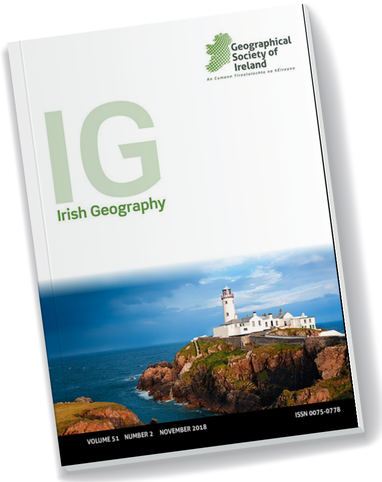

IG
Irish Geography

NOVEMBER 2018
ISSN: 0075-0778 (Print) 1939-4055 (Online)

Paraglacial evolution of the Irish landscape

Jasper Knight and Stephan Harrison

How to cite: Knight, J. and Harrison, S. (2018) 'Paraglacial evolution of the Irish landscape'. *Irish Geography*, 51(2), 171–186, DOI: 10.2014/igj.v51i2.1370

Geographical Society of Ireland
An Cumann Tíreolaíochta na hÉireann

Irish Geography
Vol. 51, No. 2 November 2018
DOI: 10.2014/igj.v51i2.1370

Paraglacial evolution of the Irish landscape

Jasper Knight[1*] and Stephan Harrison[2]

[1]School of Geography, Archaeology & Environmental Studies, University of the Witwatersrand, Private Bag 3, Johannesburg 2050, South Africa.

[2]College of Life & Environmental Science, University of Exeter, Penryn, TR10 9EZ, UK.

First received: 14 September 2018 *Accepted for publication: 19 November 2018*

Abstract: Paraglacial processes represent the dominant mechanism of geomorphic change in deglaciating landscapes worldwide and are now being increasingly recognised as controls on deglacial and postglacial landscape dynamics. This reflects the influence of glacigenic lithospheric loading/unloading cycles and patterns of glacigenic erosion and deposition. Ireland is an important location for studying the impacts of paraglacial processes in the landscape, as it was strongly imprinted by the erosional and depositional imprints of late Pleistocene glaciations and was affected by rapid shifts in North Atlantic climate. Using examples from mountains, rivers and coasts from across Ireland, this study examines some of the varied landscape responses to paraglacial relaxation in these different settings. The purpose behind this study is to show how the styles of paraglacial response may vary over time and space, even within a single regional landscape, and this can help assess the sensitivity of different environments affected by paraglacial relaxation. This study proposes an evolutionary model that describes the paraglacial sediment cascade that has shaped the Irish landscape during the lateglacial and Holocene. Consideration of paraglacial processes can yield a better understanding of the postglacial evolution of mountain, river and coastal landscapes in Ireland.

Keywords: *coastal erosion; drumlins; Ireland; mountains; paraglacial; sediment supply*

Introduction

The concept of paraglacial relaxation is increasingly being used to describe the responses of regional-scale geomorphic and sedimentary systems to the process of deglaciation (Ballantyne, 2002a; Cossart and Fort, 2008; Embleton-Hamann and Slaymaker, 2012; Cossart *et al*., 2013; Scapozza, 2016). The main reason behind this interest is concern with geohazards such as floods, landslides and debris flows that are now increasingly common in deglaciating mountain systems and regions including the Himalayas, Rockies, Andes

* jasper.knight@wits.ac.za (Corresponding Author)

and Caucasus mountains (Keiler *et al*., 2010; McColl, 2012; Knight and Harrison, 2014). A primary motivation for this body of work is to better predict how today's mountain landscapes will evolve under global warming (Owen *et al*., 2009; Knight and Harrison, 2014; Huss *et al*., 2017).

These geomorphic processes taking place in deglaciating mountains can be conceptually viewed under the broad term *paraglacial*. Paraglacial processes are defined as 'nonglacial processes that are directly influenced by glaciation' (Church and Ryder, 1972, p.3059) and these tend to become dominant in any landscape as deglaciation progresses (Knight and Harrison, 2014). Several different approaches have been taken to describe models of landscape response to deglaciation. Ballantyne (2002a, p.375) considered paraglaciation to mean 'glacially conditioned sediment release' and thus could be measured through sediment flux cascades from source areas (mainly steep mountain slopes where glaciers last longest) to sinks along coastal fringes and in the nearshore zone. Ballantyne's model described an exponential decay curve in sediment yield over time, returning to background yield rates over an (unspecified) time period that is in the order of 10^3–10^4 years. In detail, many of the interconnected parts within the paraglacial sediment system exhibit different spatial and temporal scales of behaviour. Studies of sediment release from glacial moraines (Curry, 1999; Mercier *et al*., 2009), landslides (Petley *et al*., 2007; McColl, 2012), and debris torrents (Johnson and Warburton, 2002; Micheletti and Lane, 2016) show how sediment yield can change in response to short term meteorological events, and transient antecedent conditions such as saturated ground (Keller, 2017). These studies highlight that a source-to-sink analysis of paraglacial systems does not capture the variability of controls or sediment dynamics existing within these systems, or their timescales of connection or disconnection which can interrupt the sediment cascade from one place to another within the system (Mercier, 2008; Feuillet *et al*., 2014).

Ireland is an important location for the study of paraglacial processes and landsystems. The Irish sector of the last British-Irish Ice Sheet responded rapidly to changes in North Atlantic climate, and the ice sheet also retreated rapidly. This may mean that the paraglacial record, which is amplified with rapid ice retreat, is likely to be highly developed. In addition, sediment transport pathways from source (mountains) to sink (lowlands) are short in Ireland, suggesting a more rapid sediment system response than in other regions. Better understanding of these paraglacial systems and their timings may provide insight into paraglacial responses in currently glaciated mountains undergoing global warming. The paraglacial legacy of the Irish landscape is only now starting to be appreciated (Wilson, 2017). We argue that the relationship between paraglacial processes and environmental change provides a powerful lens through which to examine lateglacial and postglacial climate change, and the processes that were driven by this. Indeed, it could be argued that even contemporary geomorphic processes shaping Ireland's mountain and coastal environments display the imprint of past paraglaciation (Carter *et al*., 1987; Wilson, 2004; Ballantyne *et al*., 2013; Knight and Burningham, 2014). This paper describes the evidence for paraglacial processes in three critical geomorphic domains identified by Ballantyne (2002b): mountains, rivers and coasts. These represent the main source, transfer, and sink locations for sediments, respectively, according to Ballantyne's (2002a) model. These three environments are discussed using specific examples from Ireland, in order to illustrate (1) the role of paraglacial processes in driving geomorphic change throughout the deglacial and postglacial period in Ireland, and (2) the different spatial and temporal scales over which these geomorphic changes have taken place. Comparison between the three environments highlights the complexity subsumed within a single paraglacial 'system' and shows that the concept of deterministic source-to-sink sediment systems is similarly complex.

Glacial imprints in Ireland

The geomorphic and sedimentary evidence for past glaciations in Ireland have been studied for over 150 years (e.g., Charlesworth, 1957; McCabe, 2008), but only in the last decades has mapping from remote sensing and radiometric dating (both radiocarbon and cosmogenic methods) provided insight into the different phases of ice advance and retreat (e.g., Greenwood and Clark, 2009; Harrison *et al.*, 2010; Ó Cofaigh *et al.*, 2012; Barth *et al.*, 2016). It is now recognised that much evidence persists in the landscape for geomorphological events early in or predating the last glacial cycle, giving rise to a palimpsest of glacial landforms, including ribbed moraines and striae (Clark and Meehan, 2001; Smith and Knight, 2011), and preservation of much older sediments in karstic depressions (Vaughan *et al.*, 2004). Although glacial erosion dominates in upland areas with extensive sediment deposition in lowland areas, modelling, geochemical and dating evidence suggests that the locations of ice dispersal domes migrated over time, accompanied by variations in basal thermal and hydrological regimes (Knight, 1999, 2010). Dating evidence also reveals variations in the timing and rapidity of ice margin advance and retreat in different ice sheet sectors (Ó Cofaigh *et al.*, 2012; Hughes *et al.*, 2014). The glacial imprints in mountain environments in Ireland are dominated by erosional features including cirque basins, glacial valleys, abraded and bare bedrock surfaces, and transported erratic boulders. These imprints dominate in the Mourne, Wicklow, Kerry, and Blue Stack mountains. In lowland areas, glacial imprints are dominated by subglacial depositional landforms including ribbed moraines and drumlins. High meltwater production during deglaciation results in formation of subglacial eskers, and proglacial landforms including moraines, deltas and outwash fans that were formed during ice retreat across lowland landscapes. The distributions of these landforms have been mapped in several regional to local-scale studies (e.g., Greenwood and Clark, 2009). Ice flow from dispersal centres inland and towards coastal lowlands resulted in convergence of ice flow vectors towards coastal embayments which acted as natural sediment sinks. Following postglacial sea-level rise, glacial imprints found in today's coastal landscapes include boulder armours within the intertidal zone and these help to develop contemporary beaches, formed by winnowing of fine matrix from glacial sediments, leaving the coarsest fraction behind (Carter and Orford, 1988; Greenwood and Orford, 2008). More widely, glacial sediments have acted as an important source for reworking into Holocene coastal landforms, including beaches, estuary infills, and coastal sand dunes (Burningham and Cooper, 2004).

Methods and approach

This study draws from our fieldwork in different physical settings across Ireland over several decades. In order to identify paraglacial landforms (*sensu* Church and Ryder, 1972) and distinguish these from glacial landforms, the methodological approach taken in this study focuses on: (1) the geomorphological mapping and identification of diagnostic paraglacial landforms in mountains, river and coastal settings; (2) sediment analysis of paraglacial sediments including stratigraphy and provenance; and (3) radiometric dating of sediment layers, where available. This study also draws from the wider literature on lateglacial to postglacial landforms and environments in Ireland, but here interpreted through a paraglacial lens.

Field evidence

This paper now discusses the evidence for paraglacial processes and landforms in mountain, river and coastal settings in Ireland. Key locations discussed in the text are marked on Figure 1.

Paraglacial imprints in mountain environments

Erosional features dominate in glaciated mountain environments, and in Ireland this is manifested as cirque basins, glaciated valleys, and ice-scoured bedrock surfaces. A combination of net erosion and ice loading provides the preconditioning for formation of pressure release joints and development of rock slope failures (RSFs) generated during ice retreat. Rock surfaces are also affected by periglacial frost shattering and development of blockfields; these are seen across many upland areas of Ireland (Ballantyne and Stone, 2015; Wilson and Matthews, 2016). Many blockfields can be considered as paraglacial landforms because their development is facilitated by the creation of ice-scoured bedrock surfaces or expanded pressure-release joints, and where cold (periglacial) environments have developed outside of glacier margins. In western Ireland, blockfields have been reactivated by slope movement, generating boulder lobes and, in places, possible relict rock glaciers (Figure 2a).

Several studies have described different mass movements which affected Irish mountains after glacial retreat. Most of these studies have been informed by methodologies previously developed for the larger and higher Scottish mountains (e.g., Jarman, 2006; Ballantyne and Stone, 2013; Ballantyne *et al*., 2014a). These have focused on regional-scale mapping of RSFs and cosmogenic exposure age dating of rock headwalls. In mountains of northwest Ireland, ^{10}Be dating suggests that RSF took place mainly during

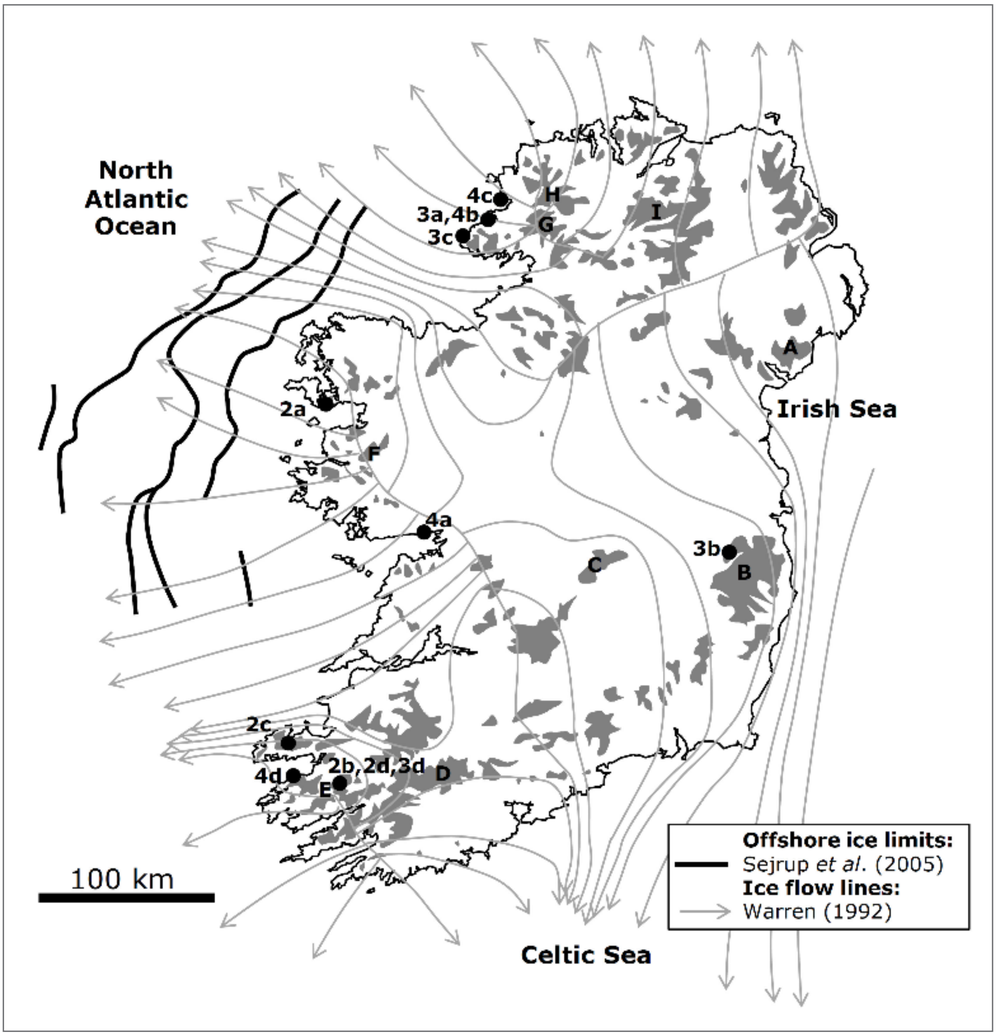

Figure 1: Map of Ireland (areas over 200m asl are shaded), showing the locations of mountain blocks named in the text (A–I), and sites shown in the photos of Figures 2–4 (numbered). Mountain blocks are: (A) Mournes, (B) Wicklow, (C) Slieve Bloom, (D) Kerry, (E) Macgillycuddy's Reeks, (F) Partry, (G) Blue Stack, (H) Donegal, (I) Sperrins.

the lateglacial and within a few thousand years of ice retreat (Ballantyne *et al*., 2013). Based on a larger dataset across Scotland and Ireland, including mountain sites that were reoccupied by Younger Dryas glaciers, an uneven age distribution emerges. This suggests that deep- versus shallow-seated failures were released at different times, or that other triggers such as seismic disturbance were involved, or that Younger Dryas glaciers moved RSF debris, causing partial disruption of their age signals (Ballantyne *et al*., 2014b). Postglacial rockfalls, debris flows and scree accumulation inside Younger

Dryas ice limits in the Macgillycuddy's Reeks (Co. Kerry), were used to calculate average rockwall retreat rates of 0.2 mm yr^{-1} during the lateglacial period (Anderson and Harrison, 2006). RSF locations in central Co. Donegal including the mountains of Errigal, Aghla More, Aghla Beg and Muckish show displaced intact or disaggregated bedrock masses, ridge crest lines and longitudinal depressions (Wilson, 2004). RSFs have also been identified along the western margin of the Antrim Plateau basalts associated with the promontories of Binevenagh, Donalds Hill, Benbradagh and Mullaghmore, Co. Derry (Southall *et al*., 2017). Cosmogenic ages (^{36}Cl) record the timing of RSF activity, whereas radiocarbon dating (^{14}C) of organic materials within RSF-generated depressions represents the minimum ages of the RSF. In this study on the Antrim Plateau basalts, 18 samples were analysed for cosmogenic dating based on a paired sampling approach, with three samples taken from each site immediately above and below failed slopes (Southall *et al*., 2017). The cosmogenic ages from this study cluster in the deglacial period 18–17 kyr, broadly representing the timing of local ice retreat and debuttressing of bedrock slopes. However, there is relatively wide scatter of the three ages from each site, with some ages not overlapping at 1σ level. In addition, the global CRONUS-Earth

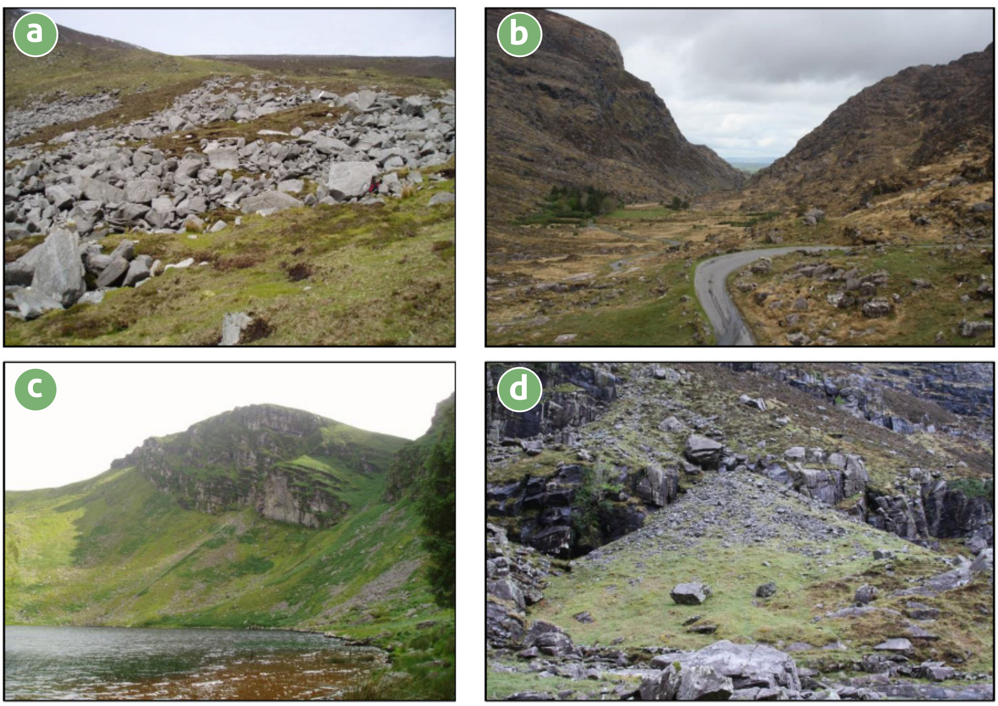

Figure 2: Examples of glacial-paraglacial imprints in Irish mountains. (a) Blockfields, remobilised into boulder lobes, on Corraun (Co. Mayo); (b) oversteepened bedrock slopes and a glacially breached valley, Gap of Dunloe (Co. Kerry); note the rock slope failure present at the back of the cirque (left middle of image); (c) scree slopes masking the lower slopes of a glacial cirque, Lough Slat (Co. Kerry); (d) talus cone, Gap of Dunloe (Co. Kerry).

calibration dataset used (Marrero *et al*., 2016) might not provide the most appropriate local nuclide production rate. The calibrated radiocarbon ages on organic sediments contained in land surface depressions associated with the RSFs cluster in the periods 1300–1500 and 300–500 cal yr BP, the former representing climatic deterioration and the latter land use change (Southall *et al*., 2017). At Muckish (Co. Donegal), Wilson and Matthews (2016) examined RSF blocks and different periglacial landforms (blockfields, talus, boulder lobes and debris cones) and used Schmidt hammer surface exposure dating to assess their relative ages. Results suggest a dominantly early Holocene age for these different features, and some evidence for late Holocene slope reactivation. These studies in Irish mountain geomorphology highlight the importance of local-scale factors including microclimate variability, aspect, rock type and structure, and feedbacks caused by vegetation and soil cover. These factors mean that calculated ages of mass movements may reflect local rather than regional (glacial unloading) controls (Southall *et al*., 2017). Today, oversteepened rock slopes still exist in the landscape, as a glacial relict, whereas other slopes may be partly or wholly covered by later scree or debris cones (Figure 2), which can be formed in both cold and warm climate regimes and thus span lateglacial and Holocene periods.

Paraglacial imprints in fluvial environments

Studies on Irish rivers have not commonly viewed their Holocene dynamics or landform record through a paraglacial lens or have been examined as source-to-sink systems (Figure 3a). There are few basic geomorphic studies on Irish rivers, including their sedimentology and dating of terrace or floodplain deposits. The most significant and irreversible impact that glaciation has on river systems is through net erosion, mainly in bedrock headwater areas, leading to local migration of drainage divides. There is some evidence for this in the Sperrin Mountains (Colhoun, 1966). More visibly, subglacial erosion either by ice or meltwater has led to 3rd- or 4th-order catchments being split up by the formation of new valleys or channels that are incised deep into pre-existing hills or ridges. These valleys are termed glacial breaches. Good examples are known from most mountain blocks across Ireland, including Hollywood Glen (Co. Wicklow) (Figure 3b). Many breached valleys, as well as many U-shaped upland valleys that have been widened by glacial incision, are deeply incised into bedrock which is exposed on valley sides or have been later infilled by (mainly deglacial and some Holocene) sediments (Croke, 1994; Hegarty, 2012). In the latter case, this results in underfit rivers with very shallow long profiles. From initial work on the River Liffey by Cole (1912), several Irish rivers are known to have changed their courses as a result of glacial erosion (and sometimes deposition), although there are few recent studies on these rivers. Mitchell and Ryan (1997) discuss several examples. On the River Shannon, retreating ice to the west acted as a blockage to southward river flow in the area of Strokestown (Co. Roscommon). This diverted river flow eastwards through a sandstone and shale ridge at Derrycarne Narrows, and into its present channel at Termonbarry and Lanesborough (Co. Longford), 10km east of its original position. In a second example, drainage of a glacial lake across a bedrock ridge north of Galbally

(Co. Limerick), cut a deep overflow channel and diverted surface water from the north-flowing River Shannon into the south-flowing River Blackwater.

Different paraglacial expressions can be identified at different points along the river long profile. Some river terrace deposits derived from the lateglacial/early Holocene period are located in river headwater areas in mountain valleys. For example, within the Gaddagh River valley, Macgillycuddy's Reeks, single and paired terraces have been linked to phases of sediment and meltwater release and subsequent phases of reworking from retreating mountain glaciers (Anderson *et al.*, 2004). The contribution of different sediment sources to these paraglacial river terraces is unknown; potentially this can include reworking of glacial moraines or outwash. Sediments within these terraces include clast-supported, imbricated conglomerates that suggest deposition from debris flows and high-energy flood events dominated by bedload transport (Anderson *et al.*, 2004). The terraces were developed inside lateglacial moraines; therefore, the river quarried pre-existing glacial material to create the terraces and the fluvial system was isolated from

Figure 3: Examples of paraglacial imprints in Irish rivers. (a) Source-to-sink fluvial sediment system of the Glen Peninsula (Co. Donegal). Sediment is contributed from paraglacial slope storage areas: (1) to the underfit river channel, (2) and then to coastal depocentres in Loughros Beg (3). However, it is unlikely that any sediment completes this journey unimpeded; (b) breached watershed in the form of a subglacial meltwater channel, Hollywood Glen, Wicklow Mountains (Co. Wicklow); (c) interlocking spurs developed in slope sediments within a confined valley, Glencolmcille (Co. Donegal); (d) aggradational paraglacial floodplain with paired terraces, Gaddagh valley (Co. Kerry).

surrounding mountain sides by the lateral moraines. Any change in the fluvial system was, therefore, climatic or related to isostatic uplift, rather than driven by sediment fluxes from valley sides. It is notable that there are areas of high paraglacial sediment storage within mountain valleys (Figure 3c, d), leading to very constricted valley floors, interlocking spurs and limited capacity for sediment export into middle river reaches. These middle reaches on Irish rivers are very little known. Gallagher (1997, 1998) used the presence of heavy minerals within alluvial and channel deposits as an indicator of erratic carriage by glaciers into the Slieve Bloom massif (Co. Offaly). Thus, mineralogical composition and other properties of river sediments such as grain size distribution may reflect a paraglacial imprint.

In lowland river landscapes, there is very limited evidence for a direct glacial imprint on the river systems. Seismic data show the positions of the lateglacial lowstand River Lagan channel in Belfast Lough (Kelley *et al*., 2006). Similar geophysical and borehole data were used to identify and map similar lowstand channels of the River Lee and Owenboy River (Co. Cork), that were subsequently infilled during postglacial sea-level rise (Davis *et al*., 2006). However, it is notable that previous interglacial sediments are also preserved within these palaeochannels (Dowling *et al*., 1998), and that they were merely reoccupied during later glacial and interglacial phases.

Paraglacial imprints in coastal environments

The paraglacial context of coastal landforms in Ireland has been discussed over a long period (Carter and Orford, 1988; Greenwood and Orford, 2008; Wilson, 2017). The basis behind this association is that glacigenic sediment was transported to and deposited in particular on the Atlantic continental shelf during the late Midlandian and was extensively reworked onshore by wind and water following ice retreat. Today's coastal environment contains large volumes of loose sandy sediments within the nearshore zone, on beaches, within sand dunes, sand flats and estuaries that are relatively immobile or relict under today's environmental conditions. This fact suggests that these sediments were derived by processes that are no longer active, or under environmental conditions that are different to those prevailing today. In addition, submarine geophysical data show that relict sandy landforms (subaqueous dunes, beaches, channels) lie preserved on the continental shelf or below wave base, showing that they were formed under different sea-level conditions and then were overstepped and drowned by postglacial sea-level rise (McDowell *et al*., 2005; Kelley *et al*., 2006). Several significant coastal landforms, found around the Irish coastline today, can be considered as paraglacial features. These are now described.

Ice convergence and sediment deposition in lowland embayments, especially in western Ireland, resulted in the formation of drumlins and ribbed moraines. Where these landforms are present within today's intertidal zone or are intersected by sea level, coastal erosion can cause undercutting of glacial cliffs leading to slope failure and sediment release to the marine environment (Forbes and Syvitski, 1994; Manson, 2002; Himmelstoss *et al*., 2006). Examples have been well described from Co. Donegal (Knight, 2011), Co. Down (McGreal, 1979), Clew Bay (Hanvey, 1988), Galway Bay (McCabe and

Dardis, 1989) and Strangford Lough (Greenwood and Orford, 2008). Following erosion of this glacial sediment by waves and tides, cobbles and boulders tend to be left within the intertidal zone as a residual lag (e.g., Figure 4a) which acts as an armour against beach erosion. Erosion of small drumlin islands over time means that progressively these obstacles are reduced to mounds of boulders, changing the morphology and sediment budget of the intertidal zone (Greenwood and Orford, 2008). In Loughros Beg (Co. Donegal), small drumlin islands are surrounded by a residual armour of boulders, and have acted as barriers that decrease tidal energy, encouraging the development of muddy intertidal creeks and saltmarsh on their landward sides (Figure 4b). Carter and Orford (1988) developed a conceptual model for coastal erosion of drumlins in Clew Bay, and the transformation of drumlin sediments into gravel ridges, prograding leeside gravel beaches, washover fans and migrating sandy barriers and spits. Fine sediments released by drumlin erosion may be washed out to sea or retained nearshore within today's estuaries and fringing saltmarshes. Cooper (2004) classified Irish estuaries based largely on their relict paraglacial status. Those in northwest Ireland are dominantly barred drowned valleys, whereas in western Ireland bar-built estuaries dominate. Back-barrier lagoon fills and saltmarsh sediments in western Ireland are derived ultimately from nearshore glacial sediment sources (Delaney and Devoy, 1995). A detailed case study of Connell's Bank, Loughros More (Co. Donegal) shows how a glacial moraine now located within the intertidal zone has been modified over time by different physical drivers and processes. These include winnowing of the cobble surface by postglacial sea-level rise, waves and tides; sediment supply to adjacent beaches and sand dunes; aeolian abrasion and formation of ventifacts; and control by the bank on the position of today's tidal channels (Knight and Burningham, 2014).

Throughout western Ireland, coastal sand dunes, sandy beaches, saltmarsh and estuaries are the expression of high postglacial sediment supply provided from glacigenic sediment sources. Thus, they can be considered to reflect enhanced paraglacial sediment supply. There are very few dating studies on Irish sand dunes, but most dates from the north coast dunes are from the late Holocene and generally correspond to cooler, windier climatic periods with higher onshore sediment supply (e.g., Wilson and Braley, 1997; Wilson *et al*., 2004). At Magilligan foreland (Co. Derry), beach ridges started to form around 7000–6500 years BP, likely associated with the mid-Holocene highstand (Wilson and Farrington, 1989). Development of very large spits (e.g., Rossbeigh, Co. Kerry, Figure 4d) attests to high sediment supply and a highly energetic Atlantic-facing coast. Luminescence dating of Inch Spit, directly opposite Rossbeigh Spit in Dingle Bay (Co. Kerry), and the high scatter of the luminescence signals in the samples, reveals both young ages of the sediment (150–600 years) and high sediment dynamics (Wintle *et al*., 1998).

Figure 4: Examples of paraglacial imprints along Irish coasts. (a) Steep eroded face of a drumlin at White Strand, Galway Bay (Co. Galway). Loose boulders excavated from the cliff face are left as a residual lag across the foreshore; (b) eroded drumlins and sand-choked estuary at Loughros Beg (Co. Donegal); (c) intertidal cobbles and sand on a gravel bank (Connell's Bank, Co. Donegal); (d) Rossbeigh spit (Co. Kerry).

Discussion

Ireland bears the erosional and depositional signatures of late Pleistocene glaciations, but its landscapes today are not a static representation of the past, but rather are in continued evolution through changing patterns of sediment availability (landforms) and sediment yield (erosion). Thus, the landscapes of Ireland can be considered to bear a strong paraglacial imprint. However, this imprint is not spatially or temporally uniform. In a sediment systems context, a paraglacial response is usually initiated in steep mountain environments. Then, high sediment yield by slope instability and high fluvial sediment transport results in high sediment yield into lowland river systems and finally to fronting coasts (Knight and Harrison, 2009). This viewpoint assumes that this sediment cascade system is integrated and that there are no time lags, imposed by sediment capture, within the system (Figure 5). However, as presented above, the paraglacial processes and signatures in mountains, rivers and coasts in Ireland do not reflect a conveyor belt-like system of sediment transport. Instead, sediment is captured (buffered) at geomorphic and topographic constrictions in the landscape, within mountains and coasts. Figure 5 presents a model illustrating how a source-to-sink paraglacial sediment conveyor belt applies in Ireland. In **mountains**, paraglacial sediment is captured in valleys and export from these valleys is restricted due to confinement of the river channel (Figure 3). Along **rivers**, low sediment supply, underfit river channels, low river gradients, and wide floodplains with very low accommodation space mean that many lowland river systems in Ireland are geomorphically ineffective except under extreme floods (Turner *et al.*, 2010). It is notable that in lowland reaches, fluvial sediment yield declines through the Holocene as floodplains are buried by peat growth (Thorp and Glanville, 2003). On **coasts**, sediment within sand dunes, estuaries, saltmarsh and beaches has built up progressively over time, mainly in the Holocene as sea level stabilised. These sediment stores have acted as a buffer against continued sea-level rise. The Irish coast receives very little 'new' sediment from incoming rivers, and present coastal dynamics involve reworking of pre-existing intertidal and nearshore landforms, including drumlins (Figure 4).

What is notable is that paraglacial sediment systems in Ireland are strongly compartmentalised, with areas of sediment constriction between the process domains of mountains, rivers and coasts (Figure 5). This contrasts with many studies in Canada and the European Alps that show strong coupling between sediment stores (Caine and Swanson, 1989; Schrott *et al.*, 2002). Ballantyne (2002a) proposed a total paraglacial system relaxation time of around 10^3–10^5 years in total; focusing on linkages between particular slope elements, Cossart and Fort (2008) proposed slightly different decadal timescales for individual slope components. These models all show that sediment yield is initially high but then decreases over time as the sediment store is depleted. Evidence from Ireland suggests that slope stabilisation and vegetation cover (including lowland peat), not decreased total sediment storage, has caused sediment yield to reduce through the Holocene.

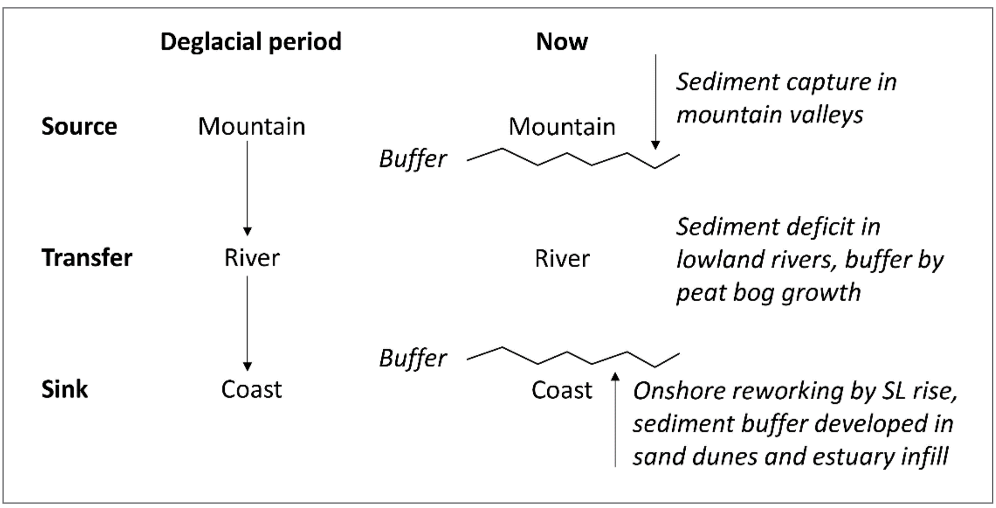

Figure 5: Model of paraglacial landscape evolution in Ireland.

Conclusions

Ireland is strongly influenced by paraglacial processes. As a result, today's geomorphological and sediment systems are still responding to the effects of late Pleistocene glaciations. However, examination of mountain, river and coastal landforms and sediment systems shows that these landscapes have, and still are, responding in different ways and over different spatial and temporal scales. As an exemplar of a landscape under paraglacial change, Ireland shows somewhat different dynamical behaviour compared to the well-studied systems of the European Alps and Canada. Here, lowland peat bog growth has acted as a hydrological and sedimentary buffer for sediment transport, limiting the connectivity between mountain source and coastal sinks (Figure 5), despite the short transport paths available in Ireland. Better understanding of mountain, river and coastal sediment systems and dynamics in Ireland can build towards a better appreciation of the role of the paraglacial process domain in shaping today's landscapes.

References

Anderson, E. and Harrison, S., 2006. Late Quaternary paraglacial sedimentation in the Macgillycuddy's Reeks, southwest Ireland. *Irish Geography*, 39, 69-77.

Anderson, E., Harrison, S., Passmore, D.G., Mighall, T.M. and Wathan, S., 2004. Late Quaternary river terrace development in the Macgillycuddy's Reeks, southwest Ireland. *Quaternary Science Reviews*, 23, 1785-1801.

Ballantyne, C.K., 2002a. A general model of paraglacial landscape response. *The Holocene,* 12, 371-376.

Ballantyne, C.K., 2002b. Paraglacial geomorphology. *Quaternary Science Reviews*, 21, 1935-2017.

Ballantyne, C.K. and Stone, J.O., 2013. Timing and periodicity of paraglacial rock-slope failures in the Scottish Highlands. *Geomorphology*, 186, 150-161.

Ballantyne, C.K. and Stone, J.O., 2015. Trimlines, blockfields and the vertical extent of the last ice sheet in southern Ireland. *Boreas*, 44, 277-287.

Ballantyne, C.K., Sandeman, G.F., Stone, J.O. and Wilson, P., 2014b. Rock-slope failure following Late Pleistocene deglaciation on tectonically stable mountainous terrain. *Quaternary Science Reviews*, 86, 144-157.

Ballantyne, C.K., Wilson, P., Gheorghiu, D. and Rodés, À., 2014a. Enhanced rock-slope failure following ice-sheet deglaciation: timing and causes. *Earth Surface Processes and Landforms*, 39, 900-913.

Ballantyne, C.K., Wilson, P., Schnabel, C. and Xu, S., 2013. Lateglacial rock slope failures in north-west Ireland: age, causes and implications. *Journal of Quaternary Science*, 28, 789-802.

Barth, A.M., Clark, P.U., Clark, J., McCabe, A.M. and Caffe, M., 2016. Last Glacial Maximum cirque glaciation in Ireland and implications for reconstructions of the Irish Ice Sheet. *Quaternary Science Reviews*, 141, 85-93.

Burningham, H. and Cooper, J.A.G., 2004. Morphology and historical evolution of north-east Atlantic coastal deposits: the west Donegal estuaries. *Journal of Coastal Research*, SI41, 148-159.

Caine, N. and Swanson, F.J., 1989. Geomorphic coupling of hillslope and channel systems in two small mountain basins. *Zeitschrift für Geomorphologie, NF*, 33, 189-203.

Carter, R.W.G. and Orford, J.D., 1988. Conceptual model of coarse clastic barrier formation from multiple sediment sources. *Geographical Review*, 78, 221-239.

Carter, R.W.G., Orford, J.D., Forbes, D.L. and Taylor, R.B., 1987. Gravel barriers, headlands and lagoons: an evolutionary model. *Coastal Sediments '87*. ASCE, New Orleans, 1776-1792.

Charlesworth, J.K., 1957. *The Quaternary Era*. London: Edward Arnold.

Church, M. and Ryder, J.M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Bulletin of the Geological Society of America*, 83, 3059-3071.

Clark, C.D. and Meehan, R.T., 2001. Subglacial bedform geomorphology of the Irish Ice Sheet reveals configuration changes during growth and decay. *Journal of Quaternary Science*, 16, 483-496.

Cole, G.A.J., 1912. The problem of the Liffey valley. *Proceedings of the Royal Irish Academy, Series B*, 30, 8-19.

Colhoun, E.A., 1966. Some examples of glacial drainage channels in the Sperrin Mountains, Northern Ireland. *BGRG Occasional Paper*, 3, 18-24.

Cooper, J.A.G., 2004. Geomorphology of Irish estuaries: inherited and dynamic controls. *Journal of Coastal Research*, SI39, 176-180.

Cossart, É. and Fort, M., 2008. Sediment release and storage in early deglaciated areas: Towards an application of the exhaustion model from the case of Massif des Écrins (French Alps) since the Little Ice Age. *Norsk Geografisk Tidsskrift–Norwegian Journal of Geography*, 62, 115-131.

Cossart, É., Mercier, D., Decaulne, A. and Feuillet, T., 2013. An overview of the consequences of paraglacial landsliding on deglaciated mountain slopes: typology, timing and contribution to cascading fluxes. *Quaternaire,* 24, 13-24.

Croke, J., 1994. The buried bedrock profile and Quaternary valley fill deposits of the Glenmalure valley, County Wicklow. *Irish Journal of Earth Sciences*, 13, 1-9.

Curry, A.M., 1999. Paraglacial modification of slope form. *Earth Surface Processes and Landforms*, 24, 1213-1228.

Davis, T., MacCarthy, I.A.J., Allen, A.R. and Higgs, B., 2006. Late Pleistocene-Holocene buried valleys in the Cork Syncline, Ireland. *Journal of Maps*, 2006, 79-93.

Delaney, C. and Devoy, R., 1995. Evidence from sites in Western Ireland of late Holocene changes in coastal environments. *Marine Geology*, 124, 273-287.

Dowling, L.A., Sejrup, H.P., Coxon, P. and Heijnis, H., 1998. Palynology, aminostratigraphy and U-series dating of marine Gortian interglacial sediments in Cork Harbour, Southern Ireland. *Quaternary Science Reviews*, 17, 945-962.

Embleton-Hamann, C. and Slaymaker, O., 2012. The Austrian Alps and paraglaciation. *Geografiska Annaler: Series A, Physical Geography*, 94, 7-16.

Feuillet, T., Coquin, J., Mercier, D., Cossart, É., Decaulne, A., Jónsson, H.P. and Sæmundsson, Þ., 2014. Focusing on the spatial non-stationarity of landslide predisposing factors in northern Iceland: Do paraglacial factors vary over space? *Progress in Physical Geography*, 38, 354-377.

Forbes, D.L. and Syvitski, J.P.M., 1994. Paraglacial coasts. *In:* R.W.G. Carter and C.D. Woodroffe (eds.), *Coastal Evolution – Late Quaternary shoreline morphodynamics*. Cambridge: Cambridge University Press, 373-424.

Gallagher, C., 1997. Alluvial heavy minerals as indicators of Late Pleistocene ice flow in the Irish Midlands. *Irish Geography*, 30, 37-48.

Gallagher, C., 1998. A reconstruction of Pleistocene ice sheet limits in Slieve Bloom using heavy minerals. *Irish Geography*, 31, 100-110.

Greenwood, R.O. and Orford, J.D., 2008. Temporal patterns and processes of retreat of drumlin coastal cliffs – Strangford Lough, Northern Ireland. *Geomorphology*, 94, 153-169.

Greenwood, S.L. and Clark, C.D., 2009. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. *Quaternary Science Reviews*, 28, 3101-3123.

Hanvey, P.M., 1988. *The sedimentology and genesis of late-Pleistocene drumlins in Counties Mayo and Donegal, western Ireland*. Unpublished DPhil Thesis, University of Ulster, 614pp.

Harrison, S., Glasser, N., Anderson, E., Ivy-Ochs, S. and Kubik, P.W., 2010. Late Pleistocene mountain glacier response to North Atlantic climate change in southwest Ireland. *Quaternary Science Reviews*, 29, 3948-3955.

Hegarty, S., 2012. The dry channels at Ballyfoyle, Co. Kilkenny: a relict landscape of subglacial water. *Irish Geography*, 45, 175-197.

Himmelstoss, E.A., FitzGerald, D.M., Rosen, P.S. and Allen, J.R., 2006. Bluff evolution along coastal drumlins, Boston Harbor Islands, Massachusetts. *Journal of Coastal Research*, 22, 1230-1240.

Hughes, A.L.C., Clark, C.D. and Jordan, C.J., 2014. Flow-pattern evolution of the last British Ice Sheet. *Quaternary Science Reviews*, 89, 148-168.

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R.S., Clague, J.J., Vuille, M., Buytaert, W., Cayan, D.R., Greenwood, G., Mark, B.G., Milner, A.M., Weingartner, R. and Winder, M., 2017. Towards mountains without permanent snow and ice. *Earth's Future*, 5, 418-435.

Jarman, D., 2006. Large rock slope failures in the Highlands of Scotland: Characterisation, causes and spatial distribution. *Engineering Geology*, 83, 161-182.

Johnson, R.M. and Warburton, J., 2002. Annual sediment budget of a UK mountain torrent. *Geografiska Annaler: Series A, Physical Geography*, 84A, 73-88.

Keiler, M., Knight, J. and Harrison, S., 2010. Climate change and geomorphological hazards in the eastern European Alps. *Philosophical Transactions of the Royal Society of London, Series A*, 368, 2461-2479.

Keller, B., 2017. Massive rock slope failure in Central Switzerland: history, geologic–geomorphological predisposition, types and triggers, and resulting risks. *Landslides*, 14, 1633-1653.

Kelley, J.T., Cooper, J.A.G., Jackson, D.W.T., Belknap, D.F. and Quinn, R.J., 2006. Sea-level change and inner shelf stratigraphy off Northern Ireland. *Marine Geology*, 232, 1-15.

Knight, J., 1999. Problems of Irish drumlins and Late Devensian ice sheet reconstructions. *Proceedings of the Geologists' Association*, 110, 9-16.

Knight, J., 2010. Basin-scale patterns of subglacial sediment mobility: implications for glaciological inversion modelling. *Sedimentary Geology*, 232, 145-160.

Knight, J., 2011. Drumlin formation in a confined bedrock valley, northwest Ireland. *Boreas*, 40, 289-302.

Knight, J. and Burningham, H., 2014. A paraglacial coastal gravel structure: Connell's Bank, NW Ireland. *Journal of Coastal Research,* SI70, 121-126.

Knight, J. and Harrison, S., 2009. Sediments and future climate. *Nature Geoscience*, 3, 230.

Knight, J. and Harrison, S., 2014. Mountain glacial and paraglacial environments under global climate change: lessons from the past and future directions. *Geografiska Annaler: Series A, Physical Geography*, 96, 245-264.

McCabe, A.M., 2008. *Glacial Geology and Geomorphology. The Landscapes of Ireland*. Edinburgh: Dunedin Academic Press, 274pp.

McCabe, A.M. and Dardis, G.F., 1989. Sedimentology and depositional setting of late Pleistocene drumlins, Galway Bay, western Ireland. *Journal of Sedimentary Petrology*, 59, 944-959.

McColl, S.T., 2012. Paraglacial rock-slope stability. *Geomorphology*, 153-154, 1-16.

McDowell, J.L., Knight. J. and Quinn, R., 2005. High resolution geophysical investigations seaward of the Bann estuary, Northern Ireland coast. *In:* D.M. FitzGerald and J. Knight (eds.), *High Resolution Morphodynamics and Sedimentary Evolution of Estuaries*. Dordrecht: Springer, 11-31.

McGreal, W.S., 1979. Cliffline recession near Kilkeel N. Ireland; an example of a dynamic coastal system. *Geografiska Annaler*, 61A, 211-219.

Manson, G.K., 2002. Subannual erosion and retreat of cohesive till bluffs, McNab's Island, Nova Scotia. *Journal of Coastal Research*, 18, 421-432.

Marrero, S.M., Phillips, F.M., Caffee, M.W. and Gosse, J.C., 2016. CRONUS-Earth cosmogenic ^{36}Cl calibration. *Quaternary Geochronology*, 31, 199-219.

Mercier, D., 2008. Paraglacial and paraperiglacial landsystems: concepts, temporal scales and spatial distribution. *Géomorphologie: relief, processus, environnement*, 2008, 223-234.

Mercier, D., Étienne, S., Sellier, D. and André, M.-F., 2009. Paraglacial gullying of sediment-mantled slopes: a case study of Colletthøgda, Kongsfjorden area, West Spitsbergen (Svalbard). *Earth Surface Processes and Landforms*, 34, 1772-1789.

Micheletti, N. and Lane, S.N., 2016. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. *Water Resources Research*, 52, 4924-4943.

Mitchell, F. and Ryan, M., 1997. *Reading the Irish Landscape*. Dublin: Town House Press, 392pp.

Ó Cofaigh, C., Telfer, M.W., Bailey, R.M. and Evans, D.J.A., 2012. Late Pleistocene chronostratigraphy and ice sheet limits, southern Ireland. *Quaternary Science Reviews*, 44, 160-179.

Owen, L.A., Thackray, G., Anderson, R.S., Briner, J., Kaufman, D., Roe, G., Pfeffer, W. and Yi, C., 2009. Integrated research on mountain glaciers: Current status, priorities and future prospects. *Geomorphology*, 103, 158-171.

Petley, D.N., Hearn, G.J., Hart, A., Rosser, N.J., Dunning, S.A., Owen, K. and Mitchell, W.A., 2007. Trends in landslide occurrence in Nepal. *Natural Hazards,* 43, 23-44.

Scapozza, C., 2016. Evidence of paraglacial and paraperiglacial crisis in alpine sediment transfer since the last glaciation (Ticino, Switzerland). *Quaternaire*, 27, 139-155.

Schrott, L., Niederheide, A., Hankammer, M., Hufschmidt, G. and Dikau, R., 2002. Sediment storage in a mountain catchment: geomorphic coupling and temporal variability (Reintal, Bavarian Alps, Germany). *Zeitschrift für Geomorphologie, Supplementbund*, 127, 175-196.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S. and Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*, 22, 1111-1129.

Smith, M.J. and Knight, J., 2011. Palaeoglaciology of the last Irish Ice Sheet reconstructed from striae evidence. *Quaternary Science Reviews*, 30, 147-160.

Southall, D.W., Wilson, P., Dunlop, P., Schnabel, C., Rodés, Á., Gulliver, P. and Xu, S., 2017. Age evaluation and causation of rock-slope failures along the western margin of the Antrim Lava Group (ALG), Northern Ireland, based on cosmogenic isotope (^{36}Cl) surface exposure dating. *Geomorphology*, 285, 235-246.

Thorp, M. and Glanville, P., 2003. Mid-Holocene sub-blanket-peat alluvia and sediment sources in the upper Liffey valley, Co. Wicklow, Ireland. *Earth Surface Processes and Landforms*, 28, 1013-1024.

Turner, J.N., Macklin, M.G., Jones, A.F. and Lewis, H., 2010. New perspectives on Holocene flooding in Ireland using meta-analysis of fluvial radiocarbon dates. *Catena*, 82, 183-190.

Vaughan, A.P.M., Dowling, L.A., Mitchell, F.J.G., Lauritzen, S.E., McCabe, A.M. and Coxon, P., 2004. Depositional and post-depositional history of warm stage deposits at Knocknacran, Co. Monaghan, Ireland: implications for preservation of Irish last interglacial deposits. *Journal of Quaternary Science*, 19, 577-590.

Warren, W.P., 1992. Drumlin orientation and the pattern of glaciation in Ireland. *Sveriges Geologiska Undersökning*, 81, 359-366.

Wilson, P., 2004. Relict rock glaciers, slope failure deposits, or polygenetic features? A re-assessment of some Donegal debris landforms. *Irish Geography*, 37, 77-87.

Wilson, P., 2017. Periglacial and paraglacial processes, landforms and sediments. In: P. Coxon, S. McCarron and F. Mitchell (eds.), *Advances in Irish Quaternary Studies*. Paris: Atlantis Press, 217-254.

Wilson, P. and Braley, S.M., 1997. Development and age structure of Holocene coastal sand dunes at Horn Head, near Dunfanaghy, Co. Donegal, Ireland. *The Holocene*, 7, 187-197.

Wilson, P. and Farrington, O., 1989. Radiocarbon dating of the Holocene evolution of Magilligan Foreland, Co. Londonderry. *Proceedings of the Royal Irish Academy, Series B,* 89B, 1-23.

Wilson, P. and Matthews, J.A., 2016. Age assessment and implications of late Quaternary periglacial and paraglacial landforms on Muckish Mountain, northwest Ireland, based on Schmidt-hammer exposure-age dating (SHD). *Geomorphology*, 270, 134-144.

Wilson, P., McGourty, J. and Bateman, M.D., 2004. Mid- to late-Holocene coastal dune event stratigraphy for the north coast of Northern Ireland. *The Holocene*, 14, 406-416.

Wintle, A.G., Clarke, M.L., Musson, F.M., Orford, J.D. and Devoy, R.J.N., 1998. Luminescence dating of recent dunes on Inch Spit, Dingle Bay, southwest Ireland. *The Holocene*, 8, 331-339.1