THE GEOMORPHOLOGY OF GOLA, NORTH-WEST IRELAND

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Abstract

The island of Gola, offshore north-west County Donegal, Ireland, shows a range of geomorphic and sedimentary features of Pleistocene and Holocene age, but hitherto these features have not been described. This study reports on the main glacigenic (Pleistocene-age) and coastal (Holocene) geomorphic features, their associated sediments, and their environmental interpretations in the context of regional Pleistocene and Holocene climate change. The contemporary geomorphology of Gola is strongly controlled by its underlying geology and Pleistocene glacial history (which includes its paraglacial inheritance), and its exposed Atlantic-facing location.

Introduction

The offshore islands of western Ireland are not well known in terms of their Pleistocene and Holocene environmental histories, as most work has been undertaken either offshore on the open Atlantic shelf or on the mainland where, by contrast, much more is known. For example, late Devensian ice limits are known with some precision on the Atlantic shelf of northwest Ireland where they have been mapped using sidescan sonar and seismic methods (Benetti *et al.* 2010; Ó Cofaigh *et al.* 2012). Ice margins have also been mapped onshore, such as around Bloody Foreland, Lough Foyle, Lough Swilly and Donegal Bay (e.g. Charlesworth 1924; McMillan 1957; Stephens and Synge 1965; McCabe 1995; Clark *et al.* 2009). The islands offshore western Ireland are a key element in reconstructing late Devensian ice retreat patterns from the Atlantic shelf, because they likely provided pinning points for ice margins during ice retreat onshore. Fragments of ice-marginal moraines, for example, have been identified on some of these islands, such as on Clare Island (Synge 1968) and Aran Island (Knight 2012). The glacigenic stratigraphies of many sites in western Ireland have been interpreted as marine-influenced, thus that high relative sea levels accompanied ice retreat (e.g. McCabe *et al.* 1986, 2007; Knight 2006; Thomas and Chiverrell 2006). Geophysical models, however, give a more complex picture of rapid sea-level oscillations during the lateglacial due to initial glacioisostatic rebound, followed by continuous sea-level rise to a mid-Holocene highstand (for sites in the northern half of Ireland) and minor sea-level fall to present (Brooks *et al*. 2008). Rapid sea-level rise in the early Holocene is most likely responsible for the paraglacial reworking of older glacigenic sediments from the shelf, and the transformation of, for example, moraine fragments into subtidal or intertidal gravel bars that may be preserved within embayments (Knight and Burningham 2014). In addition, the sandy beaches and sand dunes of western Ireland likely also correspond to the paraglacial reworking of sands that were previously transported to the shelf and coastal zone by late Devensian glaciers. This later reworking has been linked in particular to postglacial sea-level change (Carter *et al*. 1987). The landforms preserved on the west coast and offshore islands therefore likely reflect a combination of glacigenic and coastal processes spanning the late Pleistocene and Holocene. The relative interplay between these processes, and overarching controls by geology, climate or sea-level change, undoubtedly varies from place to place, however, but site-scale studies investigating these interactions are lacking.

Here, we describe the major glacigenic and coastal landforms and their associated sediments from Gola (*Gabhla*), offshore north-west County Donegal (Fig. 1). The geomorphology and sediments of this island have not been previously described despite there being some significant evidence that has potential to contribute to regional Pleistocene and Holocene environmental history. In detail, this paper summarises the bedrock geology of Gola, and describes the major landforms of the island according to their dominant processes of formation by either (1) Pleistocene glacial or (2) Holocene coastal processes. Some contemporary coastal processes and landforms are then described.

Regional context

Geologic and geomorphic setting

Gola (~2.2 km^2) is located 2 km offshore north-west County Donegal and 4.8 km from Bunbeg harbour (Fig. 1). It forms one of several small islands extending south from Bloody Foreland that are all developed in granites of the Thorr pluton which was emplaced ~400 Ma (Evans and Whittington 1976; O'Connor *et al*. 1982; Hutton 1982; Stevenson 2008). The quartzose potassic granite on Gola has been described by Whitten (1956/1957). This granite is a coarse-grained white-pink rock containing (in descending order of abundance) microcline and plagioclase feldspar, quartz, hornblende and biotite. The granite is well exposed across the island where it has been shaped by glacial abrasion during the Pleistocene. The granite is jointed throughout which has given rise to NW–SE-trending lines of weakness that have been subsequently exploited by glacial action including plucking and abrasion.

The island has steep bedrock cliffs on the north and west coasts. Glacial sediment is thickest on the south-east corner of the island. A bedrock headland overlain by recent sand dunes also extends eastwards from this south-east corner. A lake (Lough Magheranagall, 1.25 ha in area, lake surface ~5 m asl) is located in the west of the island, barred from the sea by a gravel barrier. The highest point on the island is Knockaculleen (69 m asl) (Fig. 2).

Water depths to the east of the Ireland average around 5 m within the shallow sand-covered trough between Gola and the mainland, but to the immediate west, the rocky seabed rapidly deepens to 15–20 m within 200 m of the shoreline. The tidal regime in the Gola region is mesotidal, with a mean spring tidal range of 3.29 m (based on harmonic analysis of the 2010–2014 record (inclusively) from Aranmore tide gauge, 13 km to the southwest) (data from www.marine.ie). A positive surge of 1.17 m was recorded on the 20 December 2013, but the maximum water level in this record was 3.18 m, which occurred on 5 January 2014. The wave climate is dominated by westerly North Atlantic swell: wave records from the offshore wave buoy located at the far westerly extent of Donegal Bay yield a median wave height of 2.4 m and median wave period of 7 s (2003 to 2011). The wind climate is also west-dominated; 61% of wind recorded at Malin Head is from the west (2010 to 2014 inclusively; data from www.met.ie). Median wind speed is 14 knots (7.2 m s^{-1}) and winds at gale force or above (≥34 knots; ≥ 17.5 m s^{-1}) occurred on between 13 and 26 days each year between 2010 and 2014. This vigorous energy regime provides the context for discussion of wave- and wind-formed features, given below.

Late Devensian regional ice flow

During the late Devensian glaciation, regional ice flow in north-west Ireland was towards the west and north-west, directed from an ice dispersal centre located over the mountains of central Donegal (Ballantyne *et al*. 2007) (Fig. 1). The ice traversed the offshore islands, shaping the bedrock surface and forming a range of mainly erosional bedforms. Glacial sediments are not widespread in north-west Ireland and are restricted to small accumulations of subglacial diamicton (till) within coastal embayments (e.g. Donegal Bay; Hanvey 1989; Dardis and Hanvey 1994; Knight and McCabe 1997; Loughros Beg; Knight 2011), within small bedrock hollows (e.g. on Cruit Island and Aran Island; Knight 2012), or as retreat moraines within glaciated valleys inland (e.g. Glenveagh; Charlesworth 1924). The timing of ice retreat from maximal positions on the Atlantic shelf is uncertain and likely varied between different sectors of the Donegal ice dome. In north Donegal, ice retreated onto land prior to ~18.0 cal kyr and then readvanced between ~15.8–14.2 cal kyr (McCabe and Clark 2003). In north-west Donegal, ice retreated onto land at 19.3 kyr (based on weighted mean ^{10}Be ages) (Clark *et al*. 2009). It is likely that in west Donegal ice retreated from the offshore islands at around this latter date, which is consistent with this regional evidence. Glacial and coastal landforms and sediments from Gola are now described and interpreted.

Methods

The geomorphology of Gola was examined and mapped in the field (between 2010 and 2015) and from a range of spatial data sources (aerial photographs, old published maps and hydrographic charts). Coastal landforms were surveyed and where possible were referenced to the tidal frame. Glacial sediments and lithostratigraphies were described and logged in the field using standard techniques (Hubbard and Glasser 2005). Coastal sediments in different environments were sampled and analysed for particle size using a Malvern Mastersizer (range

10–2000 µm). Medium to short-term coastal geomorphic change was assessed from available geospatial resources (aerial imagery from 2000 and 2012 at ~1:1500-scale; Ordnance Survey 1:10,560-scale maps from 1834 and 1904; hydrographic charts from 1839 (~1:40,000-scale) and 1981 (1:75,000-scale)). Data were georeferenced in a GIS that allowed the comparative digitisation of geomorphic features, including shorelines from the different data sources.

Results

Glacial geomorphology

Bedrock summits across the island are glacially smoothed and occur on different scales, ranging from symmetric, individual hills 60–80 m long and <15 m high (whalebacks), to smaller features <6 m long and 1–3 m high (roches mountonnées) which may be symmetric or asymmetric (Fig. 3). The sides of larger hills appear to be oversteepened with blocky cliff faces up to 5 m high. The long axes of these landforms are broadly oriented towards the north-west, although joint sets within the granite have strongly influenced the geometry of, in particular, the smaller forms. The whalebacks and roches mountonnées are typical erosional features of glaciated landscapes developed on hard igneous and metamorphic rocks (e.g. Glasser and Warren 1990; Olvmo and Johansson 2002; Hall and Phillips 2006). These features develop dominantly through subglacial abrasion; the general absence of angular leeside faces of the roches mountonnées on Gola suggests that plucking was not a dominant process (Sugden *et al*. 1992). This may be due to the generally high-strength rock, wide spacing of joint sets and possibly thin or warm basal ice that did not promote leeside freeze-on (Hall and Glasser 2003). Bedrock summits are often separated by shallow valleys (several tens of metres wide and <10 m deep), interpreted as meltwater channels, which may be of subglacial and/or proglacial origin (Fig. 3). These valleys often have steep lateral margins, undulating long axes and are consistently aligned NNW–SSE, which suggests a structural control. Although valleys join each other, they do not appear to form an integrated drainage network. No striae are observed on rock surfaces, or have been recorded in previous works (see Smith and Knight 2011), possibly because of low preservation potential on coarse bedrock and/or the effects of postglacial weathering.

Clasts that have been transported are often found isolated on bedrock summits where they sit directly on bedrock (only one example is located within a col) (Fig. 4). However, there is no clear spatial distribution of these clasts and they are not clustered along former ice margins as can be seen on The Rosses (Charlesworth 1924). Maximum clast dimensions are 4x3x2 m; all clasts are highly weathered and covered with lichen. The clasts are of the same granite lithology as the underlying bedrock, which means that they cannot strictly be termed erratics. In one instance, a transported clast (1.2 m longest axis) is separated from the bedrock surface by two smaller boulders, one of which is local granite and the other is a fine grained, laminated schist similar to Devonian metasediments found in south Donegal (Fig. 4B). This evidence suggests erratic carriage from south to north across Donegal, which is consistent with ice dome models (Ballantyne *et al.* 2007), but the relative timing of different ice flow phases is uncertain.

Downwasting of the granite bedrock by postglacial weathering processes is also evident. On some flat granite surfaces, shallow solutional hollows (<0.5 cm deep, <40 cm diameter) are present. These solutional hollows, similar to karstic kamenitzas (e.g. Eren and Haitipoglu-Bagci 2010), have relatively steep sides and flat floors (Fig. 4C). They are recognised as active features by the relatively fresh appearance of the pink granite sides, suggesting active exhumation of the granite which makes it unfavourable for lichen growth. Such pseudokarst features have been sometimes observed on granite bedrock (Otvos 1976; Roqué *et al.* 2013) and reflect chemical weathering within rainwater pools which can in particular affect the dissolution of quartz (Wray 1997). The effect of this weathering process can also be seen by the formation of pedestals beneath large, transported clasts, where the clast has partially protected the underlying rock from weathering attack. In an extreme case, the bedrock surface is some 8 cm higher beneath the clast compared to where the rock surface is not protected (Fig. 4D). Assuming a clast deposition age from a retreating ice margin of 19 kyr, a postglacial weathering rate of ~4.2 mm/kyr can be calculated.

Glacial sediments

Glacial sediments are present discontinuously across the island. These sediments are well-exposed in two locations (A and B on Fig. 1). Site B, where shoreline erosion has cut through a drumlin, offers possibly the best exposure of glacial sediments in north-west Ireland and has not been previously noted. Three facies are identified in total (Fig. 5). Facies 1 is a bedrock breccia that is only observed at site A; facies 2 comprises a subglacial diamicton with clast lines, shears and deformation structures including clastic dikes; facies 3 comprises channelised proglacial sand and gravel lenses. Facies 2 and 3 are observed at both sites. These facies are now briefly described and interpreted.

Site A is located in the centre of the island in a disused quarry. This section (3–4 m high) overlies a diffuse, fractured and undulating granite bedrock surface, and comprises three facies (Fig. 5). Facies 1 (0.4 m thick) is a clast-rich bedrock-derived breccia composed of angular local granite clasts (<12 cm diameter) with a minor granular matrix composed of smaller granite fragments and granite-derived weathered mineral grains (Fig. 6A). A minor (10%) component of rounded erratic clasts is found within this facies. These erratics include schists and quartzites derived from the mainland to the south and south-east. This facies is interpreted as bedrock slabs that have been plucked or sheared from rockhead by overlying polythermal basal ice, then brecciated and crushed during transport and mixed with pre-existing farther-travelled subglacial clasts (e.g. Croot and Sims 1996). Facies 2 (1.5–2.5 m thick) is a matrix supported subglacial diamicton with isolated clasts of a wide range of lithologies (in particular granites), subglacial shears, clastic dikes and deformation structures (Fig. 6B, C). Upwards, the matrix generally fines from granules to coarse sand, and the diamicton becomes more massive and clast-poor. Shears are most common at the base of the facies and are planar, 40–60 cm long and have a strike that suggests ice push towards the north (Fig. 6D, E), which is oblique to NW–SE bedrock joints. Deformation structures developed beneath or around larger clasts and within stratified elements can be seen at the top of facies 2. Facies 3 (0.5–1.5 m thick) varies from massive and poorly sorted, to poorly stratified diamicton (Fig. 6F). Clasts are subrounded to subangular pebbles (<6 cm diameter);

local granite clasts are generally absent. Poorly-demarcated beds (0.2–0.5 m thick) are matrix dominant and normally graded with welded bed boundaries. Deformed and discontinuous sand stringers are sometimes present within this facies. The boundary between facies 2 and 3 is generally sharp and erosional. These characteristics of facies 2 are typical of a subglacial diamicton (till) affected by glacier-induced strain, forming a range of brittle (shears) and ductile (deformational rotation) structures (e.g. Roberts and Hart 2005; Piotrowski *et al.* 2006). Facies 3 is interpreted as glacial diamicton that has been reworked by slope processes such as debris and mass flows following ice retreat (Mattson and Gardner 1991; Rose 1991). Reworked diamictons are commonly recorded following the readjustment of steep slopes, in particular where hummocky moraine topography is present (e.g. Andersson 1998), although hummocky moraine does not appear to be present on Gola.

Site B exposes a section of subglacial diamicton, up to 6 m high and up to 150 m long, near the margins of a drumlin on the south-east coast of the island (Fig. 7A). The limits of the drumlin form inland are not too clear because the land surface slopes shallowly inland, presumably onlapping on to rising bedrock. Two facies are identified, which are considered to be the lateral equivalents to those identified at site A (Fig. 5). The lowermost facies 2 varies in thickness across the section (from 1 to 5 m thick) and overlies a smoothed and sharply demarcated granite bedrock surface (Fig. 7B). This facies is a clast-poor diamicton with a coarse sandy matrix, is planar stratified at base, concordant with the bedrock surface, and becomes more massive upwards.

Also at the base of the facies are well developed and parallel planar to listric shear sets that are most commonly infilled with silts (Fig. 7C). The diamicton also contains vertically-aligned clastic dikes that vary from 10 cm to 1.2 m in height, and 1 to 12 cm in width (Fig. 7D). These clastic dikes are particularly common in the massive upper part of the facies, have sharply demarcated margins and are infilled with water-sorted materials including granule lenses and openwork clast clusters (Fig. 7E). Such clastic dikes are commonly recorded in western Ireland (e.g. McCabe and Dardis 1994; Knight 2006, 2014, 2015) and are formed as a result of high hydrodynamic porewater pressure within subglacial sediments caused by glacitectonic deformation. High porewater pressure is particularly common within fine grained subglacial sediments which have low permeability. In this instance, high water pressure can be achieved over an impermeable bedrock surface or where the ice is pressing against rising ground. Pressure release takes place by porewater bursting through a confining aquitard, such as an overlying low-permeability diamicton bed, carrying sediments with it that then infill the fracture as a clastic dike (van der Meer *et al.* 2009). The overlying facies 3 contains interbedded and deformed sand and granule lenses (Fig. 7F). These sediments are arranged in channel-shaped packages that comprise variably massive and poorly sorted to normally graded gravel beds overlain by a fine drape (2–8 cm thick) of laminated sands to silts that may contain climbing ripples. These sediments suggest deposition in a proglacial outwash environment with multiple but episodic subaqueous debris flows. This can account for the erosional bases of the gravel beds, their confined nature, and the overlying drape which represents quiet water rainout of fine sediments from suspension within a water body experiencing flow disturbance and water circulation.

Coastal geomorphology and sediments

Several coastal landforms, that are closely connected to each other through a shared paraglacial context in the postglacial period, are found around Gola. A gravelbarrier separates Lough Magheranagall from the open Atlantic. The gravel barrier is 80 m in width at its narrowest point and 120 m at its widest toward the centre of the Tramagheranagall bay; it extends about 225 m north to south across the bedrock–framed and deeply indented embayment between Mweelmurrinagh and Mweelmore, curving towards the east by 25 m. The main morphostratigraphy of the barrier is shown in Figure 8, where a bedrock hollow is partly infilled with subglacial diamicton, barrier cobbles/boulders and dune sand, which ramp up the low bedrock slopes of Mwellmurrinagh on the northern end of the barrier. The subglacial diamicton (<2 m thick, extending for >18 m distance) is wedge-shaped and has an eroded upper surface. The diamicton is overlain by 1 m of dune sand that contains two thin (5–10 cm thickness) buried soils. The presence of the diamicton wedge and rock lip upon which it rests suggests that the lake behind may be located in a bedrock depression and is not wholly impounded by the gravel barrier and organic cordon behind it.

The barrier itself (Fig. 9) is formed mainly of well-rounded cobbles and rounded boulders (10–120 cm diameter), but substantial sand cover is found across the intertidal zone (medium sand; D_{50} 490 μm), and windblown sand (medium sand; D_{50} 380 μm) of variable thickness is present across the barrier crest, forming a ramp dune onto the lower slopes of Mwellmurrinagh to the north. The junction between gravel and sand foreshore lies at around mean high water. The barrier reaches a maximum slope of around 15° seaward of the crest which gradually reduces to around 4° across the foreshore. Sand becomes patchier around the low water mark where cobbles and boulders are exposed, but the nearshore zone is sand-dominated. Sand (medium sand; D_{50} 440 μm) is also present across the shallow margins of Lough Magheranagall. A very small channel drains from the lake seaward across the barrier; the draining water then issues from the sandy intertidal beach. The barrier is vegetated between the crest (at around 6 m asl) and the lake margin with species associated with maritime grassland communities, dominated by *Festuca*, *Plantago* and *Armeria maritima* with *Honckenya peploides* (NVC MC9/MC10). The species assemblage and low sward heights (owing to sheep, rabbit and geese grazing) are akin to those found across west Ireland machair plains. The thickness of the windblown sand drape over the Tramagheranagall gravel barrier is quite varied, but mostly superficial, and storm boulders and cobbles are also scattered across the seaward part of the vegetated surface. Relatively recent overwash is also evident in the presence of drift lines, and the most landward of these is 46 m from the lake edge. Within 30 m of the lake, the substrate becomes boggy and organic rich with a shift in vegetation community to wetter grassland (including *Trifolium repens, Hydrocotyle vulgaris, Holcus lanatus*); *Potamogeton* and *Juncus* species occupy the littoral zone of the lake, replaced by *Phragmites australis* in a confined wetland to the south-west corner of Lough Magheranagall.

Tramagheranagall is the only west-facing beach system on Gola, but there are several other small beaches on the north, south and east coasts. Those to the east are sandy, and locally constrained by bedrock that means that alongshore extent is limited (~ 50 m in length). A more extensive beach is found between Slodamore and Portacurry on the southeast corner of Gola. In Slodamore bay, a well sorted, rounded cobble beach occupies the high intertidal and low supratidal toward the rear of an extensive rock platform that is up to 200 m wide; a sand veneer is present on the mid foreshore. To the west of this, boulders replace cobbles, and these are more discretely deposited within expanded joints in the underlying bedrock platform. To the east, the gravel deposit becomes more varied in size owing to the direct supply of sand through to boulders from the eroding drumlin shoreline (Fig. 7B).

Sand dunes (< 2 m high) are located on the south-eastern end of the island between Tranabeaky and Portacurry beaches. The dunes extend as a barrier between the mainland and a series of intertidal rock platforms that anchor the easterly part of the dune system. The barrier is narrowest at its midpoint, at around 50 m wide. The dunes are vegetated with a fixed dune community dominated by *Ammophila arenaria* that is in places mixed with species indicative of disturbance and/or agriculture (e.g. *Senecio jacobaea* and *Urtica dioica*).

Recent coastal dynamics

On the north coast of the island at Scoltydoogan, an arch has developed within a small cove (Fig. 10). The arch is around 36 m in length and occurs in the lowermost part of a cliff that is 21 m high (Hull *et al*. 1891). At the head of this cove is a recent rock deposit formed by topple from the adjacent steep bedrock slopes. This topple comprises angular, equant boulders (<1.5 m width) that do not show surface weathering.

On the south coast of the island, large boulders up to 2x2x1 m dimensions are located on the bedrock shore platform within the intertidal zone. In places, these boulders have been uplifted up to 8 m above mean high water (Fig. 11). These boulders are the same lithology as the underlying granite, are commonly well-rounded but may be angular and have a tabular morphology determined by bedrock jointing patterns. The boulders were transported and emplaced by storm waves which, in north-west Ireland, are dominantly from the south-west. Such large and high-level boulders are commonly reported from western Ireland coasts, including Donegal (Williams and Hall 2004; Hall *et al*. 2006; Williams 2010; Knight and Burningham 2011). Evidence for active recent transport comes from the presence of pulverized transport trails over bedrock and chipped edges to the boulders.

The depositional systems at Tramagheranagall (gravel barrier) and Tranabeaky (dune barrier) show considerable historical stability (Fig. 12) with evidence of only small-scale shifts in morphology over the last 180 years. The scales of change are close to the likely uncertainty in the early mapping, but there is some suggestion of persistent and progressive change. The Tramagheranagall barrier has receded (the shoreline has moved landward) by around 20 m, and in contrast, the Tranabeaky barrier has extended eastward and has shifted southward by a similar scale. Georeferencing errors were 7–10 m based on common ground control points across the island, but the scale of original surveying error is difficult to gauge, particularly around the coastline. Field visits in 2010 and 2015 provide some evidence of short-term dynamics at Tranabeaky that are not exhibited in map/aerial photograph analysis (Fig. 13). Both the north and south facing margins of the dune barrier are moderately steep. Aerial photograph evidence from 2000 and 2012 and field evidence from 2010 shows that the north face was well vegetated and only the narrow zone at the base of the dune front showed evidence of recent change. But in 2015, the north face was characterised by a distinctly erosional scarp. Storms during the winter of 2013/2014 caused localised erosion of beach-dune systems across the west coast of Donegal (Magee, 2014), and it is likely that the storm surges of 20 December 2013 and 5 January 2014, linked to this storm period, were responsible for beach lowering and dune front erosion.

Discussion

The present-day geomorphology and contemporary processes on Gola are strongly influenced by the inheritance of regional glacigenic processes from the late Devensian. Glacial erosion and deposition have directly shaped land surface topography and sediment distribution both on the island itself and in adjacent areas such as the surrounding shelf. Postglacial sea-level changes and high availability of loose glacigenic sediments resulted in a mix of transgressive and regressive sandy and gravelly coastal landforms being developed and preserved along the western Ireland coast at different point during the Holocene (Carter *et al.* 1989; Devoy *et al.* 1996). As such, the present-day geomorphology of the island reflects this paraglacial inheritance, where paraglacial is defined as 'nonglacial processes that are directly influenced by glaciation' (Church and Ryder 1972, p3059). The paraglacial context of the Irish coast has been previously noted, in particular with reference to the formation of intertidal coarse gravel barriers, interpreted as former glacial moraines (Carter *et al.* 1989; Knight and Burningham 2014). In addition, some studies have also examined the relationship between eroding Irish drumlins and their contribution to contemporary sediment supply (Carter and Orford 1988; Greenwood and Orford 2007, 2008). These studies suggest that the rate and trajectory of sea-level change are important controls on the development of paraglacial landforms, including intertidal and subtidal banks, gravel barriers, and spits. In addition, the infilling of estuaries, development of intertidal sandflats, salt marsh and sand dunes in western Ireland can also be seen as a paraglacial response (Devoy *et al.* 1996; Cooper 2006).

On Gola, the most significant impact of paraglacial modification has been through likely enhanced sediment supply to the coastal barrier at Magheranagall. This is indirectly supported by the presence of a glacial diamicton wedge at the rock lip, and the wide range of lithologies recorded in beach pebbles. It may also be the case that bedrock joint sets across Gola were expanded by glacial pressure release. This may have contributed to the rock topple noted on the north coast (although this is not a testable hypothesis) and may suggest that this landscape is still undergoing paraglacial relaxation today (see Ballantyne 2002). It is likely that the gravel beach and associated barrier is a progradational feature associated with storm wave accretion of a gravel beach that is pinned to a bedrock lip. Rising sea-levels during the mid to late Holocene may be a contributing factor to the development of such gravel barriers (Orford *et al.* 1995). This likely origin for this beach and barrier is therefore different to the morphodynamics of gravel barriers on the south coast of Ireland, where progradation is less common (Carter and Orford 1984).

Conclusions

The island of Gola offers a range of glacigenic (Pleistocene) and coastal (Holocene) landforms that reflect a paraglacial influence on both contemporary geomorphic processes and sediment supply. This shows that the effects of late Devensian glaciation in western Ireland still frame the contemporary landscape and coastal zone. The multiphase geomorphic history of Gola is likely typical of many western Ireland islands, which are as yet poorly known with respect to both glacial and coastal processes. The concept of paraglaciation provides a useful context for this discussion.

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Fig. 1. Map of north-west Ireland showing the location of Gola (bold) and other places named in the text. Land over 200 m asl is shaded. Late Devensian ice surface contours (m asl) and ice flow vectors are marked after Ballantyne *et al*. (2007). Note the ice margin terminates offshore (no ice surface data).

Fig. 2. Map of Gola showing the main geomorphic features and locations discussed in the text. Transect C–C' is shown in Fig. 9.

Fig. 3. Bedrock erosional features on Gola island. (A) Bedrock valleys, likely developed as meltwater channels, with steep rocky sides; (B) whaleback, with ice flow from right to left; (C) roches mountonnées, with ice flow from left to right; (D) blocky cliff face along meltwater channel sides, illustrating granite jointing patterns.

Fig. 4. Glacially-transported clasts and weathering of bedrock surfaces on Gola island. (A) Example of transported clasts (notebook is 20 cm long); (B) clasts of different lithologies beneath a large transported clast (pencil is 15 cm long); (C) surface weathering hollow whose sides are demarcated by pink, unweathered granite (pencil for scale); (D) transported clast showing a pink (fresh and unweathered) granite pedestal beneath the clast, contrasting with the lichen-covered and weathered granite outside of the pedestal.

Fig. 5. Generalised glacial stratigraphy and stratigraphic correlations between sites A and B on Gola. Facies are described in the text.

Fig. 6. Glacial sediments at site A, Gola island. (A) Stacked, subangular clasts of local granite, facies 1; (B) deformation structures associated with a large, rotated clast, facies 2; (C) glacitectonic deformation of massive diamicton, facies 2; (D) linear subglacial shear (black line), facies 1; (E) water escape structure (between the black lines), facies 2; (F) the sharp boundary (black line) between facies 2 (F2) and 3 (F3).

Fig. 7. Glacial sediments at site B, Gola island. (A) Massive to vaguely stratified sediments of facies 2; (B) sediments of facies 2 overlying the granite bedrock platform; (C) listric shear sets (arrowed) within facies 2; (D) upward going clastic dike within facies 2 (black lines mark its boundary) with sharp, parallel sides; (E) infilled clastic dikes (white lines) at the top of facies 2 (F2) and intersecting with facies 3 (F3); (F) interbedded sands and gravels of facies 3.

Fig. 8. Schematic representation of the shore-parallel long profile of the northernmost part of the gravel barrier on Gola, showing sediment stratigraphy. B=bedrock, T=subglacial diamicton (till), G=gravel, D=dune.

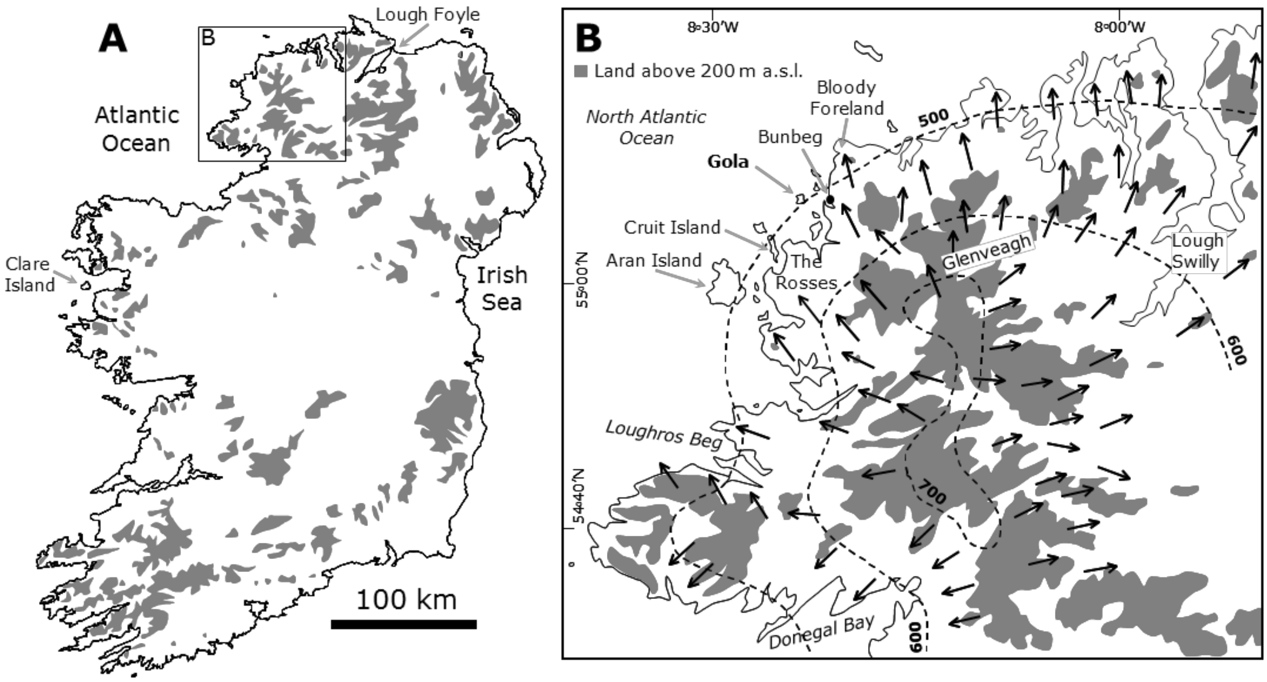
Fig. 9. View (from the north) and cross-section C–C' of the gravel barrier dividing Lough Magheranagall from the North Atlantic.

Fig. 10. Contemporary coastal processes on Gola island. (A) Coastal arch; (B) recent rock topple.

Fig. 11. Rocky shoreline features on Gola island. (A) High-intertidal platform with rounded wave-transported boulders at the cliff face; (B) slab-like granite block located above mean high water position, and thus uplifted by storm waves.

Fig. 12. Historical shoreline change at (A) the Tranabeaky/Portacurry dune barrier, and (B) the Tramagheranagall gravel barrier, derived from Ordnance Survey maps (1834 and 1904) and aerial photography (2000 and 2012).

Fig. 13. Comparison of the morphodynamic state of the dune front at Tranabeaky in 2010 (top; view to the east) and 2015 (bottom; view to the west). Note the vegetated dune face in 2010 and the highly eroded dune face in 2015.



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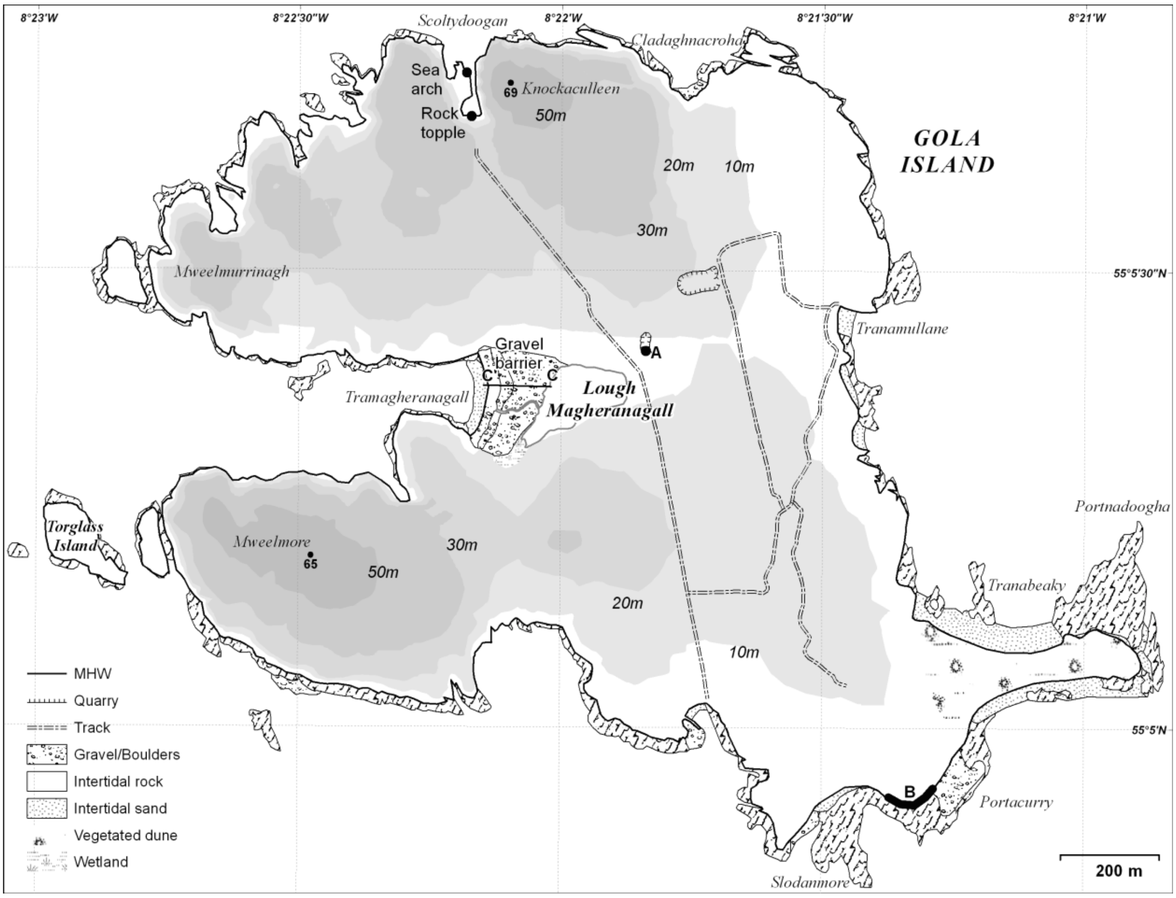

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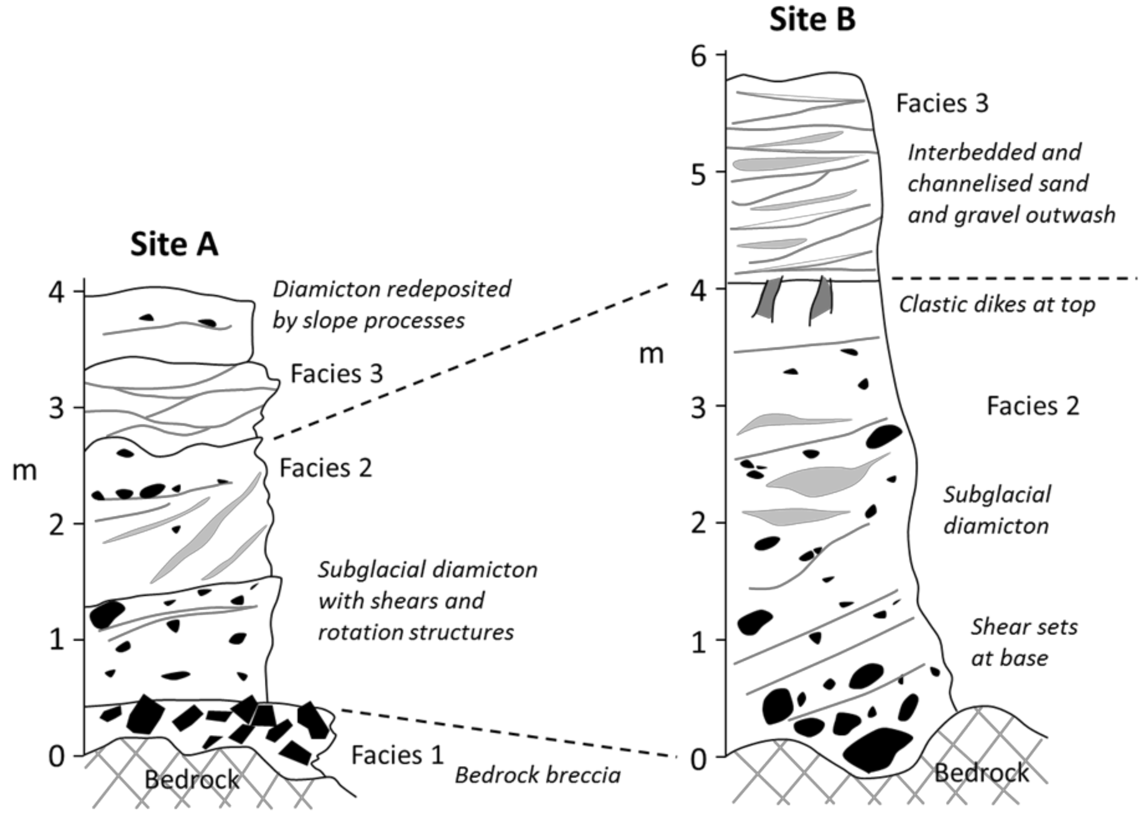

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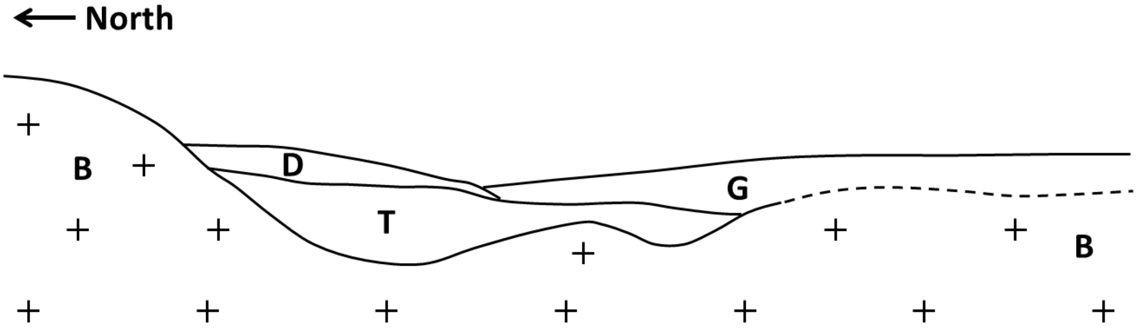

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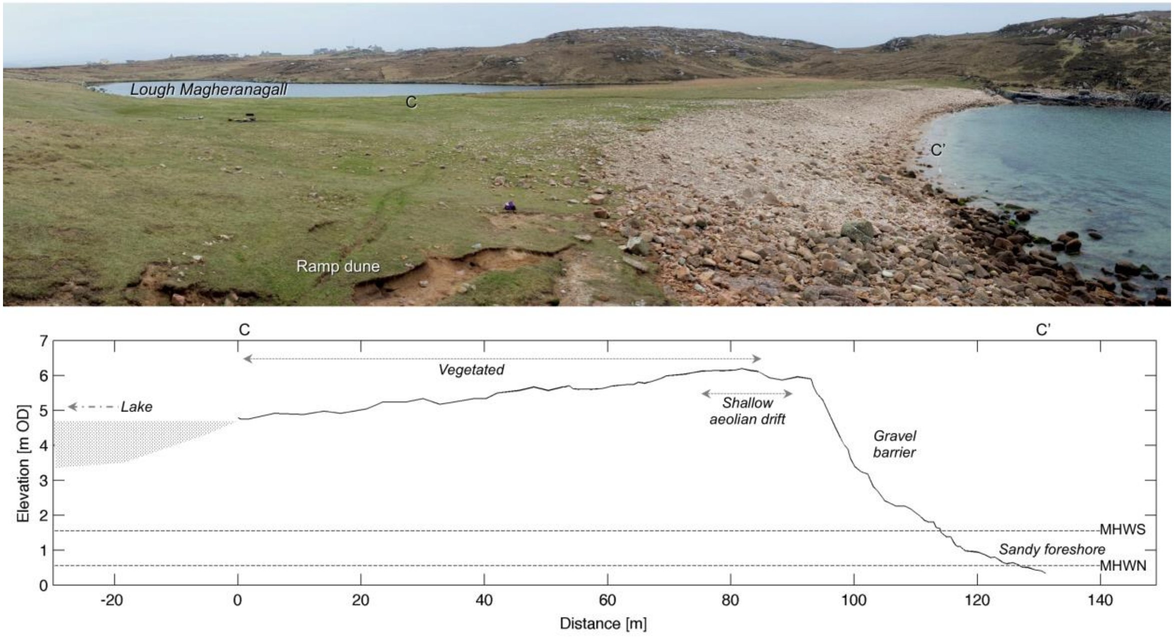

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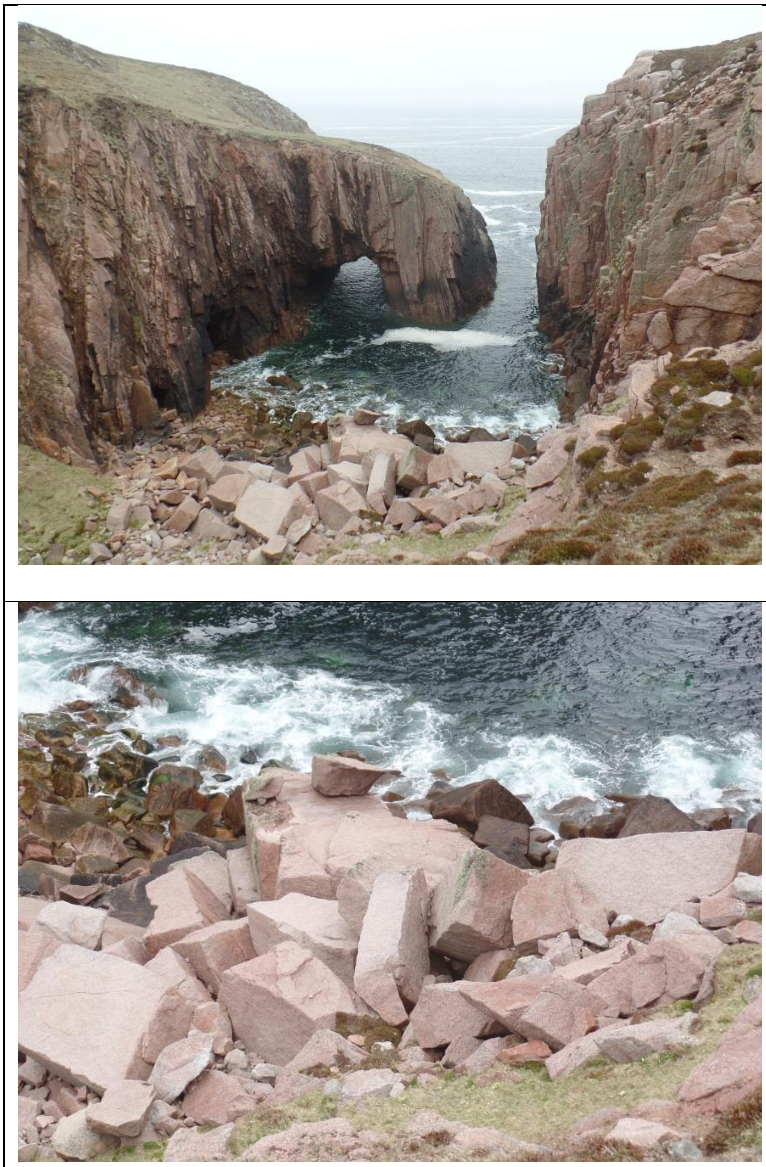

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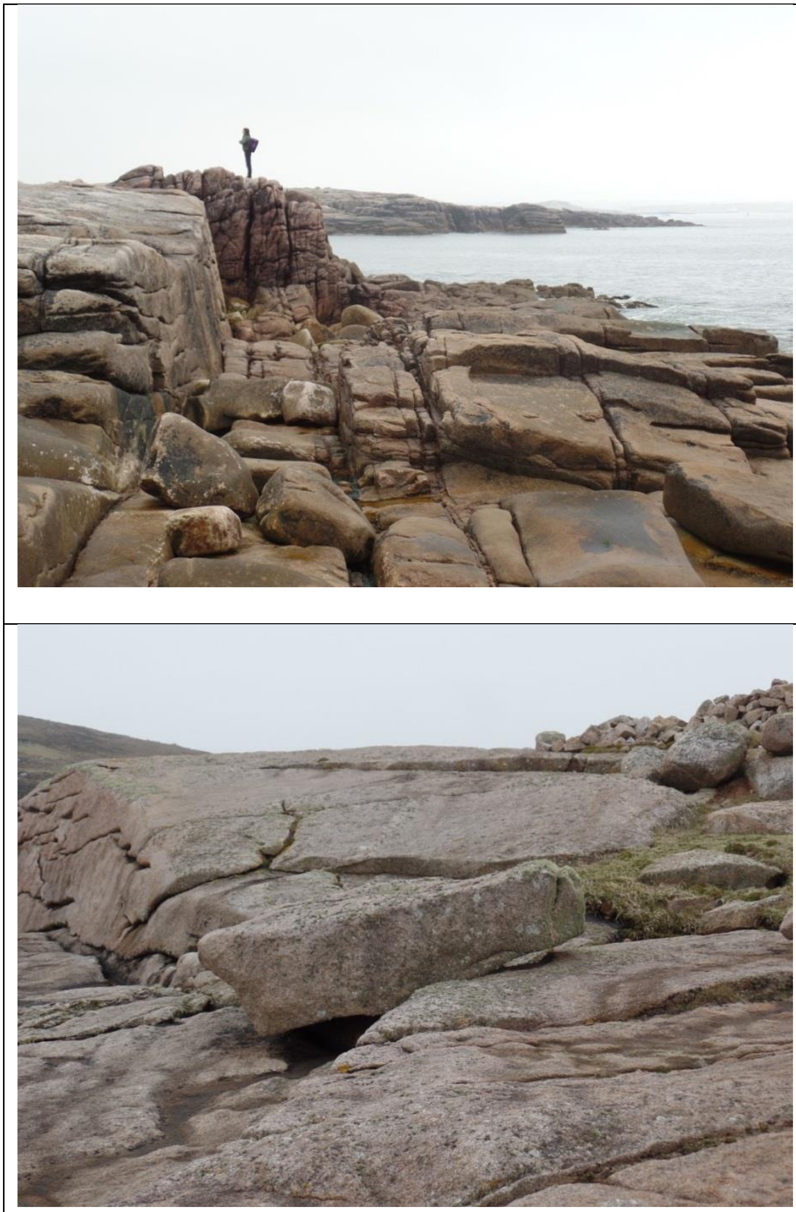

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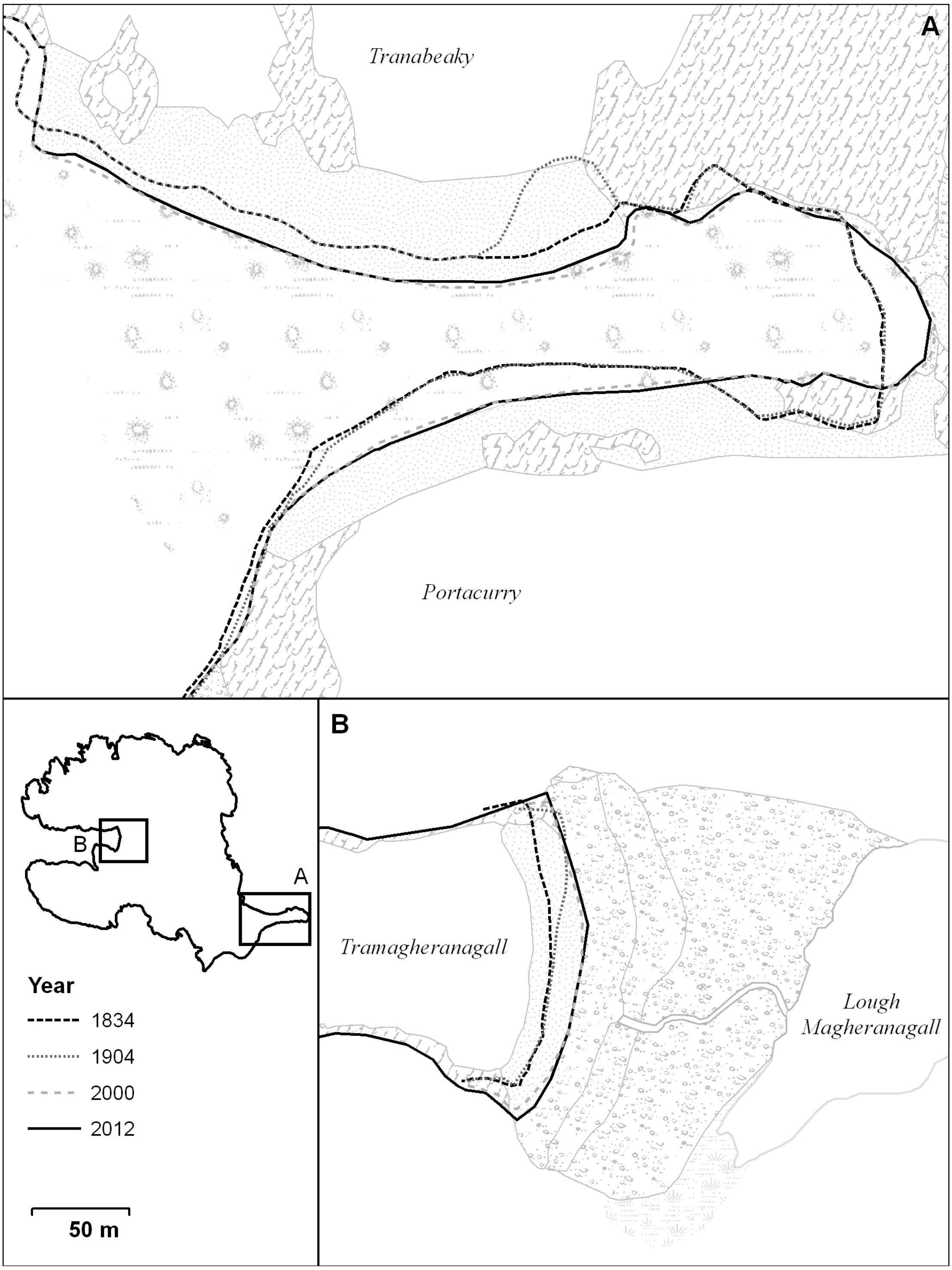

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