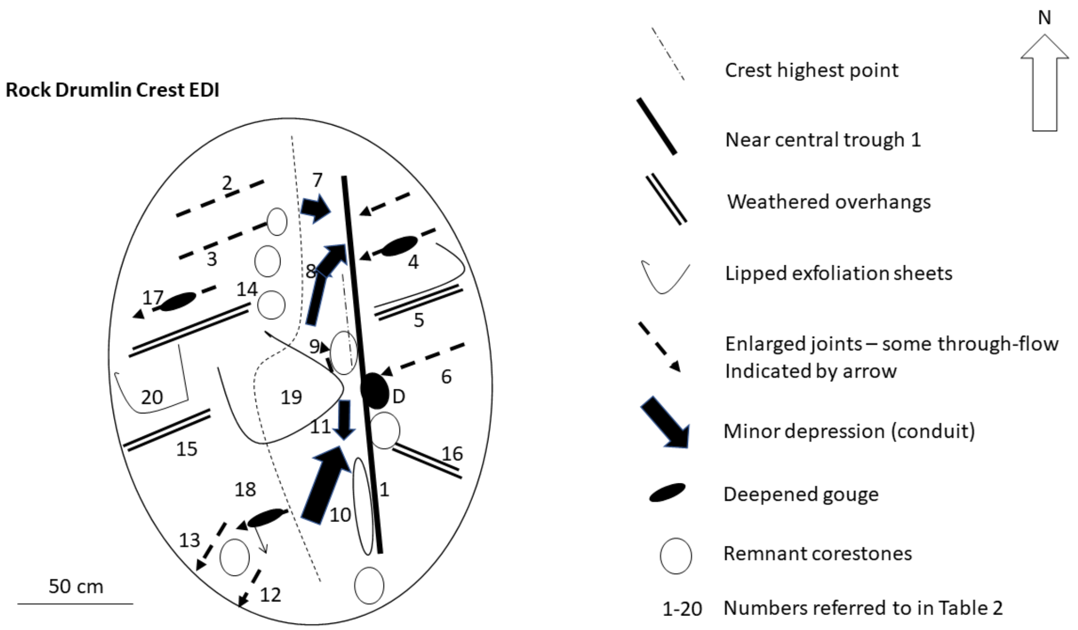
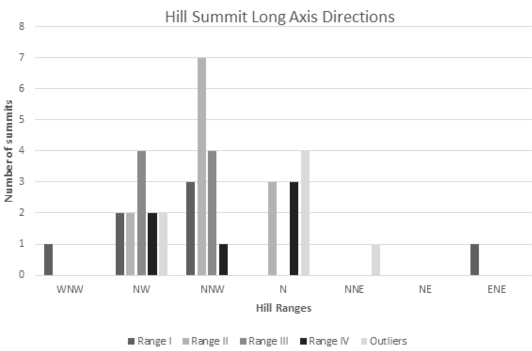


Figure 15. Northern crest (EDI) of Dalbeattie rock drumlin showing remnant granitic weathering features widened by glacial erosion. These include the central trough 1, weathered overhangs, exfoliation sheets and enlarged joints in addition to sub-glacial drainage channels. Numbered features on Table 2 (NX 828622)

a



b

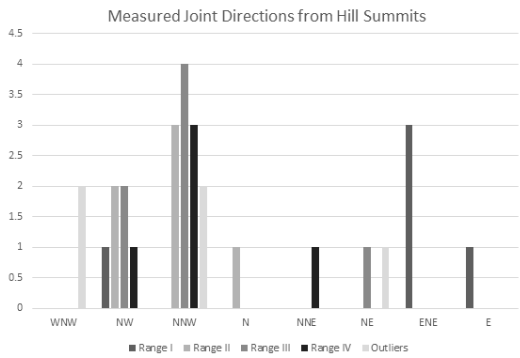


Figure 16a. Results of 40 map-based measurements taken along summit long axes
Figure 16b. Results of field derived joint orientation measurements (n=815) over 26 summits

a

b

Figure 17a. Auchengrey roche moutonnee looking eastwards from Lotus Hill over Range I hills. Ice flow is from the NNW over ENE jointed granites indicating a high degree of discordance (Location on Table 1)
Figure 17b. Glacially eroded overhang joint Dalbeattie rock drumlin (EDI) showing an enlarged (wide) joint which appears to have been created by exfoliation sheet removal. Ice flow direction shown by arrow (NX 828622)
(Hammer= 30 cm)

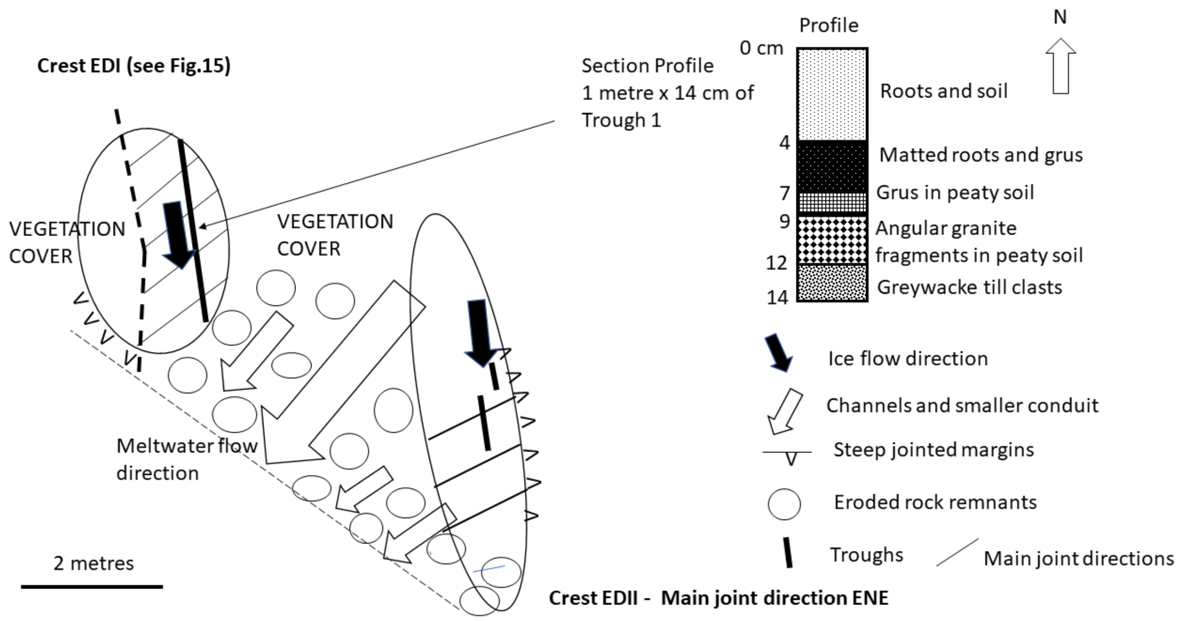


Figure 18. Diagrammatic representation of northern Dalbeattie rock drumlin showing two streamlined crest areas (EDI and EDII) and sediment profile indicating deposition of sub-glacial till clasts into EDI trough. Large lateral channels imply later meltwater flow to SW towards the Urr valley (NX 828622)

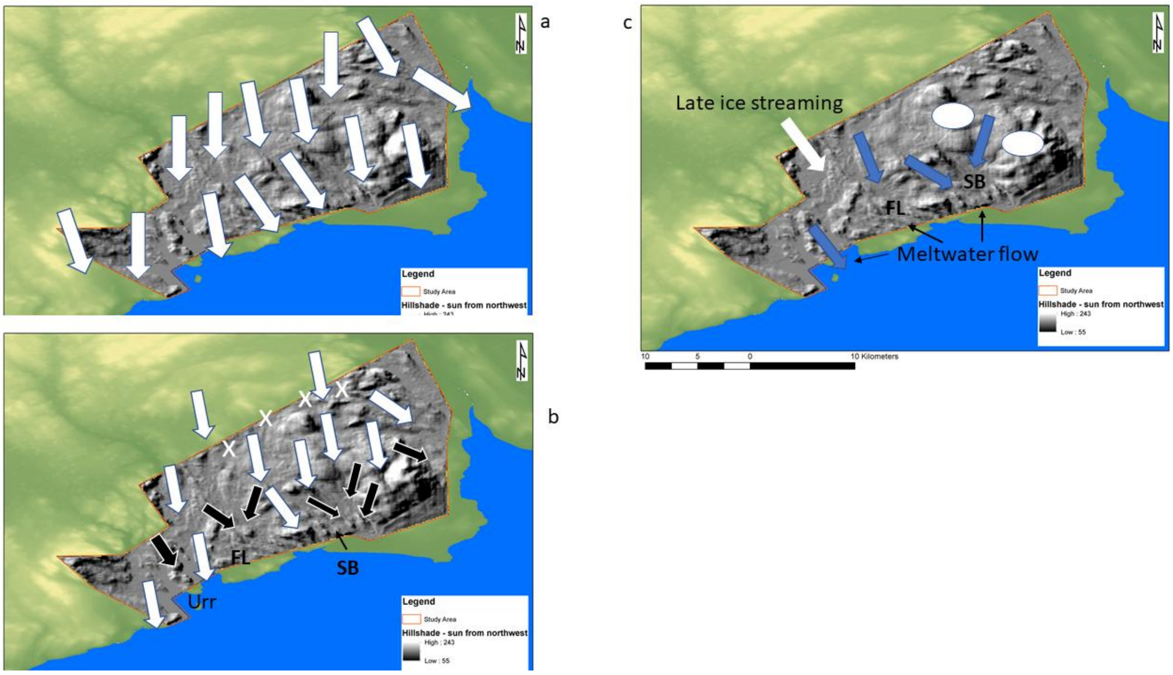


Figure 19a. Schematic representation of cumulative Pleistocene ice streaming (white arrows) over the CDGP. White arrows indicate ice flow directions based on discordance and abrasion analysis (Table 1)

Figure 19b. Schematic representation of thinner late-stage Pleistocene ice streams which underwent uphill ice flow over increasingly higher terrain leading to sub-glacial scouring and localised erosion of re-entrants (white xx). Uphill ice advance over ranges possibly induced flow divergence (black arrows) from hill-tops contributing to erosion of the Southwick basin (SB) and Firgirth Lane basin (FL)

Figure 19c. The last late Devensian ice may have comprised small ice caps on higher hills feeding meltwater flow into the basins. This was possibly synchronous with late ice streaming leading to sub-glacial erosion of the Dalbeattie rock drumlins and whalebacks prior to meltwater flow down the Urr valley