

The Pre-Quaternary Landscape of Ireland

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Abstract The effect on Ireland's landscape of glacial erosion and deposition has been profound but many of the major landscape elements are demonstrably pre-Quaternary in origin. The island's broad outline reflects the configuration of offshore post-Palaeozoic basins, while the disposition of hills and valleys commonly reflects the lithology and geological structure of the underlying bedrock. Most of Ireland's largest rivers are structurally controlled and have their origins earlier in the Cenozoic, but several aspects of the Shannon suggest that parts at least of this system are far younger. The differential relief of Ireland's landscape immediately prior to the onset of glaciation would have been greater than today, with often deeply karstified limestone lowlands interspersed with weathered silicate uplands. Glacial processes during the Pleistocene have largely scoured the weathered regolith from the uplands and buried much of the lowland karst, but a few remarkable sites afford glimpses of these pre-glacial landscapes and provide a measure of the extent, locally, of the glacial modification of this pre-existing landscape.

1 Introduction

It is a common misconception, at least in the non-scientific community, that Ireland's landscape was sculpted largely by glacial processes. Ice is very effective as an erosive agent but its role in shaping the Irish landscape has been confined very largely to the last 2.6 million years, the Pleistocene Period, when the region experienced repeated glaciations that extended across much or all of the country and for some distance offshore (Coxon and McCarron 2009). It is uncertain to what extent the earlier

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Pleistocene glaciations affected Ireland since subsequent glacial episodes have largely erased evidence of them. Spectacular evidence of this glacial legacy is ubiquitous across the landscape. Glacially scoured surfaces, overdeepened U-shaped valleys, corries and tors are abundant features of upland landscapes. Drumlins, eskers, moraines, fluvio-glacial sands and gravels, and the ubiquitous 'diamict', are integral components of many lowland landscapes today. Glacial landforms, whether erosional or depositional, are superimposed onto larger-scale landscapes developed on the various lowland and upland regions of Ireland, but to what extent might these be considered glacial landscapes? How much do they in fact owe to factors that significantly predate the onset of glaciation across this island?

It can be assumed that ice would have been insignificant as an erosive agent in Ireland in pre-Quaternary times and instead it would have been the effects of weathering and erosion in a temperate climate that would have dominated the development of the pre-glacial landscape for as much as sixty million years, from when Ireland became an emergent landmass at the beginning of the Cenozoic Era. The landforms that developed were superimposed onto, and strongly influenced by, a lithologically and structurally complex underlying geology that extends back still further, in some regions for more than a billion years. Hence, rather than being a product largely of Quaternary glaciations, the present Irish landscape owes more to events and processes that occurred tens or even hundreds of millions of years ago.

2 Landscape Processes

The fabric of a landscape arises through the interaction of several different factors. Key among these is the nature of the denudational and depositional processes that have affected the different rock types exposed in the landscape. Many conspicuous elements of the present landscape of Ireland clearly owe much to glacial processes but the focus of this chapter is the pre-glacial landscape that had developed prior to the marked climatic deterioration at the start of the Pleistocene. In a pre-glacial Irish context weathering and fluvial erosion are the predominant landscape agents. Weathering is a low energy, dispersed, and relatively continuous process that affects rocks in situ and is enhanced by the presence of a cover of soil and vegetation. Soluble components are removed in solution or are chemically altered to leave an insoluble residue, or saprolite. Especially soluble rocks, such as limestone and gypsum, often are removed in their entirety by solution. In contrast, fluvial erosion is a high energy and intermittent process, localized into channels, that involves the physical disaggregation and transport of rock particles. Furthermore, it is hindered by the presence of vegetation that can form a barrier between flowing water and the soil or weathered rock beneath while also acting as a binding agent for loose particles. In humid temperate climates, where there is abundant vegetation, flowing water must exceed a specific velocity threshold before any erosion can occur. In contrast, even static water can effect chemical weathering of the rocks with which it is in contact. The response of different rock types to weathering and erosion varies.

Some rocks are mechanically strong when fresh and so initially may resist erosion, yet their mineralogy and/or texture may render them susceptible to chemical and/or mechanical weathering. Chemical weathering of high-temperature silicates can reduce granites and other igneous rocks to clays, with thermal effects such as freeze-thaw able to disaggregate these and other, chemically resistant, lithologies. Thus weakened, they become more vulnerable to subsequent erosion. We include slope processes within this general interpretation of erosion, as it involves movement of solid material, often through the agency of water, is hindered by vegetation, and is a high-energy process. However, in the case of limestone, a rock type that underlies some 40 % of Ireland's present land surface, the process of chemical weathering actually removes the rock directly and in its entirety through solution without the necessity for physical erosion. Understanding the relative roles of weathering and erosion in a mixed-lithology landscape subjected to a temperate to sub-tropical climate is fundamental to determining how the pre-Quaternary landscape in Ireland developed (Simms 2004).

An additional factor influencing landscape evolution is the geological structure imposed by tectonic processes onto the varied rock types across Ireland, from the scale of individual fractures up to regionally significant structures developed on scales of tens of km. Fractures facilitate groundwater flow and act as foci for weathering and erosion, with zones of shattered rock adjacent to faults rendering these regions more susceptible to both weathering and erosion than surrounding rock. On a larger scale, the folding and/or faulting of rocks can juxtapose at the surface different lithologies that respond differently to weathering and erosion. With so much of Ireland's landscape developed on Palaeozoic or older rocks, tectonic structures have exerted a profound influence on landscape evolution both before and during the Quaternary glaciations. A more direct role for tectonism in the development of the Cenozoic landscape has been advocated by various authors (e.g. Dewey 2000), although direct evidence of Cenozoic faulting and its effect on the landscape is sparse.

3 Why Seek the Pre-glacial Landscape?

From the point of view of a Quaternary scientist, what might a knowledge of the pre-glacial landscape tell us about the development of the landscape and the formative processes that have operated on it through the glacial and interglacial periods of the Pleistocene? There is no escaping that many landforms, such as drumlins, eskers and corries, can be attributed directly to erosional and/or depositional glacial processes, but for others the evidence for a glacial origin, or at least some glacial influence, is more equivocal. On a landscape rather than landform scale, i.e. mountains, valleys and coastlines, a significant element of pre-glacial history seems inescapable even if subsequent modification by glacial processes has been substantial. Identifying these pre-glacial features can help to dispel the misconception that Ireland's present landscape has been moulded largely by ice, but it

is also of more direct significance because some of these large-scale landscape features may have had a profound and persistent influence on patterns of ice accumulation and movement through the Pleistocene.

To assess the extent to which elements of Ireland's pre-Quaternary topography persist in the modern landscape, and to identify those landscape features that can be attributed directly to glacial processes, we need to consider how the various landscape processes, and the geological factors that are specific to Ireland, have influenced the development of the country's uplands and lowlands, its lakes and rivers, and its coastline.

4 Ireland's Pre-glacial Foundation

Much of Ireland's geology, both stratigraphically and in terms of outcrop area, predates the Cenozoic (Holland and Sanders 2009) and it is upon this largely Palaeozoic foundation that the present landscape has been imposed. The distribution of Cretaceous marine sediments, the Ulster White Limestone Formation of the Chalk Group, demonstrates that at least north-eastern Ireland was submerged by the late Cretaceous sea while the lack of significant clastic input to these remarkably pure limestones, even adjacent to tectonically positive areas such as the Highland Border Ridge (Fletcher 1977), indicates total submergence of the region at this time. The discovery of a tiny outlier of similarly detritus-free late Cretaceous Chalk at Ballydeenlea, in Co. Kerry, (Walsh 1966) implies that this late Cretaceous submergence may have been far more extensive than this and, at its maximum extent, perhaps covered much or all of Ireland.

In the north of Ireland the evidence for early Cenozoic (Paleocene) emergence across the region is unequivocal, as evidenced by widespread karstification of the late Cretaceous Ulster White Limestone Formation over a vertical range of tens of metres (Simms 2000). Similarly the ensuing Antrim Lava Group (Paleocene) contains demonstrably subaerial lavas, palaeosols and weathering horizons (Preston 2009) and was itself followed by a further prolonged period of subaerial weathering represented by up to 80 m of saprolite developed on the Antrim Lava Group beneath the mid-Oligocene Lough Neagh Group (Mitchell 2004). The Lough Neagh Group itself provides evidence for continuing emergence, comprising lake and swamp deposits with clastics derived from weathering and erosion of the surrounding hinterland (Wilkinson et al. 1980). In fact the evidence from Northern Ireland shows conclusively that the region has been emergent throughout the Cenozoic.

Across the rest of onshore Ireland, beyond these post-Palaeozoic basins, the evidence for Cenozoic emergence is sparse but no less convincing. The apparent absence of proven Eocene deposits anywhere in Ireland suggests that the Palaeogene may have been a time of significant uplift and erosion. Evidence from apatite fission track data also indicates a period of uplift and erosion at around 50 million years ago, encompassing the Eocene (Green et al. 2000). The presence of

Oligocene to Pliocene karst infills scattered across the southern half of the country (Phillips 2001; Walsh 2001; Drew and Jones 2000) attests to widespread karstification of the limestone outcrop from at least Oligocene times while also providing qualitative limits on the scale of Neogene denudation (Simms and Boulter 2000; Walsh 2001). These various lines of evidence indicate that Ireland was an emergent landmass, subject to terrestrial weathering and erosion, for at least 60 million years before the onset of the Quaternary glaciations. Hence it would seem inevitable that significant elements of the pre-Quaternary landscape should survive in some form. So how might the landscape have changed since the Pliocene, immediately pre-glacial, and what elements of this earlier landscape might we still recognize today?

5 The Coastline

The coastline is what defines Ireland as a geographical entity. Today the island's coasts are overwhelmingly erosional in nature and there is abundant evidence from headlands and islands for many kilometres of coastal retreat through the Quaternary. We can only speculate on the extent of this retreat, but it may have exceeded 100 km along parts of the Atlantic coastline through the Neogene (Walsh 2001). Much of this retreat can be attributed both to glacial erosion during cold stages and to marine erosion during intervening interglacials, but how far beyond its present limit might the Irish coastline have extended in immediately pre-Quaternary times? Might there be defining features that are independent of the vagaries of varying erosion rates and that could place a limit on the former extent of Ireland's coastline? Of course the position of the coastline at any particular moment is a function of sea level, which has varied significantly through the Cenozoic and, especially, in response to glacial-interglacial cycles of the Pleistocene.

Ireland is a largely Palaeozoic massif but its broad outline is, to a significant extent, defined by the presence of post-Palaeozoic offshore basins (Naylor and Shannon 2009). Mesozoic and Cenozoic strata in these basins are dominated by poorly indurated non-marine clastic facies and hence it is likely that these areas formed low coastal plains during the mid-to late Cenozoic (Naylor and Shannon 2009). Indeed, Tappin et al. (1994) considered that the surface of the Celtic Sea Basin has remained close to sea level since the start of the Miocene. Subsidence on the faults bounding these basins may have contributed to Ireland's increasing geographical isolation during the late Cenozoic, even if it had not actually become an island separate from Britain at that time (Fig. 1). It is upon this broad outline that a more intricate coastline has been imposed, influenced by the interplay of lithology, topography and erosion during both glacial and interglacial stages. This is seen most clearly in the south-west, where anticlinal ridges of sandstone form headlands that flank embayments eroded into the synclinal, commonly limestone-floored, valleys. An analogous pattern of lithological control is seen at other locations, such as Galway Bay, Clew Bay and Donegal/Sligo Bay, where Carboniferous limestone

outcrops similarly form the major embayments of the west coast. The Shannon Estuary is a significant anomaly in this respect, being incised across mid-Carboniferous clastics.

The disposition and configuration of drumlin fields (Fig. 1) shows that the broad limestone-floored lowlands and coastal embayments commonly were the focus of

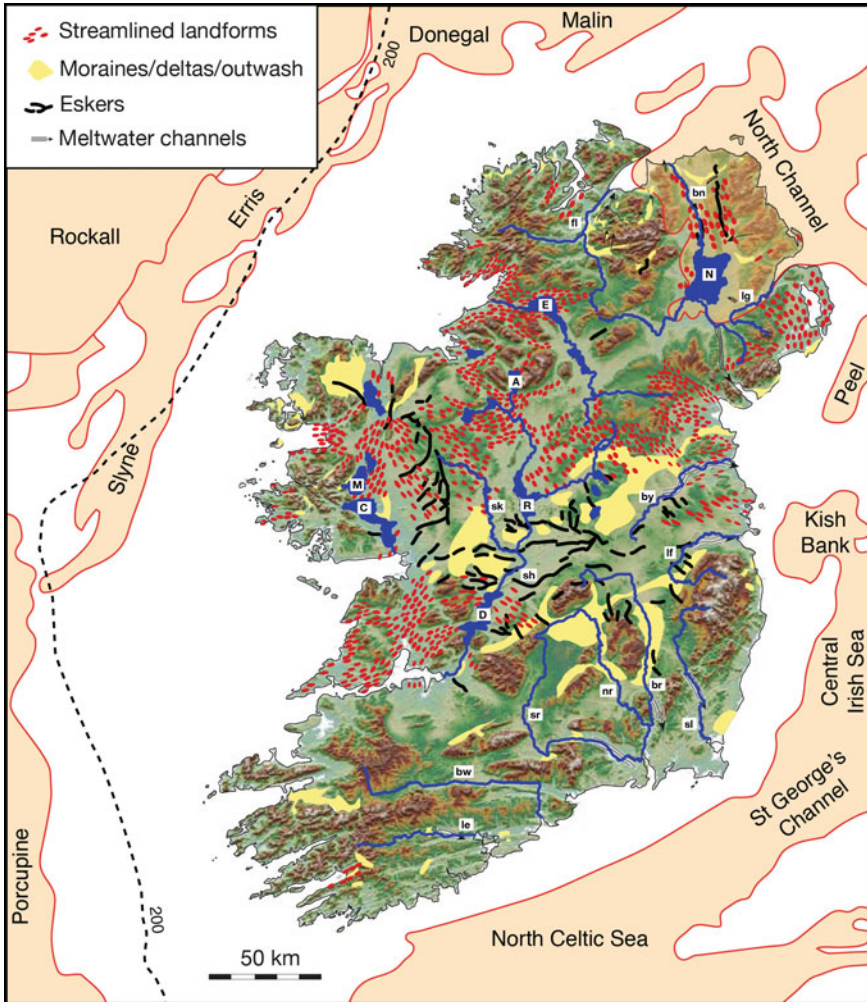


Fig. 1 The modern landscape of Ireland showing the relationship of topography and coastline to the main lakes and rivers (in blue), the offshore post-Palaeozoic basins (in pale orange), and major glacial features. Abbreviations for the lakes (loughs) are: A = Allen; C = Corrib; D = Derg; E = Erne; M = Mask; N = Neagh; R = Ree. Abbreviations for the rivers are: bn = Bann; br = Barrow; bw = Blackwater; by = Boyne; fl = Foyle; le = Lee; lf = Liffey; lg = Lagan; nr = Nore; sh = Shannon; sk = Suck; sl = Slaney; sr = Suir. Based on Coxon and McCarron (2009; Fig. 15.17) and Naylor and Shannon (2009; Fig. 17.2)

Pleistocene ice-streaming (Coxon and McCarron 2009), but did ice-streaming create these outlets or was it merely guided by a pre-existing topography? The effectiveness of glacial erosion is partly a function of the mechanical resistance of the materials over which the ice travels. Irish Carboniferous limestones are mechanically resistant even in the face of intense glacial erosion, as clearly demonstrated by the north face of the Burren hills, in Co Clare. Here a glacially smoothed scarp rises steeply above Galway Bay to a height of almost 300 m (Fig. 2), indicating that the limestone floor of Galway Bay, and its onshore extension of the Gort lowlands, owes its subdued topography largely to pre-glacial denudational processes (Simms 2005). Hence it was the pre-existence of these limestone-floored low points in the coastline that directed much of the ice-streaming rather than ice-streaming being responsible for the excavation of lowlands at these locations. It seems likely, therefore, that the dominant elements of Ireland's coastline were established several tens of millions of years ago and have been modified to only a minor extent by Quaternary glaciations.

However, during glacial maxima and the associated eustatic lowstands, ice would have extended far beyond the present coastline (Clark et al. 2012) and onto some of the offshore post-Palaeozoic basins where the relatively weakly lithified sediments may have significantly influenced ice movement and accumulation. This is true especially of the Irish Sea which was the focus of major ice accumulations during the Last Glacial Maximum and probably on numerous occasions before (Chiverrell et al. 2013).



Fig. 2 The northern scarp of the Burren Hills east of Black Head, showing the limestone strata planed smooth by ice moving south or south-westwards off the limestone lowlands now drowned beneath the waters of Galway Bay

6 Topography

In Ireland a close relationship exists between lithology and topography. Approximately 40 % of Ireland's present land area is underlain by limestone that, with few exceptions, forms lowlands that seldom rise much above 60 m. In contrast, upland areas (>150 m) almost invariably are developed on silica-dominated non-limestone lithologies such as granite, sandstone and quartzite (Simms 2004), although it must also be noted that this is not necessarily the case as in the largely lowland outcrop of the Galway granite (Coxon 2001, 2005). In terms of mechanical resistance to glacial erosion, limestone is broadly comparable with many silicate lithologies and superior to some. Hence the substantial and consistent differential relief, commonly hundreds of metres, between limestone and silicate outcrops in Ireland cannot be due to glacial erosion and must have been established largely before the onset of the Quaternary glaciations. In fact the contrasting topography of limestones and silicates is due largely to simple but fundamental differences in the way that these two broad lithological groups are denuded—dissolution versus erosion—as already described (Simms 2004). Ireland's present climate probably is not dissimilar to what prevailed here through much of the Neogene, although perhaps somewhat warmer in mid-Cenozoic times. This would have favoured weathering over erosion, causing dissolutional lowering of limestone outcrops simultaneously with the development of thick saprolites on silicate outcrops, leading to a progressive increase in Ireland's differential relief through the Neogene to a pre-glacial maximum. It seems likely that these denudational processes have prevailed since the emergence of the Irish landmass in the early Palaeogene, with surface lowering rates on limestone indicating that substantial elements of the present landscape were largely established before the close of the Palaeogene (Simms and Boulter 2000).

It has been suggested that differential fault-controlled uplift and subsidence might account for aspects of Ireland's topography (Farrington 1929; Davies 1970; Herries-Davies and Stephens 1978; Mitchell 1980) and several authors more recently have ascribed at least some elements of the present landscape to the effects of Cenozoic tectonics. Dewey (2000), Cunningham et al. (2003, 2004) and Holford et al. (2009) attribute one or more episodes of Cenozoic uplift to tectonic processes associated with compressional shortening, ridge-push effects or plume related uplift. Evidence of a tectonic role in generating topography can be proven in north-eastern Ireland where there is clear evidence of uplift and downwarping of the Paleocene surface over a vertical range of many hundreds of metres between Lough Neagh and the Mourne Mountains (Simms 2000), and there is circumstantial evidence for post-Cretaceous differential uplift in south-western Ireland too (Walsh 1966). Evidence for specifically Neogene tectonics is necessarily confined to the outcrop of the Oligocene Lough Neagh Group but it does indicate that significant tectonic movement may have continued at least locally. However, direct evidence of how Cenozoic tectonism might have affected the present topography elsewhere is difficult to find because of the prevalence of Palaeozoic and older rocks at outcrop

across much of Ireland. Some scarps in western Ireland have been attributed to faulting of a Cenozoic planation surface, but in fact they are merely a consequence of major Carboniferous faults offsetting the basal Carboniferous unconformity surface (Worthington and Walsh 2011). Supposed planation surfaces identified in other parts of Ireland have been ascribed to episodes of Cenozoic erosion. Some conspicuous examples in the southern part of Ireland, notably that developed on the southern flank of the Knockmealdown Mountains (Fig. 3); (Herries-Davies and Stephens 1978; Mitchell 1980), have been attributed to marine erosion (Miller 1939, 1955) but no marine deposits have ever been found to support this view and the widespread evidence of karstification extending back into the Palaeogene throughout the region testifies to subaerial denudation throughout this interval.

At the scale of the entire country, Ireland's limestone outcrop appears as a uniformly subdued and low-level topography punctuated by inliers and outliers of silica-dominated rocks that commonly rise above this limestone lowland (Fig. 4).

There are few substantial limestone uplands, the Burren Hills of Co. Clare and the various hills of parts of the north-west (counties Fermanagh, Cavan, Sligo and Leitrim) being notable among these. Ireland's limestone lowlands are perhaps epitomised by the low relief 'corrosion plain' of the Gort lowlands (Simms 2005),



Fig. 3 View northwards across the valley of the River Blackwater (visible in the mid-foreground) to the distant sandstone hills of the Knockmealdown Mountains. The prominent elevated planation surface of the so-called South Ireland Peneplain (Miller 1955) can be clearly seen at an altitude of around 210 m on the southern flank of the mountains

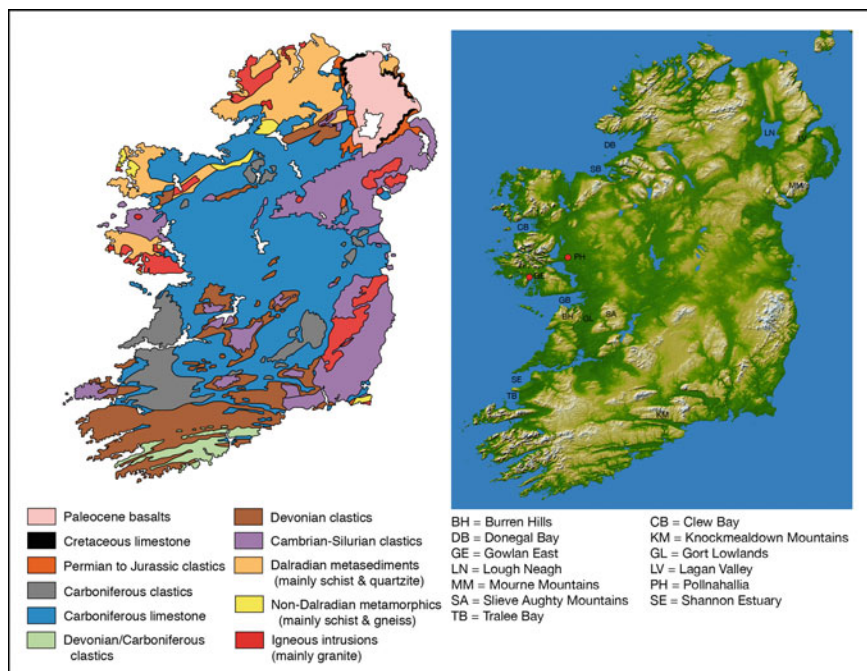


Fig. 4 Comparison of bedrock geology and topography, with locations of key sites indicated

juxtaposed as it is against the abruptly rising scarps of the Burren uplands to the west (Fig. 5) and the Slieve Aughty Mountains to the east. However, this apparent topographic uniformity of Ireland's limestone outcrop may actually be misleading. Other 'lowland' limestone outcrops show significantly greater differential relief than the Gort lowlands. In Co. Roscommon extensive limestone plateaux rise several tens of metres above broad valleys and are punctuated by various small-scale solutional karst features (Hickey and Drew 2003). Broadly similar but more striking plateaux and valleys are also found in the Bricklieve Mountains of Co. Sligo (Thorn et al. 1990). Around Castlepollard, in Co. Westmeath, scattered limestone hills rise abruptly from a lowland plain (Drew 1997), with isolated limestone hills at Dunamase and Cashel, in counties Laois and Tipperary, similarly rising above the surrounding lowlands. Still further south, around the southern part of Tralee Bay, Co. Kerry, a number of small steep-sided limestone hills have, on occasion, been compared with tower karst landscapes in parts of Asia (Waltham 2008) and considered as relics of a Cenozoic landscape (Mitchell 1980; Davies 1970). For Dunamase and the Barrow-Fenit area of Tralee Bay at least, there is evidence from boreholes and geophysics that the true relief on some of these limestone hills is significantly greater than is apparent today (George Sevastopulo, pers. comm.), with the surrounding limestone surface now buried by tens of metres

of glacial material, but could any of them really be examples of relict tower karst from the late Neogene?

At the scale of individual landforms (features from a few metres to a few kilometres across), those developed on silicate uplands and on limestone ‘lowlands’ would have been markedly different in pre-glacial times, reflecting the contrasting processes—weathering and erosion (fluvial and slope processes) versus karstification—that operate on those different lithologies. Similarly, the post-glacial topography of lowlands differs markedly from that of the uplands and reflects the contrasting glacial processes that prevailed in these different environments, with upland areas subjected to repeated glacial erosion that transferred material to lower altitudes where it now blankets extensive areas. Consequently, direct evidence of the pre-glacial landscape at a local scale has been largely eroded from the uplands and commonly buried in the lowlands.

Although we can only speculate on the exact nature of much of Ireland’s buried limestone surface, there are many examples known of deeply karstified limestone, of cave systems markedly out of equilibrium with the present landscape, or of karst drainage systems that are intimately tied to pre-glacial landscapes and hence can be assumed to have their origins earlier in the Cenozoic. Aillwee Cave, in the Burren of Co. Clare, is one example of a cave that now lies spectacularly out of equilibrium



Fig. 5 Looking south-west across the limestone ‘corrosion plain’ of the Gort Lowlands towards the eastern scarp of the Burren Hills, which is inferred to mark the approximate edge of the protective siliciclastic cover in immediately pre-glacial times



Fig. 6 The huge relict phreatic conduit of Cannahowna Cave, a shallow section of the enormous subsurface drainage network which underlies the Gort lowlands and which must have its origins in pre-glacial times

some 90 m above the valley floor and hence is inferred to be perhaps pre-glacial in origin, while the huge phreatic conduits that lie beneath the Gort lowlands (Fig. 6) must also have a history that extends back into the pre-glacial origins of that lowland karst surface even though these passages are still very much hydrologically active (Simms 2005). ‘Negative’ karst landforms such as these, protected from the worst ravages of glacial erosion by virtue of extending deep beneath the surface, hint at the extent of pre-glacial karstification in Ireland. However, the perennial problem with so many of these sites is the difficulties associated with dating them. In this respect one site is of especial importance in providing a glimpse across an immediately pre-glacial karst landscape.

Pollnahallia, a townland near Headford in Co. Galway, lies on the extensive limestone outcrop that lies to the east of Lough Mask, known as the Plains of Moytura. For the most part this vast area appears relatively monotonous, although this belies a complexity that includes numerous closed depressions, minor uplands such as the hill of Knockmaa, and elements of a mature karst drainage system that drains westwards into Lough Mask (Coxon and Drew 1986). Across the region outcrops of bare limestone are interspersed with areas where bedrock is concealed by glacial deposits, suggesting that the pre-glacial limestone surface was more irregular than might be expected for a corrosion plain. However, small-scale quarrying operations at Pollnahallia have revealed the true nature of this buried landscape, exposing elements of a karst landscape, with cliffs, caves and limestone gorges beneath a cover of Pleistocene diamict (Coxon and Flegg 1987; Coxon and

Coxon 1997). Of particular significance are the sediments that conceal this buried karst topography, with deposits of lignite overlain by pure quartzose sands. The lignites, in themselves testament to a temperate swampy environment, drape the limestone surface and have yielded a rich and diverse pollen assemblage characteristic of the Pliocene, thereby indicating that this land surface is pre-glacial in age. The white, barren, quartzose, aeolian sands are in striking contrast to the dark organic lignites beneath, with the upwards transition from organic-rich lignites into pure silica sands interpreted as evidence of climate deterioration through the Pliocene-Pleistocene transition and the establishment of periglacial conditions prior to the onset of actual glaciation (Coxon 2001). What Pollnahallia shows is that the immediately pre-glacial karst landscape across much of Ireland's limestone outcrop may have encompassed a significantly greater and more diverse topographic relief than is evident today. The 'negative landforms' seen at Pollnahallia are now largely buried beneath glacial deposits but the larger residual hills scattered across Ireland's limestone outcrop still hint at the scale of this diverse pre-glacial karst landscape.

Karst landscapes in non-glaciated regions are often characterised as much by relatively small scale 'positive' landforms, such as residual hills, cones or even towers (Fig. 7), that rise above the general land surface as by the 'negative' landforms that extend beneath the surface, and it has been suggested that such features may survive in Ireland as relics from a pre-glacial karst landscape. Some have even been referred to on occasion as 'tower karst' (e.g. Mitchell 1980; Mitchell et al. 1983; Drew 1997), but is this a reasonable hypothesis? Tower and cone karst are very specific landforms that develop through the interplay of karst



Fig. 7 Cloghnacrousta, a remarkable limestone knoll near Fenit, Co. Kerry, that has been suggested as an example of relict 'tower karst'. Several less spectacular knolls can be seen in the background with still others, partially drowned, offshore to the west

dissolution and tectonic uplift (Waltham 2008) but, although there have been suggestions for active tectonism in Ireland during the Neogene (Cunningham et al. 2003, 2004), it remains questionable as to whether suitable conditions for tower karst development ever pertained in Ireland. Furthermore, although it has been established that elements of pre-glacial topographic relief can survive beneath ice sheets (Kleman 1994), it seems improbable that these vulnerable structures might have survived repeated glaciations, or the intervening interglacial periods in which they would have been subject to temperate dissolution, through more than 2 million years since the Pliocene. An alternative view is that these features are more closely analogous to tors, and that they owe more to glacial processes than they do to karstification.

The landscape that had developed on the silicate-dominated uplands prior to the onset of glaciation would have been very different from that on the limestone lowlands. Prolonged weathering would have led to the widespread formation of saprolites, sometimes of considerable thickness which, coupled with fluvial erosion and gravity-driven slope processes, would have produced a landscape of predominantly rounded hills incised by V-shaped valleys. Subsequent cycles of glacial erosion swept away huge volumes of this weathered saprolite to reveal unweathered rock beneath, it deepened and widened many of the pre-existing valleys, and it gouged great carries out of north and east-facing slopes.

The limestone uplands of the Burren hills and Aran Islands in counties Clare and Galway, and those of Fermanagh, Cavan, Sligo and Leitrim, represent apparent anomalies in the prevailing lowland topography developed on the limestone outcrop across much of Ireland, but they provide clues to the effects of glacial erosion on siliciclastic outcrops. These uplands extend to relatively high stratigraphic levels within the limestone and locally preserve remnants of the overlying siliciclastic cover. Furthermore, karst development across much of the Burren and Aran Islands is relatively superficial compared with that encountered across much of the limestone lowlands, implying that it has not experienced the same degree of weathering. From these observations it can be inferred that the surrounding limestone uplands had been protected from dissolutional lowering by a formerly more extensive siliciclastic cover that persisted through much of the Cenozoic. Glacial removal of deeply weathered mudstones and sandstones of the Shannon Group, which overlay the Carboniferous limestones across the Burren hills and westwards onto the Aran Islands, probably did not occur until late Pleistocene times in this now anomalous upland topography (Simms 2005). In the Fermanagh, Cavan, Sligo and Leitrim region of north-west Ireland it was a cover of shales and sandstones of the Leitrim Group (Harney et al. 1996) that had protected the limestone beneath, while the more dissected limestone uplands of the Bricklieve Mountains, in Co. Sligo, perhaps reflect somewhat earlier Neogene unroofing from beneath this clastic cover. Although they form striking limestone landscapes now, in immediately pre-glacial times most of these areas would have been covered with a rounded siliciclastic cover. It is the stripping of this protective cover from across these particular areas that hints at the effects of glaciation more widely across silicate outcrops where relatively unweathered rock and blockfields are now typical.

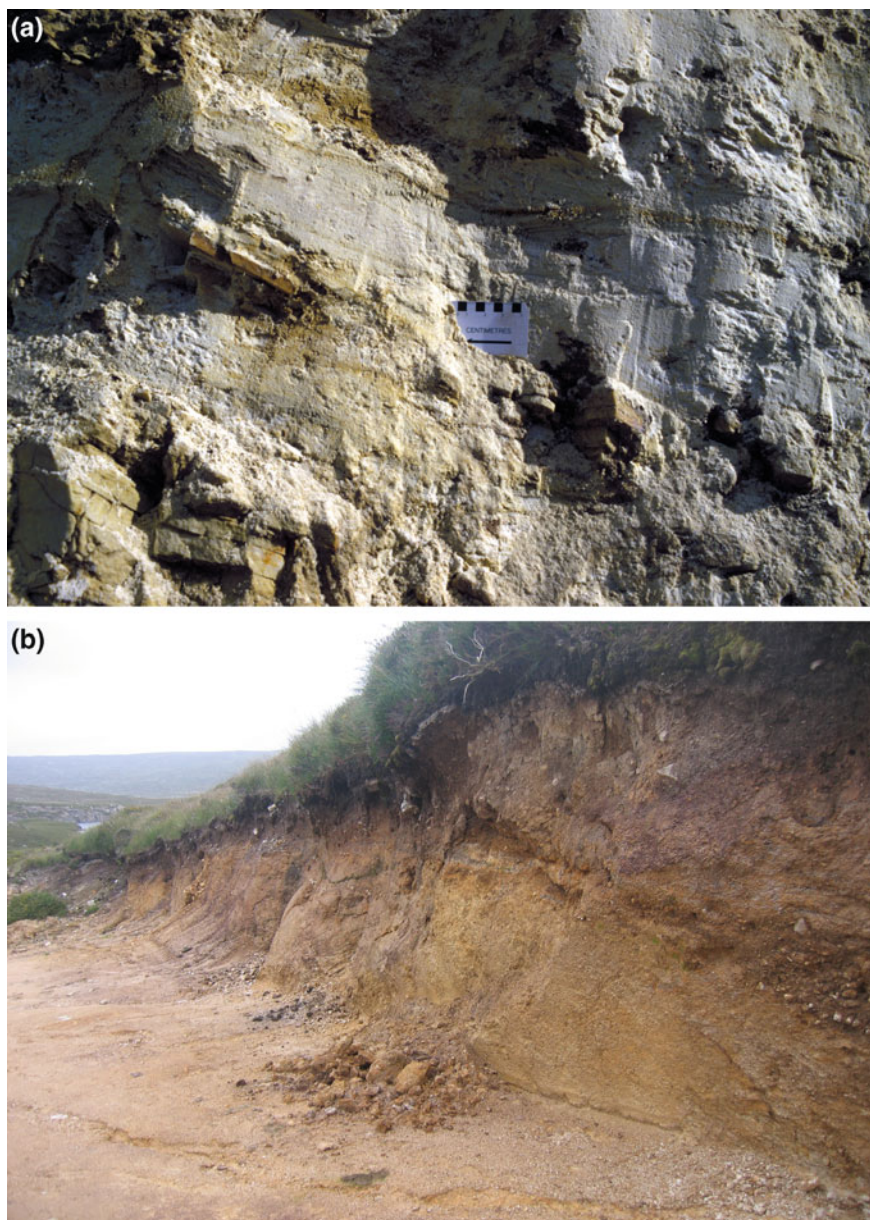


Fig. 8 Deeply weathered siliciclastics. **a** Deep weathering in quartzite near Bangor Erris, Co. Mayo. **b** Weathered granite near Carna, Co. Galway

Deeply weathered rock profiles and supposedly pre-glacial saprolites (Fig. 8) have been found in numerous locations around Ireland (Phillips 2001; Walsh 2001; Mitchell 1980) but it has proven problematic to establish firmly that any of them

Fig. 9 A pre-glacial land surface and Early Pleistocene diamict on the granite outcrop at Gowlaun East (Coxon 2001). **a** Sections at Bóthar na Scrathóg (Co. Galway). **b** Sections cleaned showing lower diamict. **c** detail of cleaned section showing a buried tor (1) and gleyed soil preserved in a joint in the tor (2) that contained a Neogene pollen assemblage



really are pre-glacial. In this respect one site in Connemara, at Gowlaun East, has proven of critical importance since it establishes unequivocally that a landscape of saprolites and palaeosols interspersed with residual tors (Fig. 9) had developed on the Galway Granite outcrop during the Cenozoic and had already experienced significant erosion and dissection by Pliocene and early Pleistocene times. Coxon (2001), (2005) describes how the weathering front across the granite outcrop at this locality is highly irregular. In places tors of unweathered granite rise several metres

above the surrounding land surface while others still remain buried beneath several metres of granite saprolite. The evidence from Gowlaun East, and from the unroofed limestone of the Burren hills, suggests that much of the present landscape that is developed on granite and other silicate outcrops may actually represent a weathering front exposed by glaciation, with minimal glacial erosion of the unweathered rock beneath. However, the position of the weathering front in a silicate rock need not necessarily reflect the surface topography since sub-surface weathering is controlled by a variety of independent factors such as rock permeability and chemistry.

7 Drainage Patterns

Glaciation is a great disrupter of pre-existing drainage networks. Ireland's landscape is studded with innumerable lakes, bogs and rivers whose location or configuration clearly owe much to glacial processes, either through erosive scouring of valleys and hollows, or by the damming and diversion of drainage networks by glacial deposits. However, among the many and diverse elements of Ireland's drainage network it might be anticipated that at least some of the larger lakes and rivers might, in part, be inherited from a pre-glacial landscape. This seems especially likely in those instances where geological structure has exerted a significant influence on the drainage configuration. Largest among Ireland's lakes, Lough Neagh is demonstrably pre-glacial in origin and occupies a structural and topographic basin that has been a focus for inland drainage since at least the Oligocene (Wilkinson et al. 1980). Although surprisingly shallow today, mostly less than 10 m, this may be a consequence of glacial lowering of the outlets—via the River Bann to the north and perhaps, at an earlier date, a southern outlet near Newry. Ireland's other large lakes are all located at least partly on Carboniferous limestones and consequently Hull (1891), p. 230 attributed their formation to dissolution. This possibility was discounted by Charlesworth (1963) who considered that all of Ireland's lakes, other than Lough Neagh and the turloughs, originated by ice action either directly through erosion or as a consequence of glacial deposition. He noted that the deepest parts of Lower Lough Erne and Lough Derg (on the Shannon) are located on silicate rocks rather than limestone, while Lough Mask is much deeper on its western side, adjacent to silicates, than on the limestone beneath its eastern side. However, he also noted that the limestone floors of the shallower parts of Lough Ree and Lough Derg, both on the Shannon, are traversed by a series of deeper trenches that are orientated approximately parallel to the dominant north-south joint set and hence suggest a solutional origin but he cited the prevalence of marl deposition in Ireland's limestone lakes as evidence against dissolution contributing significantly to lake formation. Nonetheless, there is abundant evidence that limestone dissolution can and does occur even in lakes that are in a near permanent state of carbonate saturation (Simms 2003). Evidence that dissolution has been at least a contributory factor in the formation of some of Ireland's other

lakes is found beyond the outcrop of the Carboniferous limestone, in Connemara. Sinuous strips of Dalradian marble consistently form areas of low ground now occupied by lakes, giving rise to its lithostratigraphic name of the Lakes Marble Formation (Long and McConnell 1995), yet lithologically these marbles would seem no more susceptible to glacial erosion than other adjacent rocks. It seems likely, therefore, that many of these lithologically influenced lakes may have their origins in a temperate pre-glacial climate.

Some of the major river systems in Ireland clearly owe their present configuration to geological factors. In the north the Lagan valley is orientated parallel to the prevailing ENE-WSW Caledonian trend and developed along a major fault system that juxtaposes Mesozoic and Palaeogene rocks to the north against Lower Palaeozoic greywackes to the south. The same Caledonian trend is evident in some of the other Antrim glens, which similarly may be inferred to have a pre-glacial origin even if their present form has a strong glacial overprint. The influence of geological structure on the drainage pattern is even more profound in the south-west of Ireland, in the so-called 'ridge and valley province' of Munster (Herries-Davies and Stephens 1978). Several major rivers, among them the Blackwater, Lee, Barrow, Nore and Suir, follow the structural grain of the landscape for significant parts of their course (Fig. 1). Progressive unroofing of the Dinantian limestones from beneath Namurian clastics would have exerted a profound influence on the development of drainage patterns through the Cenozoic (Simms 2004), with elements of the present configuration already established by Oligocene times (Simms and Boulter 2000). Phillips (2001) looked at the relationship between present river catchments and the extent of Palaeogene (66–36 Ma) and early Neogene (36–10 Ma) denudation as inferred from AFTA data (Allen et al. 2002). From this he concluded that the Blackwater, Suir, Bann and Lagan had their origins in the Palaeogene whereas many other rivers, among them the Barrow, Nore, Lee and Shannon, had been established in the Neogene. Despite the very evident structural influence on their course, several of these rivers exhibit anomalous features that are difficult to reconcile with either the present landscape and coastline or with specific glacial processes or events, but are perhaps better viewed in the context of a long pre-glacial history. Jukes (1862) proposed that the precursors of several of Ireland's major rivers were initiated on a southward-dipping Chalk surface and had then become superimposed onto the folded Palaeozoic rocks beneath as denudation slowly exposed this pre-Chalk surface. Mitchell (1980) maintained a similar view but favoured a 'Tertiary emergent platform' rather than a Chalk surface. However, it is difficult to see how such a consistent southward slope might be developed, and maintained, on such a geologically complex outcrop pattern for long enough for these rivers to be superimposed in the manner envisaged by Jukes (1862). Nonetheless, the gorges incised into pre-Carboniferous silicate rocks in the lower reaches of the Barrow, Nore and Suir might best be interpreted as examples of superimposed drainage resulting from prolonged slow isostatic uplift due to Cenozoic denudation (Simms 2004) and incision into an emerging barrier of Lower Palaeozoic silicate rocks. In contrast the apparent diversion of the Suir northwards, around the Comeragh Mountains (Fig. 1), may have occurred as solutional

lowering of the limestone plain kept pace with isostatic uplift, thereby favouring diversion around the emerging pre-Carboniferous silicate inlier rather than incising directly across the Knockmealdown ridge to the south, although the presence of a substantial wind gap between the Monavullagh and Knockmealdown mountains raises the intriguing possibility that the Suir perhaps did once cross this silicate barrier on a southward course to the sea. The most enigmatic drainage feature of this region is, of course, the famous ‘bend at Cappoquin’ (Herries-Davies and Stephens 1978). This too may be more readily understood in terms of drainage development in a significantly pre-glacial landscape in which the southern coast of Ireland extended substantially further to the south than it does today. As such the eastern end of the Dungarvan valley would have been blocked by a southward extension of the pre-Carboniferous silicate inlier of the Monavullagh Mountains, rising perhaps hundreds of metres above the synclinal floors and intervening anticlinal ridges, thereby necessitating the southward diversion of the Blackwater. However, quite why the rivers Lee and Bandon, further to the west, should show similarly abrupt changes of direction from eastwards to southwards, while also incising gorges through anticlinal sandstone ridges, remains enigmatic. Although the exact causes of these anomalous drainage patterns remain open to speculation, the significantly pre-glacial origin of these river systems cannot be in doubt and is supported by dated Oligocene sediments at Cahir, Ballymacadam and Ballygiblin (Watts 1957; Mitchell 1980; Phillips 2001; Simms and Boulter 2000). Although the context of Ballygiblin demonstrably is a deep phreatic cave passage (Simms and Boulter 2000), it has been suggested that some of the other occurrences of Oligocene sediments in the Barrow and Suir valleys might actually represent karstically lowered remnants of once extensive lakes (Walsh 2001). Such a model implies that substantial lake basins might have formed a significant component of these rivers earlier in their history, much as loughs Derg and Ree do today on the Shannon system. Nonetheless, whether these precursors of the present rivers included large lakes along their courses, it is clear that substantial elements of southern Ireland’s drainage have persisted in the Irish landscape despite the profoundly disruptive effects of the Pleistocene glaciations. This is in marked contrast to some of the major British rivers, such as the Thames, Trent, Warwickshire Avon and the, now vanished, Bytham which have experienced radical reconfigurations during their Pleistocene history (Rose 1994; Bridgland et al. 2015).

In this respect the pre-glacial history of Ireland’s greatest river, the Shannon, is less like some of the other major Irish rivers that demonstrably have a history extending back into the pre-glacial Cenozoic and is more comparable, in certain respects, with some of those in southern Britain. The scale and nature of certain features suggests that parts of the Shannon system may be of considerable antiquity, extending well back into the Pleistocene if not earlier, yet other parts demonstrably have been established far more recently. Unlike many of Ireland’s other great rivers, long stretches of the Shannon and its major tributaries, such as the River Suck, do not occupy distinct valleys and instead appear to be influenced much more by glacial features than by bedrock lithology or structure (Fig. 1). In its upper reaches, from its source on the flanks of Cuilcagh Mountain downstream to Lough Boderg,

the river's meandering course is influenced very strongly by the drumlin landscape through which it flows. In its middle reaches, across the Irish Midlands, it has a remarkably low gradient (average of just 7 cm per km) within a vast lowland basin across which it frequently floods. At several points along its middle reaches the Shannon cuts through late-glacial eskers (Fig. 1). This obviously indicates that the river's present course postdates the retreat of these ice sheets but it also suggests that any pre-existing course of the Shannon, if such existed in this region, had a minimal influence on the growth and decay of the ice sheets here. However, the character of the river is markedly different in its lower reaches, its course bisecting the hills that rise to around 500 m on either side of Killaloe before descending 30 m in just 30 km to enter the Shannon estuary. Kilroe (1907) and Herries-Davies (in Herries-Davies and Stephens 1978) considered this a relatively recent diversion from a previous course that followed a structurally-controlled limestone-floored lowland, between the Slieve Aughty and Slieve Bernagh hills, extending southwest from Scarriff to join the Shannon estuary south of Ennis. Glacial breaching of the watershed near Killaloe might perhaps account for the Shannon's present structurally anomalous route across this silicate inlier, and Farrington (1965) did suggest glacial diversion to account for the gorge at Killaloe. The Shannon estuary too seems anomalous when compared with the other major coastal re-entrants on the west coast. All of these, such as Galway and Donegal/Sligo bays and, in the south-west, the bays of Tralee, Dingle, Kenmare, Bantry and Dunmanus, show clear lithological and/or structural control. In contrast, the Shannon estuary cuts across a wide outcrop of Carboniferous siliciclastics in which no major geological structures are evident that might have influenced its present course.

Herries-Davies (in Herries-Davies and Stephens 1978) ascribed the present course of the Shannon to "the postglacial linkage of a series of glacially-excavated rock basins". Considering the remarkably low gradient of the Shannon in the middle reaches of the river, falling just 15.5 m in 220 km, raising the outlet from Lough Derg by just 20 m would create a vast lake system across the Irish midlands, extending from Lough Boderg in the north to Lough Derg in the south. Might the pre-glacial landscape of the Irish Midlands have been dominated by this putative 'Lough Shannon', since drained by glacial lowering of the outlet(s)? The bedrock topography to east and west of the Shannon between Carrick-on-Shannon and Killaloe certainly is sufficient to have impounded such a lake but any direct evidence of its former existence has perhaps been erased or obscured by subsequent glaciations.

8 Conclusions

The evidence for glacial modification of the Irish landscape, through erosion and deposition, is ubiquitous and pervasive but these processes have had a far more modest influence on the large-scale landscape than is commonly assumed. The overall pattern of uplands and lowlands has been very strongly influenced by broad

lithological differences, the disposition of which is a function of stratigraphy, geological structure, and the contrasting effects of denudational processes. Limestones in general form lowlands while upland regions are predominantly of siliciclastics of one sort or another. This link between lithology and topography reflects the profoundly different denudation mechanisms that affect these rock types. Geological structure and lithology have strongly influenced topography and drainage across Ireland, with some elements of the modern landscape already established by the mid-Cenozoic. This is most evident in areas with a strong structural fabric, such as in the 'ridge and valley province' of the south-west but it is probable that the general large-scale topography and drainage configuration seen today across much of Ireland is little different to what existed immediately prior to the onset of Pleistocene glaciations. At a smaller scale it is evident that glaciation has left a considerable legacy in the Irish landscape. Excavation of glacial corries and widening of pre-existing valleys attest to glacial erosion while drumlins, eskers and moraines, not to mention the ubiquitous diamict that blankets vast areas of the Irish lowlands, are evidence of deposition. Through these two processes the Irish landscape has become more subdued than its pre-glacial form. In limestone areas an intricately etched karst landscape has been smoothed over and buried beneath glacial debris. Across silicate and siliciclastic outcrops a landscape formed by deep chemical weathering and fluvial erosion has been largely stripped of weathered regolith and, locally, has been carved into crags and corries. This may have lowered surfaces by tens of metres in some cases. However, the greater effects probably occurred in the limestone lowlands where a pre-glacial relief of perhaps tens of metres was largely buried beneath successive glacial deposits. Overall the differential relief between the peaks and valley floors in the pre-glacial Irish landscape may have been significantly greater than it is today but the nature of the landscape processes that operated through the Pleistocene have largely erased or concealed this pre-glacial land surface such that it is only occasionally glimpsed at sites such as Pollnahallia and Gowlaun East.

So, in summary, what might the immediately pre-glacial (Pliocene) landscape of Ireland have looked like? The broad outline of the country was well established by the Pliocene, although as a landmass it was still continuous with that of Britain across the lowlands of what is now the Irish Sea. Coastlines to north, south and west probably extended many kilometres beyond their present limits, although it is impossible to ascertain the extent of their subsequent retreat and to what extent the cliffed Atlantic coastlines that prevail in the west today are a product of Pleistocene erosion. Onshore, Ireland's topography was broadly similar to the present but differential relief was somewhat greater at various scales. Silicate outcrops, rounded and blanketed with saprolite by prolonged weathering, were incised by a network of V-shaped valleys. Limestone outcrops were extensively and deeply karstified, imparting significantly greater relief in the lowlands than is commonly evident today. Most of the large, structurally-guided rivers were already well-established by immediately pre-glacial times, as were some of the larger lakes.

Today this pre-glacial differential relief has been reduced through erosion of the uplands and deposition in the lowlands, yet some lowland areas may still have a

differential relief comparable with that of pre-glacial times. In these instances it is due to late glacial depositional structures such as drumlins and moraines. Many more lakes have been created through glacial erosion and deposition to augment those surviving from pre-glacial times, although most are relatively small. However, it is possible that some large pre-glacial lakes, such as the putative ‘Shannon Lake’, may have been greatly reduced in size as a consequence of glacial effects. Significant elements of the country’s pre-glacial drainage have persisted to the present day but the largest drainage system of all, the Shannon, shows clear evidence of major disruption during glaciations if indeed it has a significant pre-glacial history at all.

There has been great progress in understanding the Pleistocene history of Ireland in the sixty years since the publication of J.K. Charlesworth’s monumental work on the subject (Charlesworth 1957). Glacial processes are now far better understood and we have vastly more field data from across the country, both onshore and offshore, yet to some extent we are still hostage to fortuitous discoveries of dateable interglacial and immediately pre-glacial sites. Both Frank Mitchell and Gordon Herries-Davies acknowledged the enigmatic nature of Ireland’s pre-glacial, ‘Tertiary’ history. Several decades on from their seminal publications many uncertainties still remain.

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