Landscape evolution of Lundy Island: challenging the proposed MIS 3 glaciation of SW Britain

Simon J. Carr [1]*, John F. Hiemstra[2], Geraint Owen[2]

[1]School of Geography, Queen Mary University of London, Mile End, London E1 4NS, U.K.

[2]Department of Geography, Swansea University, Singleton Park, Swansea SA2 8PP, U.K.

*corresponding author: s.j.carr@qmul.ac.uk

Abstract

Lundy Island, in the Bristol Channel of south-west Britain, holds a pivotal place in understanding the extent and timing of Quaternary glaciations in southern Britain, in particular the timing, extent and dynamics of the Irish Sea Ice Stream during the Devensian glaciation. New geomorphological observations and revised interpretations of geomorphological and cosmogenic exposure data lead to the conclusion that Lundy was not covered by ice in the last (Devensian) glaciation. Geomorphological features are related to surface lowering by means of granite weathering under mainly periglacial and cool-temperate conditions. Previously reported cosmogenic ages are re-interpreted to reflect a dynamic equilibrium of cosmogenic nuclide production and surface lowering during a prolonged period of subaerial granite weathering. This re-evaluation of the geomorphology of Lundy Island challenges recently proposed interpretations of early glacial cover of Lundy (MIS 4-3) and for cold-based ice cover at the Last Glacial Maximum (MIS 2), and instead supports existing regional ice sheet reconstructions. This study demonstrates that a robust, coherent geomorphological framework is fundamentally important to support the validity of detailed geochronological and stratigraphic investigations.

Key Words: Irish Sea Ice Stream, Chronology, Last Glaciation, Granite Weathering.

1. Introduction

Considerable attention is currently focused on reconstructing the extent, dynamics and timing of the last British-Irish Ice Sheet (BIIS) (e.g. Clark et al., 2004; 2012; Evans et al., 2005; Chiverrell and Thomas, 2010; Clark, 2014), partly as an analogue for understanding the present and future predicted stability of large ice masses in Greenland and Antarctica. The Irish Sea Ice Stream is considered to have been the main conduit for the southwards drainage of the BIIS (McCarroll et al., 2010). Whilst the southern limit of this ice stream has been reconstructed along the northern edge of the Isles of Scilly (Scourse, 1991; Scourse and Furze, 2001; Hiemstra et al., 2006; Smedley et al., 2017) and its margins have been determined in SE Ireland (Ó Cofaigh and Evans, 2001) and West Wales (Walker and McCarroll, 2001; Catt et al., 2006), ice extent elsewhere in the Celtic Sea and the Bristol Channel is less certain (Figure 1).

Lundy Island, located in the outer Bristol Channel (Figure 1) may hold critical information about the easterly extent of the Irish Sea Ice Stream and the extent of earlier Quaternary glaciations that affected the North Devon and Cornwall coasts (Stephens, 1965; Campbell et al., 1998). Former glaciation of Lundy was first proposed by Mitchell (1968), suggesting that part of Lundy was a nunatak, with the lower, northern part of the island covered by an ice sheet extending eastwards to Fremington (Figure 1) and into the Bristol Channel. Beyond speculative notes by Taylor (1974), little subsequent work was undertaken until Rolfe et al. (2012; 2014) proposed that Lundy Island was entirely inundated during Marine Isotope Stage (MIS) 3 by an ice sheet extending from the west-north-west, based on nine paired ^{26}Al and ^{10}Be exposure ages associated with a suite of glacial and periglacial landforms and sediments. They infer minimal erosion rates (effectively zero erosion) since the island was glaciated and proposed that Lundy was either ice-free or covered by cold-based ice at the maximum extent of the Irish Sea Ice Stream at the Last Glacial Maximum (MIS 2). The resulting model of glaciation of Lundy Island proposed by Rolfe et al. (2012), and repeated by Gibbard et al., (2017) requires a complex spatial and temporal juxtaposition of glacial and periglacial dynamics and landscape evolution on Lundy Island, and conflicts with regional reconstructions elsewhere in the Irish and Celtic Sea (e.g. McCarroll et al., 2010). Significant regional revision of the development and dynamics of the last BIIS is required to accommodate the reported age estimates, invoking a major ice advance that has not been recorded elsewhere in the Irish Sea basin.

Granitic and other crystalline bedrock terrains such as Lundy Island and nearby landscapes of Dartmoor (Devon) and Rosemergy (Cornwall) (Figure 1) have received recent attention as sites that are considered to preserve evidence for 'peripheral' glaciation during MIS 2 (Evans et al., 2012; Harrison et al., 2015; also see Evans, 2016). The challenges of distinguishing glacially-modified bedrock surfaces and associated glacial landforms from features associated with the complex structure, intrusion history and weathering products of granitic and gneissic terrains are substantial even in locations where past glaciation is uncontroversial (c.f. Krabbendam and Bradwell, 2014). As such, in regions of less certain glacial history, a robust geomorphological framework is essential in developing regional stratigraphies of past glaciation.

This study reports the findings of a re-investigation of the geomorphology of Lundy Island. This revised geomorphology places the exposure ages reported by Rolfe et al. (2012; 2014) into a regional context of Late Quaternary landscape evolution that resolves the conflict with the established regional model of glaciation of the Southwest British Isles noted above.

2. Geological Context

Lundy is a small island (~4.5 x ~1 km) in the Bristol Channel, located approximately 26 km west of the north Devon coast (Figure 1). Its plateau-like surface ranges from 90 - 130 m OD, with the highest elevations in the south. The coastline is dominated by sea-cliffs (Figure 2a) which drop to approximately -30 m OD. Geologically, the island is dominated (90%) by the Palaeogene Lundy Granite, intruded through late Devonian Pilton Shales and Morte Slates, which are contact metamorphosed in the south-east of the island (Dollar, 1942;

Edmonds et al., 1979; Thorpe et al., 1990; Tindle and Thorpe, 1992; Smith and Roberts, 1997). The island forms part of the Lundy Platform, a rhomboid-shaped horst bounded by strike-slip faults, and the Lundy Granite is not thought to extend far offshore (Edmonds et al., 1979; Arthur, 1989; Mackie et al., 2006). Lundy Granite is coarse-grained, comprising 20 - 30 mm diameter alkali feldspar megacrysts in a groundmass of typically 1 - 2 mm diameter crystals of alkali feldspar, quartz, plagioclase, muscovite and biotite. There are ubiquitous veins and sheets of coarse pegmatite, as well as finer aplite and microgranite (Tindle and Thorpe, 1992; Smith and Roberts, 1997). Dolerite, rhyolite and trachyte dykes (Edmonds et al., 1979) intrude the Lundy Granite, Pilton Shales and Morte Slates with a preferred orientation of WNW - ESE (Figure 2b; Tindle and Thorpe, 1992; Roberts, 1992; McCaffrey et al., 1993; Roberts and Smith, 1994).

Little is known about offshore Quaternary deposits (Tappin et al., 1994), but an extensive unit of sands and gravels in the outer Bristol Channel, locally up to 15 m thick but more typically 5 m, overlying metamorphosed Devonian and Carboniferous bedrock, is suggested by Mackie et al. (2006) to represent glacifluvial outwash emanating from an ice lobe in Carmarthen Bay during the last glaciation, with a similar lobe extending into Swansea Bay. Shelly facies within this unit represent re-working during the Holocene marine transgression. Overlying this unit are Holocene sand waves and megaripples with amplitudes of ~19 m, interpreted by Mackie et al. (2006) to have formed in the extreme tidal regime of the Bristol Channel since ~5000 BP. Elsewhere, the sea-bed often comprises a thin veneer of sands overlying bedrock, which, when exposed in limited sidescan sonar datasets (see Figure 3.7 in Gardline, 2010) does not show any evidence of streamlining or features that could be attributed to glacial scour. Thin (typically <4 m), intermittent patches of sediment overlying bedrock identified in 2D seismic profiles are speculatively suggested to be till deposits (see Figure 3.20 in Gardline, 2010,). The majority of available borehole records identify only thin recent sands overlying Palaeogene or older bedrock, but numerous cores and boreholes (Tappin et al., 1994; Geo, 2011) located to the north of Lundy contain sediments provisionally interpreted on core logs as being of glacial origin (Figure 1). In all instances, these interpretations are based on preliminary borehole logging and sporadic geotechnical data, and the detailed analysis that is essential for interpreting potential glacigenic sediments recovered from offshore environments (e.g. thin section analysis) is lacking. Despite this ambiguity, and in the absence of any reliable stratigraphic context, Gibbard et al. (2017) propose a Quaternary history of the Bristol Channel, based in large part on the Lundy chronology presented by Rolfe et al. (2012), adding further significance to ensuring a robust understanding of the Quaternary geomorphology of Lundy Island.

3: Contradictory evidence of implausible glacial and periglacial landscape evolution?

Rolfe et al. (2012) offer a geomorphological context for exposure-age data as evidence for glaciation inundating all of Lundy during MIS 4-3, followed by ice-free periglacial and/or cold-based ice sheet cover during MIS 2 (Figure 1). Whilst individual observations of glacial landforms by Rolfe et al. (2012) seem initially convincing, when considered as related parts of a landscape or landsystem, contradictory relationships emerge that violate the integrity of their landscape evolution model.

Both Mitchell (1968) and Rolfe et al. (2012; 2014) describe glacial erosional landforms, with Rolfe et al. (2012) reporting a WNW - ESE orientation of lineations particularly in the northern half of the island. Rolfe et al. (2012, p.65) interpret "*widespread streamlining and moulding of granite bedrock landforms*" as "*the most striking evidence of glaciation on the island*". Subglacial whalebacks indicate high effective normal pressures (i.e. thick, abrasive ice with relatively little basal meltwater supply), where ice overburden pressures are high, suppressing the formation of subglacial cavities (Glasser and Bennett, 2004; Benn and Evans, 2010). The interpretation of granite domed surfaces as glacial erosional landforms is often considered unreliable in the absence of other glacial erosional features (e.g. polished rock surfaces or striae) that are similarly oriented (cf. Lindström, 1988; Patterson and Boerboom, 1999; Johansson et al., 2001; Glasser and Bennett, 2004, Twidale and Romaní, 2005). Domed bedrock surfaces are also common in weathered granite landscapes, and are often mistaken for glacial erosional features (Twidale and Romaní, 2005). Rolfe et al. (2012) acknowledge that the domes on Lundy could reflect granite weathering, but regard the occurrence of ‘subglacial’ grooves and lineations on dome surfaces as supporting evidence of subglacial erosion. Rolfe et al. (2012) interpret these grooves as ice-flow parallel features that indicate ice flowing in a WNW - ESE direction.

Rolfe et al. (2012; 2014) interpret channel networks on the eastern side of Lundy Island (Figure 2) as subglacial meltwater channels formed, with the whalebacks, during MIS 4-3 glaciation of the island, based on exposure-age data. This relationship is unsound from both geomorphological and glaciological perspectives. Firstly, the implication of considerable sediment-charged basal meltwater needed to generate these channels is inconsistent with *contemporaneous* low basal meltwater pressure conditions implied by the whalebacks noted above. Secondly, as Lundy Island is elevated >120 m above the surrounding sea floor, it presents a steep-sided bedrock barrier approximately transverse to the proposed WNW - ESE ice-flow direction suggested by Mitchell (1968) and Rolfe et al. (2012; 2014). To generate subglacial meltwater channels in the specified locations, a high flux of pressurised, debris-rich subglacial meltwater would need to be forced over this topographic barrier prior to carving deep N-channels in the 'lee' of the island, where water pressures may be expected to have been substantially lower. It seems implausible for subglacial meltwater to flow over, rather than around Lundy, particularly because the two most extensive channel systems are close to the southern and northern ends of the island, and that there is no evidence for similar channels offshore (Tappin et al., 1994). As such, the interpretation that these features are of subglacial origin is at best implausible and inconsistent with the conditions implied by the extensive whalebacks located immediately adjacent to, and even within these channels.

Considerable significance is attached by Rolfe et al. (2012) to numerous widely dispersed, generally sub-rounded, Lundy Granite boulders, typically 1 - 2 m in diameter, either resting on bedrock or embedded within the local regolith, interpreted as glacially-transported boulders. The distribution of these constitutes the prime evidence interpreted by Rolfe et al. (2012) of total inundation of Lundy during MIS 4-3 glaciation. Given the restricted offshore extent of the Lundy Granite (Arthur, 1989), subglacial transport distances can only have been tens to hundreds of metres. Moreover, in Rolfe et al.'s (2012) reconstruction of events this active transport of boulders occurred during the first phase of (warm-based) glaciation, meaning that the boulders would have been subsequently exposed to intensive periglacial weathering for the same amount of time as nearby tors (described below). Yet, this exposure has not resulted in evidence of gelifraction or other surface modification of the boulders.

Finally, Rolfe et al. (2012; 2014) report upstanding tors located in cliff-top positions across the west and northeast of the island, further suggesting that some tors have been modified by cold-based ice during MIS 2, with apparent collapse in a (south-) easterly direction. The character of these tors, along with the presence of angular colluvium and ventifacts on Lundy's surface leads Rolfe et al. (2012) to speculate that Lundy experienced periglacial conditions after MIS 4-3 glaciation, followed by re-occupation by cold-based, non-erosive ice during MIS 2. However, the proximity of apparently unmodified tors to ice-moulded bedrock (often within 10s of metres, with many tors actually overlooking whalebacks) is contradictory, and requires extreme, and in our view implausible, spatial variation between very high and near-zero rates of physical weathering required to generate such juxtaposition of features. It is also important in this context to note that this explanation violates the near-zero erosion and weathering rates used by Rolfe et al. (2012) to underpin the cosmogenic age-estimates were near zero across the island, which directly contradicts the weathering rates required to generate the observed tors.

Consequently, when the data presented by Rolfe et al. (2012) is considered as a whole, inconsistencies and contradictions between the reported evidence emerge that suggest the reconstruction reported is at best extremely complex, if not impossible.

4. Methodology

The original purpose of the field research was to examine and sample patches of diamicton noted and located (reproduced in Figure 2), but not further described by Rolfe et al. (2012). The absence of visible evidence for these previously-reported diamictons (see section 5.2) led to a re-consideration of the other geomorphological context presented by Rolfe et al. (2012), as critiqued above.

The geomorphology of Lundy Island was described through field observation during September 2014 and July 2016, with individual features located using handheld GPS and referenced to the geomorphological map presented by Rolfe et al (2012). Subsequent interrogation of the Environment Agency 1 m spatial resolution LIDAR Digital Surface Model of the island was conducted using LandSerf (Wood, 2009; Fisher et al., 2004) to systematically identify key features (e.g. dry channels) and to place field observations in a whole-island context. Particular attention was given to the measurement of the orientation of elongate features visible in the field using a compass-clinometer and on the DSM, as well as the mapping of geological structures (veins, dykes, joints) in proximity to the glacial erosional features reported by Rolfe et al. (2012).

Accessible sediment sections and exposures are limited on Lundy Island, but the few sites identified (Figure 2), as well as isolated surface sediment patches were described using standard sedimentological approaches as outlined by Evans and Benn (2004). The very small size of sediment exposures precluded standard bulk sampling for clast analysis, but two hand-picked samples (n = 25 (sample A) and n = 24 (sample B)) of apparently exotic or not obviously Lundy Granite clasts were recovered from surface spreads of sediment at the north of Lundy Island for lithological identification. Whilst both recovered sample populations are very small, initial visual assessment established that these ‘ambiguous’ lithologies represent between 5 and 10% of the total clasts exposed, the remainder of which were clearly identifiable as Lundy Granite.

Finally, a re-assessment of cosmogenic nuclide dating reported by Rolfe et al. (2012) was undertaken. Rather than presuming that the measured concentrations of ^{10}Be and ^{26}Al exclusively reflect the granite's exposure time since ice retreat (assuming minimal erosion since deglaciation), we use the same concentrations to investigate the feasibility of explaining these as indicators of long-term granite surface lowering, working on an assumption that Lundy was *not* covered by glacial ice at any time during the last glacial cycle.

5. Re-assessment of the evidence for glaciation of Lundy

Rolfe et al. (2012; 2014) argue that extensive glaciation inundated all of Lundy during MIS 4-3, followed by ice-free and/or cold-based ice-sheet cover during MIS 2. This landscape evolution is based on geomorphology, sedimentology and exposure-age evidence. Each of these lines of evidence is evaluated in turn below, based on new observations and data, and each is considered as integrated components of the overall landscape, leading to an alternative model for the Late Quaternary landscape evolution of Lundy.

5.1 Geomorphological evidence

The plateau surface of Lundy Island typically displays subdued geomorphology, with few distinctive features evident on the DSM, irrespective of illumination direction. The blocky nature of the structure of the Lundy Granite is frequently visible on the DSM, particularly on the western side of the island (Figure 3), but in contrast to Rolfe et al. (2012), no preferred WNW - ESE 'grain' is observed in the surface geomorphology of Lundy. There is however a clear preferred structural trend in the orientation of major veins and dykes (Figure 2, 4a), with a preferred orientation WNW - ESE, as well as a secondary mode oriented approximately perpendicular to this. This is supported by the measurement of smaller veins and dykes located on and between the features noted below (Figure 4b), which show a strong preferred WNW - ESE orientation. Jointing and small fissures within the Lundy Granite are typically perpendicular to the trend of veins and dykes, with a preferred NNE - SSW orientation (Figure 4b).

5.1.1 'Streamlined' granite bedrock and associated landforms

Granite domes (typically <10 m diameter) are distributed across much of Lundy, mostly covered in thin regolith and grass (Figure 3); however extensive areas of North End (north of Three-Quarter Wall) comprise bare bedrock surfaces with multiple domes, where the surface of the granite bedrock appears to have been denuded of regolith (Figure 5a-d). Such domes are absent in the south-east of the island, where the underlying geology is not granite, and suggests that these features are conditioned by bedrock type and structure, rather than geomorphic processes (Figure 3c). Most domes are not elongate, but where they are, their orientation is parallel with local joint, vein and dyke systems (Figure 4a, Figure 5a-d), and they typically preserve shallow surface weathering pits (gnammas; Figure 5e).

Significant and differential rates of surface weathering on the dome surfaces are confirmed from upstanding veins and dykes. At the head of Gannets' Combe, in an area mapped by Rolfe et al. (2012) as ice-moulded bedrock, delicate, irregularly-shaped granite pinnacles ~450 mm in height protrude from some granite dome surfaces (Figure 5f,g). Similar pinnacles have been described elsewhere as weathering posts by Rodbell (1993) and Rodbell et al. (2012) in the Cordillera Blanca of Peru, and are interpreted to represent differential weathering arising from textural variations within the granite. The features in Figure 5f,g are the first reported observations of weathering posts outside the Cordillera Blanca, suggesting that the weathering regime of Lundy Island is particularly favourable for the formation of these unusual features. Rodbell et al. (2012) present a calibrated scale relating the height of weathering posts on boulders to independent age estimates, and although it is inappropriate to directly transpose this scale to Lundy, the height of the weathering post at the head of Gannets' Combe suggests that bedrock has been exposed to sub-aerial weathering for a considerable period of time (at least tens of thousands of years).

'Bedrock grooves' on Lundy observed in this study form two populations superimposed on dome surfaces (Figure 6). 'Type 1' grooves are elongate lineations up to 5 m long, 40 mm wide and 20 mm deep, with a step-like, rather than trough cross-profile (Figure 6a,b). They are cross-cut by similar lineations with inconsistent, but often perpendicular orientations (Figure 6a). In detail, the base of these grooves typically comprises a linear crack extending the length of the groove (Figure 6b). Some ‘Type 1’ grooves are offset by veins and dykes (Figure 6c), suggesting they pre-date dyke intrusion. ‘Type 2’ grooves are parallel sets of shallow elongate depressions, typically exceeding 1 m long, 500 mm wide and up to 40 mm deep (Figure 6d). These features are only found at North End, on bedrock surfaces with shallow slopes. They initiate at the highest points of a dome and terminate where they encounter veins, joints or dykes within the granite. The intervening ridges between grooves are often characterised by upstanding veins of aplite, pegmatite and rhyolite. Rock surfaces within 'Type 2' grooves are rougher than those of the intervening granite surfaces, which is inconsistent with a subglacial erosional (abrasion) origin. Other small-scale features of glacial erosion are absent; while the coarse-textured granite precludes the preservation of striae, small-scale features indicative of glacial erosion are also absent on the much finer-textured dykes and veins.

Our preferred interpretation for the domed granite surfaces, associated grooves and weathering posts on Lundy is through subaerial granite weathering, rather than subglacial abrasion. The distribution and orientation of granite domes is controlled by jointing patterns in the granite and the geometry of veins and dykes, and does not represent a single population of ice-moulded features as inferred by Rolfe et al. (2012). ‘Type 1’ grooves are interpreted here as having formed through recent enhanced weathering of sub-vertical joints within the granite, while ‘Type 2’ grooves are early-stage rillenkarren (cf. Migoń and Dach, 1995) or weathering flutes (Williams and Robinson, 1994). The very shallow nature of the grooves and the weathering pits identified elsewhere on North End suggests that these features are recent (cf. Domínguez-Villar and Jennings, 2008). Rapid subaerial physical weathering of the recently-exposed granite is facilitated by high levels of sea-salt in a coastal environment resulting in increased surface microstructural damage through fissuring between crystals (Cardell et al., 2003).

The recent fire and vegetation history of Lundy is pertinent to a simpler interpretation of the bare, domed bedrock surfaces, grooves and thin or absent regolith at North End. Three major fires occurred north of Three-Quarter Wall in the early 1930s, with wildfires in 1933 burning across North End for over 7 weeks (Langham, 1992). Vegetation and peat cover overlying the granite bedrock was completely stripped, extending to south of Gannets' Combe on the eastern side of the island, and even further south on the western side (Wilkins and Debham, 1973; Langham, 1992). The extent to which these wildfires have accelerated weathering mechanisms on the North End of Lundy Island is not clear, but the effectiveness of wildfires as geomorphological agents is well-known (Dorn, 2003; Shakesby and Doerr, 2006). The lack of obvious evidence for fire damage (e.g. blackened rock surfaces, spalling of fire-damaged rock surfaces) suggests that rates of granite surface weathering at North End since the 1930s has been sufficient to remove such evidence. The loss of the peat has restricted the re-establishment of vegetation cover (Wilkins and Debham, 1973), leaving the granite bedrock exposed for the past 80 years, resulting in the distinctive difference in surface landscape between the apparently denuded landscape at North End (Figure 7) and the rest of the island.

5.1.2 Dry Channels

There are no permanent surface streams on Lundy, but the island is fringed with gullies and dry channel systems that experience seasonal surface runoff and flushing during prolonged or intense rainfall events (R. MacDonald, Lundy Island Warden, 2014 *pers. comm*.). The majority of channels are single branch systems with limited catchments. Channels extending upstream beyond the cliff edge have been mapped from the DSM using a combination of slope curvature (Kennelly, 2008) and fuzzy analysis (Fisher et al., 2004) (Figure 8). In total, 39 separate catchments are identified, the majority comprising small, shallow single-thread systems terminating in steep gullies on the coastal margin. Sixteen channel systems incised >2 m extend on to the plateau surface (Figure 8), dominated by 9 channels either side of the Gannets' Combe watershed (Figure 9a).

With the exception of channel 8 in the south of the island, all the mapped channel systems are closely associated with previously mapped dykes, veins or geological boundaries, suggesting there is a primary structural control over their distribution (Figure 9b). In all examples, the orientation of channel fall-lines derived from the DSM is normal to the underlying slope, and none are oblique to the topographic fall-line. Channels are linear, with low sinuosity, and networks are either single channel features initiated in shallow swales on the plateau surface (Figure 9c), or simple dendritic networks with no bifurcating or anastomosing channels. Channel long profiles (Figure 10) are convex, with no undulating profiles or reverse slopes. Channels on the western side of Lundy are shorter and steeper, with greater convexity than those on the eastern side, reflecting the location of the main island watershed, but there is no significant difference in form, geometry and profile to suggest that eastern and western channels are separate populations resulting from different environmental conditions. Consequently, there is no evidence to support the four channels identified by Rolfe et al. (2012) as being a different population from the others mapped in Figure 8.

None of the mapped channels meet any of the twelve diagnostic criteria for the recognition of subglacial meltwater channels compiled by Greenwood et al. (2007: see their Table 1). It is possible that the channels may instead represent the transfer of *supraglacial* meltwater to the glacier bed, enhanced by crevassing resulting from the topographic barrier offered by Lundy Island; however, consistent geometry of albeit small drainage networks with the presence of 'swale' headwaters and the absence of potholes, plunge pools or other features that would be associated with such meltwater transfers suggests that this is extremely unlikely.

The close association between channel locations and mapped dykes and joints in the Lundy Granite suggests that pneumatolytic rotting of the bedrock and episodic fluvially-assisted removal of debris is a more plausible explanation. This process occurs at the present day (Figure 9c) in ephemeral subaerial headwater drainage systems and swales (Hack and Goodlett, 1960; Benda et al., 2005), and is likely to have been even more effective in the past, for example through nival runoff under periglacial conditions.

5.1.3 Tors

Bedrock tors, typically 2 - 5 m in height, are found at eighteen locations on Lundy Island (Rolfe et al., 2012). They are typically in cliff-top positions (Figure 11), with none located on inland summits. Some tors display clusters of pinnacles (koppies, towers: see Twidale and Romaní, 2005), but most have complex, castellated forms with combinations of loose, perched blocks, plinths and pinnacles. Many preserve weathering and edge pits up to 1 m deep, and delicate surface forms, with fretted and rounded edges of sheeting and joint structures on all examples visited (Figure 11a-c). All tors observed have a downslope boulder field of blocks and (vegetated) granular grus where local slope conditions permit (Figure 11b-d). Perched and toppled boulders have both rounded and angular morphologies. Elsewhere on the coastal fringe, numerous granite residuals (nubbins) are located, often associated with perched boulders. Examination of seven 'collapsed' tors (c.f. Rolfe et al., 2012) indicates that the direction of boulder toppling conforms with the trend of local slopes (Figure 11 b-d); the preferred eastwards trend identified by Rolfe et al. (2012) reflects that the majority of 'collapsed' tors are located on the east-facing coastal fringe.

Following the classification scheme of Hall and Phillips (2006), all tors on Lundy represent Stage 1 forms, suggesting that no glacial modification has occurred. Although delicate, minimally-modified tors can be preserved through multiple glacial cycles (Kleman and Hättestrand, 1999; Hall and Phillips, 2006; Darmody et al., 2008), this only occurs beneath cold-based ice at or close to ice divides, where there is minimal lateral movement of ice. Under the reconstruction presented by Rolfe et al. (2012), this ice-divide position is clearly not the case for Lundy Island. Consequently, we conclude that there is no evidence supporting glacial modification of tors on Lundy.

5.2 Sedimentological evidence

Rolfe et al. (2012; 2014) identify diamictons on Lundy Island, and the original aim of this study was to sample these sediment units for microscale analysis (Figure 2). Despite careful examination in the vicinity of Pondsbury no deposits of diamicton were found, and only a thin regolith was observed directly overlying granite bedrock (Figure 12a). Similar observations were made at Gannets' Combe, where Rolfe et al. (2012) report a sheet of diamicton within the dry channels previously discussed. Finally, two prisms of diamicton east of Pondsbury mapped by Rolfe et al. (2012) were noted to comprise vegetated talus-dominated openwork colluvial slopes, which are common on the coastal cliffs of Lundy. The consecrated ground around St Helena’s Church, another of the sites identified by Rolfe et al. (2012), was not revisited during this study.

The only sediment exposures found on Lundy during this study were small sections within sediment drapes that flank many of the coastal cliffs (Figure 2, 12b,c), and those within Millcombe (Figure 12d). All of these sections preserve a thin (< 1 m) coarse-grained, massive diamicton with mainly angular, locally-derived clasts preserving a downslope-oriented clast fabric, directly overlying bedrock. Where the bedrock is granite, there is typically a sharp, irregular, but conformable contact with the diamicton, suggesting the *in situ* production of regolith (grus). At Jenny’s Cove (Figure 12c) and Quarter Wall (Figure 12b), this grus is overlain by a stratified diamicton of otherwise identical sedimentary characteristics. This stratification is interpreted here to represent local downslope transport of the grus. Similar sequences are described in other areas of granite decomposition in the British Isles (Waters, 1964; Eden and Green, 1971) and record weathering of granite under cool-temperate or cold climate conditions with regular periods of nival cover. This environmental signature is supported by the exclusively angular morphology of clasts within the diamictons overlying both the Lundy granite and Morte Slates and Pilton Shales, indicative of gelifraction.

5.2.1 Erratic gravels at the North End watershed

'Large spreads' of cobble gravels in northern Lundy are described by Mitchell (1968) and Rolfe et al. (2012) as being erratic on the basis of their exotic lithologies, including schist, quartzite, flint, rhyolite, mudstone, limestone and sandstone. Consequently, both Mitchell (1968) and Rolfe et al. (2012) suggest that these gravels represent either a remnant till or outwash deposit.

North End of Lundy comprises a patchwork of bare granite surfaces and *Calluna* growing in a thin regolith (Figure 13a), with a sporadic spread of gravel, particularly at the head of Gannets' Combe. The gravel does not form a spatially-coherent sediment unit (Figure 13b), but scattered linear or clustered concentrations of pebbles and cobbles are associated with veins and dykes of similar lithology, apparently recently disaggregated from them (Figure 13c). Most clasts (>95 % based on a visual assessment) are of obvious local granite composition, but those that appear non-granitic (n = 25) were sampled for identification (sample A; Table 1) from the area described by Mitchell (1968, p. 66) as having "*an almost continuous sheet of foreign pebbles*" (SS 1312/4750).

Contrary to the view of Mitchell (1968), this study finds that apparently non-granite clasts form only a very small proportion in this area (visually estimated at <5 % of the total population). Lithological analysis of Sample A (Table 1) indicates that all the sample clasts are local in origin, comprising granite, individual mineral components of granite (quartz and feldspar), or dolerite that most likely originates from local dykes. One recovered clast was identified as pyritiferous Morte Slate, whilst the only unknown clast was a small fragment which looks to be a heavily modified weathering rind.

Figure 2a and Table 2 offer an alternative explanation for the 'foreign' clasts reported by Mitchell (1968). The position of the 'gravel spread' coincides with the intersection of three gravel tracks, built and maintained to service the lighthouse at Northwest Point. Mitchell (1968, p. 65-66) notes "*At the Southeast corner* [of Lundy]*… there is an extensive modern beach with many foreign materials* [including] *limestone, flint and sandstone…. From this beach pebbles have been carted for many years to make concrete and to* [build] *the tracks of the island*". To test this, non-granite clasts were sampled from the the main service track on Lundy (SS 1369/4621, sample B, Table 2). As with sample A, the non-granite proportion is low (~10% based on visual assessment), and comprises entirely local (i.e. Lundy) lithologies, mainly Morte Slate. Although some clasts (e.g. clast B_o) resemble chert or flint (as noted by Mitchell, 1968) on closer inspection they were identified as trachyte, again found locally in dykes on the island.

The distribution and lithology of clasts in the 'gravel spread' at the head of Gannets' Combe represents two processes. First, most of the clasts are weathered from locally exposed bedrock (Figure 13b). Localised weathering rates have probably been significantly enhanced through historical fire damage and vegetation loss (c.f. Dorn, 2003; Gómez-Heras et al., 2006; Shakesby and Doer, 2006; McCabe et al., 2007). No clasts were found displaying evidence of thermal stress (e.g. spalling, flaking, crazing; Deal, 2012), suggesting that they have originated *since* the 1930s wildfires through surface weathering. Second, 'foreign' clasts in the spread around the head of Gannets' Combe are most likely due to the transport of material from elsewhere on Lundy (mainly Landing Beach) for road and track maintenance. The transport of 'exotic' clasts is more plausibly explained by human action rather than past glaciation.

Rolfe et al. (2012) suggest that some of the 'erratic' clasts in the north of Lundy are modified into dreikanter/ventifact forms, suggesting prolonged (arid) periglacial conditions. While some clasts with apparent faceted morphology were identified (Figure 14a), these are typically located close to areas of bedrock with distinctive chevron-style joint sets (Figure 14b), the weathering of which inevitably generates clasts with an apparent faceted form. No clasts observed on Lundy Island demonstrate the characteristic smooth, wind-abraded facets separated by sharp keels considered diagnostic of ventifacts by Knight (2008) (e.g. Figure 14c).

5.2.2 Scattered large sub-rounded boulders

Large (1-2 m diameter) sub-rounded granite boulders scattered across the island, often well away from tors, are interpreted by Rolfe et al. (2012, 2014) as glacially transported. Clusters of perched boulders are found on Ackland's Moor (at the highest elevation on Lundy Island) but mainly at North End; notably, none are located on the Morte Slates in the south-east. Boulders at North End rest directly on bedrock, whilst those on Ackland’s Moor are surrounded by regolith and soil (Figure 15a). Boulders are broadly ellipsoidal in shape, sub-rounded to well-rounded, and comprise the same granite type as the directly underlying bedrock where it is visible, indicating minimal transport. The surface textures of boulders vary. Those located around Ackland’s Moor display generally even surfaces (Figure 15a), while those at North End are much more variable, typically with shallow surface pitting and rillenkarren (Figure 15b). No faceting or other evidence abrasion is evident, and there is no evidence of modification through gelifraction. Isolated boulders on coastal cliff tops (Figure 15c) are clearly residual bedrock blocks, indicating ongoing epigenetic weathering processes along sheet and block boundaries on exposed granite.

Perched boulders are described in many granite landscapes and are considered to develop in a two-stage process, whereby sub-surface weathering of granite blocks forms corestones, followed by erosion of the weathered mass to remove the finer grus, leaving boulders exposed as residual features (Twidale and Romaní, 2005). On Lundy, the uniformity of boulder size compares well to the density and geometry of joints and fissures in the granite where it can be directly observed. At SS 1312/4552, a granite corestone emerging from a matrix of grus (Figure 15d) supports the classic two-stage weathering model. The observation that most boulders are perched on bedrock, rather than embedded within regolith, suggests that the rate of grus removal is greater than the rate of granite surface lowering (Bazilevskaya et al., 2013). The pitted surfaces of boulders at North End suggest that surface weathering is recent (Twidale and Romaní, 2005), most likely facilitated by the 1930s wildfires. The lack of a glacial imprint on these boulders, minimal transport distance and lack of periglacial modification undermines the glacial transport model proposed by Rolfe et al. (2012); an origin as residual boulders derived from two-stage weathering is far more likely.

We therefore find no evidence for glacigenic sedimentation on Lundy. The sediments indicate a simple environmental history of *in situ* weathering and gelifraction of the underlying bedrock, with localised slope movement on the coastal fringes of the island. The presence of these sediments within Millcombe suggests sediment production and transport has occurred in parallel with, or subsequent to, the development of the channel systems on the island over an extended period of time.

5.3 Age data

Rolfe et al. (2012) obtained exposure ages of 31.4 - 48.8 ka (^{10}Be) and 31.7 - 60.0 ka (^{26}Al) from terrestrial cosmogenic nuclide analysis on samples of Lundy granite and pegmatite. This provides a key strand in their conclusion that Lundy was glaciated during the Devensian, but at an earlier stage than elsewhere in the Irish Sea basin, which they propose as MIS 4-3. Rolfe et al. (2012) infer that Lundy was exposed or covered by cold-based ice at the Last Glacial Maximum and assume that erosion rates have been minimal since exposure. The evidence noted above demonstrates surface weathering has been, and continues to be significant across Lundy Island. We question the assumption made by Rolfe et al. (2012) that the measured concentrations of nuclides in Lundy's rocks are a reflection of post-glaciation surface exposure and instead propose that the accumulated nuclides reflect a dynamic equilibrium of cosmogenic nuclide production and granite surface lowering.

Using Rolfe et al.'s original data (2012; Table 2, p. 68) and the Cronus-Earth calculator (Balco et al., 2008), surface erosion rates instead of exposure ages can be estimated; the feasibility of these approximated ‘required’ erosion rates can then be assessed. Taking sample LC1a as representative for modal low-end values and sample LC6b as representative of the high end of the range, erosion rates are derived ranging from 14.2 ± 1.8 m Ma^{-1} to 30.1 ± 2.3 m Ma^{-1} dependent on the used nuclide (^{10}Be or ^{26}Al) and on assumptions of constant or time-dependent production rates.

In evaluating such erosion rates, there are three important points to note. First, although this study asserts that the island has not been glaciated during the Late Devensian (MIS 2) or immediately prior (MIS 3-4: Rolfe et al., 2012; 2014), it is probable that Lundy was ice-covered in earlier, more extensive glaciations between MIS 16-6 (Gibbard and Clark, 2011; Böse et al., 2012). Surface lowering ‘required’ for this model to work would thus be in the order of ~6-13 m since MIS 12 or ~2-10 m since MIS 6). Such values of surface lowering are compatible with, and could thus provide a simple explanation for, the formation of Lundy’s 2-5 m high tors.

Second, comparing these values to those of other studies shows that similar rates can be achieved in modern periglacial environments. Matthews and Owen (2011) determined Holocene mean surface lowering rates in southern Norway of 4.8 ± 1.0 mm ka^{-1} (≡ 4.8 m Ma^{-1}) in high-grade metamorphic rocks, while another study found average rates of 15.5 ± 2.2 mm ka^{-1} (≡ 15.5 m Ma^{-1}) in calcite-bearing schist (Owen et al., 2006). Such values demonstrate that the surface lowering values for Lundy estimated above are realistic. The specific conditions on Lundy - the susceptibility to weathering of the coarse-grained Lundy Granite and the alternation between periods of periglacial conditions and cool maritime (wet and saline) climates during the Late Quaternary - would further promote the release and subsequent stripping of regolith.

Third, there are remarkable similarities between the exposure dates found by Rolfe et al. (2012) and those reported by Gunnell et al. (2013) in an investigation of tor development in the granite landscape of Dartmoor, an area with parallels to Lundy in both geology and setting. Gunnell et al. (2013: p. 74) found apparent exposure ages for Dartmoor tors to "*… cluster markedly in the Middle Devensian, with half the dates between 36 and 50 ka*". For comparison, Rolfe et al. (2012) report ages from Lundy between 31.4 and 60.0 ka. Gunnell et al. (2013) develop a persuasive argument to account for their results, considering different models of denudation, shielding by snow/ice and/or regolith, and diverse scenarios of periglaciation and cold-based or warm-based glaciation. They conclude that the tight cluster of ages implies that a single event was responsible for significant stripping of regolith at the onset of Devensian periglaciation, but that the tors in Dartmoor, which are very similar in height to those in Lundy, are "*evanescent features, which emerge and quickly disappear during every Pleistocene climatic downturn*" (p. 62). There is no reason to reject a similar periglacial landscape development for Lundy.

We therefore conclude that the exposure-age dates reported by Rolfe et al. (2012) reflect the dynamic equilibrium between cosmogenic nuclide production and granite surface lowering rather than the time since exposure and that their assumption of zero erosion rates is invalid.

6. Discussion and implications

6.1 Revised Interpretation of the Geomorphology and Landscape Evolution of Lundy Island

The geomorphological interpretation of Lundy Island presented above contrasts with the views of Mitchell (1968), Taylor (1974) and Rolfe et al. (2012; 2014) in that we find no clear evidence to support landscape evolution through glaciation (Table 3). While the individual features noted by Mitchell (1968) and Rolfe et al. (2012; 2014) can be located, their interpretation and landform assemblage does not withstand scrutiny as a coherent glacial landsystem; closely juxtaposed features indicate implausible, contrasting glacial dynamics, and the close association of features interpreted in terms of thick, warm-based ice and perfectly-preserved periglacial features is highly improbable.

The alternative interpretation of the Late Quaternary landscape evolution of Lundy presented in this study recognises four contributing factors. First, the majority of the features described from Lundy are products of the weathering of granite bedrock. Domed surfaces, perched boulders and the occurrence of grus are classic features of landscapes of granite weathering and, critically, have all been frequently mis-identified as evidence for glaciation (Twidale and Romaní, 2005). Smaller-scale features, such as gnammas and rillenkarren superimposed on the granite domes attest to ongoing surface modification of an exhumed granite surface. It is particularly notable that no ‘whaleback’ forms or perched boulders are located in the southeast of the island where the bedrock is not granitic. The observations of weathering posts, granite domes, gnammas and other related features in this study clearly demonstrate that modern-day weathering and mass-wasting processes on Lundy Island are far more effective than is suggested by the ‘near-zero’ rates required by Rolfe et al. (2012) to support their proposed Quaternary landscape evolution model and chronology.

The second factor is the control of distinctive bedrock structure on the geomorphology of Lundy Island. The distribution and geometry of streamlined landforms (proposed whalebacks), grooves and dry channels correspond closely to structures in the granite or intruded veins and dykes (Figures 4, 6 and 8). Features similar to the dry channels of Lundy have been recognised on Dartmoor and although Evans et al. (2012) tentatively interpret these as a mix of ice-marginal and subglacial meltwater channels relating to a thin, cold-based ice mass, they recognise that pneumatolytic rotting and preferential removal offers a realistic alternative mechanism for their formation. The absence of structural mapping on Dartmoor restricts the testing of such a mechanism, but the wealth of detailed structural mapping of the Lundy Granite (Tindle and Thorpe, 1992; Roberts, 1992; McCaffrey et al., 1993; Roberts and Smith, 1994; Smith and Roberts, 1997; Figure 4) indicates that a structural control over pneumatolysis is indeed a key factor in forming these features on Lundy.

The third factor is the role of wildfire on geomorphology. Wildfire can be a significantly more effective weathering agent than frost action (cf. Dorn, 2003; Shakesby and Doerr, 2006; Gómez-Heras et al., 2006), and the greater abundance of exposed granite domes and shallow surface-weathering features at North End compared with the rest of the island can be attributed to a combination of thermal fatigue of the granite surface resulting from the wildfires of 1933 (Langham, 1992), and re-invigorated surface weathering of the freshly exposed granite surfaces.

The final factor is human agency. As a small island with a long history of human occupation, Lundy's surface has been extensively remodelled by agriculture, quarrying and road-building to service past and present populations. The only readily available aggregate source on the island is at Landing Beach and, as a consequence, tracks and roadways across the island contain a mixture of local and non-local clasts. The use of this gravel on the tracks at North End, built to service the lighthouse at Northwest Point, may account for the (rare) anomalous clasts found in the sporadic gravel spread reported by Mitchell (1968).

6.2 Implications for Devensian Glaciation in Southern Britain

The re-evaluation of the geomorphology and landscape evolution of Lundy Island in terms of sub-aerial granite weathering rather than subglacial processes demands reconsideration of the conclusions and stratigraphic implications drawn by Rolfe et al. (2012; 2014) for the extent, timing and dynamics of the Irish Sea ice stream during the Devensian glaciation. Their proposal for early (MIS 4-3) warm-based ice cover of Lundy followed by ice-free or cold-based ice conditions at the Last Glacial Maximum (MIS 2) becomes redundant under this reinterpretation, and their re-drawing of the eastern margin of the Irish Sea ice stream to extend into the Bristol Channel (Figure 1) is no longer needed. This chronological model has been recently extended by Gibbard et al. (2017) to explain sporadic evidence of possible past glaciation throughout the Bristol Channel. On the basis of the evidence presented, we maintain that the Irish Sea Ice Stream by-passed Lundy Island during the Devensian glacial advance, and that none of the evidence reported in this study revises the existing model of the extent, dynamics and timing of the Irish Sea Ice Stream summarised by McCarroll et al. (2010). Consequently, we find that the model proposed by Rolfe et al. (2012) and extended by Gibbard et al. (2017) of Devensian glaciation of the Bristol Channel has no basis.

While this study rejects the proposed model for glaciation of Lundy Island during the Late Quaternary proposed by Rolfe et al. (2012; 2014), we accept that earlier, more extensive ice sheets covering the British Isles during MIS 16 and MIS 12 (Bowen et al., 1986; Böse et al., 2012) probably inundated Lundy Island. There are tantalising fragments of possible evidence for more extensive glacial cover in the Bristol Channel and the north coasts of Devon, Cornwall and Somerset (Figure 1). However, it is clear that more recent subaerial granite weathering and erosion on Lundy, far from being insignificant in their effects, have completely modified and removed the geomorphological evidence that could be attributed to pre-Devensian events. As such, we conclude that there is an absence of preserved evidence for past glaciation of Lundy Island, even though it may well have been inundated by ice sheets during the Middle Quaternary.

6.3 Implications for analysis of 'peripheral' glaciation of granite terrains

The alternative interpretations of extensive *in situ* weathering and sub-aerial modification of the granite landscape on Lundy Island favoured in this study are briefly considered by Rolfe et al. (2012) but rejected in favour of a subglacial interpretation. It is widely recognised that interpretation of gneissic and granitic terrains can be problematic in differentiating between weathering and glacial abrasion mechanisms for whaleback forms (Lindström, 1988; Johansson et al., 2001; Olvmo and Magnusson, 2002; Jansson and Lidmar-Bergström, 2004; Krabbendam and Bradwell, 2014), and in determining the relative contributions of weathering or subglacial processes in the production and modification of tors and perched boulders (Jansson and Lidmar-Bergström, 2004; Ryan et al., 2005; Hall and Phillips, 2006). Such an interpretation is challenging in regions where independent evidence already points towards past glaciation, and is therefore considerably more so in regions of uncertain glacial history, such as Lundy Island.

On Lundy Island, but elsewhere in the granite terrains of the south-western British Isles, the record of potential glaciation is best described as peripheral, where ‘below-average’ glacial conditions lead to at best subtle geomorphological signatures (Evans, 2016). A combination of short periods of ice occupancy, thin and cold-based ice cover during early stages of recession can lead to little modification of the preglacial landscape. An obvious comparison with Lundy Island is that of the glaciation of Dartmoor, where Evans et al. (2012) have reconstructed a plateau icefield during MIS 2, based largely on the mapping of anomalous dry channels, supported by drift limits and subtle latero-frontal moraines. Evans (2016) highlights the critical importance of the identification of meltwater channels in these peripheral glacial contexts, as glacier ice always has to melt, and this will typically generate meltwater channel systems. However, as noted earlier, Evans et al. (2012) recognise that other mechanisms, particularly pneumatolytic rotting, will generate such features in granite terrains. Whilst a lack of detailed structural mapping of the Dartmoor Granite precludes evaluation the significance of pneumatolysis, a glaciologically-plausible combination of other geomorphological evidence interpreted by Evans et al. (2012) collectively fits a cold-based plateau icefield landsystem model for northern Dartmoor. In contrast, on Lundy Island, a detailed structural record of the Lundy Granite demonstrates the importance of pneumatolysis in generating channel features, and that the combination of other purported glacial and periglacial landforms presented by Rolfe et al. (2012) do not combine in a spatially or temporally coherent landsystem model.

The alternative model of Late Quaternary landscape evolution proposed in this study addresses the range of geomorphology found on Lundy Island, in terms of the close proximity of tors to granite domes and dry channels, and explains all the field observations reported by Mitchell (1968), Rolfe et al. (2012; 2014) and those reported in this study within a simple but spatially and temporally coherent model that does not result in contradictions between the individual lines of evidence, both on Lundy and more widely across the SW British Isles.

7: Conclusions

In conclusion, this study finds that:

- An evaluation of the geomorphological evidence previously reported by Mitchell (1968) and Rolfe et al., (2012; 2014) in support of Devensian glaciation of Lundy Island cannot be reconciled with any glaciologically-plausible or coherent glacial landsystems.

- Re-examination of the geomorphology of Lundy Island identifies a suite of related landforms that reflect a combination of sub-aerial processes of pneumatolysis, granite weathering and slope movement operating under cool-maritime temperate and periglacial conditions, with more recent impact of wildfires and human agency. Critically, this study finds no evidence for past glaciation, contrary to previous work.

- A revised model of Late Quaternary landscape evolution of Lundy Island dominated by granite weathering periodically enhanced by periglacial conditions offers a simple and realistic explanation of previously-published cosmogenic nuclide dates.

- This revised model removes the need to explain an additional MIS 3/4 glacial advance not recorded elsewhere in the south-western sector of the BIIS, and conforms to the established regional glacial stratigraphy of the Irish Sea Ice Stream, as well as previously-reported periglacial development of tors on nearby Dartmoor.

Finally, this paper demonstrates the critical importance of ensuring a sound and rigorous geomorphological foundation to provide a robust framework for studies exploring the extent, dynamics and timing of Late Quaternary glaciation. When such a foundation is missing, the effect on the integrity of geochronological and palaeo-environmental implications can be significant. Whilst geochronological methods remain an essential component of stratigraphic research, as demonstrated by BRITICE-CHRONO (Clark, 2014), without a robust geomorphological foundation it can result in outcomes that confuse, rather than resolve the already complex investigation of Quaternary landscape response to climate change.

Acknowledgements

The fieldwork for this study was supported by a Quaternary Research Fund from the QRA. The authors would like to thank Beccy MacDonald (Lundy Island Warden), Danny McCarroll and Emrys Phillips for useful discussions and access to obscure reports on Lundy, and Martha Carr for acting as field assistant for a short extra site visit during the writing of this paper. We would like to thank Stephen Livingstone for his very constructive review and comments, and Jon Lee for his editorial support, both of which improved the paper. The comments of an anonymous reviewer were considered but the authors decided not to act upon the suggestions because it would have compromised the scientific quality and integrity of this paper.

References

Arthur, M.J. (1989) The Cenozoic evolution of the Lundy pull-apart basin into the Lundy rhomb horst. *Geological Magazine* 126, 187-198.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J. 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10^{Be} and 26^{Al} measurements. *Quaternary Geochronology,* 3, 174 – 195.

Bazilevskaya, E., Lebedeva, M., Pavich, M., Rother, G., Parkinson, D.Y., Cole, D., Brantley, S. (2013) Where fast weathering creates thin regolith and slow weathering creates thick regolith. *Earth Surface Processes and Landforms* 38, 847-858

Benda, L., Hassan, M.A., Church, M., May, C.L. (2005). Geomorphology of steep land headwaters: the transition from hillslopes to channels. *Journal of the American Water Resources Association* 41, 835-851.

Böse, M., Lüthgens, C., Lee, J.R., Rose, J. (2012) Quaternary glaciations of northern Europe. *Quaternary Science Reviews* 44, 1-25.

Bowen, D.Q., Rose, J., McCabe, M.A., Sutherland, D.G., (1986). Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews* 5, 299-340.

Campbell, S., Hunt, C.O., Scourse, J.D., Keen, D.H., Stephens, N. (1998) *Quaternary of South-West England.* Geological Conservation Review Series 14, 439 pp.

Cardell, C., Rivas, T., Mosquera, M.J., Birginie, J.M., Moropoulou, A., Prieto, B., Silva, B., van Grieken, R. (2003) Patterns of damage in igenous and sedimentary rocks under conditions simulating sea-salt weathering. *Earth Surface Processes and Landforms* 28, 1-14.

Catt J.A., Gibbard, P.L., Lowe, J.J., McCarroll, D., Scourse, J.D., Walker, M.J.C., Wymer, J.J., (2006) Quaternary ice sheets and their legacy. In: Brenchley, P.J., Rawson, P.F. (eds.)*The Geology of England and Wales (2nd Edition)*. The Geological Society, London, 429-467.

Chiverrell, R.C., Thomas, G.S.P. (2010) Extent and timing of the Last Glacial Maximum (LGM) in Britain and Ireland: a review. *Journal of Quaternary Science*, 25, 535–549.

Clark, C.D. (2014) BRITICE - CHRONO; Constraining rates and style of marine-influenced ice sheet decay [online]. Available at: http://www.britice-chrono.org/introduction-from-the-pi/ (accessed 18/12/2014).

Clark, C.D., Evans, D.J.A., Khatwa, A., Bradwell, T., Jordan, C.J., Marsh, S.H., Mitchell, W.A., Bateman, M.D. (2004) Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas*, 33, 359–375.

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C., Sejrup, H-P. (2012) Pattern and timing of retreat of the last British-Irish ice sheet. *Quaternary Science Reviews* 44, 112-146.

Darmody, R.G., Thorn, C.E., Seppälä, M., Campbell, S.W., Li, Y.K., Harbor, J. (2008) Age and weathering status of granite tors in Arctic Finland (~68º N). *Geomorphology* 94, 10-23.

Deal, K. (2012) Fire effects on flaked stone, ground stone and other stone artefacts. *USDA Forest Service General Technical Report* RMRS-GTR-42, 3, 97-111.

Dollar. A.T.J. (1942) The Lundy Complex: its Petrology and Tectonics. *Quarterly Journal of the Geological Society of London* 132, 453-459.

Domínguez-Villar, D., Jennings, C.E. (2008) Multi-phase evolution of gnammas (weathering pits) in a Holocene deglacial granite landscape, Minnesota (USA). *Earth Surface Processes and Landforms* 33, 165-177.

Dorn, R.I. (2003) Boulder weathering and erosion associated with a wildfire, Sierra Ancha Mountains, Arizona. *Geomorphology* 55, 155-171.

Eden, M.J., Green, C.P. (1971). Some aspects of granite weathering and tor formation on Dartmoor, England. *Geografiska Annaler* 53 A, 92-99.

Edmonds, E.A., Williams, B.J., Taylor, R.T. (1979) *Geology of Bideford and Lundy Island*. Memoir of the Geological Survey of Great Britain, HMSO, London, 129 pp.

Evans, D.J.A. (2016) Landscapes at the Periphery of Glacierization - Retrospect and Prospect. *Scottish Geographical Journal* 132, 140-163.

Evans, D.J.A., Benn, D.I. (eds.) (2004) *A Practical Guide to the Study of Glacial Sediments*. Arnold, London, 266 pp.

Evans, D.J.A., Clark, C.D., Mitchell, W.A., (2005) The last British Ice Sheet: A review of the evidence utilised in the compilation of the Glacial Map of Britain. *Earth Science Reviews*, 70, 253–312.

Evans , D.J.A., Harrison, S., Vieli, A., Anderson, E. (2012) The glaciation of Dartmoor: the southernmost independent Pleistocene ice cap in the British Isles. *Quaternary Science Reviews* 45, 31-53

Fisher, P., Wood, J., Cheng, T. (2004) Where is Helvellyn? Fuzziness of multiscale landscape morphometry. *Transactions of the Institute of British Geographers* 29, 106-128.

Gardline Geosurvey Ltd. (2010) *Channel Energy Limited: Outer Bristol Channel, Atlantic Array Offshore Windfarm Geophysical Survey: Survey Report*. Gardline Project Reference 8324.1. Available at: http://www.marinedataexchange.co.uk. (accessed 06/06/2017)

Geo (2011) *Channel Energy Limited: Atlantic Array Offshore Wind Farm Geotechnical Investigations and Laboratory Tests Report 2– Laboratory Tests.* Geo Project 33837. Available at: http://www.marinedataexchange.co.uk. (accessed 06/06/2017)

Gibbard, P.L., Clark, C.D., (2011) Pleistocene glaciation limits in Great Britain. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), *Quaternary Glaciations - Extent and Chronology. A Closer Look*, (*Developments in Quaternary Science* 15) 75–92.

Gibbard, P.L., Hughes, P.D., Rolfe, C.J. (2017) New insights into the Quaternary evolution of the Bristol Channel, UK. *Journal of Quaternary Science* DOI: 10.1002/jqs.2951

Glasser, N.F., Bennett, M.R. (2004) Glacial erosional landforms: origins and significance for palaeoglaciology. *Progress in Physical Geography* 28, 43-75.

Gómez-Heras, M., Smith, B.J., Fort, R. (2006) Surface temperature differences between minerals in crystalling rocks: Implications for granular disintegration of granites through thermal fatigue. *Geomorphology* 78, 236-249.

Greenwood, S.L., Clark, C.D., Hughes, A.L.C. (2007) Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: application to the British Ice Sheet. *Journal of Quaternary Science* 22, 637-645.

Gunnell, Y., Jarman, D., Braucher, R., Calvet, M., Delmas, M., Leanni, L., Bourlès, D., Arnold, M., Aumaître, G., Keddaiuche, K., (2013). The granite tors of Dartmoor, Southwest England: rapid and recent emergence revealed by Late Pleistocene cosmogenic apparent ages. *Quaternary Science Reviews* 61, 62-76.

Hack, J.T., Goodlett, J.C., (1960). Geomorphology and forest ecology of a mountain region in the Central Appalachians. *USGS Professional Paper* 347, Virginia, 66 pp.

Hall, A.M., Phillips, W.M. (2006) Glacial modification of granite tors in the Cairngorms, Scotland. *Journal of Quaternary Science* 21, 811-830.

Harrison. S., Knight, J., Rowan, A.V. (2015) The southernmost Quaternary niche glacier system in Great Britain. *Journal of Quaternary Science* 30, 325-334.

Hiemstra, J. F., Evans, D.J.A., Scourse, J.D., McCarroll, D., Furze, M.F.A., Rhodes, E. (2006). New Evidence for a grounded Irish Sea glaciation of the Isles of Scilly, UK. *Quaternary Science Reviews*, 25, 299–309.

Jansson, K.N., Lidmar-Bergström K. (2004) Observations on weathering forms at the Caniapiscau Reservoir, North-Central Quebec, Canada. *The Canadian Geographer* 48, 1-10.

Johansson, M., Olvmo, M., Lidmar-Bergstrom, K. (2001) Inherited landforms and glacial impact of different palaeosurfaces in southwest Sweden. *Geografiska Annaler* 83A, 67-89.

Kennelly, P.J. (2008) Terrain maps displaying hill-shading with curvature. *Geomorphology* 102, 567-577.

Klemen, J., Hättestrand, C. (1999) Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum. *Nature*, 402, 63-66.

Knight, J. (2008) The environmental significance of ventifacts: A critical review. *Earth Science Reviews* 86, 89-105.

Kor, P.S.G., Shaw, J., Sharpe, D.R. (1991) Erosion of bedrock by subglacial water, Georgian Bay, Ontario: a regional review. *Canadian Journal of Earth Science* 28, 623-642.

Krabbendam, M., Bradwell, T. (2014) Quaternary evolution of glaciated gneiss terrains: pre-glacial weathering vs. glacial erosion. *Quaternary Science Reviews* 95, 20-42.

Langham, A.F. (1992) The Lundy fires of 1933. *Annual Report of the Lundy Field Society* 42, 99-100.

Laverdiere, C., Guimont, P., Pharand, M. (1979) Marks and forms on glacier beds: formation and classification. *Journal of Glaciology* 23, 414-416.

Lindström, E. (1988) Are roche moutonées mainly preglacial forms? *Geografiska Annaler* 70, 323-331.

Mackie, A.S.Y., James, J.W.C., Rees, E.I.S., Darbyshire, T., Philpott, S.L., Mortimer, K., Jenkins, G.O., Morando, A. (2006) *The Outer Bristol Channel Marine Habitat Study. — Studies in Marine Biodiversity and Systematics from the National Museum of Wales*. BIOMÔR Reports 4: 249 pp. & Appendix 228 pp.

Matthews, J.A., Owen, G. (2011) Holocene chemical weathering, surface lowering and rock weakening rates on glacially eroded bedrock surfaces in an alpine periglacial environment, Jotunheimen, southern Norway. *Permafrost and Periglacial Processes* 22, 279-290.

McCabe, S., Smith, B.J., Warke, P.A. (2007) Sandstone response to salt weathering following simulated fire damage: a comparison of the effects of furnace heating and fire. *Earth Surface Processes and Landforms* 32, 1874-1833.

McCaffrey, R., Stewart, S., Dalzell, P., McCaffrey, L., McElroy, J. (1993). A reconnaissance magnetic survey of the Lundy Tertiary igneous complex, Bristol Channel. *Proceedings of the Ussher Society* 8, 193-197.

McCarroll, D., Stone, J.O., Ballantyne, C.K., Scourse, J.D., Fifield, L.K., Evans, D.J.A., Hiemstra, J.F. (2010) Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream. *Quaternary Science Reviews* 29, 1844-1852.

Migoń, P., Dach, W. (1995) Rillenkarren on granite outcrops, SW Poland, Age and Significance. *Geografiska Annaler* 77A, 1-9.

Mitchell, G.F. (1968) Glacial gravel on Lundy Island. *Transactions of the Royal Geological Society of Cornwall* 20, 65-68.

Ó'Cofaigh, C., Evans, D.J.A. (2001) Deforming bed conditions associated with a major ice stream of the last British ice sheet. *Geology* 29, 795-798.

Olvmo, M., Johansson, M (2002) The significance of rock structure, lithology and pre-glacial deep weathering for the shape of intermediate-scale glacial erosional landforms. *Earth Surface Processes and Landforms* 27, 251-268.

Owen, G., Matthews, J.A., Shakesby, R.A. (2006) Rapid Holocene chemical weathering on a calcitic lake shoreline in an alpine periglacial environment: Attgloyma, Sognefjell, southern Norway. *Permafrost and Periglacial Processes* 17, 3-12.

Patterson, C.J., Boerboom, T.J. (1999) The significance of pre-existing, deeply weathered crystalline rock in interpreting the effects of glaciation in the Minnesota River valley, USA. *Annals of Glaciology* 28, 53-58.

Roberts, C.L. (1992) Magnetic considerations of the volcanic dykes of Lundy Island. *Annual Report of the Lundy Field Society* 42, 34-41.

Roberts, C.L., Smith, S.G. (1994) A new magnetic survey of Lundy Island, Bristol Channel. *Proceedings of the Ussher Society* 8, 283-297.

Rodbell, D.T. (1993) Subdivision of late Pleistocene moraines in the Cordillera Blanca, Peru, based on rock weathering features, soils, and radiocarbon dates. *Quaternary Research* 39, 133-143.

Rodbell, D.T., Frey, H.M., Manon, M.R.F., Smith, J.A., McTurk, N.A. (2012) Development of unusual rock weathering features in the Cordillera Blanca, Peru. *Quaternary Research* 77, 149-158.

Rolfe, C. J., Hughes, P.D., Fenton, C.R., Schnabel, C., Xu, S., Brown, A.G. (2012). Paired ^{26}Al and ^{10}Be exposure ages from Lundy: new evidence for the extent and timing of Devensian glaciation in the southern British Isles. *Quaternary Science Reviews*, 43, 61–73.

Rolfe, C.J., Hughes, P.D., Brown, A.G. (2014) Timing of maximum extend of late Pleistocene glaciation in N.W. Europe: evidence from Lundy. *Journal of the Lundy Field Society* 4, 7-18.

Ryan, R.J., O'Beirne-Ryan, Zentilli, M., (2005) Rounded cobbles that have not travelled far: incorporation of corestones from saprolites in the South Mountain area of southern Nova Scotia, Canada. *Sedimentology* 52, 1109-1121.

Scourse, J.D. (1991) Late Pleistocene stratigraphy and palaeobotany of the Isles of Scilly. *Philosophical Transactions of the Royal Society of London* B334, 405-448.

Scourse, J.D., Furze, M.F.A. (2001) A critical review of the glaciomarine model for Irish Sea deglaciation: evidence from Southern Britain, the Celtic Shelf and adjacent continental slope. *Journal of Quataernary Science* 16, 419-434.

Shakesby, R.A., Doer, S.H. (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* 74, 269-307.

Smedley, R.K., Scourse, J.D., Small, D., Hiemstra, J.F. Duller, G.A.T. Bateman, M. D., Burke M. J. Chiverrell, R. C.; Clark C. D., Davies S. M., Fabel, D., Gheorghiu D. M.; McCarroll, D., Medialdea, A., Xu., S. (2017) New age constraints for the limit of the British-Irish Ice Sheet on the Isles of Scilly. *Journal of Quaternary Science* 32, 48 - 62.

Smith, S.G., Roberts, C.L. (1997) The Geology of Lundy. In: Irving, R.A., Schofield, A.J., Webster, C.J. (eds) *Island Studies*. Lundy Field Society, Bideford 59-66.

Stephens, N. (1965) Some Pleistocene deposits in North Devon. *Biuletyn Peryglacjalny* 8, 103-114.

Tappin, D.R., Chadwick, R.A., Jackson, A.A., Wingfield, R.T.R., Smith, N.J.P. (1994) *United Kingdom offshore regional report: the geology of Cardigan Bay and the Bristol Channel*. HMSO for the British Geological Survey, London. 107 pp.

Taylor, C.G. (1974) Some Notes on the Pleistocene Geomorphology of Lundy. *Lundy Field Society, 25th Annual Report*, 65-68.

Thorpe, R.S., Tindle, A.G., Gledhill, A. (1990) The petrology and origin of the Tertiary Lundy granite (Bristol Channel, UK). *Journal of Petrology* 31, 1379-1406.

Tindle, A.G., Thorpe, R.S. (1992) Lundy - Site of a Tertiary Volcano? *Annual Report of the Lundy Field Society* 42, 27-33.

Twidale, C.R., Romaní, J.R.V. (2005) *Landforms and Geology of Granite Terrains*. Taylor and Francis, Abingdon, 354pp.

Waters, R.S. (1964). The Pleistocene legacy to the geomorphology of Dartmoor. In Simmons, I.G. (ed.) *Dartmoor Essays*. Devonshire Association, 73-96.

Walker, M.J.C., McCarroll, D. (2001) *The Quaternary of West Wales: Field Guide*. Quaternary Research Association, London, 184 pp.

Wilkins, P., Debham, J.R. (1973) Some preliminary observations on the re-colonisation of the North End of Lundy. *Annual Report of the Lundy Field Society* 24, 42-50.

Williams, R.B.G., Robinson, D.A. (1994) Weathering flutes on siliceous rocks in Britain and Europe. In Robinson, D.A., Williams, R.B.G. (eds.) *Rock weathering and landform evolution*. Wiley, Chichester, 413-432.

Wood, J. (2009) *Landserf [online]*. Available at www.landserf.org (accessed 19/12/2014)

Figure Captions

Figure 1: Location and context of Lundy Island, with respect to suggested Last Glacial Maximum and maximum Pleistocene ice sheet limits (Bowen et al., 1986; McCarroll et al., 2010; Gibbard and Clark, 2011). The additional extent of glaciation thought to have inundated Lundy Island immediately prior to the LGM suggested by Rolfe et al. (2014) is also illustrated. Locations of sites previously suggested to preserve evidence of Pleistocene glaciation that may be related to Lundy Island are also noted, as are borehole locations thought to contain glacigenic sediments.

Figure 2: Maps of Lundy Island, showing key features. **a:** Geography of Lundy Island: the island comprises a relatively flat plateau surface fringed with coastal cliffs. The island is divided into four zones by three prominent stone walls. Locations of diamictons identified by Rolfe et al. (2012) are noted. **b:** Bedrock geology and structure, compiled from sources noted in the text. The majority of Lundy Isle comprises one or more facies of Tertiary Lundy Granite, intruded through Devonian and Carboniferous slates and shales. Contact metamorphism is well developed in the south-east corner of the island. There is widespread subsequent Intrusion of dykes into pre-existing fractures within both the granite and shales/slates comprising chemically distinctive veins of mainly dolerite, trachyte and rhyolite (Compiled from Dollar, 1941; Edmonds et al., 1979; Thorpe et al., 1990; Tindle and Thorpe, 1992; Smith and Roberts, 1997).

Figure 3: 1m resolution Digital Surface Model of Lundy Island, with illumination from 035º. The main DSM demonstrates that there is no consistent WNW - ESE 'grain' to the surface geomorphology of the island. © Environment Agency copyright and/or database right 2014. All rights reserved. Inset **a:** Detail of Gannets' Combe. **b:** Detail of 'box-grid' pattern of granite domes and 'whalebacks' on western side of the island defined by veins, dykes and fractures. **c:** Detail of the change in surface topography at the boundary between granitic and non-granitic terrains.

Figure 4: **a:** Structural analysis of minor veins and dykes on Lundy Island, superimposed over the larger scale structures previously mapped (see

references in main text). Main modes of orientation of veins and dykes intruded through domed bedrock surfaces (black arrows) and smaller scale fissures and joints found within in the granite (red arrows) are indicated. Identified modes tend to be parallel to mapped dykes, or bisect the dykes at right angles. **b:** Rose diagrams compiling orientations of all measured fissures and joints (top) and dykes and veins (bottom).

Figure 5: Granite domes and related surface features on Lundy Island. a: low-angle bornhardt at SS 1313/4769, sampled by Rolfe et al. (2014) for cosmogenic isotope age estimation (LC4b). Note that although broadly whaleback in form, elsewhere the rock surface uneven and irregular. Also note the granular weathering residuals and shallow gnammas in the foreground. b: Small granite dome adjacent to Quarter Wall at SS 1311/4506, oriented N-S. Also note the other similarly-oriented whaleback features in the background. c: Small granite dome, with an apparent ‘roche-moutonnée’ morphology, with the lee-side face oriented towards the NW. d: Low-relief bornhardt at SS 1313/4703, corresponding to sampling point LC1a of Rolfe et al. (2014). The joint structure of the granite suggests a WNW-ESE orientation (as noted by Rolfe et al., 2014), but the exposed dome is almost circular in plan-form, with no directional streamlining, and the granite surface is pitted and heavily weathered, showing no evidence of abrasion or bevelling of joint faces. e: Small weathering pit, or gnamma, located at SS 1372/4582, close to Halfway Wall. Note the granular quartz weathering residuals within the gnamma. f: Weathering post on apparently ‘streamlined’ granite domes at the head of Gannets’ Combe. This delicate weathering pinnacle points towards the WNW. g: Weathering posts on the ‘streamlined’ granite domes at the head of Gannets’ Combe.

Figure 6: Selected 'groove' features on Lundy Island. a: b: Network of Type 1 ‘grooves’ that cross-cut and bisect one another in a variety of orientations at SS 1313/4764, and are clearly joints within the bedrock rather than glacial erosional features. b: Type 1 linear groove at SS 1328/4744 on otherwise weathered granite. The inset shows a sharp, linear fracture within the granite that demonstrates this feature is a weathering product rather than representing linear abrasion. c: Type 1 linear groove bisected and dislocated by a small pegmatite dyke at SS 1322/493, in the vicinity of sample location LC3b of Rolfe et al. (2014). f: Type 2 linear groove, associated with a bedrock dome and granite pedestal at SS 1322/4793, in the vicinity of sample point LC3b of Rolfe et al.,

(2014). The overall large-scale structure at this site is a dyke oriented WNW-ESE, with the linear depression conditioned by the location of an upstanding pegmatite dyke. The dyke begins beneath the 'lee' of the granite pedestal, which is interpreted as a corestone developing into a perched boulder. Note that the rock surface within the groove is rougher than the surrounding flatter bedrock surfaces.

Figure 7: View northwards to North End of Lundy Island, illustrating the 'denuded' surface of the island, apparently associated with higher frequency of granite domes.

Figure 8: Identification and mapping of distinctive surface channel features. a: Fuzzy analysis to identify the location and geometry of channel systems extending beyond the coastal fringe and onto the plateau surface of Lundy. b: Location and geometry of channel networks incised >2 m (solid lines, numbers refer to channels plotted in Figure 10) or >1 m (dashed lines) into the plateau surface of Lundy Island, extracted from analysis of curvature and fuzzy analysis.

Figure 9: Dry channels on Lundy Island a: Image of a typical channel (Channel 3 on Figure 8b), Gannets' Combe, demonstrating a distinctive cross profile of steep channel sides and a relatively flat channel floor. The channel floors tend to be very irregular, with the vegetation covering a very bouldery channel bed. Note that there is no morphostratigraphic cross-cutting relationship between the 'streamlined' bedrock and the channel edges, implying contemporaneous modification of rock surfaces. b: Small, steep-sided channel with a flat, irregular bed, controlled by the presence of a vein (arrowed), suggesting pneumatolysis resulting in enhanced erosion into the edge of Channel 3, indicating that channel formation is an ongoing process. c: Shallow swale with evidence of recent movement of the thin regolith downslope over the granite surface, at the head of channel 4, Gannets' Combe.

Figure 10: Long profiles of channels >2 m deep identified in Figure 8b. Note that all channels have a convex long profile with no reverse slopes.

Figure 11: Tors on Lundy Island. a: Pinnacle >3 m height on the eastern coastal fringe of Lundy, at SS 1380/4580. Note the deep edge pits, open block structure and delicate superstructure of the tor that indicates no glacial modification. b: Complex of delicate tor pinnacles at The Cheeses (SS 1328/4561), with some evidence of toppled blocks and local transport downslope. Again, there is no evidence to suggest any modification of the original tor form. c: Rare example of

a toppled tor on West coast with eastward toppling of blocks; however, the structure and close associations of the individual (unmodified) tor pinnacles account for the apparent eastwards transport of the blocks, which can all be explained by gravitational movement rather than removal and transport by ice. d: Toppled tors on Northeast coast: in this case the blocks have been transported eastwards due to gravitational movement and are sitting on, or are embedded within a slope debris mantle.

Figure 12: Photos of sites suggested to have a sediment cover. a: Location of reported diamictons at Pondsbury reported by Rolfe et al. (2014). A very thin regolith directly overlies granite bedrock in this area. Also note the perched boulder in the background of the image. b: Small section of massive diamicton overlain by a stratified diamicton near Quarter Wall at SS 1380/4510. c: Sediment drape on West coast at Jenny's Cove. d: Stratified diamicton (Dcs) comprising angular and very angular clasts derived as gelifracted shales and slates within Millcombe at SS 1396/4398.

Figure 13: 'Erratic' gravel spread at the head of Gannets' Combe and North End of Lundy Island. a: Overall view (looking North from SS1312/4750), showing a sporadic scatter of pebble and cobble-sized clasts, dominated by granite. Field notebook is 190 mm in length. b: Cobbles and pebbles being weathered out of a small dyke of rhyolite (arrowed), the shapes and forms of these emergent clasts is identical to that of the broader gravel spread noted across the area, suggesting a common origin. c: Granite and rhyolite clasts weathering out of the rock surface, with a range of morphologies.

Figure 14: Ventifacts on Lundy Island. a: Example of apparently faceted, prism-shaped clasts at the head of Gannets' Combe suggested by Rolfe et al. (2014) to be ventifacts. Note the lack of clear facets divided by sharp keels. b: Distinctive chevron joint sets found close to location of 'ventifacts' identified in (a): the distinctive form of clasts is clearly inherited from pre-existing joint patterns c; For comparison, a 'true' ventifact recovered from Veluwe, the Netherlands.

Figure 15: Perched, isolated boulders on Lundy Island. a: Perched boulder surrounded by regolith and grus, south of Old Lighthouse on Ackland's Moor. b: Perched boulder near Northeast Point with distinctive linear fluting/rillenkarren features indicative of weathering. c: Clearly in situ perched granite blocks, preserved as residuals of weathering of the joint surfaces in the underlying granite. d: Granite

corestone weathering from surrounding grus, just south of The Cheeses, on the west coast of Lundy.

Table 1: Clast lithological analysis of Sample A (n = 25) collected in the 'gravel spread' at the head of Gannets' Combe. Sampling focused only on clasts that were not obviously of Lundy Granite (estimated <5% of clasts visible on bedrock surface).

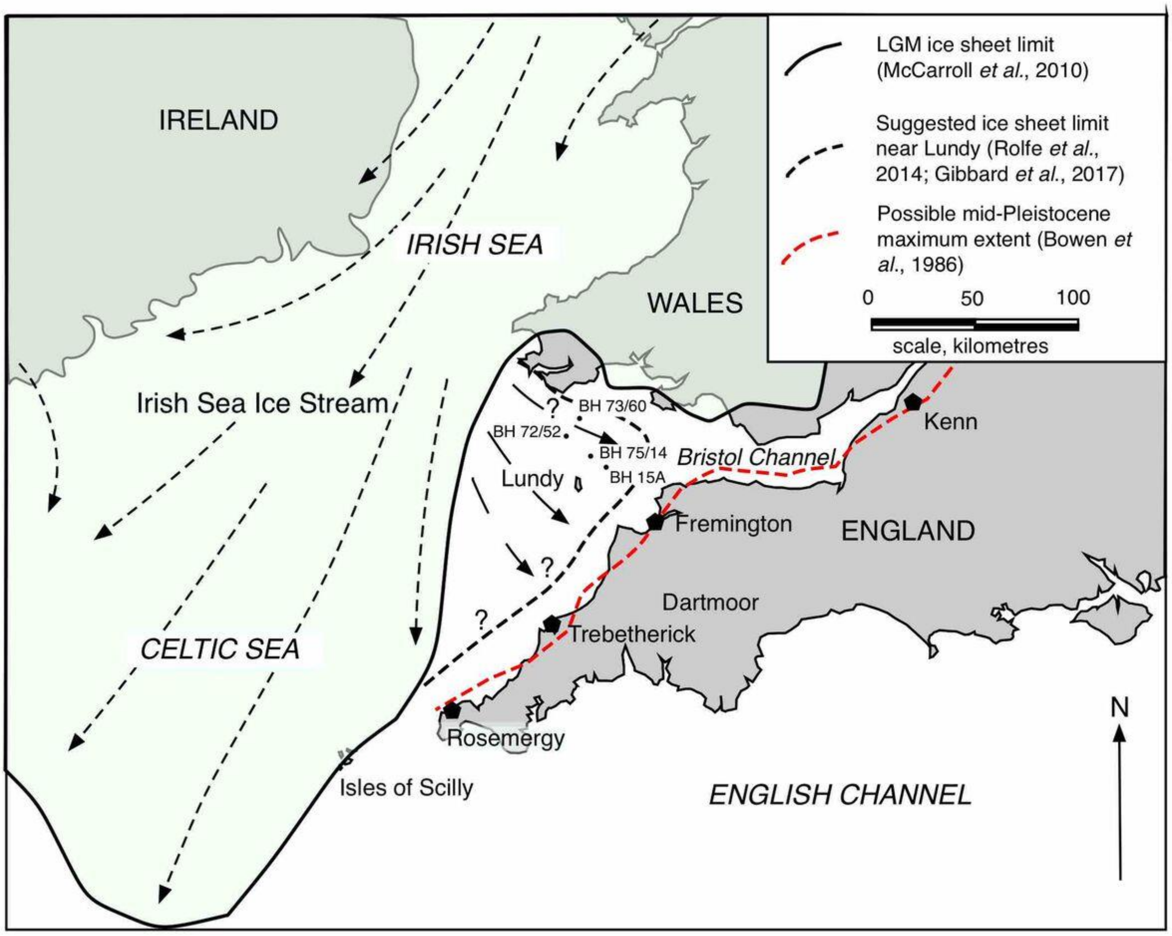
Sample	Lithology	Origin	Notes
a	Feldspar crystal	Local	from Lundy granite
b	Granite	Local	mostly algae-covered
c	Dolerite	Local	
d	Feldspar crystal	Local	from Lundy granite
e	Quartz (glassy)	Local	from Lundy granite
f	Dolerite (weathered)	Local	White surface is a weathering rind
g	Granite (fine grained)	Local	
h	Granite	Local	
i	Granite	Local	granular
j	Quartz	Local	from Lundy granite or Morte Slates
k	Quartz (glassy)	Local	from Lundy granite (Feldspar fragment attached)
l	Granite	Local	granular
m	Granite	Local	granular
n	Granite	Local	granular
o	Quartz (vein)	Local	
p	Granite	Local	granular, with euhedral phenocrysts
q	Dolerite	Local	weathered surface of clast
r	Granite	Local	
s	Granite	Local	
t	Unknown	Unknown	very small (<8mm) clast, possibly a weathering rind
u	Granite	Local	
v	Granite	Local	
w	Dolerite	Local	weathered surface of clast
x	Dolerite	Local	weathered surface of clast
y	Dolerite	Local	weathered surface of clast
z	Pyritiferous slate	Local	Morte slate.

Table 2: Clast lithological analysis of Sample B, (n = 24) collected from the main track on Lundy at SS 1369/4621. Sampling focused only on clasts that were not obviously of Lundy Granite (estimated ~10% of clasts visible on road surface).

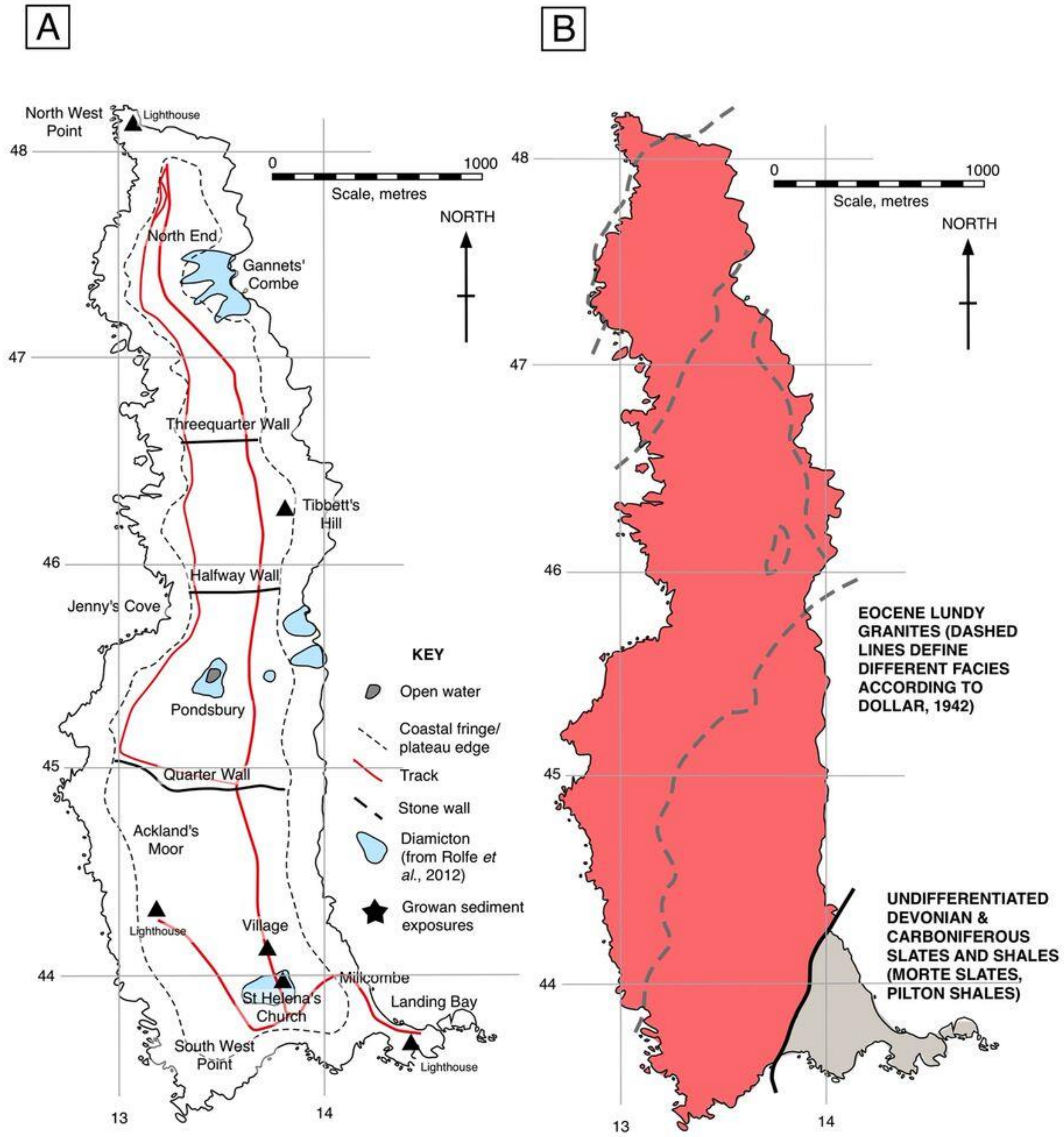
Sample	Lithology	Origin	Notes
a	Grey slate	Local	Morte Slate
b	Granite	Local	fine grained: Lundy Granite
c	Quartz	Local	derived from Lundy Granite
d	Granite	Local	Lundy Granite
e	Grey slate	Local	Morte Slate
f	Granite	Local	Lundy Granite
g	Granite	Local	Lundy Granite
h	Granite	Local	Lundy Granite
i	Grey slate	Local	Morte Slate
j	Grey slate	Local	Morte Slate
k	Grey slate	Local	Morte Slate
l	Calcareous sandstone	Anthropogenic	Concrete made from local materials (rounded quartz grains, angular slate grains, calcareous cement)
m	Grey slate	Local	Morte Slate
n	Grey sandstone	Local	Morte Slate
o	Trachytic dyke	Local	Dark, fine-grained siliceous rock. Surface looks similar to flint/chert, but does not show conchoidal fractures.
p	Grey slate	Local	Morte Slate
q	Grey slate	Local	Morte Slate
r	Granite	Local	Lundy Granite
s	Grey slate	Local	Morte Slate
t	Quartz	Local	Derived from Lundy Granite
u	Quartz	Local	Derived from Lundy Granite
v	Fine grained sandstone	Local	Morte Slate
w	Grey slate	Local	Morte Slate
x	Granite	Local	Lundy Granite
y	Grey slate	Local	Morte Slate

Table 3: Summary of geomorphological evidence and interpretations

Feature	Interpretation from Rolfe et al. (2012; 2014)	Interpretation from this study
Streamlined granite domes	Subglacial whaleback bedforms of thick, abrasive ice flowing WNW-ESE prior to 35-40ka BP	Granite weathering domes/bornhardts. Sub-aerial weathering continuing to the present day.
Grooves and other surface features	Subglacial lineations (grooves/ p-forms?) associated with whaleback formation.	Granite weathering structures: gnammas, lapies, rillenkarren, posts. Sub-aerial weathering continuing to the present day.
Erratic gravels at the head of Gannets' Combe	Glacifluvial outwash spread associated with production of dry channels. Sub-marginal ice sheet position, with high pore-water pressures and ample sediment load. Age of glaciation unspecified, but channels are associated with whaleback forms, therefore implied to be prior to 35-40ka BP.	Mostly local material. Rare non-local clasts derived from scattering of track-building materials collected from Landing Beach.
Perched granite boulders	Glacially-transported boulders (age of glaciation not specified)	Corestones (granite weathering residual). 2-stage weathering of granite continuing to the present day.
Dry channels	Subglacial meltwater channels. Assumed age of glaciation prior to 35-40ka BP.	Modern ephemeral headwater drainage channels: structural control over form and geometry.
Tors (including toppled tors)	Periglacial features generated during a cold-phase between two glacial episodes. Modification and toppling caused by subsquent cold-based ice (LGM?)	Periglacial features with no evidence of glacial modification. Toppling associated with local slope conditions.
Faceted clasts	Ventifacts / Dreikanters formed during cold, ice-free conditions. Not modified or transported during subsequent LGM glaciation	Weathered clasts from dykes, notably in vicinity of bedrock with distinctive chevron joint patterns.
Diamictons	Ice dammed lake (St. Helena's Church); no interpretations offered for other sites.	None found in mapped locations (St. Helena's Church not investigated)
Other diamictons (angular, coarse grained)	Breccia, colluvium	~1m thickness of weathered granite (grus), gelifractate and associated local down-slope transport.

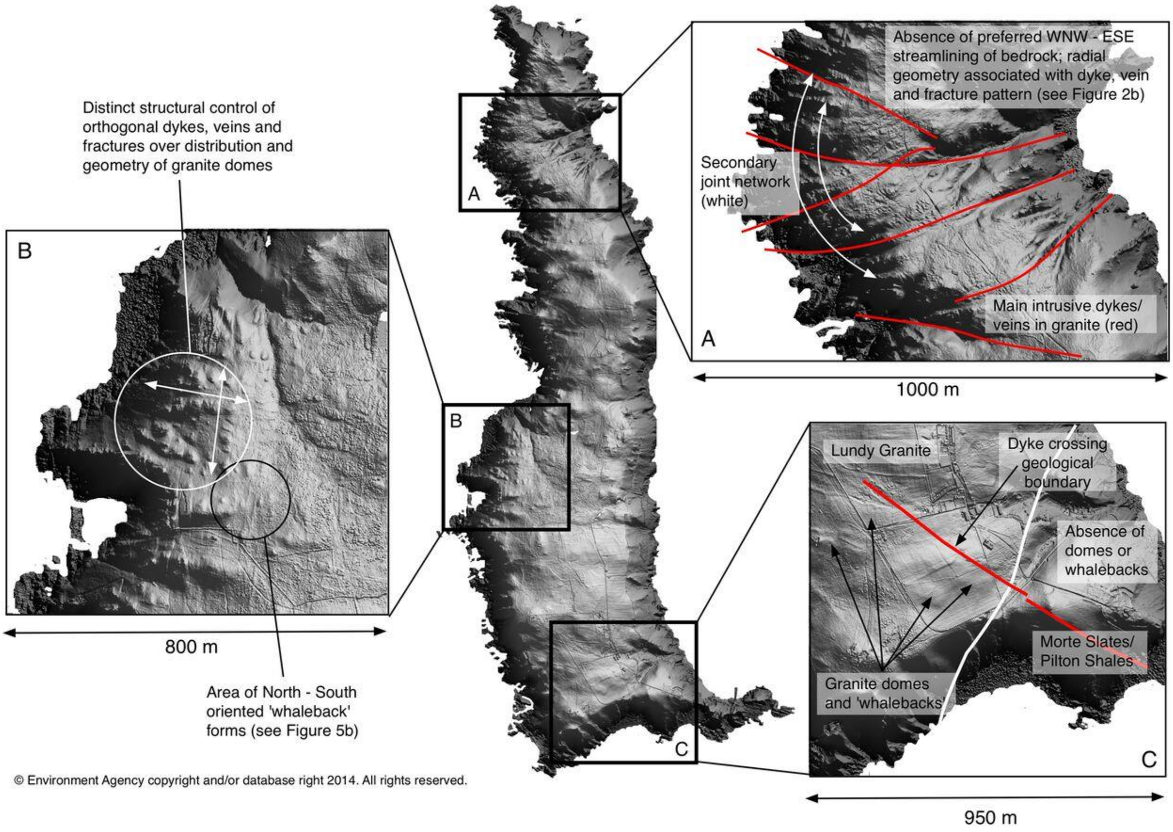

LGM ice sheet limit (McCarroll et al., 2010)
Suggested ice sheet limit near Lundy (Rolfe et al., 2014; Gibbard et al., 2017)
Possible mid-Pleistocene maximum extent (Bowen et al., 1986)
0 50 100
scale, kilometres
IRELAND
IRISH SEA
WALES
Irish Sea Ice Stream
BH 73/60
BH 72/52
BH 75/14
BH 15A
Bristol Channel
Kenn
Lundy
Fremington
ENGLAND
Dartmoor
Trebetherick
CELTIC SEA
Rosemergy
Isles of Scilly
ENGLISH CHANNEL
N

1



A
B
North West Point
Lighthouse
0
1000
Scale, metres
NORTH
North End
Gannets' Combe
Threequarter Wall
Tibbett's Hill
Halfway Wall
Jenny's Cove
Pondsbury
Quarter Wall
Ackland's Moor
Lighthouse
Village
St Helena's Church
Millcombe
Landing Bay
South West Point
Lighthouse
KEY
Open water
Coastal fringe/ plateau edge
Track
Stone wall
Diamicton (from Rolfe et al., 2012)
Growan sediment exposures
48
47
46
45
44
13
14
EOCENE LUNDY GRANITES (DASHED LINES DEFINE DIFFERENT FACIES ACCORDING TO DOLLAR, 1942)
UNDIFFERENTIATED DEVONIAN & CARBONIFEROUS SLATES AND SHALES (MORTE SLATES, PILTON SHALES)

Figure 2



Distinct structural control of orthogonal dykes, veins and fractures over distribution and geometry of granite domes
B
800 m
Area of North - South oriented 'whaleback' forms (see Figure 5b)
© Environment Agency copyright and/or database right 2014. All rights reserved.
A
B
C
Absence of preferred WNW - ESE streamlining of bedrock; radial geometry associated with dyke, vein and fracture pattern (see Figure 2b)
Secondary joint network (white)
Main intrusive dykes/ veins in granite (red)
A
1000 m
Lundy Granite
Dyke crossing geological boundary
Absence of domes or whalebacks
Morte Slates/ Pilton Shales
Granite domes and 'whalebacks'
C
950 m

3

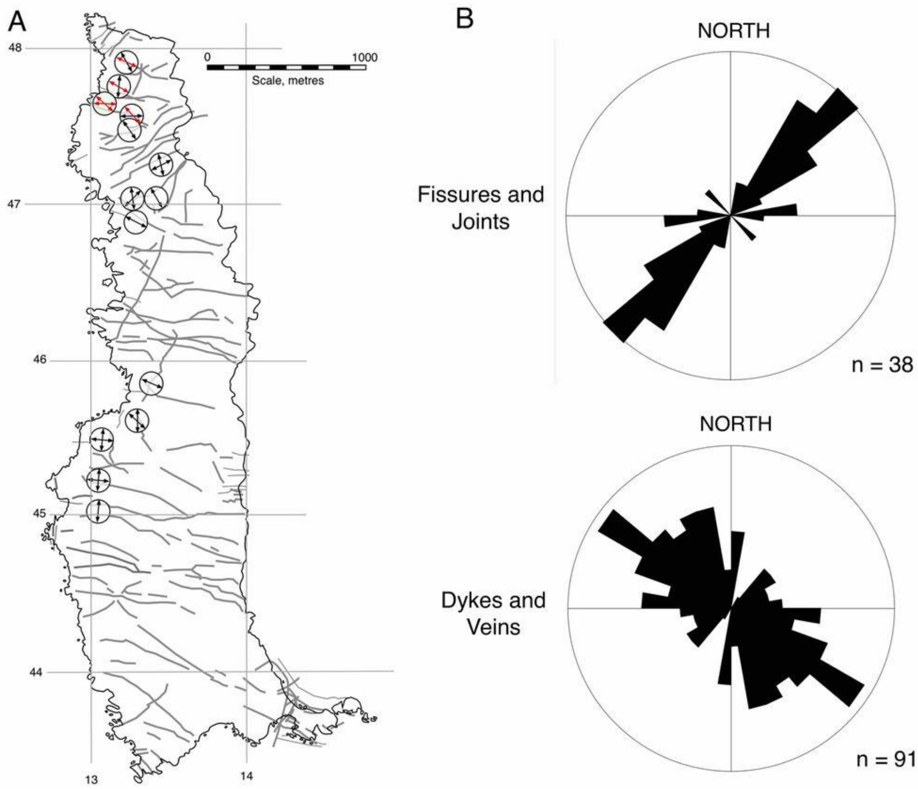

A
B
48
47
46
45
44
13
14
0
1000
Scale, metres
NORTH
Fissures and Joints
n = 38
NORTH
Dykes and Veins
n = 91

Figure 4

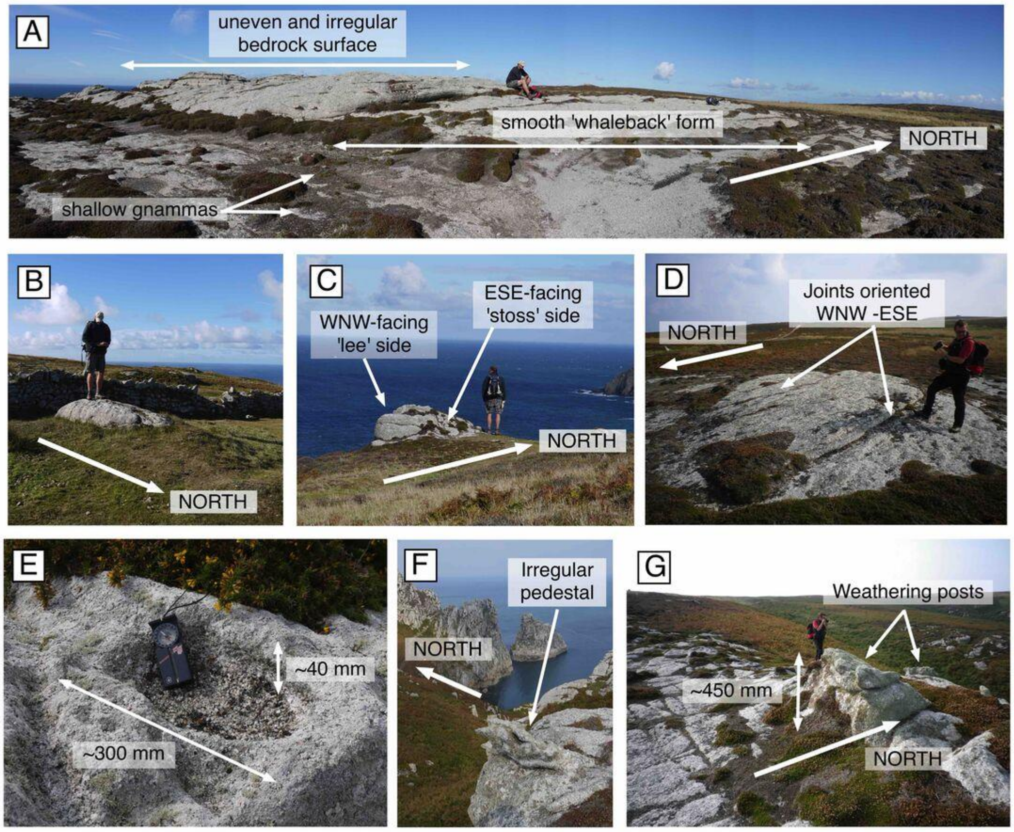
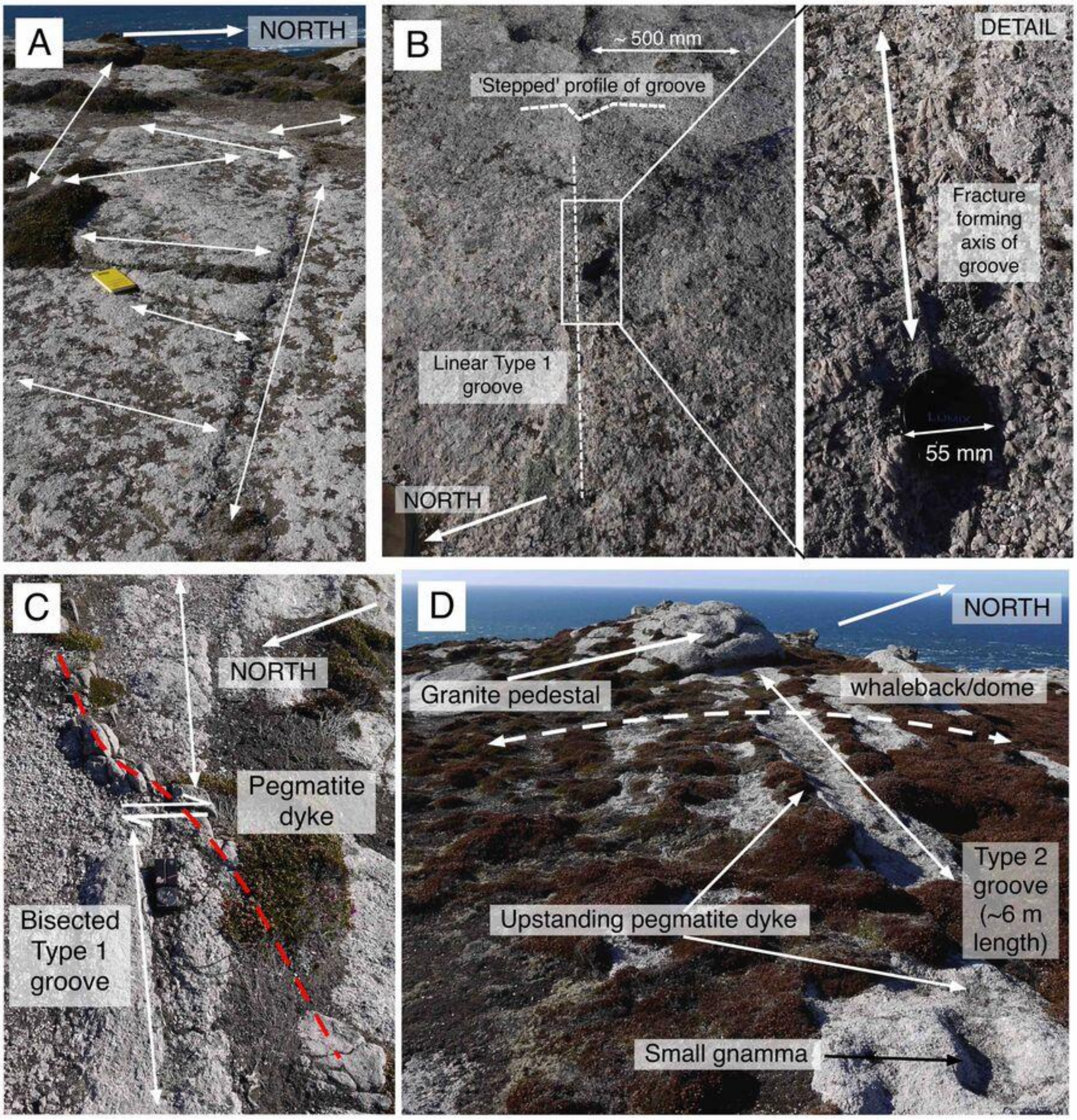
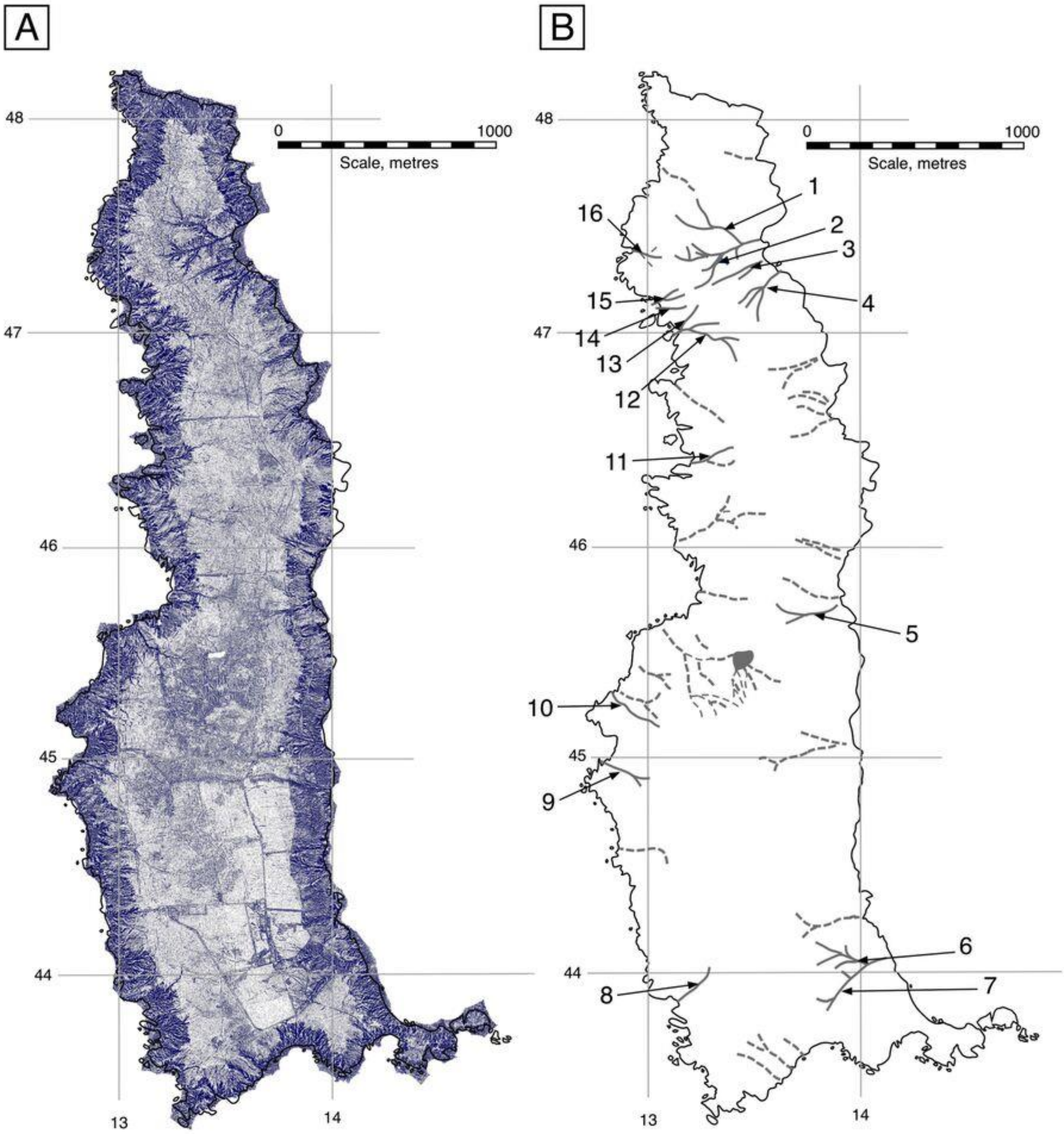

A
uneven and irregular bedrock surface
smooth 'whaleback' form
NORTH
shallow gnammas
B
NORTH
C
WNW-facing 'lee' side
ESE-facing 'stoss' side
NORTH
D
NORTH
Joints oriented WNW -ESE
E
~40 mm
~300 mm
F
Irregular pedestal
NORTH
G
Weathering posts
~450 mm
NORTH

Figure 5



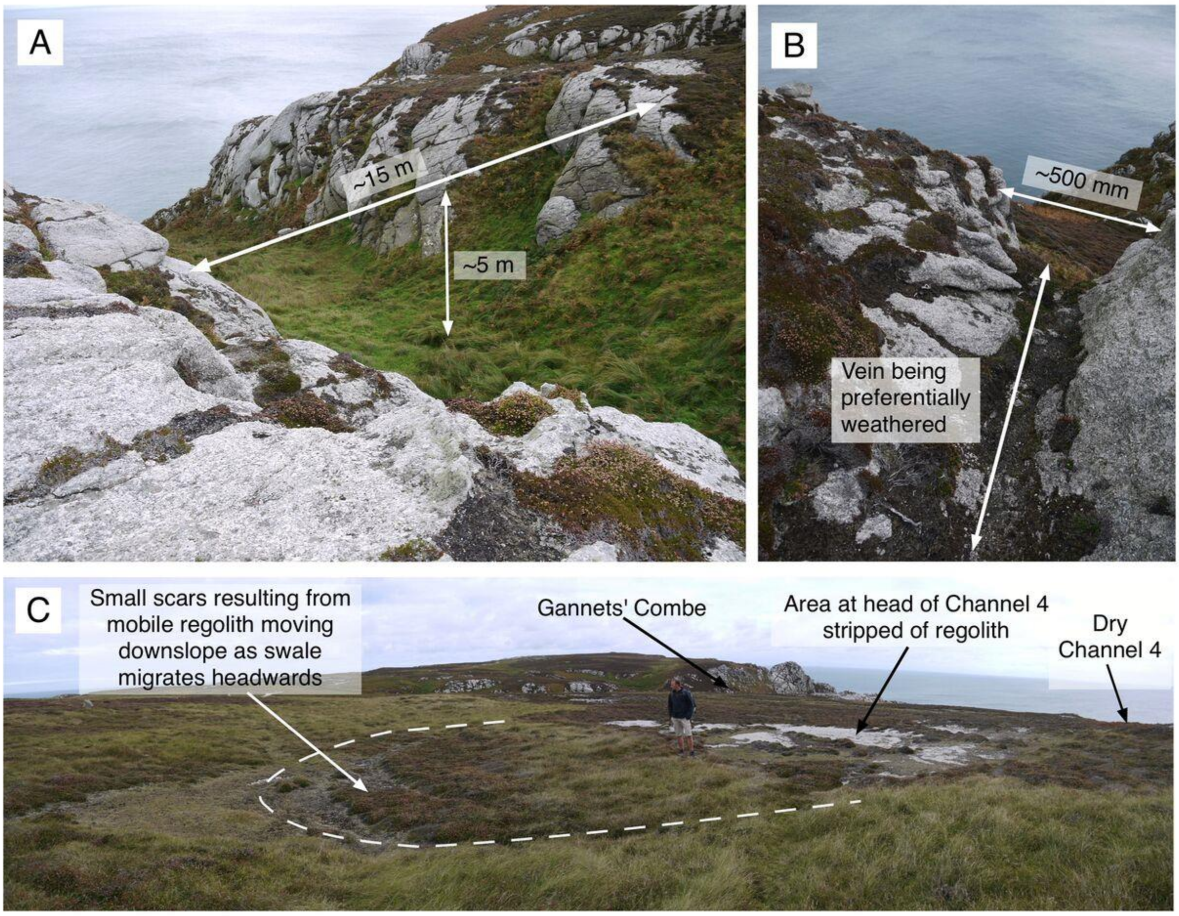
A
NORTH
B
~ 500 mm
'Stepped' profile of groove
Linear Type 1 groove
NORTH
DETAIL
Fracture forming axis of groove
55 mm
C
NORTH
Pegmatite dyke
Bisected Type 1 groove
D
NORTH
Granite pedestal
whaleback/dome
Type 2 groove (~6 m length)
Upstanding pegmatite dyke
Small gnamma


7

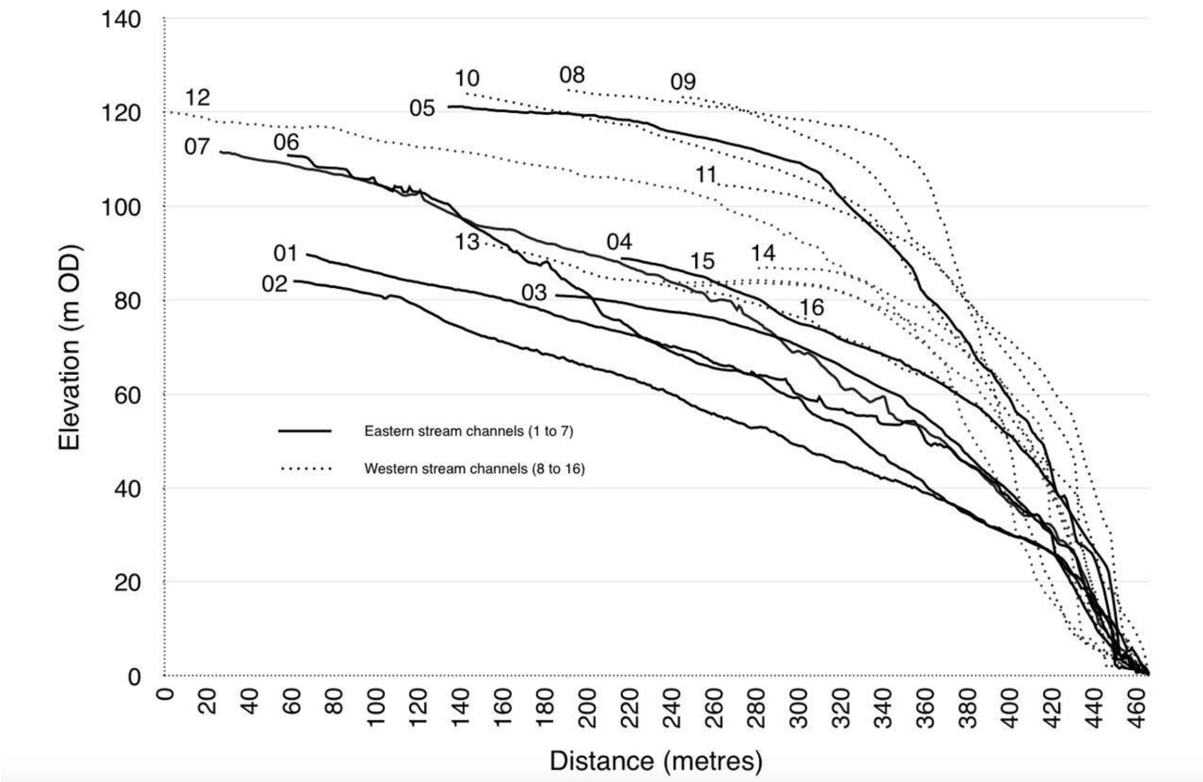


A
B
48
47
46
45
44
13
14
0
1000
Scale, metres
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Figure 8


A
~15 m
~5 m
B
~500 mm
Vein being preferentially weathered
C
Small scars resulting from mobile regolith moving downslope as swale migrates headwards
Gannets' Combe
Area at head of Channel 4 stripped of regolith
Dry Channel 4

9


Elevation (m OD)
Distance (metres)
Eastern stream channels (1 to 7)
Western stream channels (8 to 16)
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
10

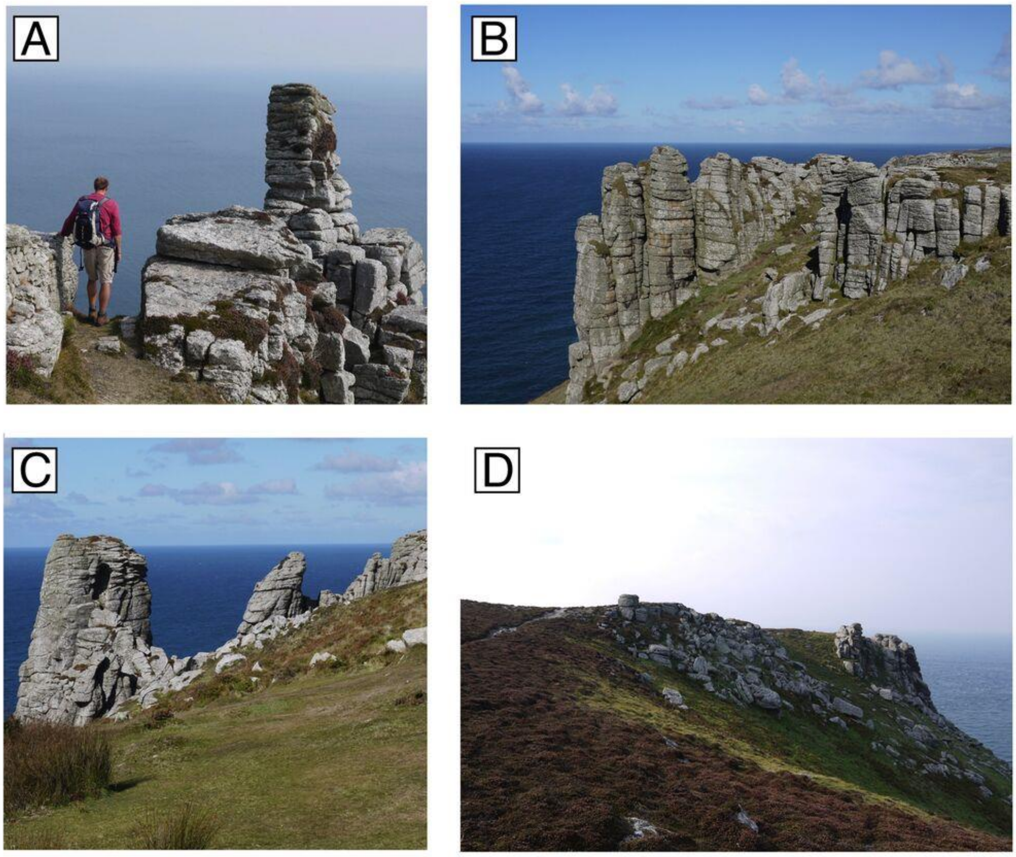


Figure 11

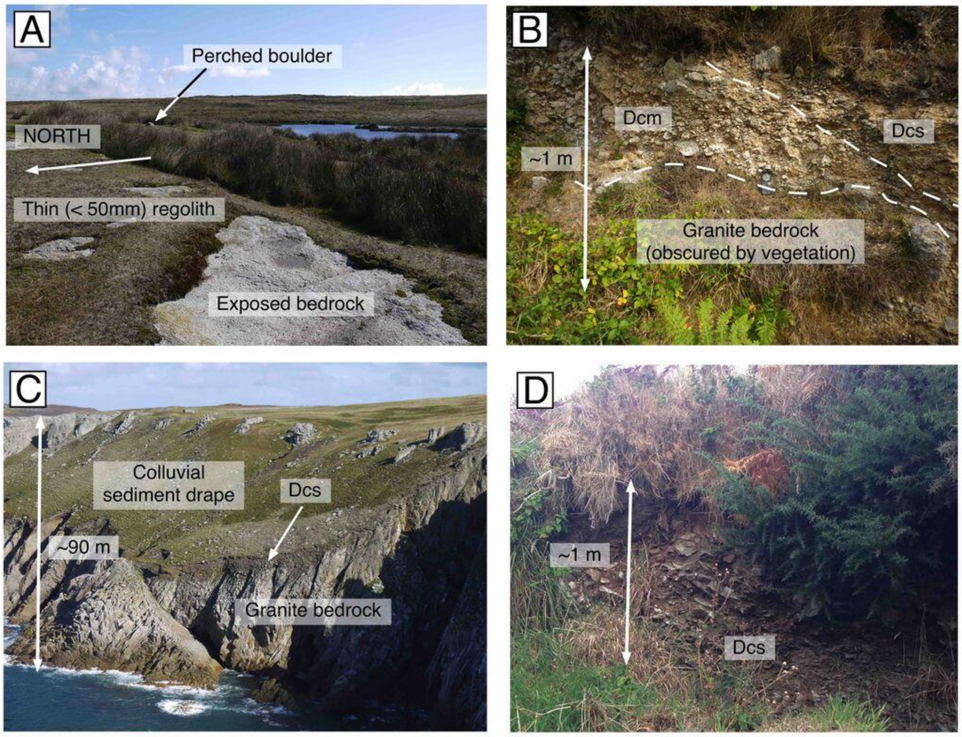

A
Perched boulder
NORTH
Thin (< 50mm) regolith
Exposed bedrock
B
Dcm
Dcs
~1 m
Granite bedrock
(obscured by vegetation)
C
Colluvial
sediment drape
Dcs
~90 m
Granite bedrock
D
~1 m
Dcs

Figure 12

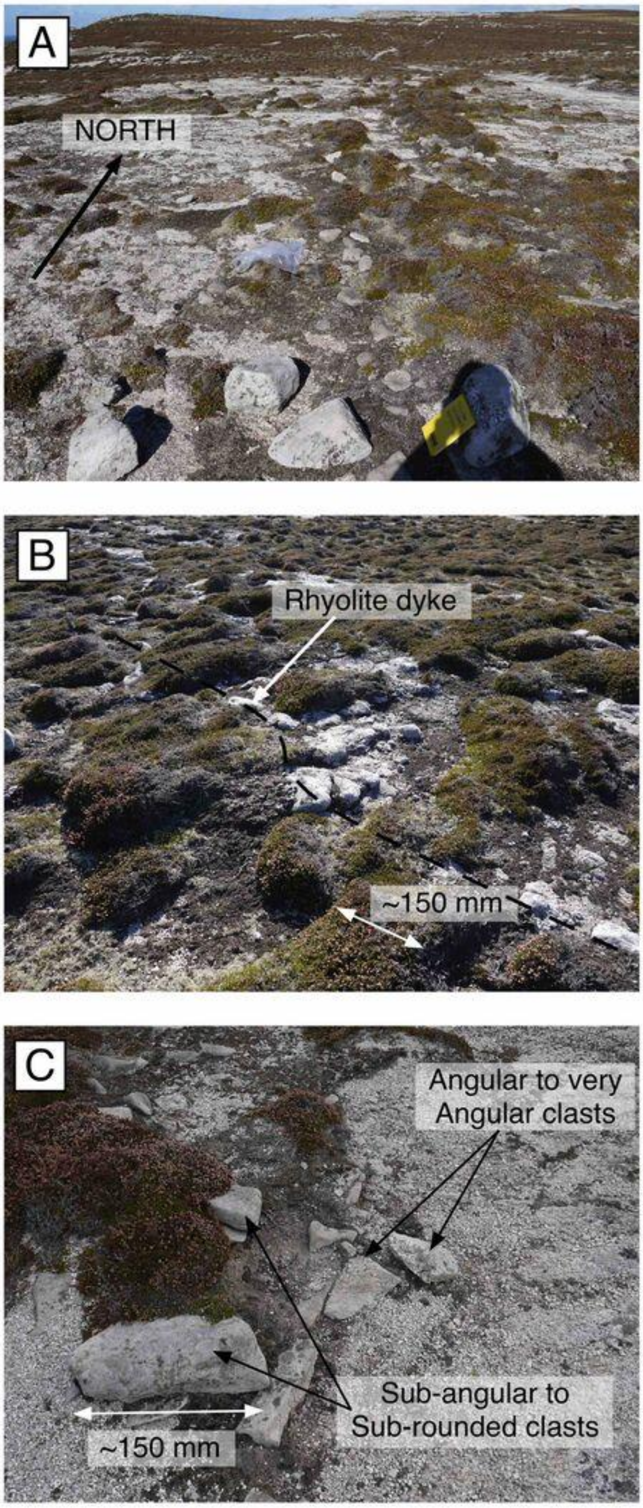

A
NORTH
B
Rhyolite dyke
~150 mm
C
Angular to very
Angular clasts
Sub-angular to
Sub-rounded clasts
~150 mm

Figure 14

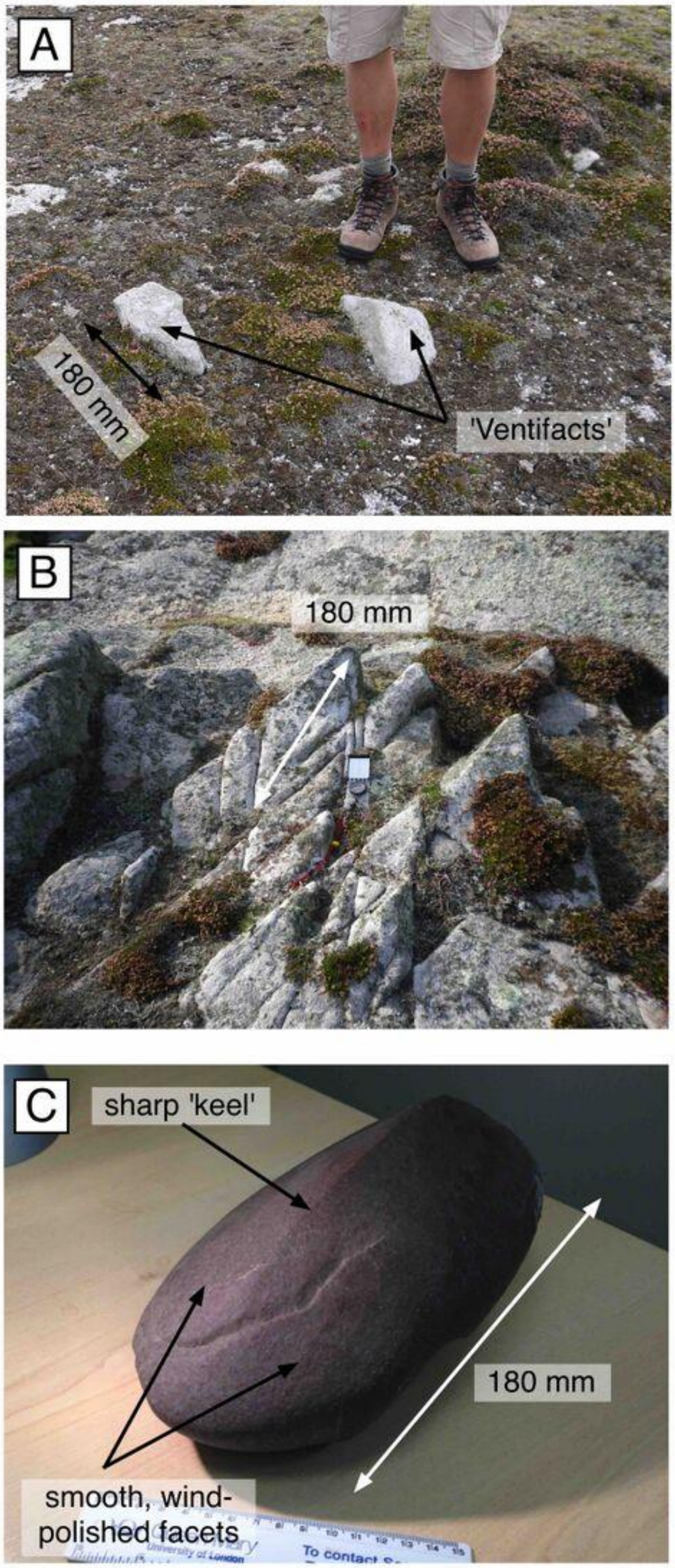

A
180 mm
'Ventifacts'
B
180 mm
C
sharp 'keel'
180 mm
smooth, wind-
polished facets

Figure 14

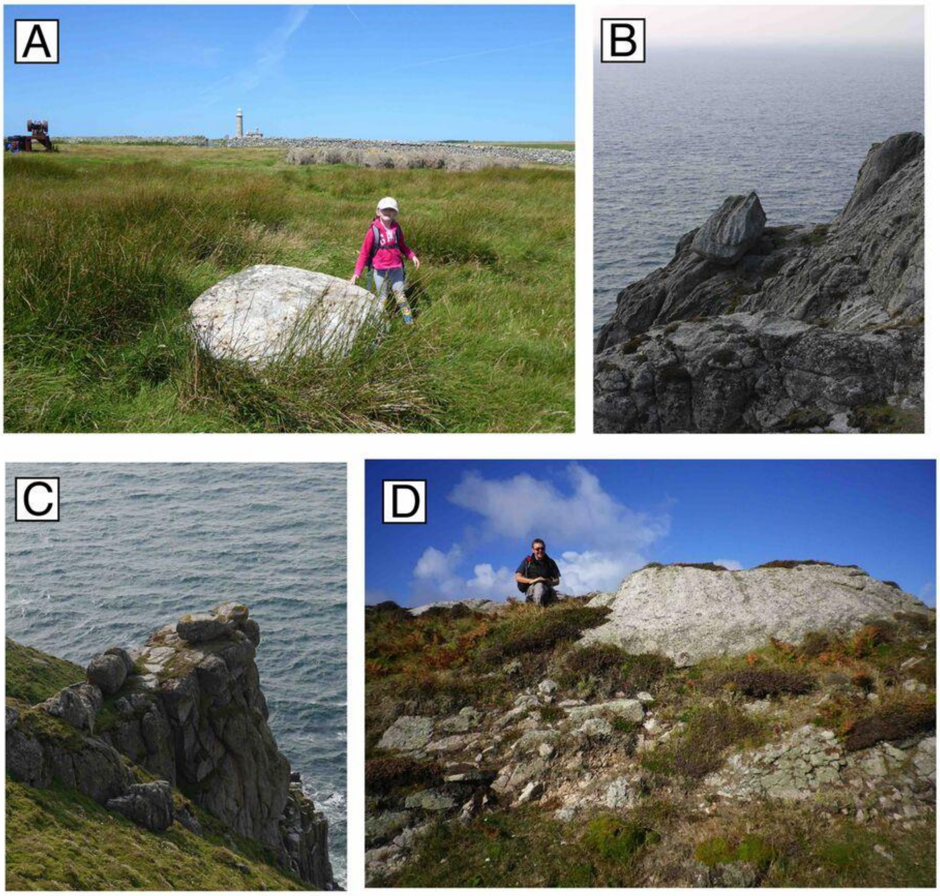


Figure 16