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Atlantis Advances in Quaternary Science
Series Editor: Colm Ó Cofaigh

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Advances in Irish Quaternary Studies

Atlantis Advances in Quaternary Science

Volume 1

Series editor

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Aims and Scope of the Series

The aim of the Atlantis book series ‘Advances in Quaternary Science’ is to bring together texts in the broad field of Quaternary Science that highlight recent research advances on aspects of glaciation and sea level change, the development and application of Quaternary geochronological methods, records of climate change from marine and terrestrial settings, geomorphology and landscape evolution and regionally-focused reviews of Quaternary environmental change. The series comprises monographs and edited volumes that require extensive illustration and substantial space, and which provide state of the art thematic and regional reviews on Quaternary related topics often focusing on processes and associated responses within the fields of geology, geomorphology, glaciology, geochronology and palaeo-biology. In the last two decades technological developments in dating methods, remote sensing and techniques for the analysis and interpretation of sedimentary and climatic archives have resulted in significant advances of climate and ocean change across a range of time-scales from annual to millennial. Publications in the Atlantis book series ‘Advances in Quaternary Science’ capture these developments and show how they have increased understanding of Pleistocene to Holocene climate, cryosphere and ocean change across a range of spatial and temporal scales.
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Preface

The richness of the Irish Quaternary landscape has ensured that Ireland has been the focus of sustained research for almost two centuries. However, our interaction with the Irish Quaternary goes beyond an academic interest due to its critical social, cultural, and economic significance. Managers of the Irish landscape at local and national levels must take account of our national Quaternary heritage in addressing topics as broad as siting wind turbines, mitigating landslides, and protecting aquifers and the societal impact of sea level rise. Our agricultural soils, peat bogs, etc., are of Quaternary origin, and managing these in concert with other concerns such as aquifer protection requires knowledge of the landscape's origins. In addition to immediate economic and societal issues, the Irish Quaternary provides unrivalled data on the causes and consequences of global climate change. Irish sedimentary archives of environmental responses to climate change are essential for improving our adaption to and mitigation of possible future climate scenarios. Future research in Ireland will build on the rich legacy described briefly here and in other chapters, and thus, we hope this book proves to be an important resource in these endeavours.

This volume summarises some of the notable advances in a number of fields of Quaternary research in the last 30 years:

Chapter "The Pre-Quaternary Landscape of Ireland" (Simms and Coxon) reviews our current understanding of Ireland's pre-Quaternary landscape; Chapter "Interglacial Sequences" (Coxon et al.) reviews current evidence for the nature, distribution, and age of interglacial deposits in Ireland; Chapter "Glacial Geomorphology of the Last Irish Ice Sheet" (Meehan) outlines the geomorphological evidence for glaciation collated in Ireland; Chapter "The Last Irish Ice Sheet: Extent and Chronology" (Ballanytne and Ó Cofaigh) details our current understanding of the development and behaviour of the last BIIS, gained from ever-improving geochronological constraint; Chapter "Deglaciation of the Northern Irish Sea Basin" (Knight) focusses on detailing a relatively well age-controlled subset of Ireland's glacial records, those from the northern Irish Sea Basin; Chapter "Relative Sea-Level Change Around the Irish Coast" (Edwards and Craven) reviews our current understanding of pre- and post-glacial relative sea level change gained from models and studies of Irish coastal sites; Chapter "Periglacial and Paraglacial Processes, Landforms and Sediments" (Wilson) outlines our current understanding of evidence for the form and occurrence of periglacial landforms and sediments in Ireland; Chapter "Irish Quaternary Vertebrates" (Monaghan) summarises our understanding of Quaternary faunal population changes, and Chapter "The Human Colonisation of Ireland in Northwest European Context" (Warren) looks at the evidence for human colonisation of Ireland during the Holocene period in the context of pan-European archaeological evidence.

Dublin, Ireland — Peter Coxon
Maynooth, Ireland — Stephen McCarron
Dublin, Ireland — Fraser Mitchell

Contents

Introduction: Advances in Irish Quaternary Studies

Peter Coxon, Stephen McCarron and Fraser Mitchell

Abstract Investigation of Ireland's Quaternary heritage has a long history that extends back prior to the setting up of the Geological Survey of Ireland in 1845. Ireland's rich Quaternary deposits and land forms have ensured that it continues to be a key location for international research. The publication of *The Quaternary History of Ireland* in 1985 (Edwards and Warren 1985) has served the Quaternary community extremely well for three decades but it is now timely to review the substantial body of recent research into the Irish Quaternary. This chapter serves to provide a historical context to the syntheses of recent research that are reported in the subsequent chapters of this book.

1 The Background to the Irish Quaternary

Investigation of Ireland's Quaternary heritage has a long history that extends back prior to the setting up of the Geological Survey of Ireland in 1845. Quaternary sections had been extensively described and many were assigned to the classification of 'drift' explained at the time by the widely accepted Marine Submergence Theory.[1] The Geological Society of Dublin, founded in 1831, included an address

[1]The history of the Geological Survey of Ireland and its early work is interestingly summarized in Herries-Davies' (1995) book "North From The Hook". Chapter 8 "Delving the Drift" may be of particular interest to the reader.

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on the marine origin of esker ridges but scientific knowledge was changing fast in the early 19th century and, although not immediately accepted, the theory of the 'Ice-Age' was being formulated, analysed and applied elsewhere in Europe. Agassiz visited Dublin in 1835 to attend the British Association and again in 1840—the second time to deliberately seek evidence for former glaciation. His trip to Ireland saw him identifying moraines in the Wicklow Mountains amongst other features some time before geologists in general accepted the glacial theory. Interestingly it was the existence of widespread 'shelly boulder clays' that forced retention of the Marine Submergence Theory and ironically it is the fossiliferous character of many Irish glacial sediments that still promotes debate today.

The middle 19th century saw a plethora of Quaternary information published by natural historians, academic geologists and the officers of the Ordnance and Geological Surveys. This work is published in many outlets and the publications are far too numerous to cite here but examples include the maps of Sollas (1896) and Kilroe (1888). Indeed, by 1867 Close had prepared a map of the glaciation of Ireland (Fig. 1) that clearly outlines ice movement patterns and the widespread ice cover that we now accept and Kinahan (1865) had correctly identified and commented upon the interglacial deposits that we now know as the Gortian type-site. The mapping, classification and description of the Irish Quaternary geology gathered pace during the latter part of the 19th century and it is interesting to consider the huge impact that the 1″ to the mile (1: 63360) Ordnance Survey maps (1st Edition 1857–1861) and the 6″ to the mile 1: 10560 (1832–1846). These were the DEMs and satellite images of the day (Fig. 2).

Into the 20th century the development of Quaternary Science in Ireland continued to benefit from rigorous investigations by many amateur scientists in addition to the few professional Quaternary geologists based in Irish academic institutions. In addition to the officers of the Geological Survey, frequent visitors to Ireland from all corners of the globe published through the Royal Irish Academy, the Irish Naturalists Journal and other scientific outlets. Herries-Davies (1995) marks the arrival of Lamplugh and his inauguration of a drift survey in 1901 as the '… *dawn of the modern era in the survey of Ireland's Pleistocene legacy*…' and it was at this time that the remarkable William Bourke Wright was appointed to the Survey. Wright mapped extensively in and around Howth and the Dublin Mountains (noting correctly that the many deeply incised dry valleys were glacial meltwater channels). In 1903 Wright began mapping in Cork where he and Herbert Brantwood Muff made the discovery of what we now know as the Courtmacsherry raised platform (Wright and Muff 1904; Fig. 3). Wright went on to be one of the most influential Quaternary geologists of his time publishing the first edition of his book, *The Quaternary Ice Age* in 1914 in what was a major turning point in the basis of Quaternary studies at the time (Wright 1914). At the turn of the century in Ireland the inclusion of Quaternary sequences on geological maps of the time is exemplified by the map drawn by Hallissy (1914), part of the Royal Irish Academy's classic Clare Island Survey (Fig. 4).

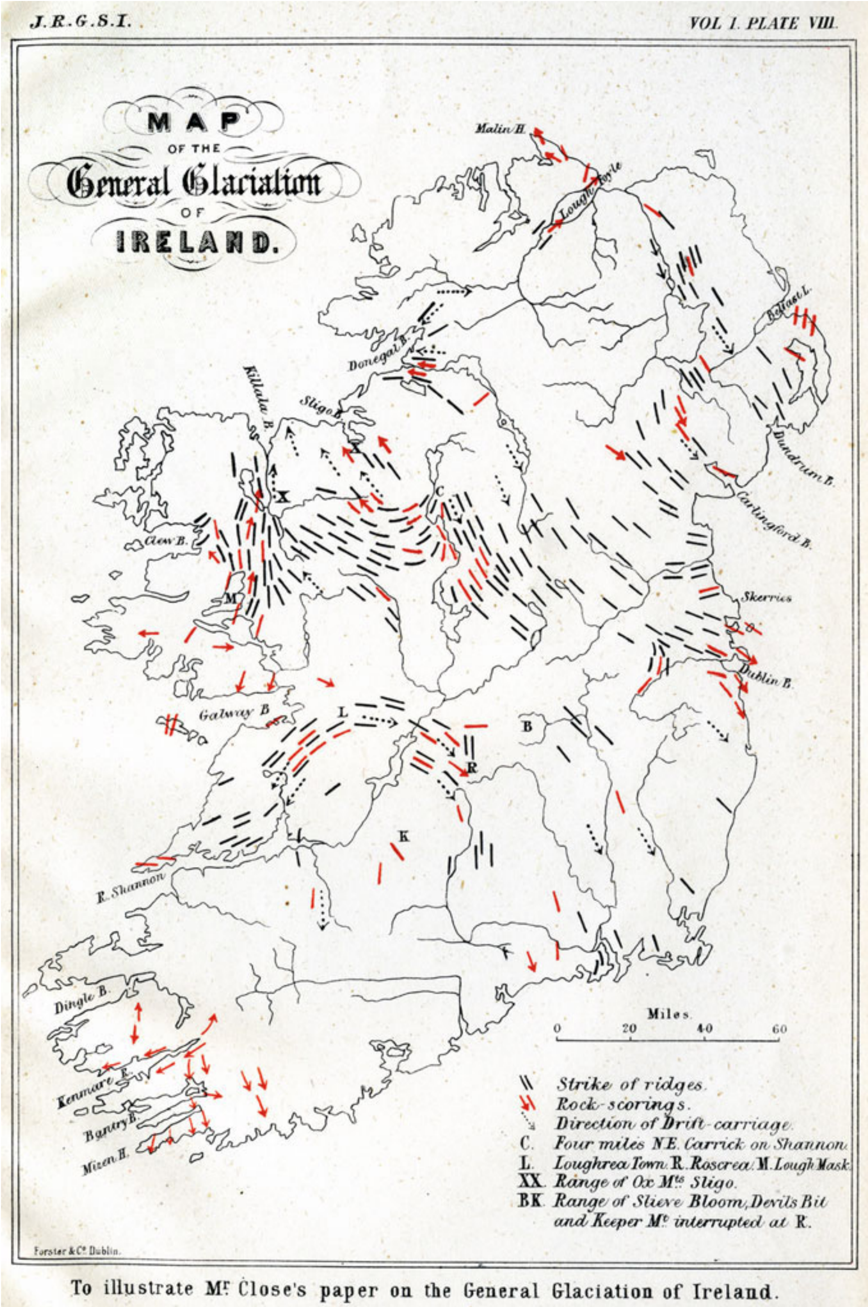


Fig. 1 Close's (1867) map of the glaciation of Ireland

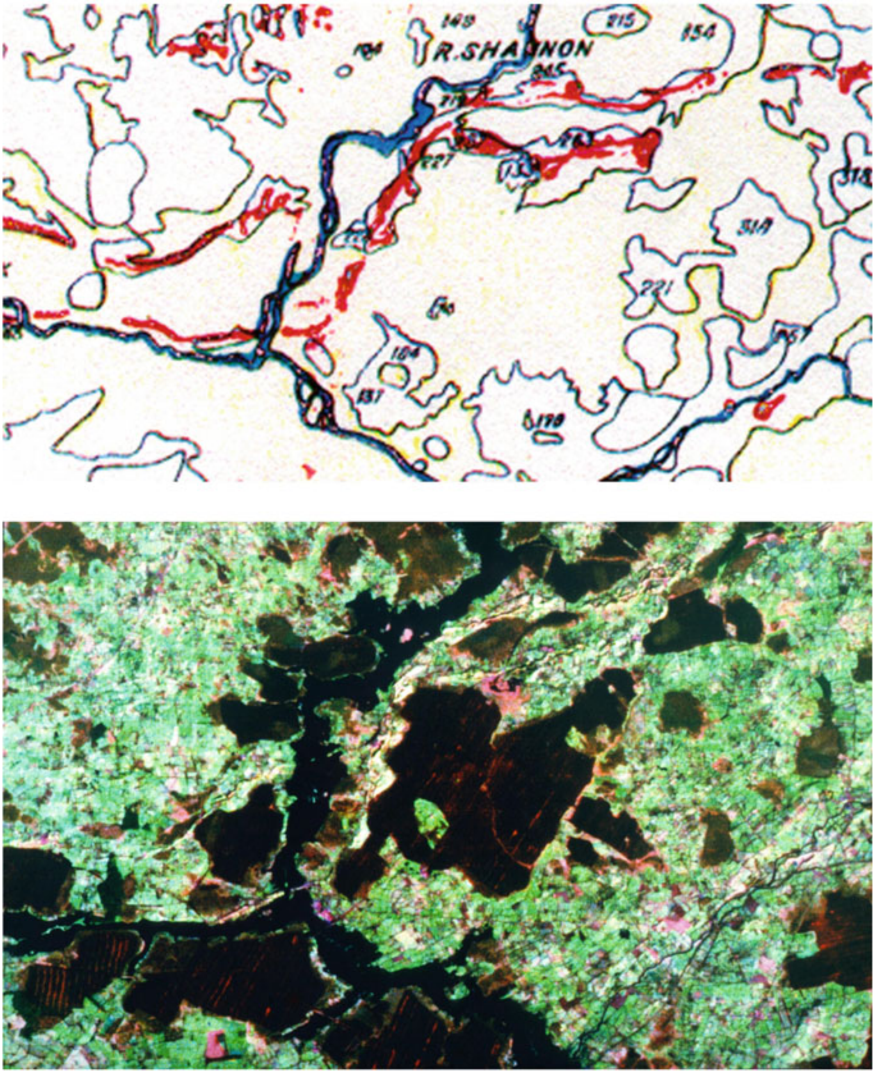


Fig. 2 *Upper* detail of Sollas' (1896) map of the Irish eskers and *Lower* An early (1981) LANDSAT image (ERA Maptec) of the same area as in the map above. The OS maps used by the GSI in their mapping were the advanced technology of the time

The mapping and description of Ireland's Quaternary cover continued in the 1920s and 1930s with a succession of papers by John Kay Charlesworth and Anthony Farrington and subsequently into the 1960s and 1970s by Synge (e.g. Synge 1968) and others (Fig. 5). As well as mapping Quaternary sediments

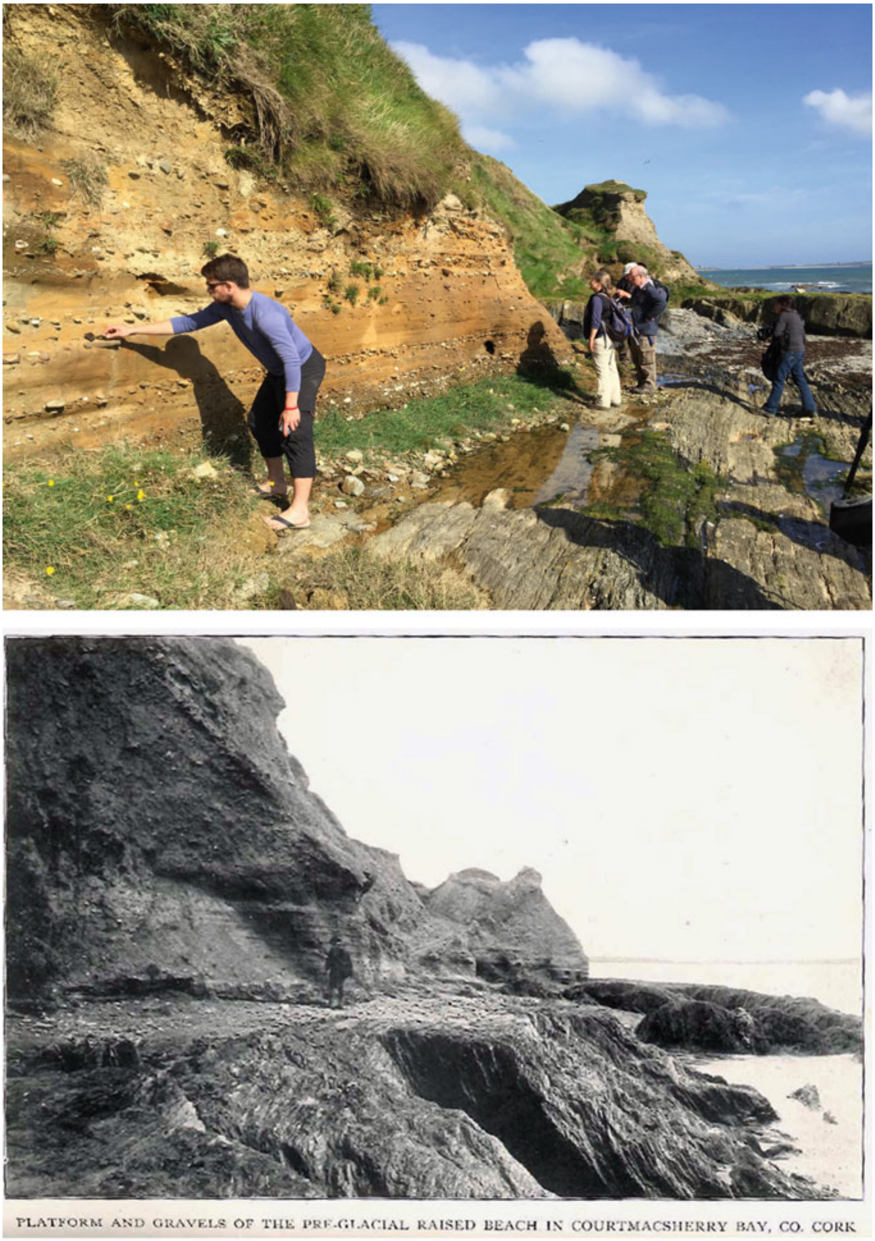
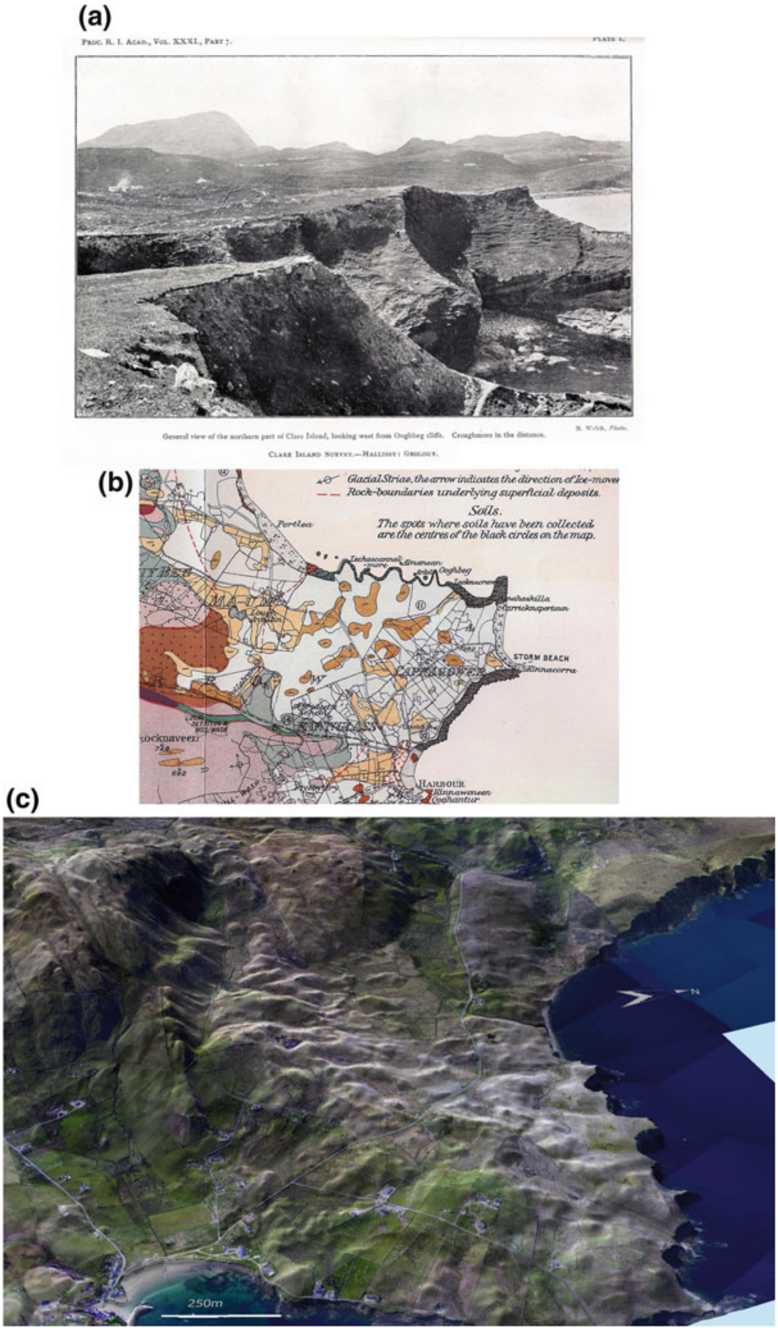


Fig. 3 The raised marine wave cut platform in Courtmacsherry Bay. *Upper* The IQUA/QRA fieldtrip (September 2015) to the type locality. The raised beach overlying the platform can be seen as well as the overlying horizontally bedded gravels and sands. The latter have been OSL dated to 36–71 ka BP (Ó Cofaigh et al. 2012). *Lower* The platform as seen by Wright and Muff (1904)


(a)
Proc. R. I. Acad., Vol. XXXI., Part 7.
General view of the northern part of Clare Island, looking west from Ooghbeg cliffs. Croaghmore in the distance.
Clare Island Survey.—Hallissy: Geology.
(b)
Glacial Striae, the arrow indicates the direction of Ice-mover
Rock-boundaries underlying superficial deposits.
Soils.
The spots where soils have been collected are the centres of the black circles on the map.
Portlea
Ooghbeg
STORM BEACH
Kinnacorra
Harbour
Ooghantur
(c)
250m
N

◀ **Fig. 4** Hallissy (1914) **a**—photograph from Clare Island Survey and **b**—detail from a map of Clare Island featuring in the Royal Irish Academy's classic and recently repeated Clare Island Survey. Comparing Hallissy's excellent map with the new LiDAR imagery available **c** shows just how detailed the surveys were over 100 years ago (by kind permission of the Royal Irish Academy)

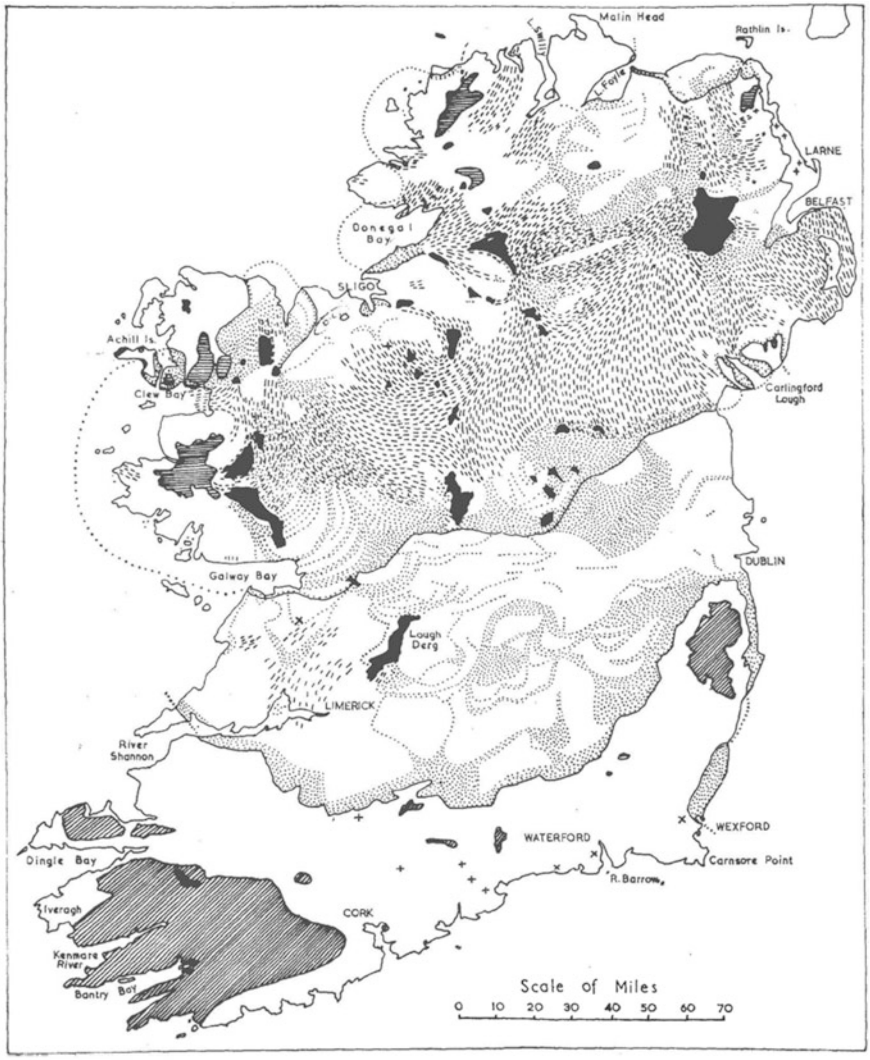


Fig. 1. **Glacial map of Ireland showing the Tipperary Line, Carlingford Readvance and Antrim Coastal Readvance; the distribution of drumlins (dashes) and eskers and moraines (dots); and the interglacial (×) and mammoth (+) localities.**

Fig. 5 Charlesworth (1963) map of the glaciation of Ireland (by kind permission of the Royal Irish Academy)

Fig. 6 Jessen (on *left*) at work on Gortian Sections 1935 *photograph* G.F.Mitchell

progress was made on understanding other spheres of Quaternary interest including the study of Ireland's vegetation history. Erdtman (1927) published the first Irish pollen diagram and the visit to Ireland by the notable palaeoecologist Knud Jessen in 1934 triggered a surge in our knowledge of Ireland's past flora (Fig. 6). Jessen was a State Geologist in Denmark and he was invited to Ireland by the Committee for Quaternary Research in Ireland, chaired by Irish naturalist, Robert Lloyd Praeger, to study the history of Irish bogs and their flora. Farrington was the Secretary of this committee and the invite of Jessen was designed to allow active collaboration with Irish scientists and to demonstrate the expertise of the Danish Survey. Jessen and Jonassen arrived in 1934 and immediately set to work. Frank Mitchell was chosen as a field assistant to train in the methodologies of Quaternary research and was introduced to Jessen by Farrington prior to prolonged field excursions by these scientists. The visit by Jessen brought about great strides in our knowledge of the Quaternary including seminal work on the Late-glacial from Ballybetagh Bog (Jessen and Farrington 1938), on Holocene vegetational history (Jessen 1949) and on interglacial deposits (Jessen et al. 1959). Jessen influenced, trained and worked with Irish scientists and quickly the volume of published work accelerated—especially that of Frank Mitchell (e.g. Mitchell 1951). Over 475 pollen diagrams from locations throughout Ireland detailing successions over a range of time spans and from a variety of archives have now been catalogued and published in the Irish Pollen Site Database (IPOL) (Mitchell et al. 2013).

Quaternary geological mapping during the 1950s also started to undergo a change with a more detailed approach to the sedimentology visible in sections as

PROC. R. I. ACAD., VOL. 53, SECT. B. PLATE III.

FIG. 1.—TRANSVERSE SECTION OF THE GALTRIM MORAINE AT BATTERJOHN, SHOWING ITS DELTAIC STRUCTURE.

Note unbedded morainic deposit overlying the deltaic gravels. Height of section about 50 feet.

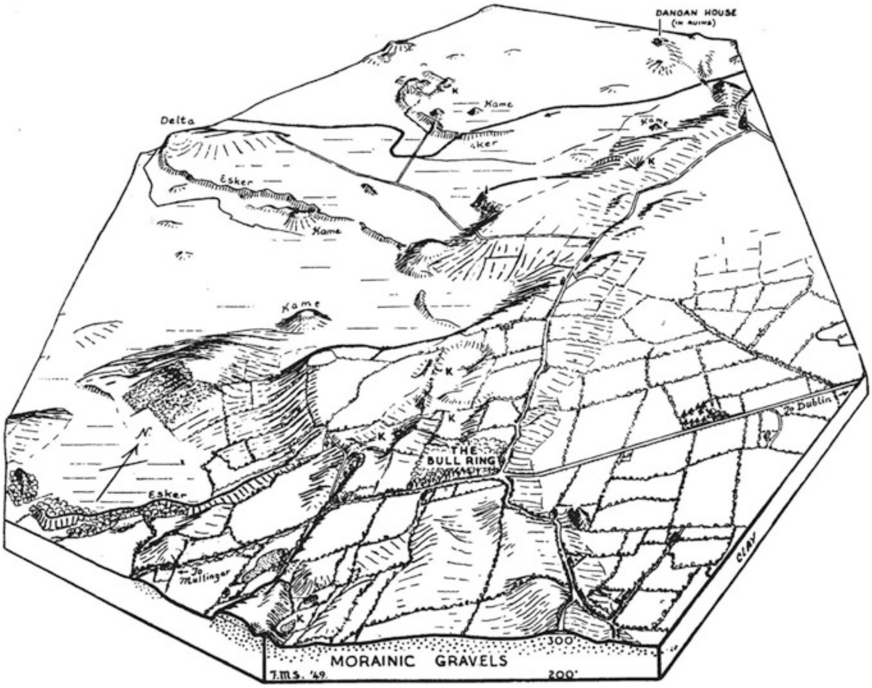


Fig. 7 A page from Synge's (1950) treatise on the Meath eskers

well as on morphology—perhaps exemplified by Synge's work (1950) on the esker and moraine complex around Trim, Co. Meath (Chapter "Glacial Geomorphology of the Last Irish Ice Sheet" and Fig. 7). The mapping of glacial landforms culminated in 1979 with Synge's (1979) map in the RIA *Atlas of Ireland*, firmly establishing Last Glacial Maximum (LGM) ice limits at a 'South of Ireland End Moraine' (SIEM) (see Chapter "The Last Irish Ice Sheet: Extent and Chronology") and a major deglacial readvance at the 'Drumlin Readvance Moraine (DRM)' across the north central midlands and north east Ireland (Chapter "Deglaciation of the Northern Irish Sea Basin"). This map was not dissimilar to Charlesworth's (1963) map however there are differences, with the inclusion of eskers and details of 'terminal'moraines in Synge (1979). The publication of *The Irish Landscape* (Mitchell 1976) uniquely brought together the current state of knowledge, and interaction, of Ireland's glacial history, vegetation history and archaeology into one volume that was written to be accessible to a wide readership. It was a consolidated Quaternary history of Ireland, which went on to be revised in several further editions/revisions (Mitchell 1986; Mitchell and Ryan 1998).

By the 1980s it was becoming clear from more advanced sedimentological, stratigraphical and geomorphological research by a range of workers that there was

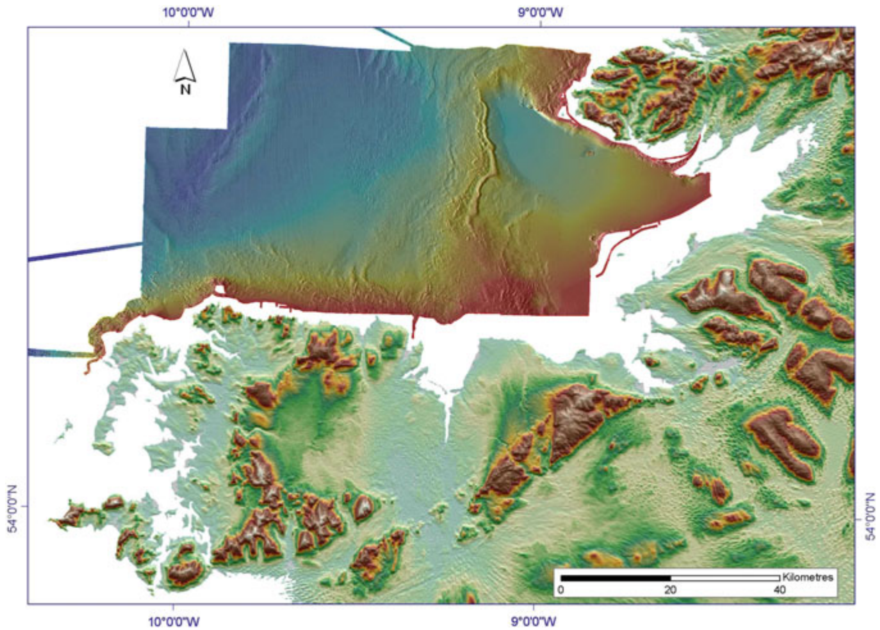


Fig. 8 A render of Irish National Seabed Survey (INSS) multibeam echosounder bathymetric data of the Donegal Bay seabed, north-west Ireland and NASA SRTM topography. The image shows multiple, nested and cross-cutting moraine ridge sets related to the retreat and possibly minor readvance of Late Midlandian tidewater ice margins during ice sheet recession from the continental shelf

an impending step change coming in the description, analysis and interpretation of Irish glacial deposits (e.g. Dardis and McCabe 1983; Dardis et al. 1984). In an influential review of Pleistocene stratigraphy in Ireland, McCabe (1987) reproduced the landform distribution of Synge (1979) and combined it with the sedimentological description of key (mainly coastal) sites. The major conceptual change implicit was a move from relative ('layer cake') chronologies to detailed, localised sedimentological studies. Depositional and palaeoglaciological settings were then inferred from sedimentological and process models developed for analogous sediment sequences in modern glacially influenced settings e.g. Alaska (e.g. Powell 1983, 1984) and Greenland (Hughes 1986). Paleoenvironmental determinations arising led to regional correlations associated with modified basinal sequence stratigraphy analysis (the 'depositional systems' approach of Eyles and McCabe 1989) to regional event stratigraphies, constrained by radiometric dating (e.g. McCabe and Clark 1998; Knight 2003; McCabe et al. 2007).

The level of geomorphological detail that has become available from the remote sensing of terrestrial and marine surfaces through iniatives such as NASA's Shuttle Radar Topography Mission and the Irish National Seabed Survey (INSS) of the Geological Survey of Ireland (GSI; www.gsi.ie) and Marine Institute (MI; www.marine.ie) since 1985 is exemplified by the rendering of Donegal Bay's seabed morphology in Fig. 8.

2 Debate Within Glacial Studies

In particular, the positioning in 1989 of circum—Irish Sea Basin sediment sequences (Chapter "Deglaciation of the Northern Irish Sea Basin") within a 'depositional systems' framework aimed to link fossiliferous sediment bearing sequences with genetically associated landforms e.g. 'up-ice' moraines and drumlin fields (Eyles and McCabe 1989). The model has frequently been termed the 'glaciomarine hypothesis', as the veracity of hypothesised processes which link fossiliferous marine (tidewater) sediments to associated subglacial and ice-marginal landforms (e.g. drumlins, bounding moraines and rogen moraines e.g. Knight and McCabe 1997; McCabe 1997) is dependent on the fossiliferous sediments being in situ glaciomarine sequences. This circular linkage has been the subject of much debate (e.g. McCarroll 2001), particularly for sites farther from the centre of BIIS-related isostatic crustal depression e.g. the southern Irish Sea Basin (Chapter "The Last Irish Ice Sheet: Extent and Chronology").

However, modifications to the spatial reach of the 'depositional system' later omitted some of the more contentious high level (>100 m O.D.) tidewater sites from the model e.g. Banc y Warren, South Wales and the Carey Valley, Co Antrim (cf McCabe 2008). Chronostratigraphic work since the 1980s on several key sites within the northeastern ISB (e.g. Dundalk Bay and the Kilkeel Steps; Chaps. 5 and

6) has constructed a widely accepted, relatively high-resolution deglacial ice sheet history for this phase of deglaciation at least. Age constraint has also facilitated the correlation of ice sheet events (e.g. readvance) during deglaciation across multiple BIIS sectors in Ireland (McCabe et al. 1998; McCabe and Clark 1998, 2003; McCabe et al. 2005, 2007). In-phase events across the ice sheet indicate that during the last (Late Midlandian) deglaciation (Termination 1), a climatically sensitive last BIIS underwent large-scale readvances reflecting rapid binge-purge cycles on broadly millennial timescales (McCabe and Clark 1998; Chiverell et al. 2013) (Chapter "The Last Irish Ice Sheet: Extent and Chronology"). Importantly, this is in keeping with the temporal pattern of other climatic and oceanic cycles (e.g. Bond and Lotti 1995) observed in the circum-North Atlantic ice-ocean-atmosphere system (McCabe and Clark 1998).

3 Advances from Absolute Dating

As exemplified by the correlation of ice sheet events with wider North Atlantic paleoenvironmental change (Sect. 2), the advent of radiometric dating had a major impact on the study of Quaternary and Holocene events. During the 1950s to 1980s, many suitable Late-glacial and archaeological sites in Ireland were sampled and dated, with organic sediment samples being provided by Frank Mitchell, Francis Synge and others to Libby's scintillation counting laboratory in Chicago. Irish dates were among those in the first lists published from that source. Chicago and subsequently Yale, Groningen, Cambridge, Trinity College Dublin (TCD), University College Dublin (UCD) (both for a short time) and Queen's University Belfast (QUB) dated Irish palaeoecological and archaeological materials from the 1950s onward, so that by 1985 Edwards was able to cite 965 published dates (Edwards 1985). Palaeoecological work throughout the period from 1950 to 1980 can be seen to be blooming with Tertiary (Watts 1957, 1962; 1970) interglacial (Watts 1964, 1985) and Late Quaternary sequences (Craig 1978; Watts 1977, 1985) all subject to thorough analyses. The groundbreaking work for over 40 years of the Dendrochronology laboratory and laterally 14 Chrono AMS radiocarbon dating facilities at QUB have had a significant impact on developing late Quaternary chronologies not just in Ireland but internationally (e.g. Reimer 2013).

Since 1985 major advances in the technology surrounding atomic mass identification using mass spectrometry and particularly Accelerated Mass Spectrometry (AMS) has allowed the development of new approaches and opportunities to use isotope-dating (radiocarbon ^{14}C and other cosmogenic nuclides e.g. ^{10}Be in the age constraint of (smaller) organic and non-organic samples including AMS radiocarbon dating (Preece et al. 1986; Cwynar and Watts 1989), OSL (Ó Cofaigh et al. 2012) and cosmogenic dating (Ballantyne et al. 2006). Many of these advances have been rapidly applied to the dating of important Irish sites (e.g. Heijnis et al.

1993; Gallagher and Thorp 1997; Ó Cofaigh and Evans 2007; Ó Cofaigh et al. 2012; Chiverell et al. 2013; Gallagher et al. 2015) and the evaluation of relative sea level history models (e.g. Lambeck 1996; Brooks et al. 2008; Plets et al. 2015; see Chapter "Relative Sea-Level Change Around the Irish Coast").

Within Quaternary glacial studies, much of this work has been applied to the sediments of the Irish Sea Basin and resolution of the stratigraphic position of historically enigmatic features along the south coast of Ireland. These include the Courtmachsherry raised beach and wave-cut platform and the south coast 'Irish Sea till' (Chapter "The Last Irish Ice Sheet: Extent and Chronology"). Relatively small sample sizes and reduced age determination costs have made it possible to not only use small quantities of material but also date multiple samples from reworked populations to find the 'youngest' and thus maximum deposition-constraining age (i.e. the enclosing sediment cannot be older than the biogenic inclusion). The addition of radiometric dates to glacial sedimentology has radically changed the context within which palaeoglaciological models are tested. For example, the maximum-age constraint of south coast subglacial sediments to the last glacial period (Evans and Ó Cofaigh 2007) has effectively confirmed the position of the (up-ice) SIEM (Charlesworth 1929) as a retreat stage landscape feature, not a limit to Late Midlandian ice extension. Ice extension across the south coast is also supported by radiocarbon dates on a rapid last glacial ice extension to the outer margin of the Celtic Shelf by the Irish Sea Ice Stream (Praeg et al. 2015).

Difficulties remain in the interpretation of geologic data constrained by radiometric dates however. These include the (as yet) unknown deglacial levels of marine radiocarbon reservoir effects within ice marginal waters e.g. a partially enclosed embayment such as the ISB. Making process linkages across different regions and using data sources, while vital to a fuller understanding of the climatic sensitivity of modern ice sheets, are thus inherently difficult to make with a high degree of confidence. This is especially true with the necessity for precision in the chronostratigraphic control of an inherently complex sedimentological system within an equally complex paleoenvironmental context.

Conceptually, establishing an ice sheet deglacial geochronology in Ireland has begun the move from documenting 'what' (a limit of the stratigraphic approach) to hypothesising 'why' (correlating ice sheet events to their controls e.g. relative sea level change, climate amelioration or deterioration). The availability of such a robust age constrained evidence set is needed to test numerical ice sheet models that aim to replicate BIIS ice dynamics (Hubbard et al. 2009) using palaeoclimatic forcing. In this approach, geological evidence is removed from any circular arguments i.e. when the evidence has also used been to constrain model boundary conditions. Instead, the geological evidence from Ireland including ice limits or isostatic depression amplitudes form a set of discriminatory tests for ice sheet growth and dynamic responses to multiple possible model boundary condition sets (effectively hypotheses) e.g. atmospheric circulation patterns, bed conditioning.

4 The Position of Irish Quaternary Research

In a time of accelerating environmental change, more dramatic perhaps than even late-glacial climatic variability, our knowledge of the past remains an important guide to future behaviour of the global climate system. The quantity and quality of high precision paleoenvironmental records may have vastly increased globally with heroic and painstaking efforts to document the past climates of polar regions for example, but these records do not directly evidence Quaternary change *in* Ireland. Therefore Irish sedimentary, palaeobotanical and archaeological archives, in all their ubiquity and variability, remain the only evidence of how the Irish landscape has developed to this point in time. It is hoped that scientists working in Ireland and Irish laboratories e.g. the 14 Chrono radiocarbon laboratory at Queen's University Belfast will continue to be at the fore in developing and applying the tools needed to 'Read the Irish Landscape' as enthusiastically and accurately as the late Prof. Frank Mitchell (e.g. Mitchell 1976, 1986; Mitchell and Ryan 1997). These workers are detailing incredibly high quality Quaternary archives in Ireland and on her marine shelves, records that hold the key to elucidating past NW European, circum-North Atlantic and global environmental change. So, in step with global improvements in our understanding of the Quaternary Period, the following chapters aim to outline how Irish Quaternary studies have advanced to this end over the last 30 years.

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The Pre-Quaternary Landscape of Ireland

Michael J. Simms and Peter Coxon

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, fluvioglacial 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