15

Cenozoic: Tertiary and Quaternary (until 11,700 years before 2000)

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The ages on table 15.1 below are discussed in Bowen and Gibbard (2007) who suggest placing the base of the Quaternary at the Gauss–Matuyama polarity reversal at 2.6 Ma. The onset of the Holocene has recently been assigned an age of 11,554 (Svennson et al., 2005) or 11,784 ± 69 (Rasmussen *et al.*, 2006) ice-core years b2k (before 2000) based on evidence from the NGRIP ice core record. The archived NGRIP core has been suggested as constituting the Global Stratotype Section and Point (GSSP) for the base of the Holocene at 11,700 ± 99 yr b2k (Walker *et al.*, 2008, 2009). This approach is considered to provide more accurate (i.e. calendrical) age estimates than can currently be obtained by calibration of radiocarbon dates. The Quaternary Period is the subject of an excellent recent review by Walker and Lowe (2007).

Dates in the text are given as ka (thousands of years) and Ma (millions of years) BP (before present). The ages of the MIS boundaries on Table 15.2 are taken from Shackleton (1969), Bowen *et al.* (1986), and Martinson *et al.* (1987). Radiocarbon dates are given in '^{14}C ka BP' (thousands of radiocarbon years before present) or, if calibrated, as 'cal ^{14}C ka BP'. These dates are quoted from the original publications in years before 1950 (BP), an accepted standard for radiocarbon dates.

Table 15.2 presents the current knowledge of Irish Pleistocene stratigraphy and key sites are located on Figure 15.1. Formal stratigraphical names have also been proposed (McCabe, 1999) and to facilitate correlation to that scheme the authors have included the marine Oxygen Isotope Stage (MIS – see Figure 15.2), where applicable, in the text.

Table 15.1 The Cenozoic time scale.

Erathem (Era)	System (Period)	Subsystem (Subperiod)	Series (Epoch)		Age of base of unit
Cenozoic	Quaternary		Holocene		11.7 ka
			Pleistocene	Late	127.2 ka
				Middle	780 ka
				Early	2.6 Ma
	Tertiary	Neogene		Pliocene	5.3 Ma
				Miocene	23 Ma
		Palaeogene		Oligocene	33.9 Ma
				Eocene	55.8 Ma
				Palaeocene	65.5 Ma

Where ka = years x 10^3 Ma = years x 10^6

Table 15.2 The subdivision of the Quaternary Period in Ireland. Possible correlations to Marine Oxygen Isotope Stages (MIS) are shown.

Series	MIS	Irish regional stage	age (ka)	Irish regional substage	Comments
Holocene	1	Littletonian			
Pleistocene	2	Midlandian – Late	11.7	Late-glacial: Nahanagan Stadial	Named after glacier activity at Lough Nahanagan in the Wicklow Mountains (Colhoun & Synge 1980). Extensive glaciation has not been recognised in Ireland but many periglacial features and the evidence of small glaciers are found (Coxon 1988; Gray & Coxon 1991; Wilson 1990a, 1990b; Walker *et al*. 1994; Anderson *et al*. 1998).
Pleistocene	2	Midlandian – Late	12.6	Late-glacial: Woodgrange Interstadial	This complex interstadial (with an early phase of climate amelioration and containing at least one period of erosion and climate deterioration) is recorded in many biogenic sequences from Irish Late-glacial sites (Watts 1977, 1985; Cwynar & Watts 1989; Walker *et al*. 1994). The Woodgrange Interstadial is named after a site in Co. Down (Singh 1970)
Pleistocene	2	Midlandian – Late	14.7	RIIs KPS LIs CHS CPIs	Distinct events recording millennial scale oscillations of the BIIS during deglaciation of the ISB. Associated with phases of streamlining and moraine formation (McCabe *et al.* 1986; McCabe 1985, 1987, 1993; McCabe & Clark 1998; McCabe, 2005; McCabe *et al*, 2005, McCabe *et al*, 2007b)
Pleistocene	2	Midlandian – Late	19	Glenavy Stadial	Growth of the BIIS ice sheet to offshore limits at or before 22ka (Bowen et al, 2002). Sediments at Aghnadarragh (McCabe *et al*. 1987b), cosmogenic dates (Bowen et al, 2002), and dates of deglaciation intiation (McCabe *et al*, 2007a, b) constrain this phase of extensive glaciation to the Late/Middle Midlandian.
Pleistocene	3	Midlandian – Middle		Derryvree Cold Phase	Organic silts found between two tills at Derryvree (Colhoun *et al*. 1972) show a treeless, muskeg environment. The mammal remains from Castlepook Cave (Mitchell 1976, 1981; Stuart and van Wijngaarden-Bakker 1985) date from this period (34—35ka). Recent dates for mammal faunas from caves range from 32ka-20ka (Woodman and Monaghan 1993) indicating the possibility of ice free areas in Cork during the Glenavy Stadial.
Pleistocene	3	Midlandian – Early	*c*. 40	Hollymount Cold Phase	Organic muds found at Hollymount (McCabe, Mitchell *et al.* 1978), Aghnadarragh (McCabe *et al*. 1987b) and Greenagho (Dardis *et al.* 1985). Fossils suggest cold, open, treeless environments. Possibly a continental climate with high seasonality.
Pleistocene	3	Midlandian – Early	> 48	Aghnadarragh Interstadial	Pollen and beetle evidence from Aghnadarragh (McCabe *et al*. 1987b) suggests cool temperate conditions with woodland, similar to that of Fennoscandia today. Dated to >48ka and tentatively correlated to the Chelford Interstadial (McCabe 1987).
Pleistocene	4	Midlandian – Early		Fermanagh Stadial	Till pre-dating organic beds at Derryvree, Hollymount (McCabe, Mitchell *et al* 1978) and Aghnadarragh (McCabe, Coope *et al.* 1987) are believed to have covered most of Ulster. Evidence (from the presence of certain tree taxa in the subsequent interstadial) suggests that the glaciation may have been short-lived (Gennard 1986; McCabe 1987).
Pleistocene	5d/5c	Midlandian	*c*. 115	Kilfenora Interstadial	UTD dates place cool temperate organic deposits at Fenit in Co.Kerry early within the Midlandian Glaciation (118,000 years BP -Heijnis 1992; Heijnis *et al.* 1993). The biogenic sediments represent cool conditions during Oxygen Isotope Stage 5a or (more likely) 5c.
Pleistocene	5e	Last Interglacial	*c*. 120		Knocknacran (Co. Monaghan) is a critical site (see text) and may prove to be a Late Pleistocene interglacial of some importance -possibly correlatable to MIS 5e. A reworked ball of organic sediment within the Screen Hills moraine containing a *Carpinus* -rich pollen assemblage (McCabe & Coxon 1993) may also represent a Late Pleistocene warm temperate stage but the evidence from this site is far from conclusive.
Pleistocene	6	Munsterian	*c*. 132ka		Many deposits of this cold stage are now believed to be Midlandian in age (McCabe 1987; O'Cofaigh 1993; McCabe & O'Cofaigh 1996) but dates on raised beach deposits show that some south coast sequences may indeed belong to MIS 6 (Gallagher & Thorpe 1997)
Pleistocene	7 or 9	Gortian	Minimum date MIS 7: 198ka (or MIS 9: 302ka) Maximum date MIS 7: 252ka (or MIS 9: 338ka)	Gn IV Gn IIIb Gn IIIa Gn II Gn I Pre-Gn l-g	Thirteen sites have been described from around Ireland that record part of a characteristic temperate stage deposit with a biostratigraphically similar record. The Gortian is represented by a record of vegetational succession and by a number of fossil assemblages that represent stages which have been described in a number of ways (e.g. by Mitchell 1981; Watts 1985; Coxon 1993, 1996a). Particularly notable aspects of the Gortian are its sudden truncation (Coxon *et al.* 1994) and biogeographically interesting flora (Coxon & Waldren 1995, 1997). Opinion is divided as to the age of the Gortian (Warren 1985; Watts 1985; Coxon 1993, 1996). Biostratigraphically it resembles the Hoxnian of Britain and the Holsteinian of Europe. Amino-acid racemisation results on marine Gortian sediments from Cork Harbour (Scourse *et al.* 1992; Dowling *et al*., 1998) confirm it is older than MIS 5e and the interglacial may represent MIS 7 or 9 (Dowling *et al.,* 1998; Coxon 1996a). UTD dating of the Gortian has so far proved inconclusive but the method holds promise.
Pleistocene		Pre-Gortian			Prior to the Gortian are sediments of late-glacial aspect, suggesting the temperate stage was preceded by a cool/cold stage.This stage is not represented by long or datable sequences, and the age is unknown.
Pleistocene		Ballyline	date unknown possibly > 428ka		A deposit of laminated, lacustrine, clay over 25 metres thick was discovered in 1979 by the Geological Survey of Ireland filling a solution feature in Carboniferous Limestone below glacial sediments near Ballyline, Co. Kilkenny (Coxon & Flegg 1985). From the evidence available the pollen assemblages can be seen to be typical of Middle Pleistocene sequences in Europe, but a firm correlation to a particular stage is not possible.
Pliocene	103?	Pollnahallia (Pliocene-Pleistocene boundary?)	*c*. 2.6Ma		A complex network of gorges and caves in Carboniferous Limestone at Pollnahallia, Co.Galway, contains lignite deposits —now covered by superficial material including wind-blown silica-rich sands (Tertiary weathering residues) and glacigenic deposits. Palynological results (Coxon & Flegg 1987; Coxon & Coxon 1997) suggest that the lignite infilling the base of the limestone gorge is Pliocene or Early Pleistocene in age. Further work is reported in the text.

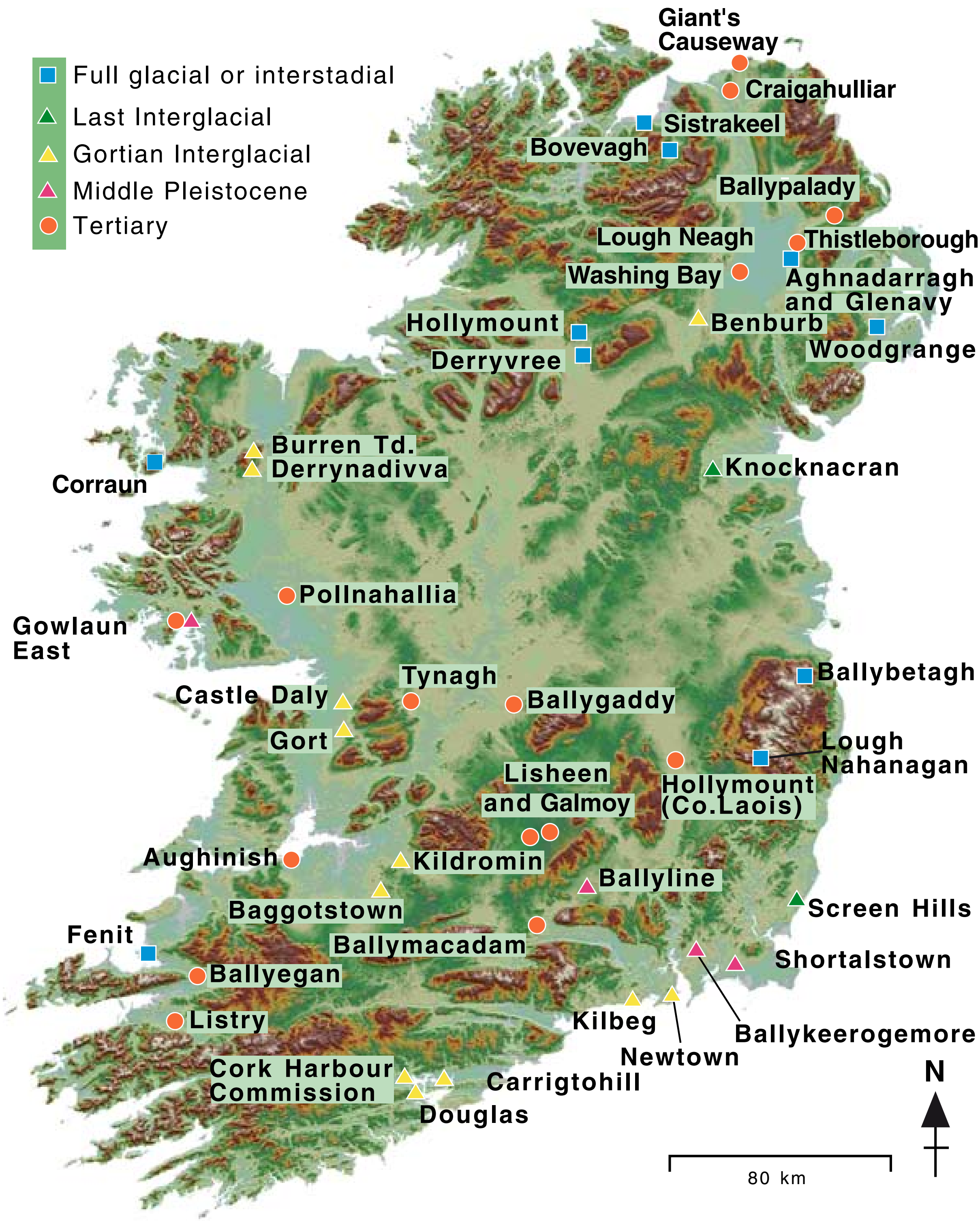

Figure 15.1 Location of important sites referred to in the text.

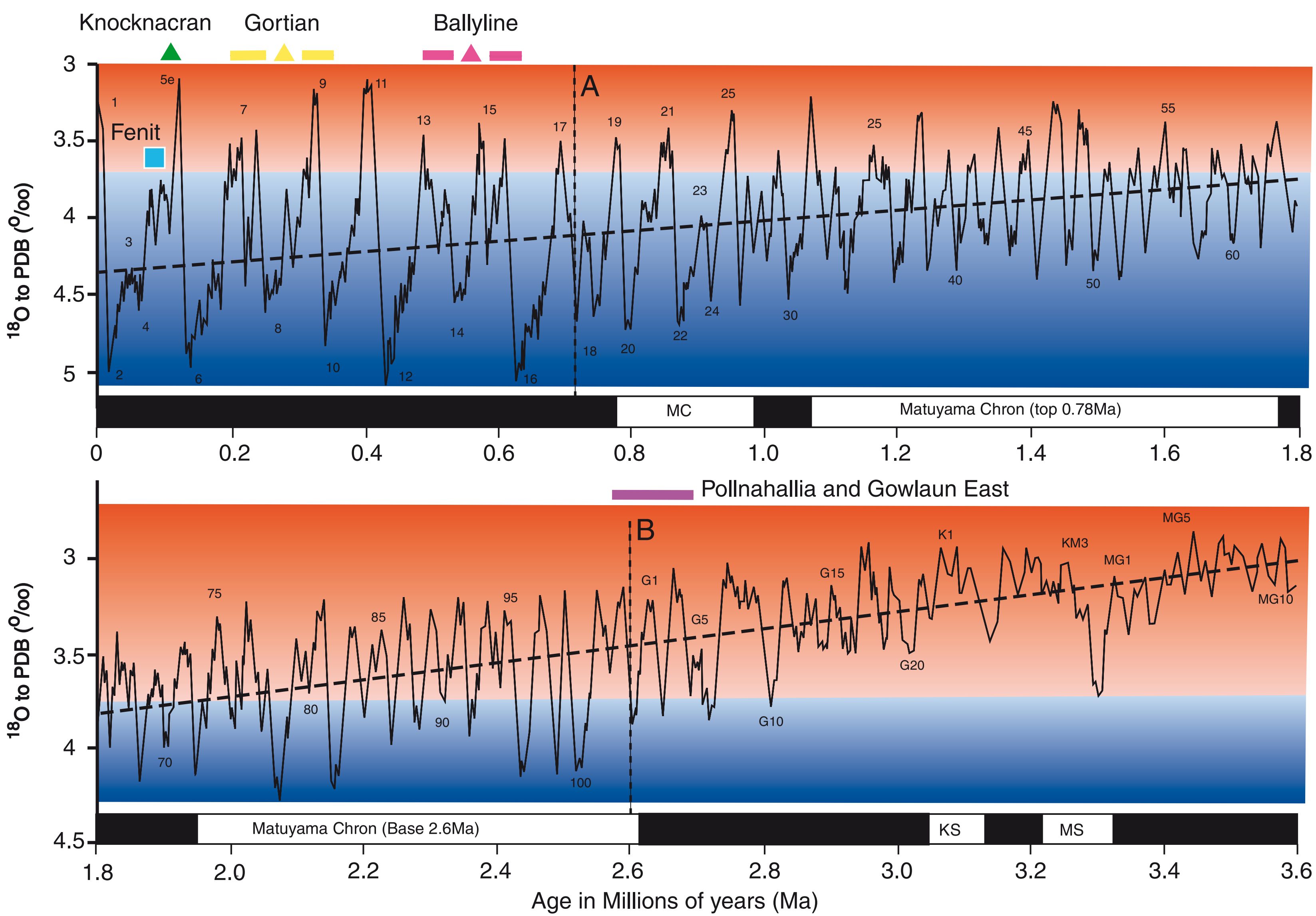

Figure 15.2 A composite oxygen isotope curve for the last 3.5 Ma (*after* Lisiecki and Raymo, 2005; from Walker and Lowe, 2007). The marine isotope stage numbers (MIS) are indicated. The long-term decline in global temperature, the increasing magnitude of climate signals towards the present, the change in climate forcing from a 40,000 year cycle to a 100,000 year cycle (dotted line at A) and the onset of the Quaternary (B) are all apparent. The correlations to the Irish record are tentative only and given to provide an impression of the complexity of the Pleistocene climate record from the ocean cores and the incomplete nature of the terrestrial record. *Reproduced by kind permission of the Geological Society of London.*

Figure 15.3 A – Tor exhumed by quarrying in Gowlan East, Connemara. B – Residual limestone tower near Fenit, Co.Kerry. C – Karstified limestone, Stone Forest, Kunming, China: possible analogue for Ireland's Late Tertiary limestone surfaces (e.g. at Pollnahallia).D – Limestone towers, Li river, SW China. E – Section at Bothar na Scrathog, Connemara, showing exposed bedrock tor (E1), Neogene palaeosurface and possible Middle Pleistocene palaeosol (E2) separating two tills (see Coxon, 2001, 2005).

Tertiary landscape and vegetation

Relict geomorphological elements of a Tertiary landscape in Ireland were reviewed by Mitchell (1980, 1985) who identified basins, pediments, tectonism, erosion surfaces, limestone solution, and deeply weathered bedrock in many areas of the country. Tertiary rocks in Ireland vary from the extensive (*c.*390,000 ha) basalt plateau and its associated palaeosurfaces (Interbasaltic Beds) found in the north-east, to restricted intrusions and depositional fills or weathering residues. The latter are commonly found within karstic depressions in areas of Carboniferous limestone (Table 15.3 and Figures 15.3 and 15.4) and are associated with palaeosurfaces on other lithologies. The age of the Tertiary deposits, like their geomorphology, is variable, ranging from the Palaeocene of north-eastern Ireland to the less extensive Oligocene sediments found as karstic infills (e.g. Ballymacadam) and the Miocene deposits at Hollymount, County Laois. The latter two examples are well documented, whilst other deposits of possible Tertiary age are less so (see Table 15.3 and Figure 15.4).

Table 15.3 Tertiary sites of note in Ireland.

Site	Nature of evidence/Age	Publication(s)
Interbasaltic Beds, e.g. Giant's Causeway, Craigahulliar and Ballypalady, County Antrim and Washing Bay, County Tyrone	Extensive and numerous organic horizons (some blanket peats or peaty soils) lying on subaerially weathered basalt surfaces. The palaeobotany of these organic sediments tentatively suggests an Early Palaeocene age. Plant fossils include: *Pinus, Tsuga, Cupressus, Araucaria, Alnus* and a number of angiosperms and ferns.	Watts, 1962, 1970 (review); Curry *et al.*, 1978; Mitchell, 1981.
Lough Neagh Clays, southern part of Lough Neagh, e.g. Washing Bay, County Tyrone and Thistleborough, County Antrim.	350m of predominantly lacustrine and swamp sediments deposited in a large subsiding basin. Although the palaeobotany (like that of the Interbasaltic Beds) requires modern research an Oligocene age (Chattian or Rupelian) can be implied. Plant fossils include: *Sequoia, Alnus, Nyssa, Quercus* (?), *Tilia* (?), and Taxodiaceae. The last, and associated taxa, suggest that the vegetation was predominantly that of a lowland swamp.	Watts, 1970; Curry *et al.*, 1978; Boulter, 1980; Wilkinson *et al.*, 1980
Ballymacadam, County Tipperary	A solution pipe in Carboniferous limestone with an infill (*ca.* 10m thick) including clay sediments rich in biogenic material. The pollen content of gymnosperms, '*Quercus*-type', *Engelhardtia, Symplocus*, Ericaceae, and occasional Palmae represents a vegetation with Oligocene affinities, probably similar in age to that of the Lough Neagh Clays	Watts, 1957, 1970; Boulter and Wilkinson, 1977; Curry *et al.*, 1978; Boulter, 1980
Aughinish Island, County Limerick	Deep karstic hollows encountered during site investigations for an aluminium smelting plant. Limited palaeobotanical information implied a Middle Tertiary age.	Clark *et al.*, 1981; Mitchell, 1985
Tynagh, County Galway	Altered sulphide ore lying in karstic hollows developed along faults. Authors suggest that a log of *Cupressus* wood may imply a middle Tertiary age.	Mitchell, 1980; Monaghan and Scannell, 1991
Galmoy and Lisheen, Counties Kilkenny and Tipperary	Deep (40m+) karstification of limestone identified in mineral exploration boreholes. Palynology of organic clays in the depressions suggests a middle Tertiary age.	Unpublished reports
Hollymount, County Laois	20m of quartz sand, lignite and other organic sediments infilling a karst solution hole. Detailed palynology indicates a Miocene or earliest Pliocene age and taxa include *Pinus, Quercus, Corylus, Myrica* , Ericales, *Taxodium* type, *Symplocus, Tsuga, Sciadopitys, Liquidambar* and Palmae type.	Hayes, 1978; Watts, 1985; Boulter, 1980
Ballyegan, County Kerry	Palaeosols containing gibbsite and quartz are exposed in a limestone quarry capped with glacigenic sediments. The authors suggest the weathering is pre-glacial (possibly 'Pliocene?' but noting that they recovered no palynomorphs to prove this conclusion).	Battiau-Queney and Saucerotte, 1985; Battiau-Queney, 1987
Ballygaddy Townland, County Offaly	Karst depression (possibly 40m deep) containing weathered stony clays. A possible Tertiary age was inferred by the authors.	Beese *et al.,* 1983
Listry, County Kerry	A weathered silicious breccia in a matrix of iron-rich sandy clays. A possible Tertiary age is suggested by the author.	Walsh, 1965
Pollnahallia, County Galway	See text	
Gowlan East, County Galway	See text	

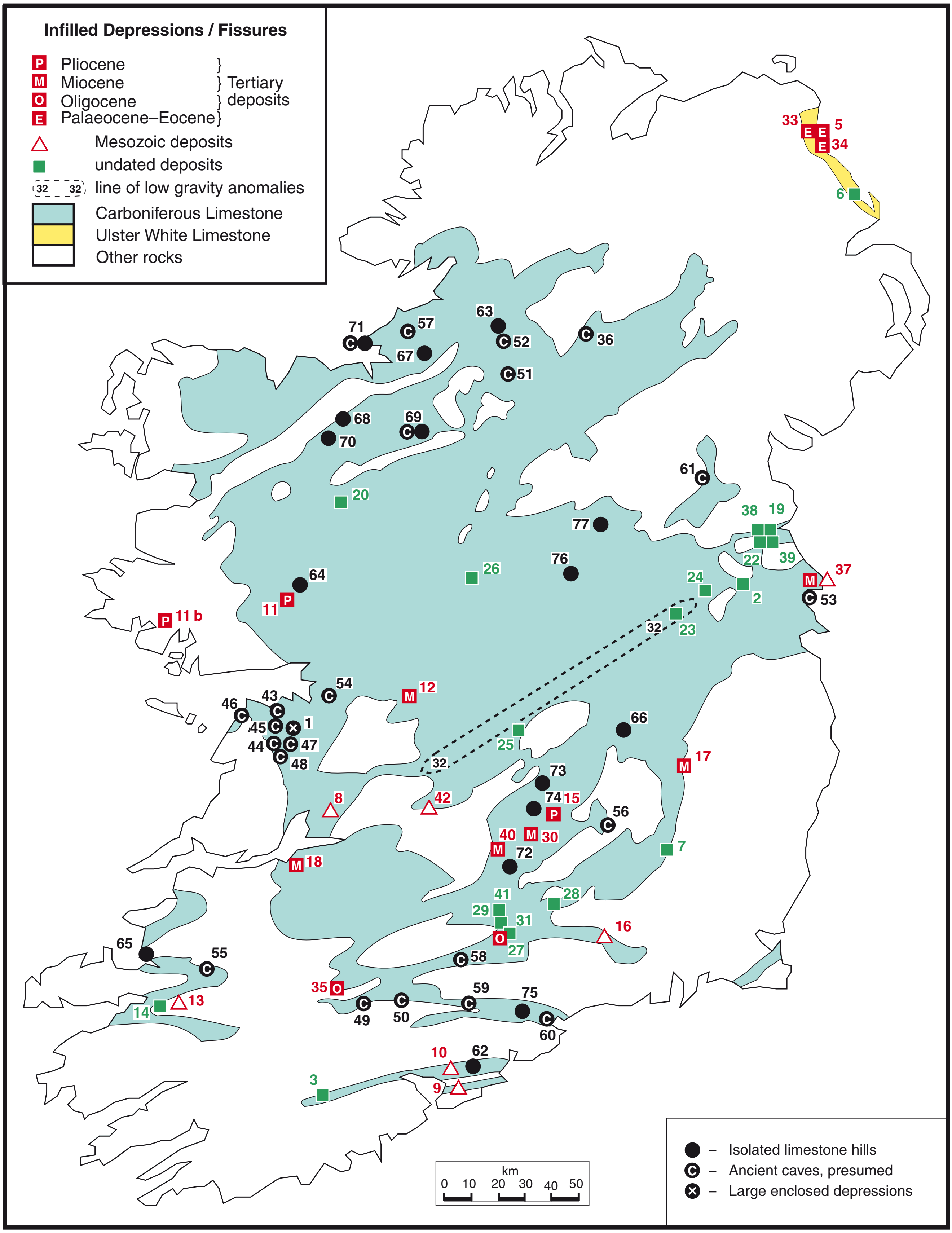

Figure 15.4 Presumed ancient karstic sites and landforms including Pollnahallia (site 11) and Gowlan East (not a karstic feature, site 11b). The figure is modified after Drew and Jones (2000) and the full key to the karstic sites is given in their Table 1.

References in the literature to undated landforms of possible Tertiary age are numerous (Drew and Jones, 2000), as are unpublished reports of deeply weathered limestone and associated infills. Phreatic passages and extensive cave systems now far above (and below) current water table levels have also been widely commented upon (e.g. Simms, 2000a). Some of the landforms recorded are large-scale and thought to be of considerable antiquity, most probably Tertiary, (e.g. the area of The Doons in County Sligo, which may be an area of 'cockpit karst' – Herries Davies and Stephens, 1978; see review by Drew and Jones, 2000 and Coxon, 2006).

The geomorphology and the palaeoecology of the pre-Pliocene Tertiary deposits are summarised in Table 15.3 and Figure 15.4 and the later Tertiary is outlined below.

The Pliocene and the Pliocene-Pleistocene transition

Late Tertiary palaeosurfaces and accompanying palaeosols and sediment fills have been described from limited areas in western Ireland, and they provide a remarkable record of pre-glacial landscape inheritance (reviewed by Coxon, 2006). These relict surfaces have been discovered on limestone, at Pollnahallia in County Galway, and on granite farther west on the flanks of Cnoc Mordáin, near Kilkieran in Connemara.

Gowlan East, Iorras Aintheach, Connemara

Evidence from Connemara to date (Coxon, 2001, 2006) consists of weakly developed palaeosols draping buried tors in the townland of Gowlan East, between Bertraghboy and Kilkieran Bays (the peninsula of *Iorras Aintheach*). This magnificent landscape is scattered with granite tors, some exhumed from the surrounding growan and others still buried (Fig. 15.2). Flanking the northern slopes of Cnoc Mordáin are extensive debris-mantled slopes, and along the toe of one such slope a number of small quarries have exposed buried bedrock tors overlain by tills, soliflucted tills, and palaeosols (location: Fig. 15.1, sections Fig. 15.3). The lower palaeosol lies directly on the buried bedrock and is Neogene (probably Pliocene) in age (Coxon, 2001). The upper palaeosol, probably Middle Pleistocene in age, separates two distinctive tills (Fig. 15.3).

The Pliocene soil contains relatively sparse but well-preserved pollen (see Coxon, 2001, 2006) and the presence of the pollen of *Tsuga, Taxodium, Sequoia, Carya,* and *Castanea* suggests that a diverse forested environment existed here some 2.6 to 5 Ma ago. The assemblage is characteristically Neogene and most likely Pliocene in age (the more exotic taxa of the Miocene being absent). The occurrence of *Quercoidites* (*Tricolpopollenites* cf. *T. microhenrici*) and *Betulaepollenites* type also suggests a pre-Pleistocene age. The discovery of the buried Pliocene soil horizon also defines a palaeosurface and suggests that the granite surface was extensively weathered (the soil is laterally extensive and formed in weathered granite). The existence of tors separated by weathered granite and a palaeosol (now covered by till) suggests that stripping of a weathered mantle had already occurred by the Pliocene and that the landscape was one of exhumed granite tors surrounded by forested soils developed in remnants of the weathering mantle.

The onset of the Pleistocene saw further stripping of the weathered mantle, ice moulding of the bedrock protuberances, and partial (or complete) burial of some bedrock tors by glacigenic or periglacial sediments (Fig. 15.3).

Pollnahallia, County Galway

Far more complete Tertiary sediment sequences are available from the fascinating site at Pollnahallia (location: Figure 15.1). Pollnahallia lies in a geomorphologically complex region on Viséan limestone that includes large shallow depressions (up to 5 m deep), deeper depressions and fractured limestone (up to 15 m deep), deep gorges (up to 20 m deep) and cave passages. The landscape in the immediate vicinity of Pollnahallia (*c.*3.3 km^2 area around the site) is extensively karstified with Pliocene lignites part filling a limestone gorge (Figs 15.5, 15.6) and even draping the surrounding limestone surface (for a detailed summary see Coxon *et al.*, 2005). The lignite (both inside the gorge and on the limestone surface, see Figure 15.5) was sampled in 1987 and a continuous core was obtained from within a limestone gorge. The latter borehole (Fig. 15.6) was 20.26 m long, and from the base upwards the sediment succession is one of laminated clays, silts, organic detritus and lignites alternating with numerous sandy horizons. Lignite predominates portions of the core whilst the upper part of the core shows an upward transition from silt and clay into laminated silts and clays, into laminated silts, and finally into laminated yellow clays with sand horizons. The loss on ignition data (Fig. 15.6) displays the variable nature of the organic content and shows a marked variability associated with sandier horizons.

The sedimentological interpretation (allied to the geomorphological information) is that the sediments were laid down in an open gorge cut into limestone

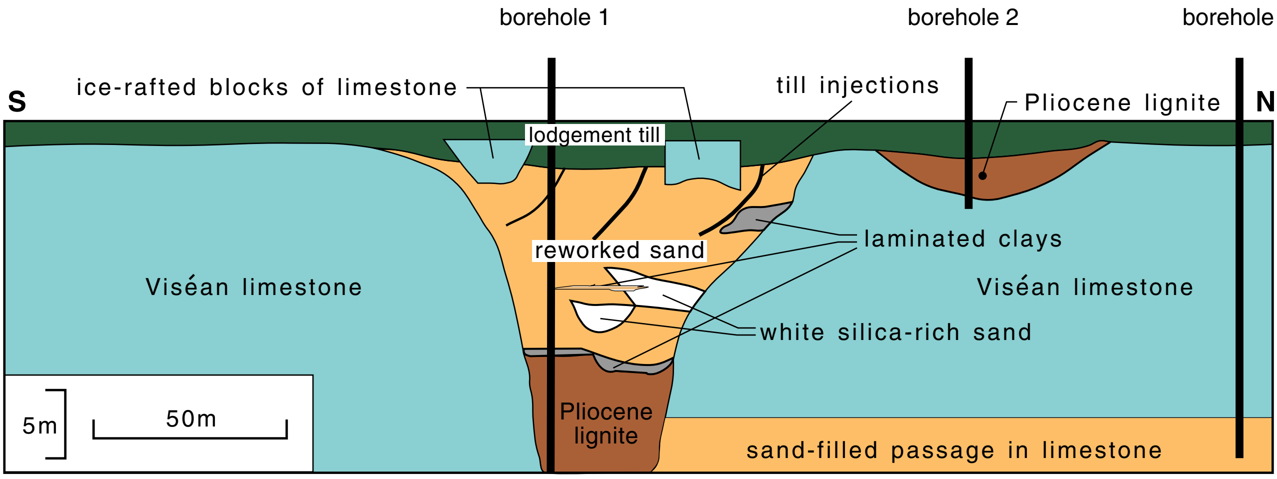

Figure 15.5 A. Schematic cross-section of the Pliocene and Pleistocene deposits at Pollnahallia, County Galway (from Coxon and Coxon, 1997 and Coxon and Flegg, 1987). *Reproduced by kind permission of the Geological Society of London.*

bedrock under conditions with long periods of quiet (or still) water deposition interspersed by occasional flows capable of transporting sand. A considerable volume of organic debris from rotting vegetation accumulated in the narrow gorge. Presumably the latter sediments were derived both allocthonously and autochthonously.

The palaeoecology of the biogenic sediments from Pollnahallia is as fascinating as the geomorphology. The palynology is summarised on two pollen diagrams (Fig. 15.7), and these diagrams can be subdivided into five pollen assemblage biozones (pab).

pab	depth (cm)	assemblage
87/1–5	1050–1100	*Pinus–Betula–Larix*–Gramineae
87/1–4	1100–1275	*Pinus–Corylus*–Ericaceae–*Carya*
87/1–3	1275–1575	*Pinus–Taxus–Taxodium*–Ericaceae
87/1–2	1575–1875	*Pinus–Corylus*–Ericaceae
87/1–1	1875–2012	*Pinus–Taxodium*–Ericaceae–*Sequoia*

The pollen assemblages indicate a vegetation cover dominated by *Taxodium*, ericaceous, cupressaceous and coniferous trees, a diverse assemblage of tree types and assorted shrubs (see Table 15.4 for a summary).

The important biostratigraphical elements of the pollen diagram include the presence of typical late Tertiary taxa; e.g. *Sequoia, Taxodium, Nyssa, Liquidambar, Castanea, Ostrya, Juglans, Sciadopitys, Carya,* and *Pterocarya*. Such taxa are frequently found in Pliocene deposits in the Netherlands (Zagwijn, 1960) and this, the absence of pre-Pliocene marker taxa and the apparent climatic deterioration recorded in the upper part of the sequence, allows a probable correlation to be made to the Reuverian of the Netherlands (Coxon, 1993), possibly Reuverian C.

Pollen zones 87/1–1 to 87/1–4 (i.e. the bulk of the biogenic sediment sequence) are characterised by their diverse assemblages dominated by swamp cypress, cypresses, heathers and pine. The landscape must have been magnificent and the vegetation cover diverse and, in the autumn, very colourful with an affinity to the modern vegetation of the swamps of eastern North America. The assemblages suggest that frosts must have been negligible and the climate (at least in the gorge at Pollnahallia) was warm and wet.

Zone 87/1–4 sees a decrease in the swamp cypress cover associated with a sedimentological change at 12.55 m, and subsequently in pab 87/1–5 there is a marked assemblage change associated with the facies change to laminated clays with sand horizons (at 11.00 m in borehole 87/1). The change involves an increase in taxa indicating climatic deterioration (e.g. the rising values of Ericaceae and *Juniperus*) and the disappearance of a number of the thermophilous taxa. The lithological and palynological changes suggest that the top of the organic sedimentation may represent climatic deterioration at the end of the Pliocene and the beginning of the Pleistocene.

One striking element in the Pollnahallia pollen diagram is the exotic nature of some of the flora. Many of the taxa recorded are no longer native to Europe, and indeed some have a distinctly disjunct modern distribution occurring only in North America and Asia. Table 15.4 partly illustrates this point and the flora, palaeobotanical correlations and a comparison with deposits

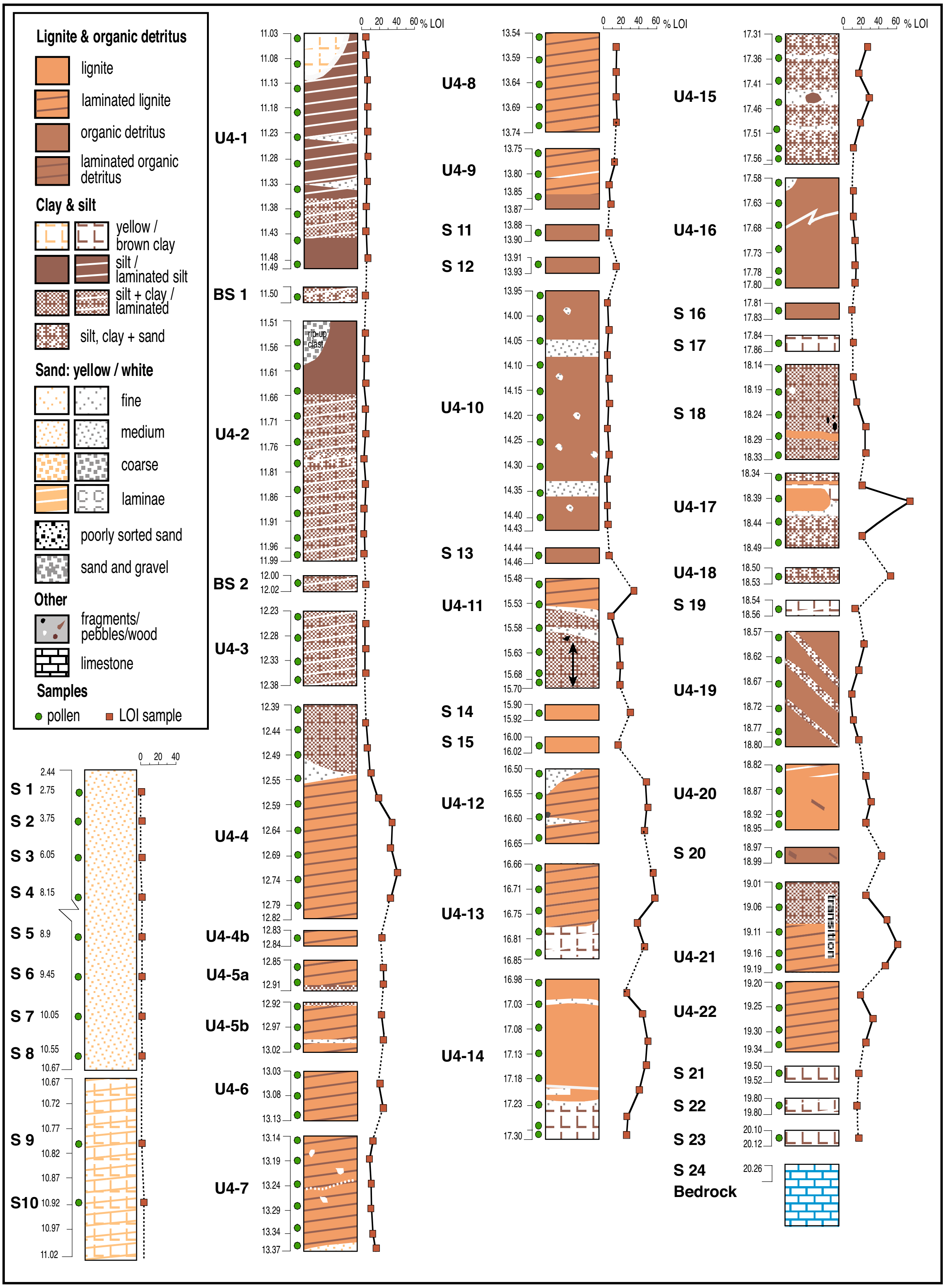

Figure 15.6 The log of borehole 87/1 at Pollnahallia showing the depositional sequence, cores, pollen samples and loss on ignition values (*after* Coxon *et al.*, 2005).

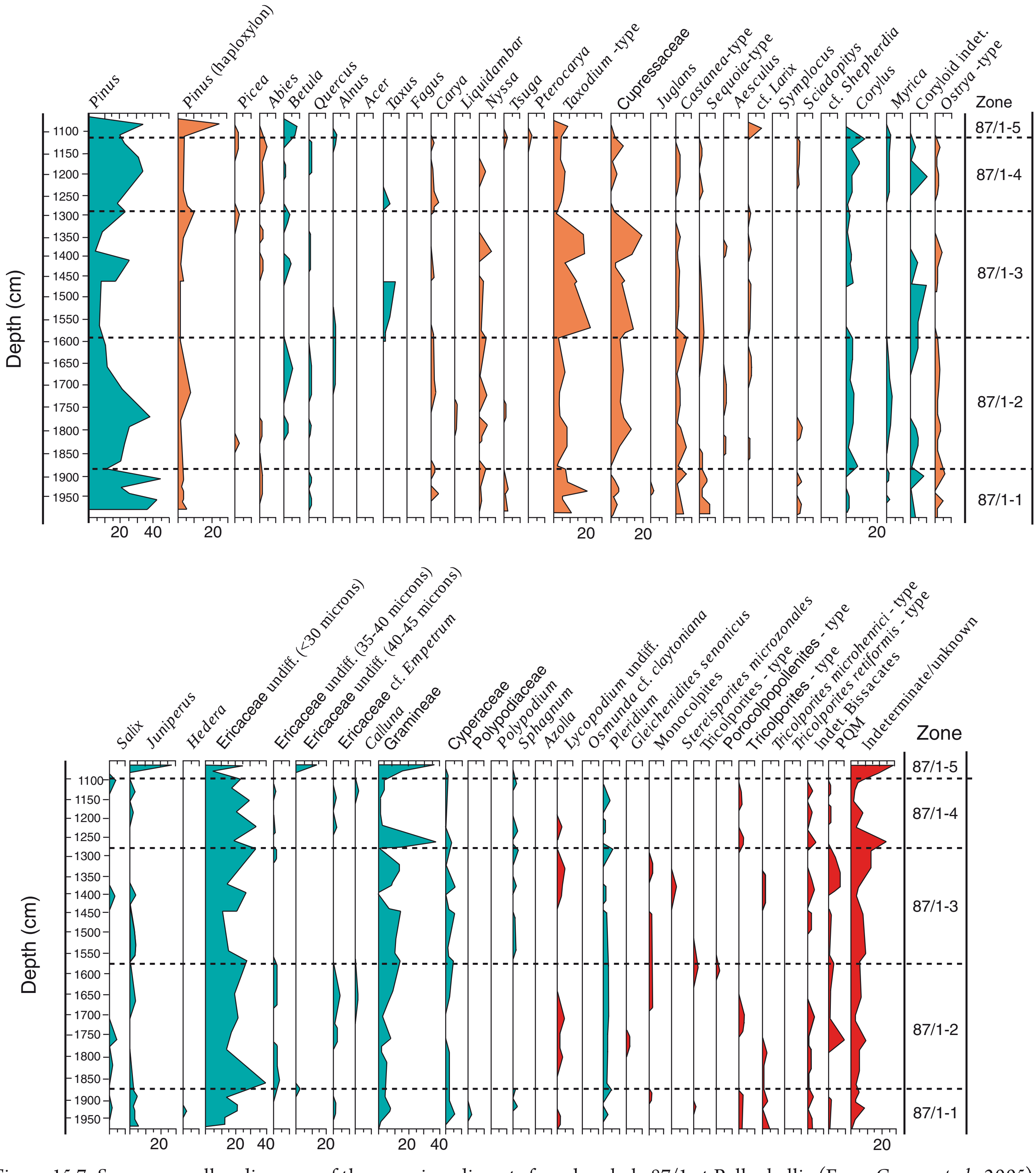

Figure 15.7 Summary pollen diagrams of the organic sediments from borehole 87/1 at Pollnahallia (From Coxon *et al.*, 2005). The taxa are colour coded (a general scheme) as follows: blue – taxa that could be native in the Irish Holocene, orange – taxa found in European Late Tertiary and Early Pleistocene, red – form genera and unknown taxa. *Reproduced by kind permission of the Quaternary Research Association.*

in the UK are made in Coxon and Coxon (1997) whilst Coxon and Waldren (1997) discuss the flora with reference to range retraction during the Pleistocene (Coxon *et al.*, 2005).

The lignite grades upwards into a laminated silt and clay sequence that becomes increasingly sandy, eventually passing into pure silica sand which is at least 9 m thick and fills an elongate basin in the limestone that

Table 15.4 A summary list of the taxa found in the Pliocene biogenic sediments at Pollnahallia (from Coxon *et al*., 2005).
n.b. Some of the families and genera have many members (e.g. within the Fagaceae family the genus *Quercus* (oak) contains 600 species) making the identification to species level using palynology difficult/impossible. A further problem is that with deposits of Tertiary age some of the individual species are probably extinct, indeed some authors refer to Tertiary taxa as form genera only (i.e. they describe the pollen morphology rather than attempt an identification to any living taxa e.g. *Tricolpollenites*-type) whilst others might refer to a genus but avoid a direct classification to a living member of that genus, i.e. *Quercoidites*).

botanical name (Family or Genus/species)	common name
Abies	fir
Acer	maple
Aesculus	horse chestnut
Alnus	alder*
Azolla	water fern
Betula	birch*
Calluna	heather (ling)*
Carya	hickory
Castanea	sweet chestnut
Corylus	hazel*
Coryloid indet.	possibly hazel? (or another of numerous triporate pollen taxa)
Cupressaceae	cypress family
Cyperaceae	sedge family*
Empetrum	crowberry*
Ericaceae	heather family*
Fagus	beech
Gleicheniidites senonicus	tropical/warm temperate fern
Gramineae	grass family*
Juglans	walnut
Juniperus	juniper*
Larix	larch
Liriodendron	tulip tree
Liquidambar	sweetgum
Myrica	bog myrtle*
Nyssa	sourgum
Osmunda regalis	royal fern*
Osmunda cf. claytoniana	north American/east Asian fern
Ostrya	hop-hornbeam
Picea	spruce
Pinus (subgenus Diploxylon)	pine*
Pinus (Haploxylon) (Haploxylon pines have a different pollen morphology and represent a subgenus of different species to Diploxylon pines)	pine
Polypodiaceae	ferns*
Pterocarya	wingnut
Quercus	oak*
Salix	willow*
Sciadopitys (cf. *S.verticillata*)	Japanese umbrella pine
Sequoia	giant redwood
Sphagnum	moss*
Taxodium	swamp cypress
Taxus	yew*
Tsuga	hemlock

* denotes representatives native to Ireland in Holocene. (Note many of the taxa listed have been introduced to Ireland but are not native.)

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slopes downwards from 5 m below surface in the west to a depth of 27 m in the east. The sand is very well sorted and exhibits large-scale foreset bedding, but no smaller scale sedimentary structures were visible in the undisturbed unit. The sands are probably aeolian, but fluvial and glacifluvial reworking has affected some of the material.

The origin of these sands could have been deeply weathered sandstone, quartzite, or even granite, and Mitchell (1980, 1985) has suggested that such weathering, under moist and warm conditions, could have occurred throughout the Tertiary, producing deep residual deposits on the landscape. The onset of the Pleistocene, with the subsequent decline in vegetation cover, would have provided environmental conditions suited to the erosion and transport of such weathered mantles. Several possible source rocks for the sand exist (Coxon and Flegg, 1987) but, given the high purity of the sand and the absence of staining, the most favourable source would be a rock that was virtually monomineralic and also not heavily stained. The quartzites of Connemara are situated 30 km west of Headford and present the most likely source (Coxon and Coxon, 1997).

Glacial action, including that of meltwater, has reworked some of the sand and rafted large sheets of limestone to cover parts of the gorge, as well as depositing an overlying lodgement till (Figs 15.5, 15.8) that was injected into the sand to a considerable depth. Friction at the base of the ice has transported the rafts of limestone and also moved some of the sand body en bloc (post till injection), causing shearing of the injection structures in the direction of ice movement.

As Davies (1970) pointed out, the information available to us from the Tertiary is scant, but fragments of information from sites such as those above give an indication that Ireland's surface was subjected to warm-temperate or sub-tropical conditions for much of the 63 Ma of the Tertiary and was probably deeply weathered and karstified during this time. At the onset of the Quaternary drastic environmental changes began to modify an extremely old landscape.

Figure 15.8 A) The silica sand quarry at Pollnahallia, County Galway. The sand is exposed in the background of the photograph. The main borehole was made in the floor of the pit. B) A till injection down into the silica sands at Pollnahallia. C) A core of lignite being extruded in the field at Pollnahallia. D) Pliocene lignite exposed subaerially at Pollnahallia showing remarkable preservation of a Late Tertiary palaeosurface as the modern soil. E) A pollen grain of *Taxodium* (*cf. distichum*) – swamp cypress. The pollen grain is 30 μm in diameter. F) Swamp cypress in its native habitat, South Carolina: a possible analogue for lowland Galway in the Pliocene.

The Quaternary: 2.6 million years to 11,700 years before 2000

Introduction

The Global Cenozoic sequence from long marine, lacustrine, and terrestrial records exhibits a characteristic record with a decline in temperature throughout the Miocene culminating in numerous step-like changes in climatic conditions over the last 2.6 Ma (Figure 15.2). Research over the last three decades has confirmed that global climate changes are controlled by regular, orbitally induced, insolation variation (the development of these theories is described in Imbrie and Imbrie, 1979, 1980 and Kutzbach and Webb, 1991). Climate change during the Pleistocene has been noticeably variable in magnitude and frequency, with earlier cyclicity (2.0 Ma–1.4 Ma and 1.4 Ma–0.9 Ma) having a shorter wavelength than later cyclicity. During the period between 0.9 Ma and 1.4 Ma isotopic fluctuations suggest a predominant 41 ka cycle (Ruddiman *et al.*, 1986), whilst from 0.9 Ma to the present the cold stages occur over 100 ka intervals (Shackleton and Opdyke, 1976). This variation is (at least in part) due to the changing relative importance of the three orbital climate-forcing parameters, which have different periodicity (precession 22 ka, tilt 41 ka, and eccentricity 100 ka) (Hays *et al.*, 1976). The climate signal preserved in oxygen isotope records from marine sediments and ice cores displays both the complexity and the regularity of global climate change from the late Tertiary to the end of the Pleistocene. Figure 15.2 shows such a record (oceanic) and allows a comparison to the Irish record as well as putting the latter into a global perspective.

Irish Pleistocene biostratigraphy

Early and Middle Pleistocene

Figure 15.2 shows the paucity of the Irish record from the late Pliocene (c. MIS 103) up until the late Middle Pleistocene (c. MIS 11). Indeed, apart from the uppermost organic sediments at Pollnahallia, there is no documented record of the early Pleistocene in Ireland apart from a glacially reworked fauna of marine shells that originated in the Irish Sea basin (Mitchell, 1981).

Middle and Late Pleistocene

This period of time has been reviewed in detail by Dowling and Coxon (2001) and the bulk of known evidence postdates MIS 11. One interglacial sequence, over 25 m thick, from a solution feature in Ballyline, County Kilkenny (Coxon and Flegg, 1985) is worthy of mention, but the site requires further sampling and subsequent reanalysis. The pollen assemblages from Ballyline can be seen to be typical of Middle Pleistocene sequences in Europe and contain *Abies*, *Picea*, *Ulmus*, *Alnus*, *Quercus*, *Carpinus*, *Pterocarya,* and *Taxus* with areas covered by Gramineae, Ericales, and numerous herbs. The deposits representing this forest/heath/grassland stage are 10 m thick.

Late-Middle Pleistocene: the Gortian Interglacial

Kinahan (1865, 1878) described an interglacial deposit of peat and mud lying below glacial deposits in the banks of the Boleyneendorrish River, near Gort, County Galway. Subsequently the deposit was studied in detail (Jessen *et al.* , 1959) and has been used as the type site of the Gortian Interglacial. We now have the details of thirteen other interglacial sites with Gortian affinities from around Ireland (some are shown on Figure 15.9). The interglacial sites are variable in depositional and geomorphological setting and in the length of the temperate stage that is recorded. The ranges determined from pollen assemblages of the sites are reviewed on Figure 15.10. The Cork Harbour area (Figs 15.11, 15.12) has provided three long Gortian sequences of estuarine and lacustrine sediments up to 18 m thick that have been the subject of considerable research (Dowling, 1997; Dowling *et al.*, 1998; Dowling and Coxon, 2001). One of the pollen diagrams is reproduced here as Figure 15.13.

The palaeobotany and biogeography of the Gortian exhibits an interesting, diverse flora, and the reader is directed to the original papers for details (Watts, 1985; Coxon and Waldren, 1995, 1997; Coxon, 1996a). Abbreviated pollen diagrams from six of these sites are shown on Figure 15.9 and the vegetational sequences can be seen to follow a general pattern (Watts, 1985). However, the interglacial does not seem to complete a full cycle (*sensu* Iversen, 1958, Turner and West, 1968) but comes to an abrupt end (see figure 15.10). The biostratigraphy of the Gortian is summarised in Table 15.5.

The vegetational record differs slightly between Gortian sites, e.g. *Taxus* is present to a varying degree depending upon local soil conditions. Some of this variation is simply accounted for by the differing substages of the interglacial that are represented at each site. However, as Figures 15.9 and 15.13 show, the principal vegetational succession is distinctive, with *Pinus* and *Betula* remaining important throughout the temperate sequence.

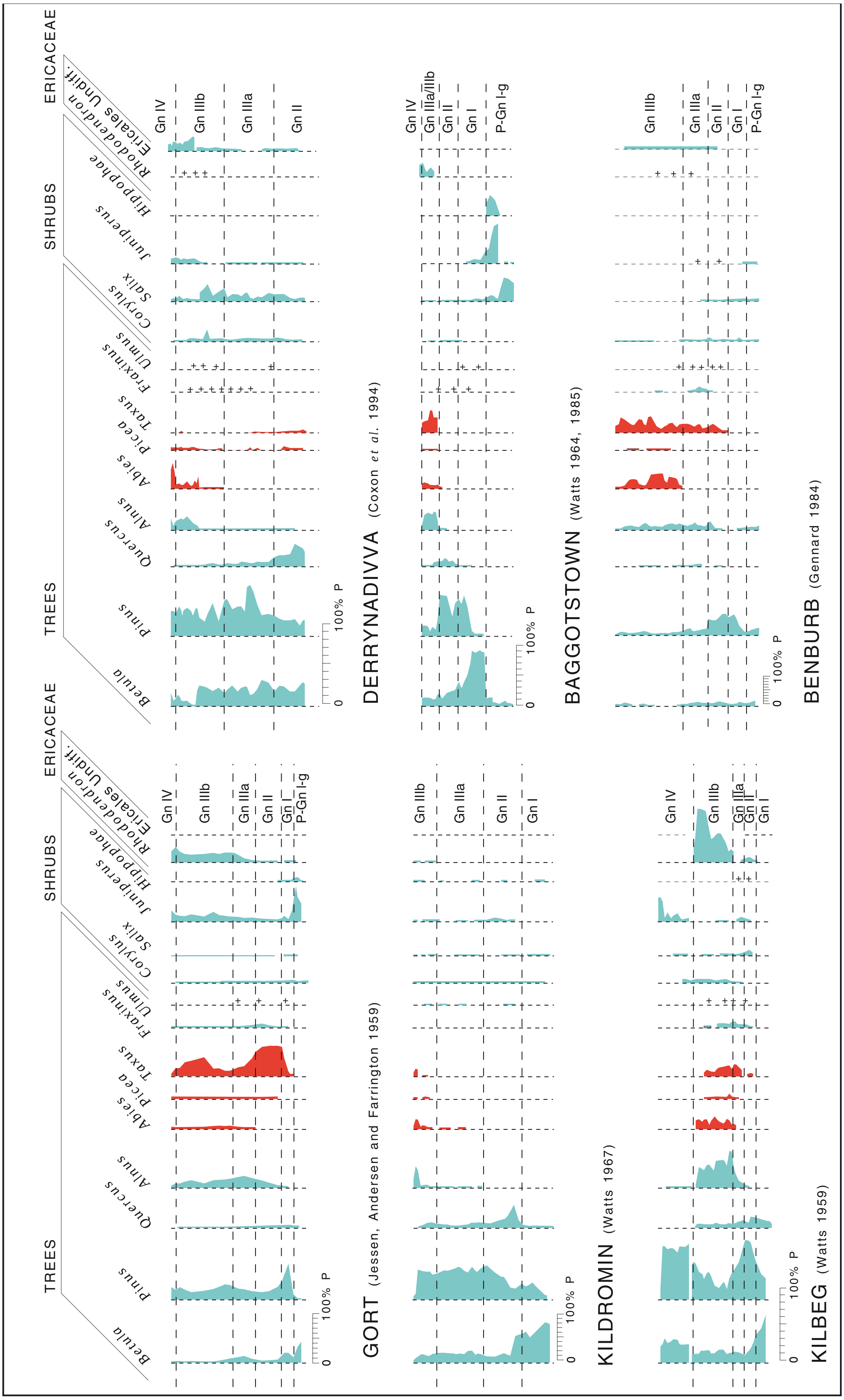


Figure 15.9 Pollen diagrams of selected taxa from the more complete Gortian sequences (*after* Coxon, 1996a).

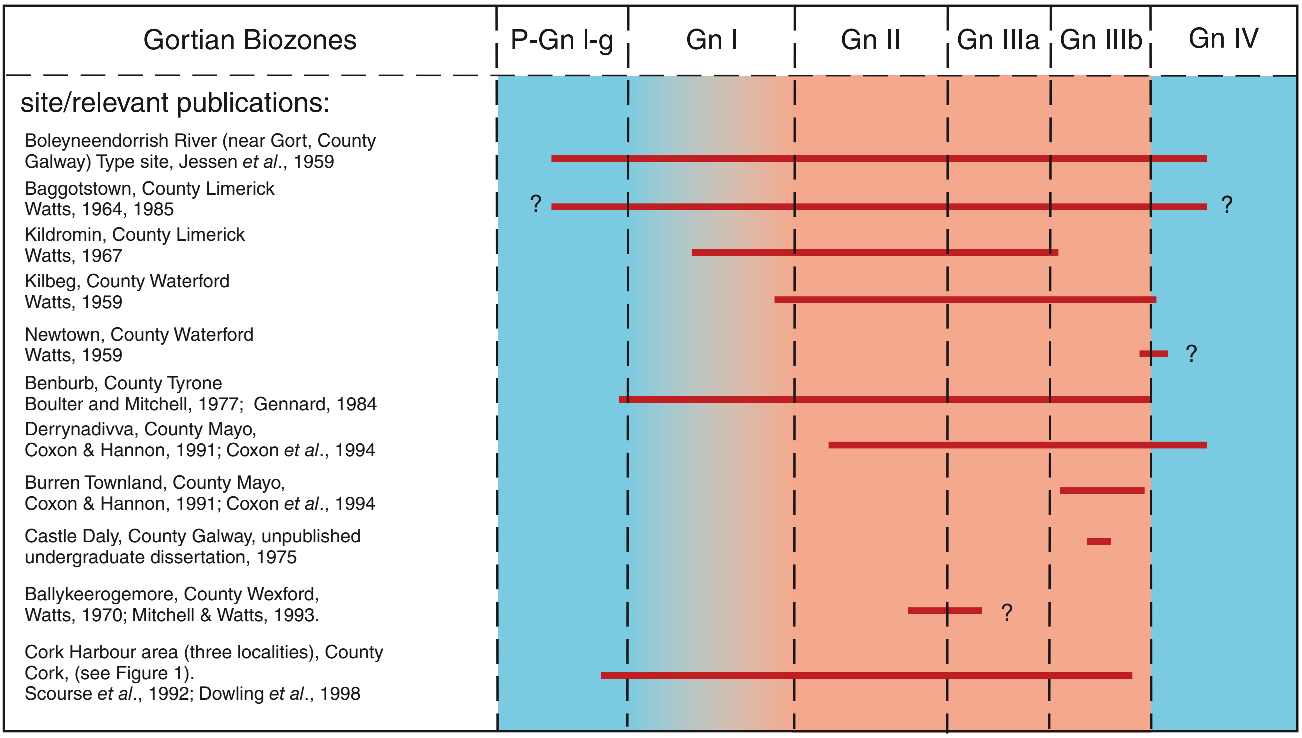


Figure 15.10 Pollen zone ranges for Gortian Interglacial sites (from Coxon, 1996a).

Opposite Figure 15.11 Interglacials. A – Drilling Gortian sediments at Douglas, Cork Estuary. 16 metres of interglacial sediment lie just below the surface in a large channel-fill deposit. B – Organic sediments interbedded within clays and in a closed-system at Fenit Co.Kerry. U–Th dates obtained from these organic deposits suggest an age of *c*.118,000 years, i.e. towards the end of MIS 5e. C – Possible modern analogue for Gortian vegetation. *Rhododendron ponticum* amongst mixed woodland. County Kerry. D – Gortian temperate stage peats, Derrynadivva, County Mayo. E – A monolith of sediment deposited at the closing stage of the Gortian Interglacial at Derrynadivva, County Mayo. F – Organic sediments, possibly last interglacial in age (MIS 5e) below drumlinised till and filling a collapse feature in karstified Permian gypsum, Knocknacran, County Monaghan.

The age of the Gortian temperate stage

Biostratigraphy

The poor Irish Quaternary record, unlike that of Britain (e.g. West, 1980; Jones and Keen, 1993) and continental Europe (e.g. Zagwijn, 1985; Reille and De Beaulieu, 1995; De Beaulieu and Reille, 1995), complicates correlation, making it impossible to place Gortian deposits in the context of a firm Quaternary stratigraphical framework beyond that presented in Table 15.2.

The traditional dating of the Gortian has relied upon biostratigraphical correlation based on the presence/absence of key taxa in assemblages from temperate stage deposits in Britain and continental Europe. This approach has been taken because the age of overlying glacigenic sequences has never been unequivocally established. The crucial biostratigraphical correlation that has linked the Gortian to the Hoxnian of Britain includes the following:

1. 'Relic' taxa, associated with the early Pleistocene in northern Europe, are not recorded (these taxa include *Tsuga* and *Eucommia*) suggesting that the Gortian is late-Middle Pleistocene.
2. Abundant *Hippophae* is present at sites exhibiting the Pre-Gortian late-glacial.
3. Presence of abundant *Abies* in Gn III.
4. Presence of *Azolla filiculoides* .
5. Relative lack of *Carpinus* (cf. last interglacial/MIS 5e records).
6. Presence of Type X (up to 7% ΣP at some sites) throughout stages Gn II –Gn III.
7. Records of *Pterocarya* from Derrynadivva and Cork Harbour.

Nevertheless the correlation has been the subject of some criticism (Warren, 1979, 1985; Coxon, 1993, 1996a) and the Gortian assemblages do imply possibly cooler conditions than those prevailing in the Hoxnian.

If the Gortian is the equivalent of the Hoxnian and Holsteinian temperate stages this suggests that it belongs within MIS 11 (e.g. De Beaulieu and Reille, 1995) that would suggest an age between 352 ka and 428 ka. However,


A
B
C
D
E
F

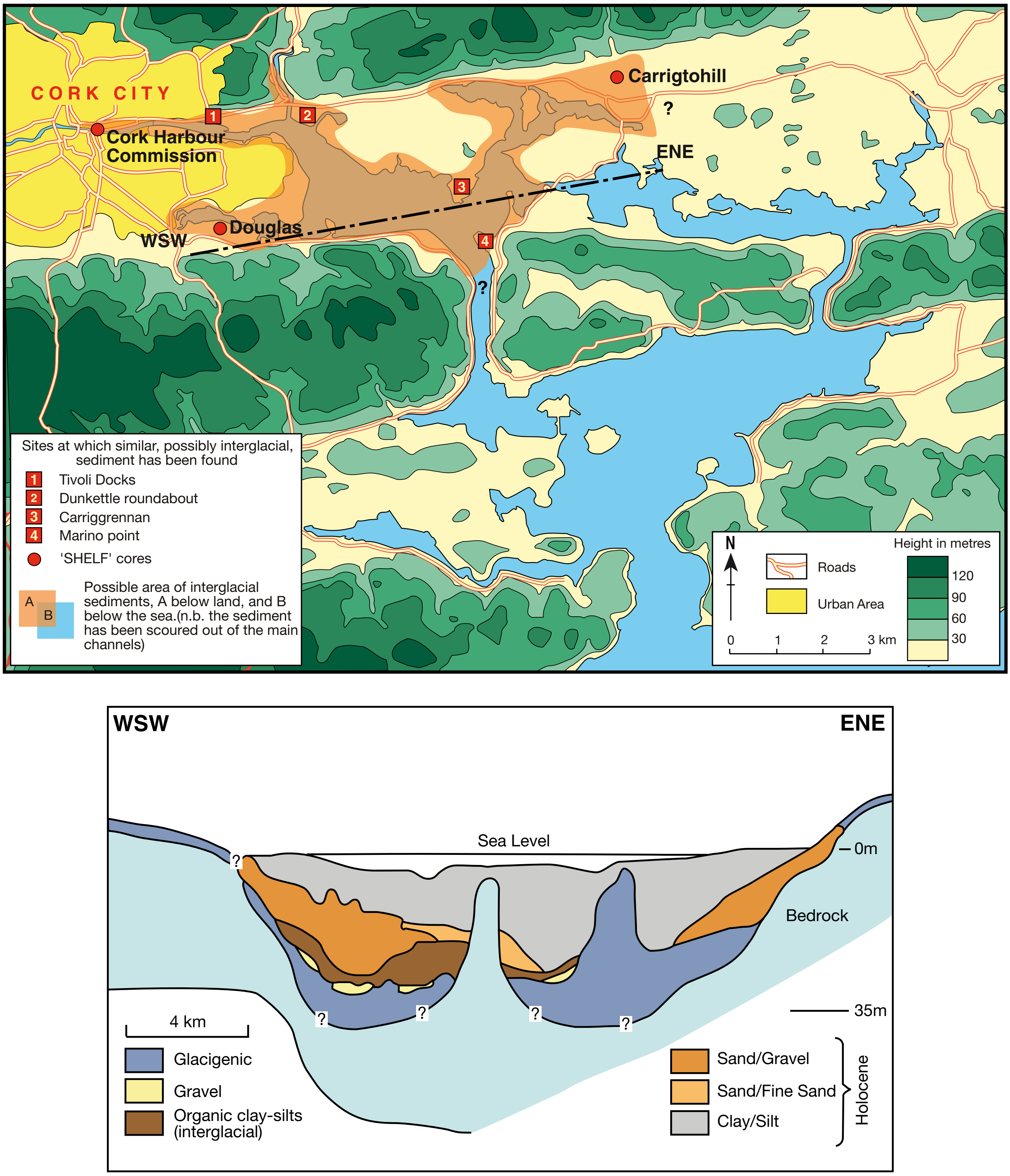


Figure 15.12 The extent of estuarine sediments of Gortian age in the Cork Harbour area and a lithostratigraphic cross-section of the area (*after* Dowling and Coxon, 2001 and Crowley *et al.*, 2005).

if the biostratigraphical correlation is viewed more critically, then it may be realistic to accept the possibility that the rather weakly developed interglacial sequence of the Gortian may represent MIS 9 (302 ka–338 ka) or more likely MIS 7 (195 ka–251 ka).

Table 15.5 The biostratigraphy of the Gortian.

Gortian Substage	Pollen assemblage and vegetation history
Gn IV	**Marked termination of record during *Abies-Picea*-Ericaceae assemblage with notable reworking of thermophilous taxa.** At sites that contain a long record the sequence is abruptly terminated and, although some Gortian deposits are ice-rafted lenses and not *in situ,* there is sufficient evidence of a conformable transition from the wooded, ericaceous heath of GnIII to an open landscape vegetation to conclude that sudden climatic deterioration truncated the interglacial cycle. This record of the closing stages of the Gortian Interglacial at Derrynadivva is a remarkable one as it shows a sudden climatic deterioration evidenced by the extensive reworking of pollen and spores (Coxon *et al.*, 1994). This rapid end to the interglacial may have been due to the proximity of Ireland to the important polar front of the North Atlantic during the onset of the subsequent glaciation – a situation not unlike that proposed to explain marked environmental change during the Nahanagan Stadial.
Gn IIIb	***Pinus–Betula*–with *Alnus–Taxus–Abies–Picea*–Ericaceae (including *Rhododendron ponticum*) assemblage.** The latter part of the Gortian Interglacial is typified by the appearance and/or dominance of *Picea, Abies, Alnus, Taxus,* and a very diverse flora of Ericaceae which, along with sedimentological evidence, indicates that wet conditions and bog development were predominant. These taxa either migrated late into the landscape or were favoured by the wetter conditions and decreasing soil fertility.
Gn IIIa	***Pinus–Betula*–with *Alnus–Taxus–Abies–Picea* assemblage.**
Gn II	***Pinus–Betula-Quercus* assemblage. *Taxus* very important at some sites, with *Hedera* and occasional tree taxa including *Fraxinus*, *Corylus*, and *Ulmus.*** The well-developed and diverse mixed oak forest so characteristic of British temperate stage floras does not develop during the Gortian and *Quercus*, although important at some sites, does not remain a major contributor to the pollen rain after an early peak. This early peak of *Quercus* at Gortian sites (*see* Gort, Kildromin, and Derrynadivva on Figure 15.9) is reminiscent of a similar peak on Hoxnian pollen diagrams from biozone Ho IIa and Ho IIb (e.g. from Marks Tey, Turner 1970). However, in Hoxnian pollen diagrams the diverse woodland contains persistent levels of *Ulmus*, *Corylus*, *Tilia,* and *Fraxinus,* amongst others, from the Early and Late Temperate zones (Ho II and III) whilst the level of these taxa in Gortian sequences is masked by the preponderance of *Pinus* and *Betula*. It is apparent from this that the Gortian temperate stage may be rather poorly developed with the possibility of cooler conditions prevailing. Gortian biozones Gn II and Gn IIIa are also notable for the persistent appearance of charcoal fragments both on the pollen slides and in the macrofossil samples at some sites (Coxon and Hannon, 1991; Coxon *et al.*, 1994; Coxon, 1996a). Fire frequency may have influenced the vegetation and *Pinus*, which can withstand fire events more successfully than the other trees present, may have expanded at the expense of the more fire sensitive taxa.
Gn I	***Betula–Pinus* assemblage.** As soils stabilised and the climate improved the late-glacial pioneering vegetation was shaded out by *Betula* and *Pinus* woodland and many other thermophilous trees and shrubs (e.g. *Quercus, Ulmus, Ilex,* and *Corylus*) were expanding from their glacial refugia and migrating into Ireland.
P-Gn I-g	***Salix–Juniperus–Hippophae* assemblage including a herbaceous component.** A late-glacial vegetation that developed during climatic amelioration and included pioneering plants such as *Salix, Juniperus,* and *Hippophae* as well as a diverse herb flora and *Betula* scrub.

Uranium–thorium dating and amino acid ratios

Attempts have been made to date the Gortian using amino acid racemisation and uranium–thorium disequilibrium dating (UTD). The latter has given ages of 180 ka and 191 ka from Burren Townland and >350 ka (a 'preliminary result') from the type site at Gort (Heijnis, 1992). More recently, UTD results from Cork Harbour suggest an age of 135 ± 35 ka, 120 ± 35 ka, and $150\ ^{+165}/_{-70}$ ka (i.e. MIS 5e or 7) but the dates have very wide errors. Amino acid racemisation results suggest a pre-Eemian (MIS 5e) age (Scourse *et al.*, 1992; Dowling *et al.*, 1998). These data suggest that the Gortian is the equivalent of part of the complex MIS 7 or MIS 9. It is unfortunate that there is still no absolute answer to the problem of the age of the Gortian. The dates quoted here require verification (and a greater degree of between-site consistency) before a firm conclusion can be reached.

Late Pleistocene biostratigraphy

If the Gortian represents marine MIS 7 or 9 that leaves the problem of the missing temperate stages of the Irish Pleistocene. The scale of the problem is apparent on Figure 15.2. In particular, the enigma of the missing last interglacial (MIS 5e) has bedevilled Irish Quaternary studies (see Warren, 1979, 1985; Mitchell, 1981; Watts, 1985; Coxon, 1993). Although well-documented from Britain (as the Ipswichian Interglacial – e.g. West, 1980; Jones and Keen, 1993), from Europe (as the Eemian Interglacial – e.g. Watts, 1988), and from ocean cores as MIS 5e dated to between 132 ka and 122 ka (Fig. 15.2), the last interglacial has not been unambiguously identified in Irish terrestrial sediments (but see Knocknacran below).

Mitchell, (1976, 1981) tentatively suggested that the upper part of the sequence at Baggotstown (Watts, 1964) and the estuarine sand at Shortalstown, County Wexford (Colhoun and Mitchell, 1971) might represent the last interglacial. However, the Baggotstown stratigraphy is unclear; the sediments at Shortalstown are glacitectonically disturbed; and the pollen assemblages (Fig. 15.14) may represent Middle (or Early) Pleistocene sediment redeposited from the Irish Sea basin – a scenario made more possible by the occurrence of a seed of *Decodon* sp. and a pollen grain of *Tsuga* (Colhoun and Mitchell, 1971).

A buried podsol recorded from Corraun in County Mayo has been cited as last interglacial in age (Synge, 1968; Finch, 1977) but the deposit has never been analysed in detail and its age remains unknown. The reported

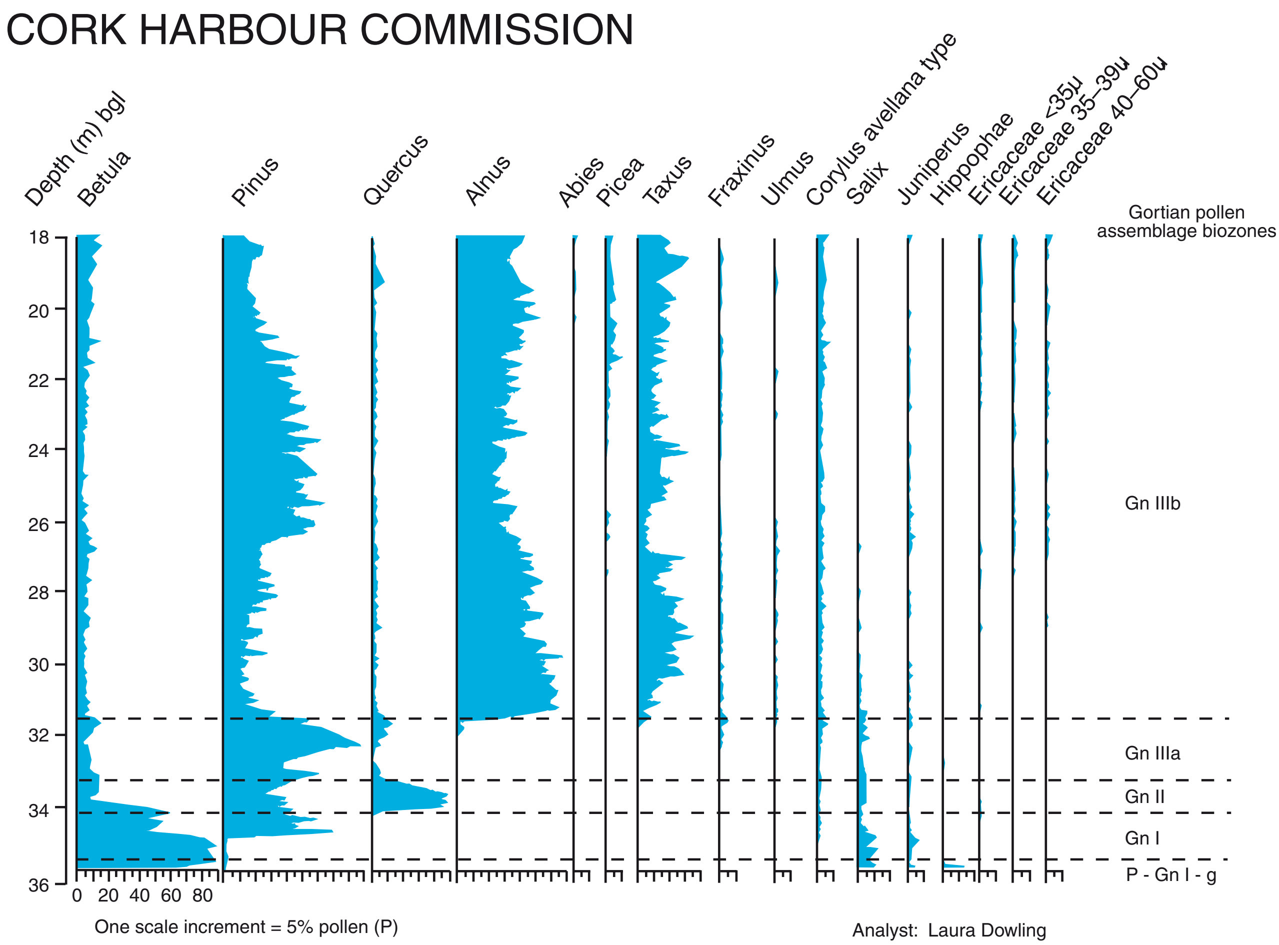


Figure 15.13 A summary pollen diagram (Dowling, 1997) from the remarkable 17.5 m Gortian sequence from Cork Harbour (the depths are 'below ground level', i.e. the top of the Customs House Quay). The inner part of the Cork Harbour estuary is lined with over-consolidated clays, silts and organic sediments up to 18 m thick which belong to the Gortian temperate stage. Interglacial sediments were recognised in 1979 during site investigations for the Eamon de Valera Bridge in Cork City. The widespread nature of the estuary fill and the uniform age has been confirmed in the detailed work of Dowling (1997) and Dowling *et al.* (1997). The pollen diagram has been divided into pollen assemblage biozones as described in the text and the original work defines more local zones.

pollen assemblage is described as follows: '*...Some deciduous tree pollen is present at this site but 30–60 per cent of the total tree pollen is pine. Thick forest cannot have been present, because the bulk of the pollen is from shrubs and grasses...*' (Synge, 1968). With such a description it is impossible to assign a firm correlation, and the pollen assemblage suggests interstadial rather than interglacial conditions.

A redeposited ball of organic sediment within the sands and gravels of the Screen Hills moraine contained a *Carpinus*-rich pollen assemblage (McCabe and Coxon, 1993) with a pollen assemblage that is very similar to those found in Continental Eemian deposits. The assemblage appears to belong to a Late Pleistocene temperate episode.

Knocknacran temperate stage

In 1996 an 18 m wide and 5 m thick organic fill within a solutional feature in gypsum and below drumlinised Midlandian till was recorded from Knocknacran, County Monaghan (Vaughan *et al.*, 2004, Figs 15.11, 15.14). The solutional fill is a glacitectonised and sheared breccia with an organic matrix. The deposit is very woody in parts (*Quercus* and *Taxus*). Pollen recovered from the deposit include *Quercus, Corylus, Taxus, Betula,* Gramineae, *Pinus, Salix, Ulmus,* Cyperaceae, and *Hedera*. (Vaughan *et al.*, 2004). Interestingly, *Picea* and *Abies* are absent, as are taxa indicative of the late-Middle Pleistocene or earlier. As such the pollen assemblage is unlike any other recorded in Irish deposits (Fig. 15.14) and the site most likely represents the last interglacial (MIS 5e). Infinite

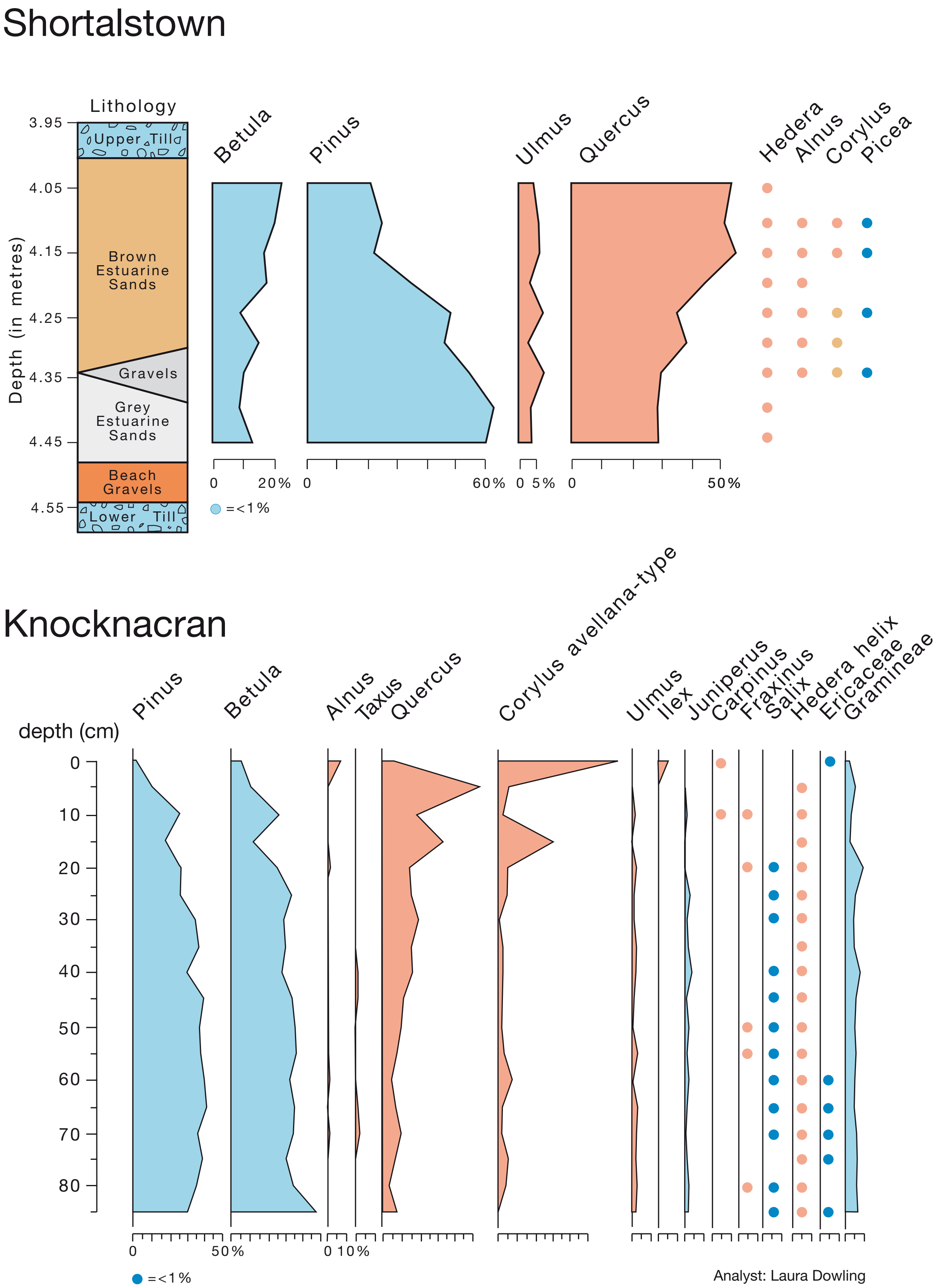


Figure 15.14 **A** – Pollen diagram from the deposit at Shortalstown (*after* Mitchell, 1976 from Colhoun and Mitchell, 1971). **B** – Pollen diagram from the deposit at Knocknacran (*after* Vaughan *et al.*, 2004). This pollen sequence is probably the best palaeoecological evidence of last interglacial deposits in Ireland.

(i.e. beyond the accepted range of radiocarbon dating) dates of >47 ka BP and >48 ka BP show the deposit to predate the Middle Midlandian whilst uranium–thorium dates suggest an age within MIS 4 or 5 (Fig. 15.16).

The Kilfenora Interstadial

The Quaternary deposits in cliff sections between Spa and Fenit along the north shore of Tralee Bay were the subject of an important paper by Mitchell (1970). The sequence of a raised wave-cut bedrock platform overlain by raised beach sediments, biogenic sediments, lower solifluction deposit, glacigenic sediments, and upper solifluction deposit has been summarised by Mitchell (1970, 1981) (see Fig. 15.15).

Research by Ruddock (1990), Heijnis (1992), and Heijnis *et al.* (1993) has shown that the biogenic sediments were deposited in cool temperate conditions. Uranium–thorium disequilibrium (UTD) dating of the biogenics gives an age of between 114 ka and 123 ka. Isochron plots allowed an age estimate of 118 ka (+5 ka/−4 ka) to be made. The lithofacies and their associations suggest that the organic sediments represent deposition in small pools or a lagoon environment frequently inundated with inorganic material. A pollen diagram from one of the organic sites (site F, Ruddock, 1990) is reproduced here on Figure 15.15.

Zone F1 reflects a period when there were open pinewoods in the area, with a field layer composed of Gramineae, Cyperaceae, and other herbs with some Ericaceae. *Pinus* is the dominant tree in Zone F2, but there is also some pollen of *Alnus*. The Ericaceae have increased, indicating that conditions were possibly becoming more oceanic or cool. In the peat layer above this level (Zone F3) *Pinus* pollen disappeared and herb pollen increases. However, *Quercus* pollen is present in greater quantities than below, and at site G *Alnus* is also recorded. Zone F4 at both sites records *Quercus, Alnus, Corylus,* and *Ilex*, indicating a possible amelioration in climate towards the top of the sequence. The pollen diagram is very similar to the data presented by Mitchell (1970) that recorded a thicker sequence and an earlier silt horizon (containing abundant *Pinus*). Mitchell also recorded single grains of *Abies* and the pollen of *Taxus* and *Rhododendron*, whilst Ruddock (1990) recorded a wider range of herb taxa and a single grain of *Picea* from the section that she studied.

The pollen assemblages from these sections are unique in Ireland. Although they contain some taxa found in the Gortian, the assemblage as a whole does not resemble those of the known later parts of that temperate stage (see above and Coxon, 1993, 1996b).

The pollen record of Figure 15.15 seems to be reasonably continuous across lithological boundaries and suggests that the sequence represents cool temperate, sparsely wooded conditions with a predominance of open ground, possibly with increasing thermophilous taxa late in the depositional phase. The pollen sequences may represent the onset of interstadial conditions early in the Midlandian cold stage or a minor amelioration of climate to warmer conditions during the end of a temperate stage.

The pollen assemblages recorded at Fenit cannot be correlated with interstadial floras recorded from the Early Midlandian (e.g. at Aghnadarragh; McCabe, Coope *et al.*, 1987; see below) and for this reason, and the fact that they are dated, they have been named as the Kilfenora Interstadial by Heijnis *et al.* (1993).

The dating of these sediments is crucial, and the dates (between 114 ka and 123 ka) indicate that they represent the latter part of the Eemian (or last) Interglacial or the Early Midlandian. The organic sediments at Fenit appear to belong within MIS 5, possibly towards the end of MIS 5e (132 ka–122 ka) or during 5d or the beginning of 5c. The latter age is suggested by the pollen, indicating a slight amelioration in climate towards the top of the deposit. The age of the interstadial makes it unlikely to be related to the Aghnadarragh Interstadial (below), as it must come before a major expansion of Early Midlandian ice (Table 15.2).

At least some of the raised marine sediments at Fenit are shown to be younger than MIS 5e but the age of the underlying erosional platform remains unknown (for reasons outlined by McCabe, 1987).

The record of the Irish cold stages

Quaternary geological evidence

As previously outlined, the Quaternary has been characterised by large, relatively rapid, periodic changes in climate and environmental conditions. In north-western Europe these climatic oscillations are manifest in a succession of 'glacial' and 'interglacial' stages. Ice core evidence tells us much about the last glaciation and its associated climatic variability – see Figure 15.16.

The long 'glacial' stages are probably better termed *cold stages*, as periods of widespread glaciation (stadials) only made up a small part of their ~100 ka length. In addition to stadials, cold stages also include 'cold phases' and

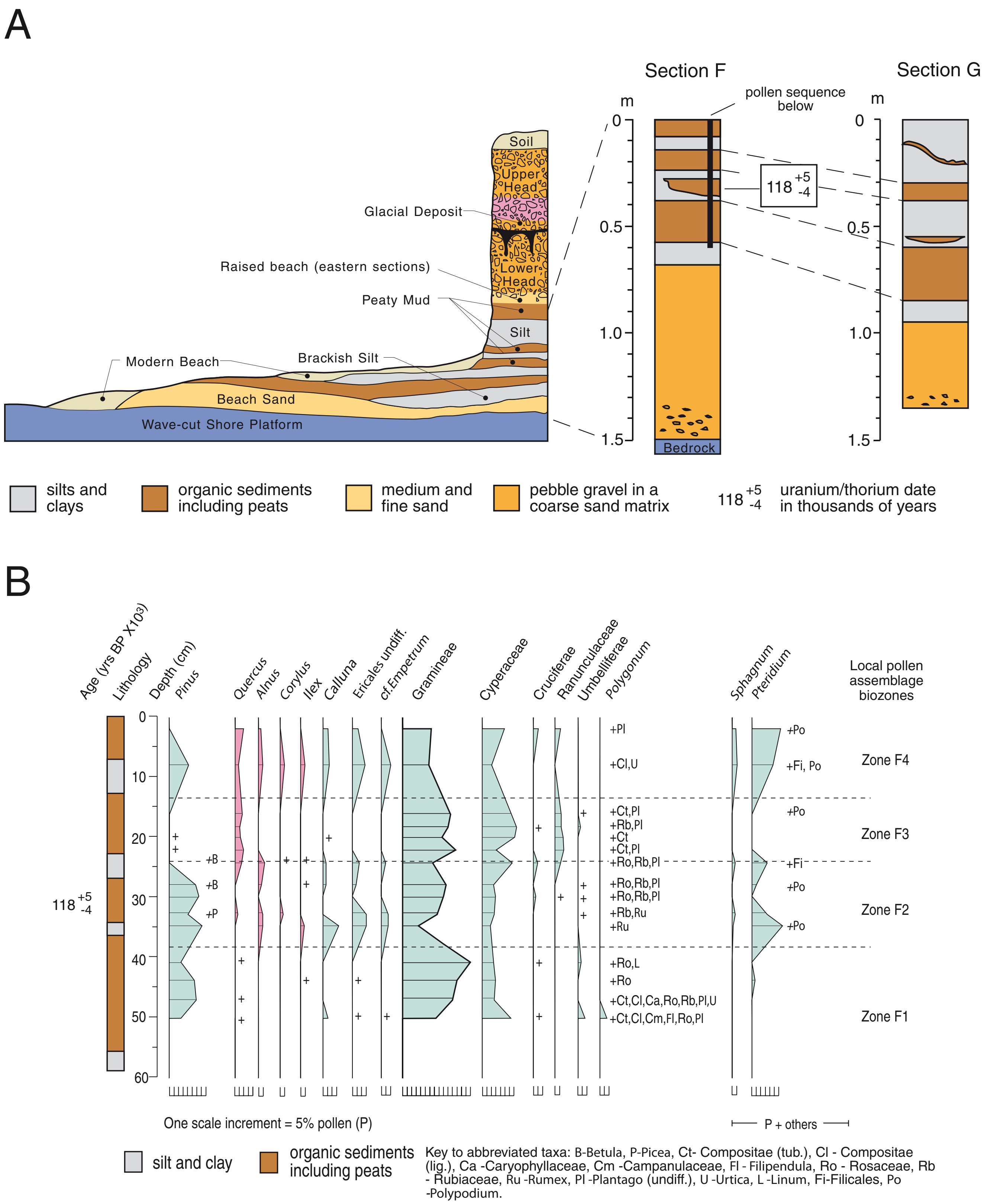


Figure 15.15 Stratigraphy (A) and pollen record (B) from the Late Pleistocene Kilfenora Interstadial, Fenit, County Kerry (*after* Heijnis *et al.*, 1993, from Coxon, 1996b).

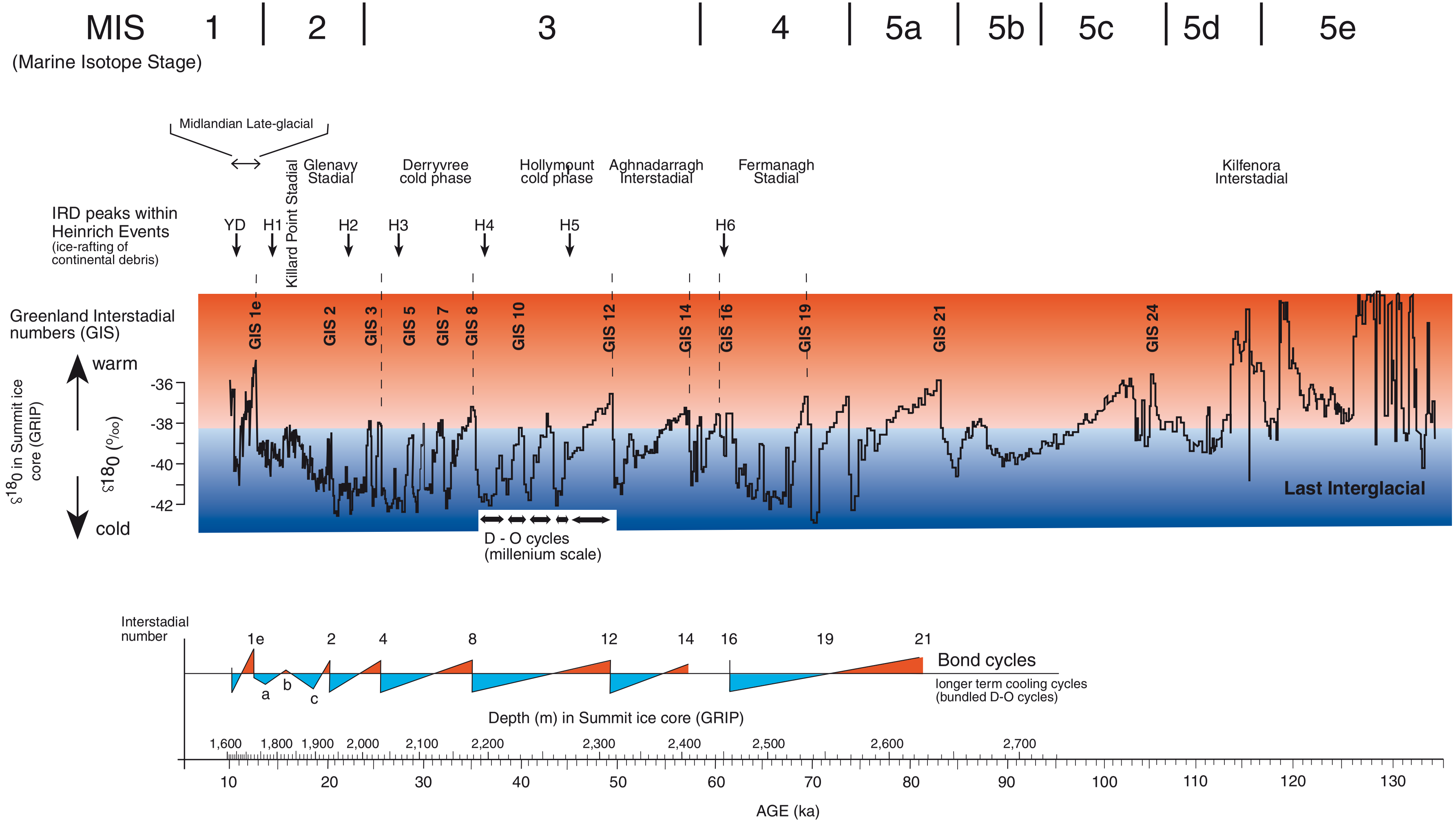


Figure 15.16 The last cold stage showing ∂^{18}O values from the GRIP ice core along with a summary of the long-term cooling cycles (Bond cycles), Dansgaard-Oeschger cycles, and ice-rafted detritus (IRD) peaks within Heinrich events (*after* Bond *et al.*, 1993). The phases of the Midlandian cold stage (Table 2) are also shown.

'interstadial' periods during which the climate ameliorated to some degree, possibly with temperatures almost reaching those of the present day (or warmer) for short periods (i.e. 1–2 ka rather than the 10 ka to 20 ka duration of a full Interglacial stage). Ireland has a physical record of two major cold stages, but may have experienced anything up to five in the last 750 ka (see Figure 15.2). Each one was a long and complex event of ice build up and decay interspersed by cold, periglacial, conditions and by cool (or even warm), interstadial periods.

The terrestrial record of the Irish cold stages is far from complete, and successive glacial events have left only fragmentary evidence, each stadial probably eroding and reworking the products of preceding events. Building on the long tradition of Quaternary geology in Ireland established by workers such as Close, Hull, Dwerryhouse and others, more recently Charlesworth, Orme, Farrington, Mitchell, Synge, McCabe and others have mapped the spatial distribution of Ireland's populous and extensive onshore glacial features (Figure 17). Remote sensing, and continuous all-island digital elevation datasets at decimeter resolution, have provided an additional toolset with which to map glacial features and allowed the recognition of hitherto unrecognised glacial bedforms and ice-flow patterns (e.g. Knight and McCabe, 1997a; Clark and Meehan, 2001). Offshore bathymetric data collection offers the possibility of extending the field constraints of former ice limits on the continental shelf (e.g. King *et al.*, 1998) and near-shore sea level lowstands (e.g. Kelley *et al.*, 2006).

Many good descriptive accounts of Irish glacial features exist, but a definitive stratigraphy recording glacial/non-glacial climatic variability throughout the Quaternary has proved elusive for a number of reasons. Firstly, there is a lack of sufficient dating control. This is true in all areas of the country for glacial events older than the last cold stage (Midlandian), and in many areas older than the last widespread stadial ('Main Phase' of the Late Midlandian/Glenavy Stadial/Last Glacial Maximum[LGM]). Continually tighter dating control of the 'last Termination' (deglaciation from LGM limits) has, however, been proceeding where possible, allowing the context of driving forces (climatic or otherwise) to be considered in the study of Irish glacigenic sediments (McCabe *et al.*, 2005).

Secondly, glacigenic sequences are complex and cannot be analysed simply in terms of advance and retreat cycles (McCabe, 1987). Thus, many 'layer-cake' sections thought to record glacial advance/retreat cycles may have been misinterpreted. Detailed lithofacies analysis has shown that many such sequences in fact comprise lithofacies assemblages formed in generically linked depositional environments (Eyles and McCabe, 1989a).

The nature of past ice sheets.

Climatic deteriorations resulted in the repeated growth and decay of ice sheets covering most of the landmass of the British Isles (stadial periods). Whilst generated from independent ice source areas on Ireland and Britain, ice flow patterns indicate that at least during the existence of the last widespread ice sheet, Irish and British sectors were coincident along the axis of the Irish Sea Basin, and can be termed the British Irish Ice Sheet (BIIS). Erratic carriage also evidences ice flows radiating outwards from the Scottish uplands and into the north of Ireland (e.g. forming the Armoy Moraine; Stephens *et al.*, 1975). The distribution of Scottish ice is thought to have been even more widespread throughout Ireland in earlier stadials, transporting erratics from the Firth of Clyde as far west as Donegal, Wexford, and Cork. In contrast, Irish ice dispersal centres formed in upland; e.g. Donegal, Connemara, and lowland areas (as domes); e.g. Omagh Basin, Lough Neagh Basin, north Central Midlands; and Irish ice radiated outwards from these areas, resulting in the vast majority of Irish glacial landforms. Ice sheets were probably comprised of multiple 'sectors' controlled by influences on dynamics such as bedrock topography and their relative proximity to shifting precipitation sources. The presence of marine margins at the limits of Late Midlandian ice sheets was a primary control on deglacial dynamics.

Sediments and products

Ice sheet bedrock erosion and the reworking of pre-existing sediments by repeated glaciation have left a significant imprint on many aspects of the Irish landscape (Fig. 15.18). Ice and meltwater sculpted many distinctive erosional landforms along pre-existing topographic lows and structural weaknesses, e.g. *Glacial valleys*: Glenmacnass and Glendalough, County Wicklow; Glenveagh, County Donegal; Glenahoo, County Kerry; *Fjords*: Killary Harbour, County Clare; Lough Swilly, County Donegal; Carlingford Lough, County Down/Louth. Flowing glacial ice also deposited thick piles of relatively consolidated, impervious, subglacial diamict (till) where conditions within the ice sheet allowed, principally throughout Ireland's lowlands. Subglacial reworking of previous sediment accumulations and gradual

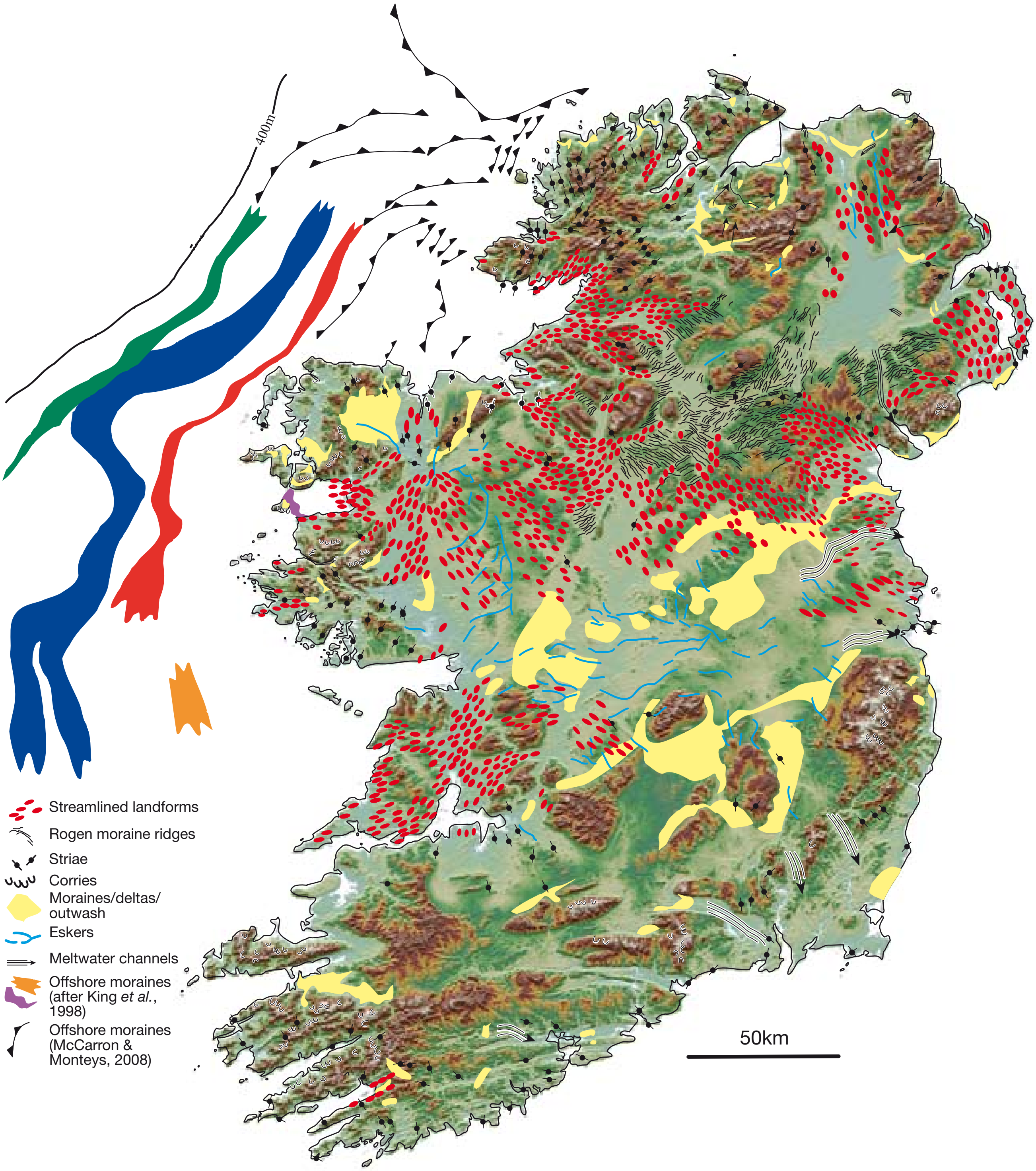


Figure 15.17 The distribution of glacial landforms in Ireland and on the continental shelf (*after* Synge, 1979, McCabe, 1987, 1993; King *et al.*, 1998).

Figure 15.18 A – Lough Nahanagan within Camaderry Mountain corrie, County Wicklow. B – Extensive deltaic foresets, Blessington, County Wicklow. C – Sample site in laminated glaciomarine mud, Corvish, County Donegal. D – Rapidly eroding section in glaciomarine sediment pile, Killiney, County Wicklow. E – Glaciomarine mud, intertidal boulder pavement and subaqueous outwash, Cooley Point, County Louth (*Photo*: Prof. A. M. McCabe, published with permission of the Director of the GSNI). F – Emergent postglacial sequence, Portballintrae, County Antrim.

transfer of sediment towards ice-marginal areas was probably an important process throughout the oscillation between glacial and non-glacial episodes. Some organic material has also survived repeated stadials in isolated pockets, and provides a very fragmentary biostratigraphical record. Preservation of such sediment tends to have occurred in hollows within karstic, uneven parts of the pre-glacial landscape (Coxon and Coxon, 1997; Vaughan *et al*., 2004; Coxon, 2005a).

The last ice sheet to have covered Ireland decayed rapidly, leaving an extensive legacy of glacial features including the ice-contact, ice-proximal, and ice-distal glaciofluvial and glaciolacustrine deposits that mantle many areas (McCabe, 1987; Coxon and Browne, 1991; Warren and Ashley, 1994). The decay and retreat of ice sheet margins towards centres of ice dispersal left the sand and gravel sediment washed from subglacial sources as eskers, outwash plains, kames and deltas. Some of these stratified accumulations are relatively large, and by the nature of their specific depositional criteria, e.g. the presence of an ice-proximal waterbody or subglacial drainage routes, are spatially concentrated; e.g. the eskers of the central Midlands; near Blessington, north-west County Wicklow; the Sperrin Mountain valleys, County Tyrone; and the Dungiven basin, County Derry. Where they occur, they provide a valuable but diminishing natural resource.

Ice sheet event chronologies

The extent and timing of ice sheet buildup in Ireland was reviewed by McCabe (1987). He noted that, to that date, the sequence of glacial events was known in a relative sense only, predominantly based on morphostratigraphical rather than biostratigraphical or chronometric evidence. Until recently, geochronological constraint of the pattern and timing of ice sheet growth and decay has been as scarce in Ireland as in other regions of the British Isles. The relative paucity of dated ice sheet events, due largely to the relative scarcity of datable organic material on or between glacial sediments (compared to around the margins of the Laurentide ice sheet in North America for example), has prevented confidence in the correlation of glacial advance and/or retreat of sectors of the last BIIS with each other and events recorded elsewhere.

Significant amounts of additional data points, building a geochronological framework constraining ice sheet events (advances/retreats) in the Late Midlandian, have been added since then. This has largely been through AMS ^{14}C dating of *in situ* populations of marine microfauna shells extracted from Irish coastal sediments (e.g. McCabe and Clark, 1998; McCabe and Clark, 2003; Clark *et al.,* 2004; McCabe *et al.*, 2005; McCabe and Clark, 2007a, b). In addition, the quantity of cosmogenically produced ^{10}Be and ^{36}Cl nuclide accretion in 'fresh' rock surfaces (eroded by >2.5 m during the last glacial advance) can provide a minimal date for erosion of that surface (by ice for example) (Bowen *et al*., 2002; Ballantyne *et al*., 2006, 2007, 2008). Continued refinement of the application and interpretation of the results of both techniques promises continued advances in bracketing ice events at particular locations into absolute timeframes.

Ice sheet flow patterns

Patterns of ice flow during stadials were not constant and unidirectional, as traditional compilations of ice flow directions reconstructed from grouped ice flow indicators would perhaps suggest (e.g. Mitchell *et al*., 1973; Warren and Ashley, 1994). Alternatively, ice sheet reorganisation because of internal dynamics and/or climatic forcing produced overprinted bedform sets ('palimpsest' landscapes) in many areas of Ireland, especially throughout the central northern 'drumlinised' lowlands (McCabe *et al*., 1999; Clark and Meehan, 2001) and around large coastal embayments on the western seaboard (Knight and McCabe, 1997b). Around an isostatically depressed Irish landmass, deglaciation was possibly driven by internal dynamics linked to rapid calving front losses and marine downdraw towards tidewater glacial limits (~7 km/a across a floating terminus 800 m thick and 6 km wide; Jakobshavn Effect, Hughes, 1986). The orientation of streamlined landform long axes in the direction of the major bays of the west of Ireland is unmistakable and gives a strong indication of linkages between marine-influenced ice sheet margins and ice sheet bedform streamlining (Knight and McCabe, 1997b). Large ice volume transfers, high pressure subglacial water, and saturated, deforming sediment layers, would erode and streamline the underlying deposits and deliver large sediment volumes to the marine margins, allowing the reconstruction of significant morainic belts which have field associations with drumlin belts (McCabe *et al*., 1984).

Deglacial palaeoenvironments around the Irish coastline

In Ireland, a more detailed and age-constrained geological record exists to document the deglaciation of the Irish Sea Basin (ISB) than any other series of glacial events. This is due principally to the presence of tidewater glaciers on the margins of the ISB during deglaciation. Temporary stillstands of the ice front and progressively less extensive ice sheet readvances during overall deglaciation resulted in a generally northward-offlapping sequence of fossiliferous subaqueous sediment wedges along the east coast. Since the publication of Eyles and McCabe (1989b), it has been argued that many of these glacigenic sequences around the ISB are the product of generally glaciomarine conditions (high relative sea levels: HRSLs) at ice margins during deglaciation (Clark *et al*., 2004; McCabe, 1997; McCabe and Clark, 1998, 2003; McCabe and Haynes, 1996; McCabe *et al*., 1987a, 1998, 2005, 2007a, b).

Based on published reconstructions of events from detailed sedimentological studies and dated marine fauna, HRSLs in this region were created at a time of a global eustatic minimum (Yokoyama *et al*., 2000). Isostatic depression resulted in ice sheet destabilisation in rapidly calving tidewater environments and the 'early' onset of deglaciation at about 26 ka BP, preceding the time of the global LGM (McCabe *et al*., 2007a). The ice thicknesses required to produce enough crustal flexure to result in +30 m HRSLs along the central eastern Irish seaboard (~1 km thickness in the central Irish Sea) follow from the onshore ice sheet thicknesses advocated to explain the pattern of trimline formation in Wicklow (Ballantyne *et al*., 2006).

Not all authors agree with the model of such levels of isostatic depression and tidewater glaciomarine deposition during deglaciation (e.g. Lambeck, 1996; McCarroll, 2001; Scourse and Furze, 2001; Evans and O'Cofaigh, 2003; Boulton and Hagdorn, 2006). Temporary ice-marginal glaciolacustrine environments are postulated to explain the formation of large subaqueous sediment banks and spreads on the eastern Irish seaboard, south coast, and on the Isle of Man (e.g. Thomas, 1977; G.S.P. Thomas *et al*., 2004). Deterministic geophysical models combining estimates of earth rheology, ice sheet and substrate configurations (e.g. Shennen *et al*., 2006; Roberts *et al*., 2006; Boulton and Hagdorn, 2006), parameterised using Late Glacial and Holocene data, do not produce solutions which agree with age-constrained field evidence for palaeo-sea levels at higher than current elevations around the Irish coastline during the last Termination (McCabe, 1997).

However, revisions of the glaciomarine model are spurred by continuing advances in the production of an internally consistent geochronological framework spanning the Last Termination (see Table 15.6). Dates

Table 15.6 Millennial-scale deglacial events during the Last Termination.

Stage	**Approximate date range (^{14}C ka BP)**	**Description***
Cooley Point Interstadial (CPIs)	≥17 – ≥ 15.0	Along eastern, western and northern Irish seaboards, at Cooley Point (Co. Louth), Cranfield Point and Kilkeel Steps (Co. Down), Fiddauntawnanoneen, Belderg Pier and Glenulra (Co. Mayo) and Corvish (Co. Donegal), dated monospecific samples of Elphidium clavatum from raised in situ massive to laminated marine muds fall in the period from 16,970 ± 190 to 14,705 ± 130 (McCabe *et al*., 2005). Sediment sequences and dates indicate a period of HRSLs post-dating the global LGM associated with glaciomarine sedimentation along Irish seaboards during deglaciation from offshore limits.
Clogher Head Stadial (CHS)	≤15.0 – ≥ 14.2	At Cooley Point, Co. Louth eastward prograding subaqueous outwash spreads and ice-pushed facies cover laminated to massive mud facies dated to 15,020 ± 110 which underlie an intertidal boulder pavement. At Port, marine muds dated to 15,190 ± 85 are deformed and sheared into overlying subglacial diamict (McCabe *et al*., 2005; McCabe and Clark, 2007). At Corvish, Co. Donegal deformation of marine muds and formation of an ice-pushed moraine, dated to 15,025 ± 95 (McCabe and Clark, 2003), is correlated with this readvance (McCabe and Clark, 2007).
Linns Interstadial (LIs)	14.2 – ≥13.8	Open marine embayment conditions in Dundalk Bay associated with deglaciation from the Clogher Head Stadial readvance limits and mud formation at both Linns (14,157 ± 69) and Rathcor (14,250 ± 130 14C BP) on the southern and northern bay margins respectively (McCabe *et al*., 2005).
Killard Point Stadial (KPS)	<14.2 – >13	Marine muds interbedded with stacked, channelised gravels in an ice contact subaqueous morainal bank or apron at Killard Point are dated to 13,995±105 (McCabe *et al*., 1986). The morainal bank is associated with a regional scale ice sheet reorganisation associated with amphi-North Atlantic climatic events (McCabe and Clark, 1998). Deformation of a diamict at Linns is also associated with KPS readvance to inside CHS limits in Dundalk Bay (McCabe and Clark, 2007) (Figure 16.19).
Rough Island Interstadial (RIIs)	~13.0-	Downdraw of the BIIS during the KPS towards marine calving bays (McCabe and Hynes, 1996; McCabe *et al*., 1998) and subsequent in situ ablation of the lowered ice sheet profile resulted in rapid Stagnation Zone Retreat and preservation of streamlined bedforms associated with subglacial sediment transfer during KPS. Marine muds comprising part of an inter-drumlin drape are dated to 12,740 ± 95 at Rough Island, Co. Down (McCabe and Clark, 1998). Mud deposition indicates continued HRSLs following drumlinisation and a suppression of isostatic rebound recovery rates relative to the earlier stages of deglaciation (McCabe *et al*., 2005).

* Dates are ^{14}C yr BP unless stated; Samples corrected for assumed 400yr reservoir effect)

constraining ice sheet events occurring on broadly millennial timescales are derived from AMS ^{14}C dating of *in situ* marine microfauna extracted from fine-grained facies within deglacial sediment sequences (Fig. 15.19). These facies have been shown to contain *in situ* marine biocoenoses, dominated by the foraminiferan *Elphidium clavatum* (89–95%), an opportunistic benthic microfauna species that inhabits low salinity, cold (0.5–2.5°C), turbid water (Hald *et al*., 1994). The facies are devoid of reworked temperate species forms and therefore provide a robust method to constrain the age of associated glacial events (Haynes *et al*., 1995).

Geochronological constraint and positioning the sediments within a depositional systems framework (linking fossiliferous sediment deposition and associated landform creation) has allowed the construction of an event history that links ice sheet sector activity across the island and in other sectors of the last BIIS (McCabe *et al*., 1998; McCabe and Clark, 2003, 2007; McCabe *et al*., 2005, 2007a, b). Dated events indicate that during the Last Termination largescale events within the last BIIS occurred on broadly millennial timescales, in keeping with other climatic cycles recorded in the ice–ocean–atmosphere system (Bond *et al*., 1993). The geological evidence indicates an ice sheet that was sensitive to the hemispheric and global scale climatic and glacioeustatic events recorded elsewhere in ice, deep sea sediment, and coral palaeoclimatic archives (McCabe *et al*., 1998; McCabe and Clark, 1998; Clark *et al*., 2004). The possible link between drumlinisation in Ireland and Heinrich event 1 (McCabe and Clark, 1998; McCabe *et al*., 1998) is of considerable importance in understanding ice sheet–climate linkages in the ice–ocean–atmosphere system which have relatively long, crudely defined response-time lags (Ruddiman, 2005). Geological evidence of the response time of the BIIS to other globally significant oceanic events (Clark *et al*., 2004) demonstrates for the first time the strong links between the behaviour of terrestrial ice masses and the timing of palaeoenvironmental changes in the North Atlantic. The apparent near-synchroneity of events recorded in oceanic and ice cores (Bond and Lotti, 1995) has led to theories of global, or at least circum-North Atlantic, climate change in a coupled ice–ocean–atmosphere system of which the last BIIS was part.

Quaternary chronology

The Munsterian cold stage (MIS 8/6)

Ireland is believed to have been widely glaciated during at least two cold stages: the Munsterian (MIS 8/6) and the Midlandian (MIS 4-2). Given the large number of Quaternary cold stages it is almost certain that pre-Midlandian (>150 ka BP; MIS 5e) glacigenic deposits do exist. However, there is not a single site where such an age can unequivocally be demonstrated for glacigenic sediments. Widespread glacigenic sediments in the southern part of Ireland (Munster) have long been regarded as belonging to an 'older' glaciation on the grounds that they show distinct assemblages of erratics, striae, and glacial limits as well as exhibiting subdued relief, deep weathering profiles, and a lack of 'fresh' glacial landforms (Mitchell *et al*., 1973; Synge, 1968; Finch and Synge 1966; McCabe 1985, 1987). These older (Munsterian) glacial deposits were thought to have originated from sources both in Scotland, which affected much of the eastern and northern parts of the north of Ireland (Stephens *et al*., 1975), and from Irish inland centres, in particular the uplands of southern Connemara (Charlesworth, 1929).

The lack of chronometric control has meant that, although the Munsterian deposits exhibit certain unique characteristics, e.g. the widespread distribution of Galway granite recorded by Synge (1979) and Lewis (1974) (but see Warren, 1992) and the recognition of extensive deposits recording glacial advance and retreat (Stephens *et al*., 1975), the age(s) of the glaciation(s) giving rise to the sediments is unknown. The field relationships of Munsterian and Midlandian glacigenic deposits need to be clarified by detailed mapping; and even then, the inherent complexity of glacial sequences (which hinders lithostratigraphical correlation) and the lack of biostratigraphical markers will continue to make the dating of the Munsterian difficult.

An example of the problem is that research has shown that many sequences of 'Irish sea drift' along the southern and eastern coasts of Ireland traditionally considered to be Munsterian have been shown to be Midlandian in age. This evidence is based on mapping, patterns of crustal deformation, radiocarbon dates, and amino acid ratios (McCabe, 1987). Glaciomarine muds (originally recorded as Munsterian 'shelly tills') in north Mayo have been dated to ~17 ^{14}C ka BP [~19 Cal ka BP] (McCabe *et al*., 1986; McCabe *et al*., 2005) and it is likely that many of the subaqueous sedimentary sequences around Ireland's coast also date to the Late Midlandian (<30 ka Cal BP)

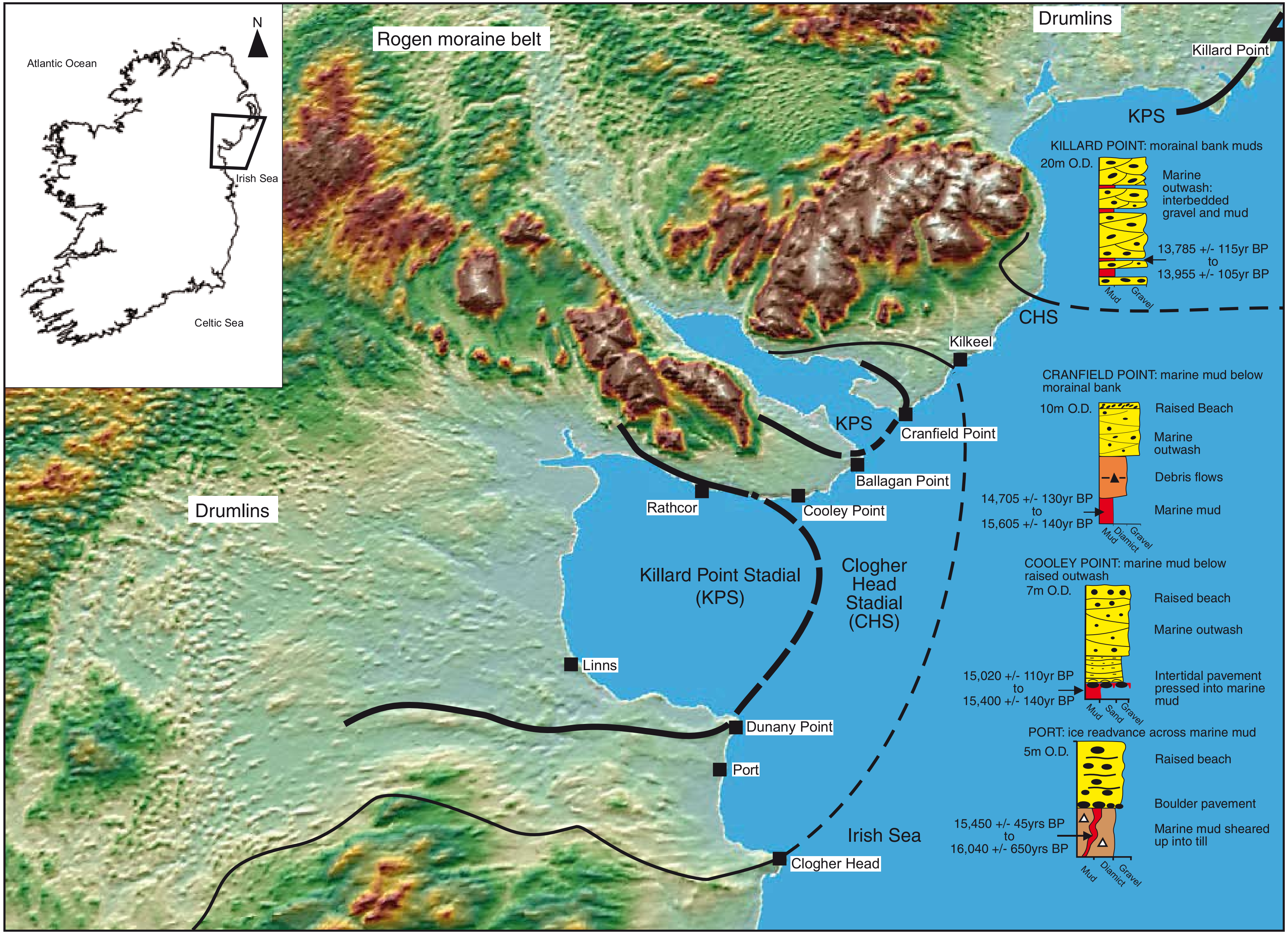


Figure 15.19 Geological evidence of the timing of deglaciation in and around northeast Ireland. (authors' interpretation, and *after* McCabe and Dunlop, 2006).

(e.g. McCabe and Ó'Cofaigh, 1996). Cosmogenic dating of erosion surfaces is redefining the timing and extent of Midlandian glaciations and therefore the probability of finding Munsterian age surficial sediments in the south of Ireland (e.g. Bowen *et al.*, 2002).

Against a background of uncertainty regarding the age of the Gortian Interglacial, and with a lack of recent field mapping and of radiometric dates, the possible presence of pre-Midlandian cold stage deposits remains an enigma. Without geochronological control, the stratigraphical position of deposits assigned to that cold stage remains uncertain.

The Midlandian Cold Stage (MIS 4-2)

Like the Munsterian, the Midlandian has been given no representative type site (Mitchell *et al.*, 1973). Evidence of glaciation and cold climates dating to the last glaciation are very widespread in Ireland, but the diversity of depositional environments and their spatial heterogeneity has meant that the choice of a meaningful type section for the entire cold stage has not been possible.

On a global scale the last cold period (MIS 4, 3, and 2) was an extremely complex event, involving at least two major build-ups of regional scale ice sheets interspersed by a sequence of climatic oscillations that have been recognised from terrestrial evidence (e.g. Coope, 1977), from ocean floor sediments (Bond *et al.*, 1993; Rasmussen *et al.*, 1997), and from the Greenland ice cores (e.g. GRIP, 1993). The latter two have given a detailed picture of millennial-scale climatic oscillations (Dansgaard–Oeschger (D–O) cycles) and longer term cycles (Bond cycles). These have been related to massive effluxes of ice-rafted detritus (IRD) originating from ice sheets around the margins of the North Atlantic ocean (Heinrich layers or Heinrich events; Heinrich, 1988), which were spread across the North Atlantic floor (Gwiazda *et al.*, 1996; Bond *et al.*, 1999; Scourse *et al.*, 2000; Zaragosi *et al.*, 2001). Analyses of deep ocean floor sediments and Greenland ice cores has given a detailed insight into the nature and complexity of ice sheet oscillations during the last cold stage, which can be seen on Figure 15.16.

Evidence of oscillating ice marginal extents on millennial timescales during the last Termination has been identified (McCabe *et al.*, 2005). Interpreting any apparent correlations between ice-sheet and climatic events remains problematic, however, due to the complicated relations between climate and ice sheet behaviour. Continued redefinition of radiocarbon calibration curves and other possible sources of error, including variable ocean water carbon reservoir estimations, all add unquantifiable uncertainty to potential correlations.

However, evidence from biological (pollen, plant macrofossil, and entomological) data, cosmogenic exposure age, and AMS^{14}C dating techniques allows us to reconstruct the nature, extent and timing of Midlandian stadials with more certainty than was previously possible (Table 15.6) (e.g. McCabe *et al.*, 1987b; Bowen *et al.*, 2002; McCabe, 1998; McCabe *et al.*, 2005, 2007a, b). In particular, many dates are becoming available for the build-up, oscillation and retreat of Late Midlandian ice (e.g. McCabe *et al.*, 2007a, b). In addition, studies addressing the sedimentology of Irish glacial deposits have given an insight into the nature, dynamics and timing of the last stadials. The evidence now available from around Ireland allows the stages outlined on Table 15.2 to be identified. The incomplete nature of the Irish sequence is obvious when compared to the complex oxygen isotope record of hemispheric climatic fluctuations.

The Fermanagh Stadial (MIS 4)

Dated organic evidence, which from pollen and insect biocoenoses indicates interstadial rather than interglacial conditions, has led to inferences about a period of glaciation in at least the north of Ireland preceding the lower boundary of MIS 2, but post-dating the last interglacial (MIS 5e) (Fermanagh Stadial in Ireland: McCabe, 1969; Colhoun *et al.*, 1972; Mitchell, 1977, 1981; Bowen *et al.*, 1986b; McCabe *et al.*, 1987b; McCabe, 1991; McCabe, 1999). This period has been named as the Fermanagh Stadial after a number of disparate sites in the county including Derryvree, where *in situ* freshwater organic silts located between two major (regional) till sheets have been dated to 30.5 ± 1.1 ka BP (Colhoun *et al.*, 1972). At Hollymount, also in County Fermanagh, freshwater organic mud overlying a glacial diamict (till) and underlying a streamlined till provided an infinite ^{14}C age of >41.5 ka BP (McCabe *et al.*, 1978). Freshwater organic materials at Aghnadarragh, on the shores of Lough Neagh, County Antrim, are also located between two regionally extensive till sheets, the lower of which contains a distinctive erratic suite from the Tyrone Igneous Complex in the Sperrin Mountains to the west (McCabe, 1987). This ice transport vector (E–W) is not traditionally associated with Late Midlandian (MIS2) ice flows in this region. Wood fragments in the gravels yielded infinite traditional ^{14}C dates of >48.1 ka BP and >47.35 ka BP (McCabe *et al.*, 1987b) and >46.2 ka BP (McCabe, 1999). At Benburb, County Armagh, *in situ* compressed peat and lake mud dated to >46 ka BP and >46.45 ka BP is overlain by drumlinised till (Boulter and Mitchell, 1977) or possibly remobilised till (Dardis, 1980).

Farther north, intact shells of *Turritella communis* taken from gravels at Bovevagh, near Limavady, yielded infinite ^{14}C dates of >45 ka BP (McCabe, 1999). D-aIle/L-Ile ratios (amino-acid racemisation) from marine macrofossils found at the same location are inconclusive, but may indicate an Early Devensian (MIS 4) age (McCabe, 1999). Colhoun (1971) argued that his shelly Bovevagh till from the same region, which contains reworked erratics from a southerly source related to a still earlier glaciation (his Early Sperrin glaciation), was deposited during the onshore movement of ice from the north and north-east which incorporated shells of *Turritella communis*, bivalve shells, crustacea, and foraminiferans as it crossed the North Channel from Scotland. McCabe (1999) argued that the geometry of the gravel beds suggests that the sediments at Bovevagh are *in situ* glaciomarine deposits. At Sistrakeel, just north of Bovevagh on the southern margins of the Foyle Basin, a marine mud containing well-preserved *Arctica islandica* shells and a microfauna dominated by *Elphidium exclavatum* yielded infinite ^{14}C dates of >46,785 BP, >55,100 BP and >55,500 BP (McCabe, 1999). D-aIle/L-Ile ratios on macrofossil fragments indicate they may be Middle Midlandian (MIS 3) in age (McCabe, 1999). The mud stratigraphically overlies a basal diamict containing erratics (chalk, basalt) associated with easterly and north-easterly sources.

When placed in the context of other 'old' dates from the North of Ireland and neighbouring regions, with infinite ^{14}C dates of at least 30 ka BP, glacial diamicts underlying shelly sediments in this area may also possibly be assigned an MIS 4/3 (Early/Middle Midlandian) age (McCabe, 1999). Deposits are also associated with ice expansion of this age in Scotland (Sutherland, 1981) and Scandinavia (Mangerud, 1981). Although the evidence indicates an Early Midlandian (MIS 4) glaciation, no deposits unequivocally attributable to the last interglacial (MIS Substage 5e) have been documented from stratigraphically below the 'older' deposits (cf. Worsley, 1991).

The Aghnadarragh Interstadial (MIS 3)

Organic sediments from between two till sheets at Aghnadarragh, County Antrim gave ages beyond the radiocarbon method (an infinite ^{14}C date of >48,180 BP being the oldest) and have been described in detail by McCabe *et al.* (1987b). The lowest biogenic material in the sequence is a shallow water sequence comprising woody detritus peat containing plant and insect fossils beneath which is a deglacial succession of bottomsets, gravelly muds, and diamicts. This in turn overlies a glacial diamict that represents the Fermanagh Stadial (Table 15.2). The Aghnadarragh Interstadial and the other deposits predating the Glenavy Stadial (MIS 2) probably belong in the complex of MIS 3 (between 59 and 28 Cal ka BP).

The predominant plant fossils include the pollen of *Pinus*, *Betula*, 'Coryloid' (*Corylus/ Myrica*), *Picea,* and a number of herbs and aquatic plants. The macrofossil plant remains include wood, cones and leaves of *Pinus* and *Picea*, fruits of *Betula* (including *B.* cf. *nana, B.* cf. *pubescens* and *B.*cf. *pendula*), nuts of *Corylus avellana,* seeds of *Taxus baccata* (the latter were possibly derived), and megaspores of *Selaginella selaginoides*.

Abundant insect fossils (Coleoptera) were also recovered from the detrital peat. Although the assemblage was allocthonous, it represents species that might be expected to have been living in available habitats in the locality. The fauna suggest that both acid swampy conditions (with little open water) and drier, partially bare, habitats were present. Two weevils in the fauna, *Rhyncolus strangulatus* and *R.elongatus*, feed on dead or dying *Pinus* or *Abies* trunks and branches, showing that conifers were present at the site.

The insect assemblage includes species that only reach as far north as the southern half of Fennoscandia at the present day and there were no obligate high northern species. The authors concluded that the thermal climate of the Aghnadarragh Interstadial was as follows (and interestingly was just within the present day range):

Mean July Temperature	+15°C to + 18°C
Mean January Temperature	-11°C to + 4°C

Interstadial conditions appear to have been clement enough over a sufficient period to allow the immigration of plants to occur after the preceding stadial. The resultant *Betula–Pinus–Picea* woodland with its adjacent areas of swamp, dry bare ground, and local pools is probably similar in environment to the cool temperate conditions prevailing in Fennoscandian woodlands with similar tree types today.

The wider stratigraphical position of the Aghnadarragh Interstadial is partly based on the correlation of plant and insect assemblages with deposits at Chelford, Cheshire (Simpson and West, 1958; Coope, 1959), where similar woodland species are recorded. One difference between the two sites is the absence of *Ulmus* and *Carpinus* in the Aghnadarragh Interstadial. This was used by McCabe *et al.* (1987b) to suggest that the organic sedimentation at the site did not follow on immediately from an interglacial, and that the *Picea* present was therefore not of interglacial origin.

The absence of *Ulmus* and *Carpinus* and the presence of *Corylus* and *Taxus* (macrofossils and pollen) at Aghnadarragh may raise some doubts concerning the correlation of the interstadial with that at Chelford. A further complication arises with the realisation that there may be many more interstadial periods within the last cold stage than was formerly realised (Fig. 15.16), making such correlations rather tenuous. However, the stratigraphical position of the Aghnadarragh Interstadial seems to place it firmly within the Midlandian.

The Hollymount and Derryvree cold phases (MIS 3)

Three sites in the north of Ireland preserve organic sediments between two (Midlandian) till sheets that contain fossil assemblages with cold climate affinities. These biogenic sediments represent two broad time periods, which together probably cover part of a long, relatively cold period during the Early and Middle Midlandian (MIS 3). The contained fossil assemblages do not suggest very significant climatic deterioration relative to Holocene conditions, and for this reason the term 'cold phase' has been used here in preference to 'interstadial' (Bowen *et al.*, 1986b).

The first of these cold phases is named after the organic muds found at Hollymount, County Fermanagh by McCabe *et al.* (1978), and dated to >41.5 ka BP. Deposits of a similar type have been found at Aghnadarragh (unit 8) and dated to >46.62 ka BP (McCabe *et al.*, 1987b) and to 34.46 ka BP at Greenagho, County Fermanagh (Dardis *et al.*, 1985). Palaeobotanical evidence from Hollymount and Aghnadarragh shows that the landscape during this period was rather barren, with a northern open ground-flora dominated by Gramineae and Cyperaceae, along with *Betula* (cf. *B. nana*), Ericaceae (including *Calluna vulgaris*), *Empetrum* sp., *Salix* (including *S. herbacea*), *Artemisia, Thalictrum*, and *Selaginella selaginoides*. At Aghnadarragh it was apparent that some of the pollen was reworked.

The insect assemblages from unit 8 at Aghnadarragh also indicate open ground with sparse vegetation and little open water. There are no southern species and the present day southern limit of some species (e.g. *Diacheila arctica*) is in Arctic Fennoscandia. The authors estimate the thermal climate as follows:

Mean July Temperature	+11°C to + 13°C
Mean January Temperature	-18°C to + -7°C

The later part of this long Midlandian cold episode has been called the Derryvree cold phase, after a site in County Fermanagh (dated to 30.5 ka BP, Colhoun *et al.*, 1972). The fossil content of organic sediments sandwiched between two tills at Derryvree suggested an open tundra landscape. The flora (predominantly Gramineae, Cyperaceae, *Juniperus* and herbs) is diagnostic of an open, tree-less, muskeg environment, and it is associated with a moss flora. The insect assemblages also suggest a muskeg environment with open pools, rich in plant matter and surrounded by mosses. Colhoun *et al.* (1972) concluded that the climate was harsh with cold winters, and the date places the period as later than the Upton Warren Interstadial (MIS 3) of Britain.

A relatively impoverished fauna from Castlepook Cave, County Cork (Mitchell, 1976, 1981; Stuart and Van Wijngaarden-Bakker, 1985; Stuart, 1995) produced two dates, 35 ka BP and 34.3 ka BP, from bones of mammoth (*Mammuthus primigenius* Blumenbach) and spotted hyaena (*Crocuta crocuta* (Erxleben)) respectively. These appear to date the fauna to the Derryvree cold phase. Other mammals found in the cave included wolf (*Canis lupus* L.), brown bear (*Ursus arctos* L.), stoat (*Mustela erminea* L.), red fox or arctic fox (*Vulpes* or *Alopex*), arctic lemming (*Dicrostonyx torquatus* Pallas), arctic or mountain hare (*Lepus timidus* L.) and reindeer (*Rangifer tarandus* L.)(Fig. 15.20).

The Hollymount and Derryvree cold phases cover a long time period that includes the range of the British Upton Warren Interstadial with which they can, in part, be correlated. The Upton Warren Interstadial Complex (Coope, 1975, 1977) started with a warm interval between 43 ka–42 ka, following which the climate became much colder (after ~40 ka), possibly becoming progressively more severe up to the onset of stadial conditions (the Dimlington Stadial in Britain, <26 ka: Rose, 1985; Bowen *et al.*, 1986b). There is no known evidence in Ireland of climatic amelioration equivalent to the onset of the Upton Warren Interstadial. However, the ensuing cold, barren tundra landscape has been likened to conditions in Ireland during the Hollymount and Derryvree cold phases (Lowe and Walker, 1997).

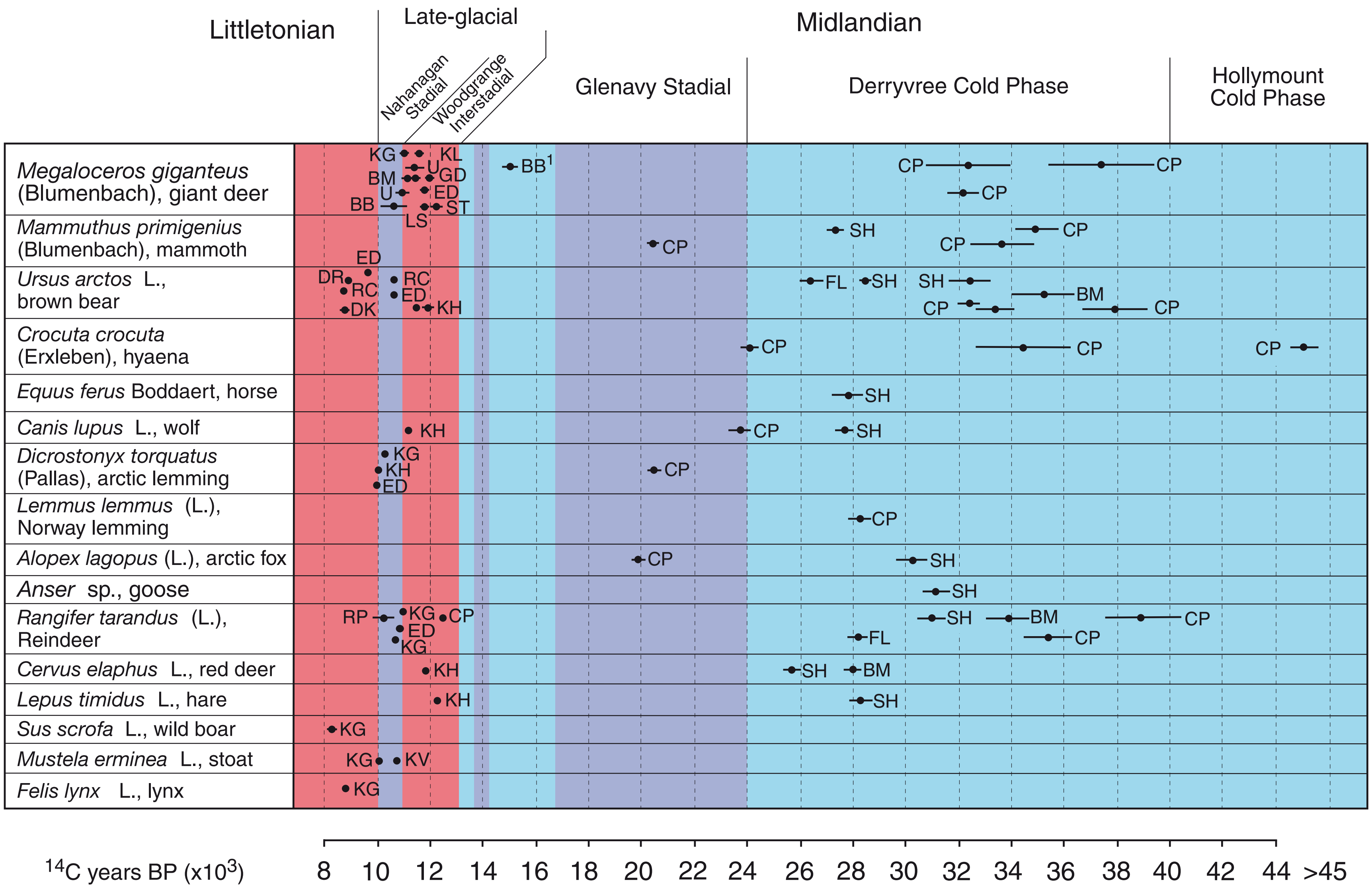


Figure 15.20 Radiocarbon dated mammal remains (showing the one standard deviation estimate of error of the dates) from the Midlandian and early Holocene. Data are from Stuart and Van Wijngaarden-Bakker (1985) and Woodman *et al.* (1997) who quote errors and site details. Key to localities: BB – Ballybetagh Bog, Co. Wicklow (BB[1] – Ballybetagh date possibly too old due to contamination with paraffin preservative), BM – Ballynamintra Cave , Co. Waterford, CP – Castlepook Cave, Co. Cork, DK – Derrykeel Bog, Co. Offaly, DR – Donore Bog, Co. Laois, ED – Edenvale Cave Complex, Co. Clare, FL – Foley Cave, Co. Cork, KG – Kilgreany Cave, Co. Waterford, KH – Kesh Corran Cave Complex) Co. Sligo, KL – Killuragh Cave, Co. Limerick, LS – Liskelly Stream, Co. Cork, RC – Red Cellar Cave, Lough Gur, Co. Limerick, RD – Roddans Port, Co. Down, SH – Shandon Cave, Co. Waterford, ST – Shortalstown, Co. Wexford (date is from associated plant remains) and U – unprovenanced.

The Glenavy Stadial (MIS 2)

The last widespread glaciation of Ireland occurred during the period of generally stable global sea levels and stable polar climate during MIS Stage 2 known as the Last Glacial Maximum (LGM) (23–19 ka Cal. BP; Yokoyama, *et al.*, 2000; Mix *et al.*, 2001). The glaciation in Ireland that encompasses the LGM has been referred to as the Glenavy Stadial, following the proposed Aghnadarragh type-site near Glenavy in County Antrim (McCabe, 1987). Ice-flow indicators (e.g. striae, overlapping belts of streamlined landforms) also indicate the eventual formation and dominance of lowland ice domes that formed the principal ice dispersal centres in the north and north-west of the island. Ice caps also existed on some upland areas e.g. Cork/Kerry (Wright, 1927; Warren, 1977; Herries Davies and Stephens, 1978), Wicklow (Farrington, 1957) and Antrim (Stephens *et al.*, 1975). Glacial ice also extended out of the many steep-sided, bowl-shaped corries that occur on the slopes of Irish upland areas (e.g. Lough Doon and Lough Adoon, Owenmore Valley, Dingle Peninsula, County Kerry; Coumshingaun, Comeragh Mountains; Lough Nahanagan, Camaderry Mountain, County Wicklow (Figure 15.18).

Recent work has indicated ice sheet extents beyond the southern coastline and stadial conditions of much longer duration than previously thought (Bowen *et al.*, 2002). Although MIS Stage 2 expansion of the last BIIS in different sectors was probably slightly diachronous, the main phase of glacial build-up, ice dome migration and ice frontal advances during the Glenavy Stadial have traditionally (e.g. Mitchell *et al.*, 1973) been bracketed between 28 and 22 ka Cal BP and limited to onshore areas north of the South of Ireland End Moraine (Charlesworth, 1928). Erosional features south of this line (McCabe, 1998), south coastal morpho-sedimentary evidence (McCabe and O'Cofaigh, 1996) and the application of cosmogenic dating techniques (Bowen *et al.*, 2002) have all indicated ice extension from Irish lowland sources to just across the southern Irish coastline into the Celtic Sea at this time.

Dating of deglacial sediments in Mayo to ~40–21 ^{14}C ka BP (McCabe *et al.*, 2007a) shows ice sheet advance beyond the western coastline before the traditional timing of the LGM ice sheet maximum extents. Along with cosmogenic exposure age dates from locations around the margins of Ireland (Bowen *et al.*, 2002), and the extent and pattern of Late Midlandian isostatic crustal depression (e.g. McCabe *et al.*, 2007a) the geological data indicate the persistence of ice sheets on Ireland during MIS 2 and into MIS 3. These data seemingly contradict the occurrence of organic materials defining the Hollymount and Derryvree Cold phases late in MIS 3 (above) and evidence from similar paraglacial locations in Scotland (Brown *et al.*, 2007) of open tundra conditions during MIS 3. However, it is conceivable that the sites in Ireland could at least have been outside the limits of an ice sheet localised on the western seaboard uplands at this time, and giving rise to the 'cold phase' (not 'interstadial') conditions in the lowlands farther north. As in the late Midlandian, it is probable that ice sheet sectors responded rapidly to millennial-scale climatic variability in the amphi-North Atlantic. The persistence of the ice masses may also help explain the erroneous extent and patterns of isostatic depression around the Irish coastline derived from deterministic ice sheet models parameterised, calibrated and tested using Holocene data (e.g. Roberts *et al.*, 2006, Boulton and Hagdorn, 2006).

The Last Termination

The Last Termination describes the period from the onset of BIIS deglaciation off the continental shelf through to the onset of the Holocene. The term is used to indicate that the period was one marked not only by general deglaciation but also by distinct events recording millennial-scale oscillations of the BIIS including significant periods of ice mass rejuvenation and ice-marginal readvance during overall deglaciation of the ISB. This period is also associated with phases of streamlining and drumlin formation (McCabe *et al.*, 1986) and is discussed in detail by McCabe, 1993, 1996; McCabe and Clark, 1998; McCabe *et al.*, 1998, 1999; McCabe, 1995; McCabe *et al.*, 2007). The evidence indicates at least two significant temporary reversals in the overall pattern of deglaciation, the Clogher Head Stadial (CHS) and Killard Point Stadial (KPS). Events during the last Termination, as currently understood from age-constrained geological evidence, are summarised in Table 15.5. Key locations in the Dundalk Bay area are shown on Figure 15.19.

The Midlandian Late-glacial (13 ^{14}C ka–10 ^{14}C ka BP)

The last glacial–interglacial transition is an event of considerable complexity that can be recognised on a global scale (e.g. see NASP Members: Executive Group 1994; Walker *et al.*, 1994; Troelstra *et al.*, 1995), and this cold to warm climate transition can be neatly summarised by the comparison of the GRIP ice core and the record of the planktonic foraminiferan *Neogloboquadrina pachyderma* shown on Figure 15.21.

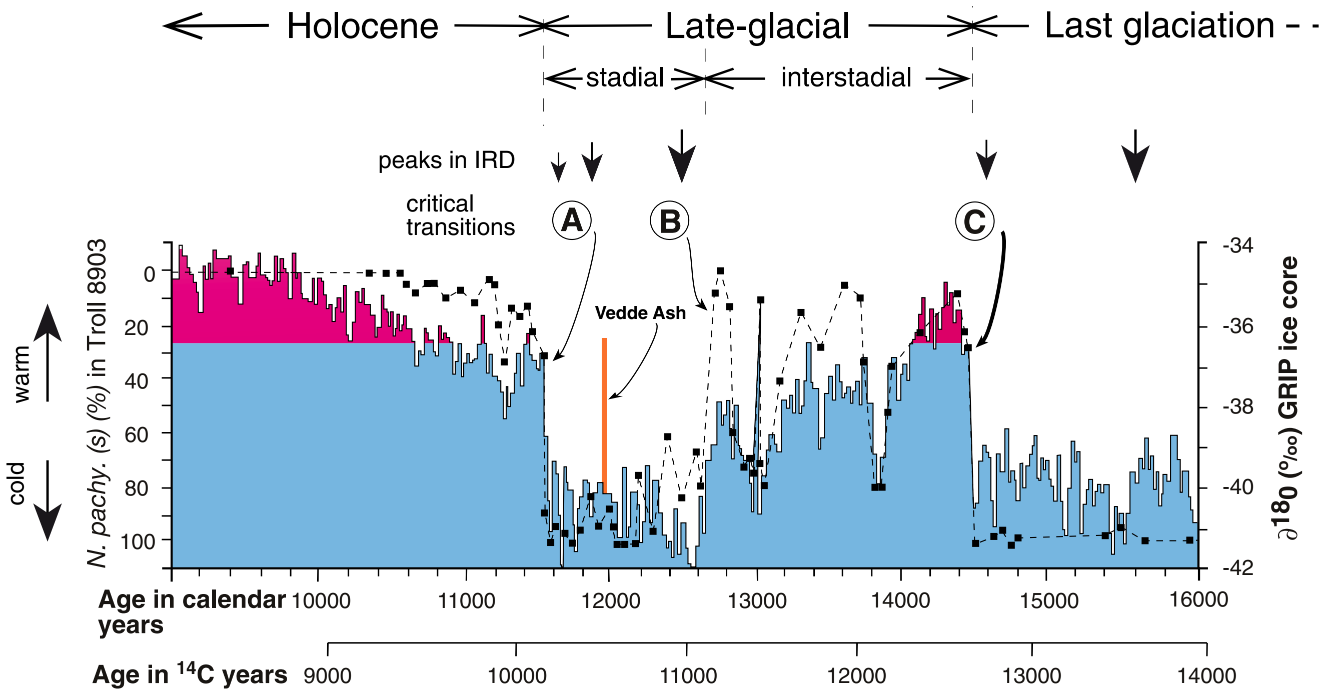


Figure 15.21 The stable isotope record (∂[18]O) from the GRIP ice core (histogram) compared to the record of *N.pachyderma* a planktonic foraminiferan whose presence indicates cold sea temperatures) from ocean sediments (dotted line). High concentrations of IRD from the Troll 8903 core are marked with arrows. *After* Haflidason *et al.* (1995). The transition times for critical lengths of the core were calculated from the sediment accumulation rates by the authors and these gave the following results: Transition A: 9 years; Transition B: 25 years; and Transition C: 7 years. Such rapid transitions have been corroborated from the recent NGRIP ice core data.

In Ireland the period from 13 ^{14}Cka to 10 ^{14}Cka BP is known as the Midlandian Late-glacial and is recorded from many sites, particularly from lake sediments, where extensive palaeoenvironmental information has been obtained (Watts, 1977, 1985; Andrieu *et al.*, 1993; Walker *et al.*, 1994; O'Connell *et al.*, 1999). Indeed, the first study of this period in the British Isles was carried out at Ballybetagh by Jessen and Farrington (1938). The Irish Late-glacial can be subdivided into the Woodgrange Interstadial (*c.*13 ^{14}Cka to 10.9 ^{14}Cka BP) and the Nahanagan Stadial (*c.*10.9 ^{14}Cka to 10 ^{14}Cka BP). Further palaeo-environmental information and more accurate chronologies are likely to be forthcoming from work on speleothems providing uranium–thorium dates and stable isotope proxies for climate (McDermott *et al.*, 2001; McDermott, 2004) as well as from the identification of tephra horizons within sediment sequences (Chambers *et al.*, 2004) as those records are successfully extended into the Late-glacial.

A summary of the palaeoenvironment of the Irish Late-glacial is presented on Figure 15.22. It is important to realise that these subdivisions are simplifications of a complex and global climatic event.

The Woodgrange Interstadial

At 13 ^{14}Cka BP the North Atlantic polar front had retreated from its glacial maximum position. The retreat of the polar front was probably the result of massive meltwater discharges into the North Atlantic and the ensuing collapse of marine-based ice masses (Berger and Jansen, 1995; McCabe and Clark, 1998). The climate of Ireland rapidly ameliorated and we find the first evidence of plant colonisation following the Glenavy Stadial. Initially grasses and herbs flourished, but these were followed by *Rumex* and *Salix herbacea* as biological productivity on the fresh soils increased. About 12.4 ^{14}Cka BP a first peak in *Juniperus* occurs in Irish pollen diagrams associated with organic lacustrine sediments, the period of *Juniperus* domination ends abruptly, sediments become less organic, and an initial phase of soil erosion is suggested by inwashed inorganics at many sites (12 ^{14}Cka to 11.8 ^{14}Cka BP). The vegetation was dominated by grassland and an open herbaceous flora (Figure 15.22).

This steppe-like environment of the Woodgrange Interstadial was home to herds of giant deer (*Megaloceros giganteus*), the fossils of which have been found widely dispersed in Ireland. The male of the species, with its

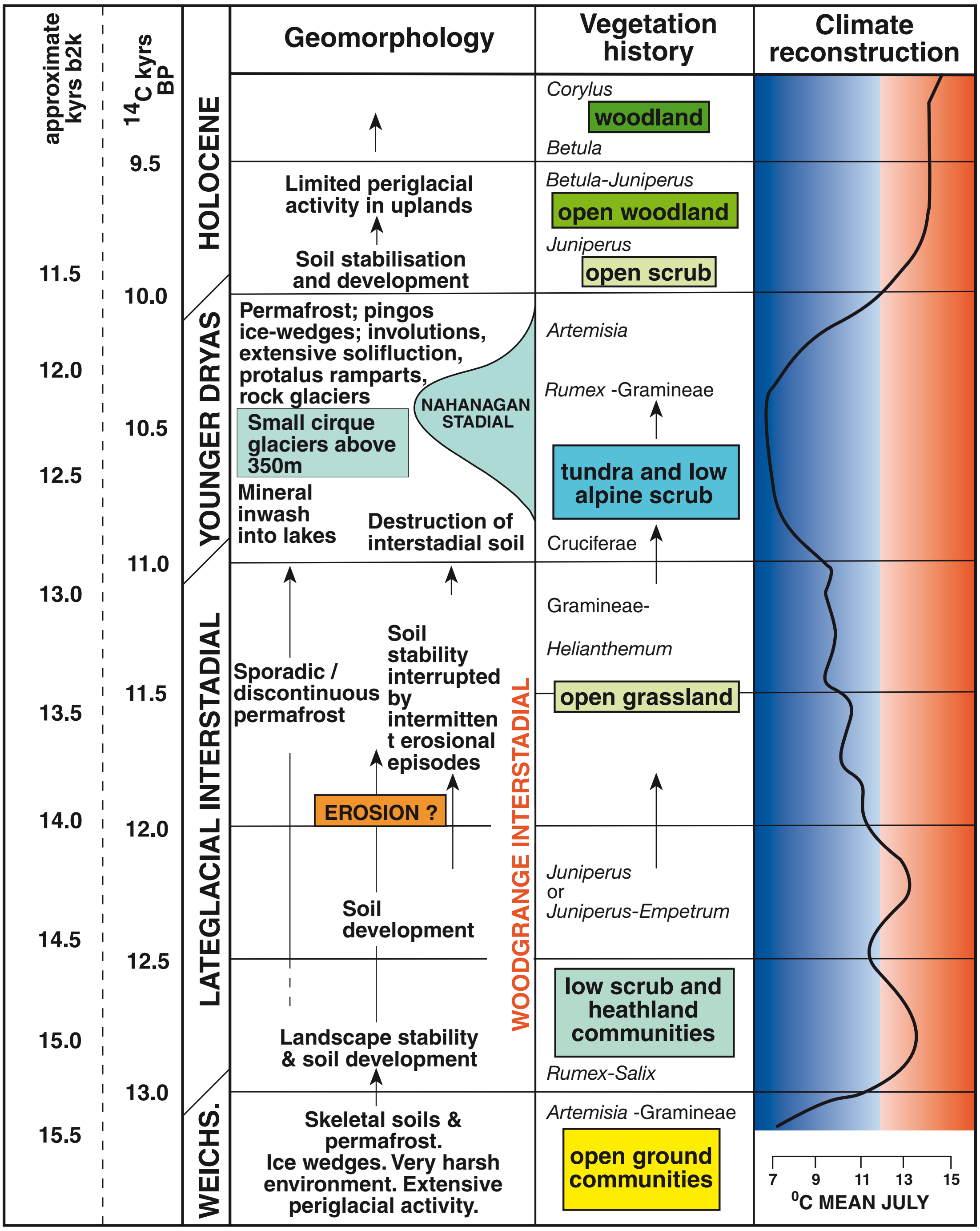


Figure 15.22 Late Midlandian Late-glacial geomorphology, vegetation history and climatic reconstructions (*after* Walker *et al.*, 1994 with modification by the authors).

magnificent antlers, wintered in sheltered sites like Ballybetagh in County Dublin (Jessen and Farrington, 1938), where winterkill led to many younger animals dying (Barnosky, 1985). The giant deer could not survive the ensuing cold and it became extinct at the end of the Woodgrange Interstadial. The ranges of other mammals during the Late-glacial are shown on Figure 15.20.

The Nahanagan Stadial

At 11 ^{14}C ka BP the polar front migrated southwards across the Atlantic and had a dramatic effect on the climate of north-western Europe. The period is known regionally in Europe as the Younger Dryas (YD) and in Britain, where extensive upland glaciation occurred, the cold phase is known as the Loch Lomond Stadial (Gray and Coxon, 1991).

In Ireland the YD has been named informally by Mitchell (1976) as the Nahanagan Stadial. This term stems from work by Colhoun and Synge (1980) at the corrie lake of Lough Nahanagan (Fig. 15.18A) where small moraines formed after the Woodgrange Interstadial. This site does not provide particularly good stratigraphical control; for example it lacks radiocarbon dates bracketing the glacial activity that produced the inner corrie moraines. However, it remains the only site in Ireland that unequivocally shows renewed glaciation in the Late-glacial Stadial through lithostratigraphical analysis, biostratigraphical information, and radiocarbon dating.

The Nahanagan Stadial in the rest of Ireland is well represented lithostratigraphically and biostratigraphically (predominantly from lacustrine sequences; Gray and Coxon 1991) as an inorganic (usually clayey and often containing coarse sand or pebbles) sediment sequence and an *Artemisia* pollen assemblage respectively (Watts, 1977, 1985). Numerous radiocarbon dates are available from this period (e.g. Craig, 1978; Cwynar and Watts, 1989; Browne and Coxon, 1991; Andrieu *et al.*, 1993; Walker *et al.*, 1994; O'Connell *et al.*, 1999) but no published work, other than that detailed above, proves actual glacial activity during the Nahanagan Stadial.

The short cold interval of the Nahanagan Stadial is not only recognised in lake sediments but is also a period during which widespread cold-climate geomorphological processes were active. The environment during this stadial was one of cold tundra with unstable, geliflucting soils and with small glaciers occupying the north-eastern corners of upland cirques. Figure 15.23 is a compilation of periglacial features that have been identified in Ireland and Figure 15.24 illustrates some of these features. Although very few of these landforms are dated, many are considered to have formed in the Nahanagan Stadial (Gray and Coxon, 1991) on the grounds that they are 'fresh' landforms (i.e. they are within areas that underwent severe glaciation during the Glenavy Stadial and hence must postdate it) or that they contain (or are overlain by) material dated to the end of the stadial or the Early Holocene. The problem of dating is apparent when one considers that some protalus ramparts have an Irish name (*Clocha snachta* or snow stones). Wilson (1988) suggested that they could be quite recent, i.e. possibly of a Little Ice Age date (Seventeenth to mid Nineteenth Century).

Examples of the more important features that may be of Nahanagan Stadial age are outlined below:

Feature	Dating evidence	Author(s)
Pingo remnants	Post Glenavy Stadial/ fresh. Features contain 14C dated sediments	Mitchell, 1971, 1973, 1977; Coxon, 1986; Coxon and O'Callaghan, 1987.
Rock glaciers	Post Glenavy Stadial/ fresh Schmidt hammer measurements (see Fig. 23)	Wilson, 1990 a,,b, 1993; Anderson *et al.*, 1998; Harrison and Mighall, 2002.
Protalus ramparts	Post Glenavy Stadial/ fresh Schmidt hammer measurements	Colhoun, 1981; Coxon, 1985; Wilson, 1990 a, b, 1993; Anderson *et al.*, 1998.
Patterned ground Stone stripes	None. Could be Glenavy Stadial and formed on nunataks. May be Nahanagan Stadial or older.	*see* Lewis, 1985; Quinn, 1987 Coxon, 1988; Wilson, 1995.
Landslides	Post Glenavy Stadial/ fresh	Colhoun, 1971; Remmele, 1984; Coxon, 1992.
Solifluction lobes	Post Glenavy Stadial. Ubiquitous and of various ages including Late Holocene	Lewis, 1985; Author's observations; Anderson *et al.*, 1998.
Involutions, Solifluction deposits	Widespread and of various ages but many near surface features are probably Nahanagan Stadial age	Lewis, 1985; Author's observations.

The periglacial landforms for which we have some dating control give both an insight into the geomorphological processes operating in Ireland during the Nahanagan Stadial and the prevailing temperatures at the time. Wilson (1990a) summarises the palaeoclimatic inferences of rock glaciers in detail suggesting a depression of mean annual temperature of c.8.5°C relative to the present. This compares well with estimates made by Colhoun and Synge (1980) of a temperature depression of c.7.2°C. When considering other periglacial evidence as well (pingos and ice wedge casts), Wilson (1990a) suggested that the mean annual temperature of the Nahanagan Stadial was probably lower, with values reaching −2°C to −5°C. Of course the whole Irish YD may not have experienced these low temperatures, and the short-lived stadial may have been a complex event. We shall not know for certain until further geomorphological work is carried out and more dates are available.

One other interesting aspect of the Late-glacial involves the immigration of plants and animals back into Ireland during a rapid rise in sea-level. As Ireland recovered isostatically from the weight of Midlandian ice, relative sea-level fell, but rapid eustatic rise in sea-level is supposed to have isolated Ireland, which may have been linked to Britain by a 'tenuous landbridge'

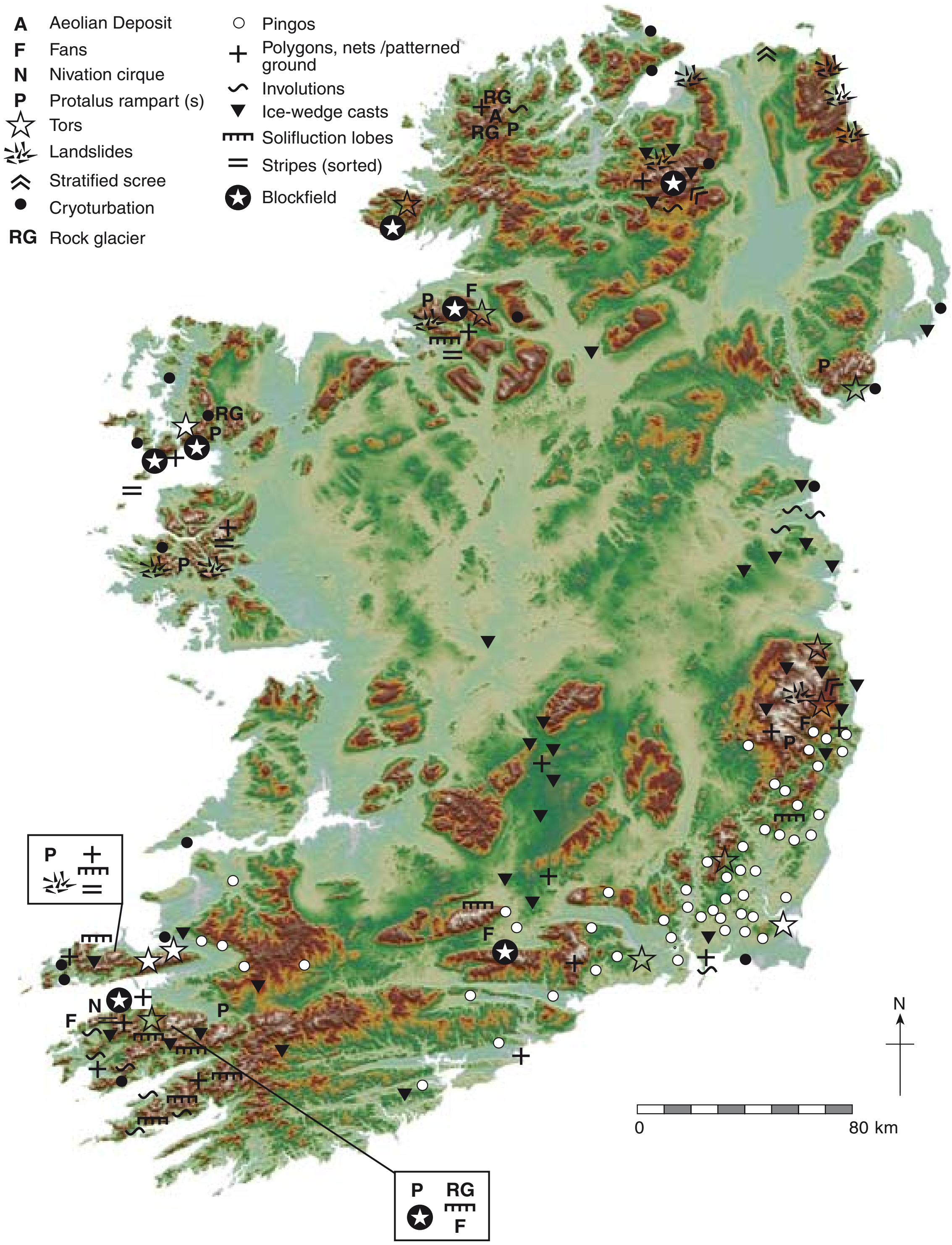
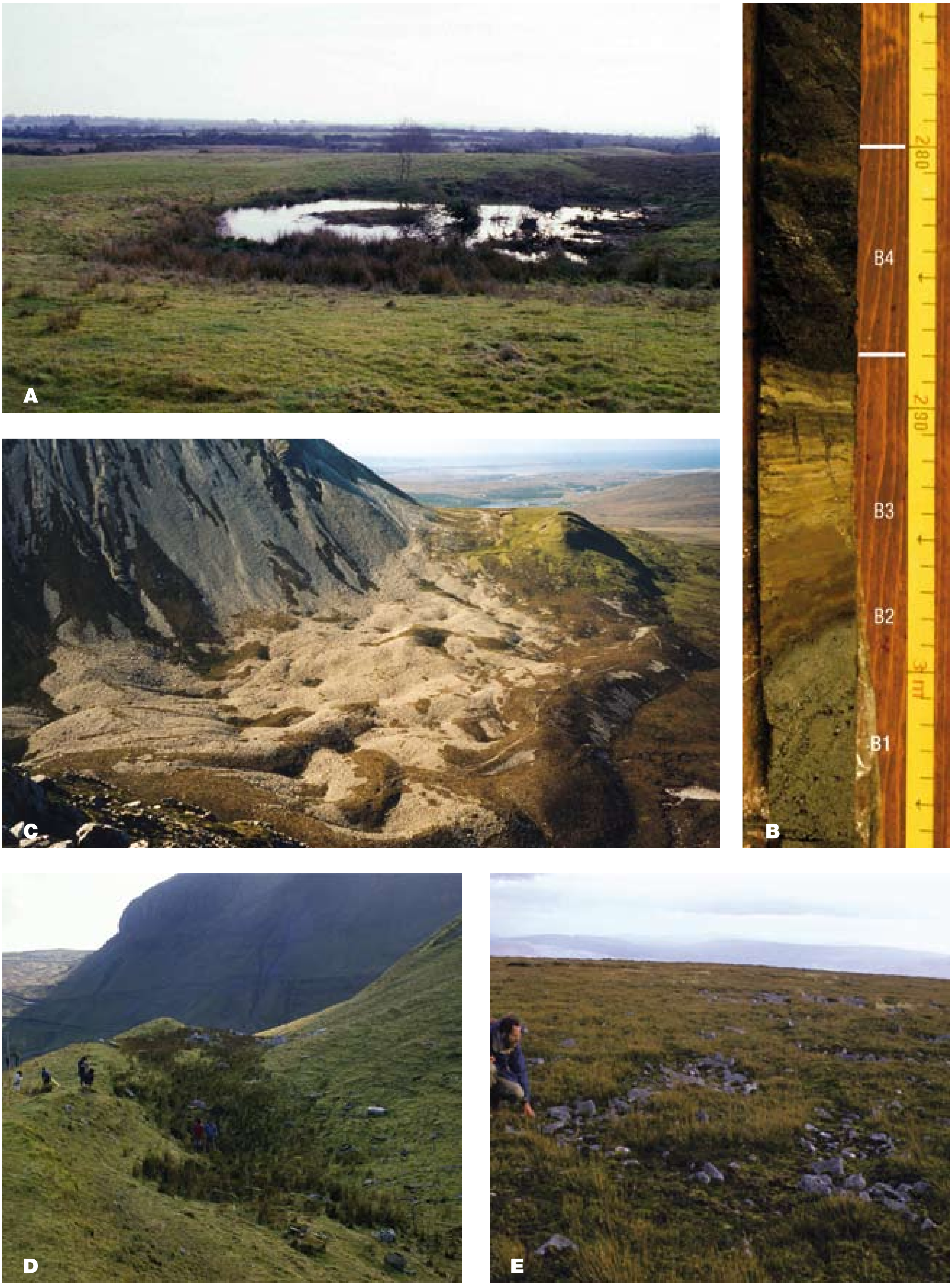


Figure 15.23 Periglacial features in Ireland (*after* Lewis, 1985 with additional information from Wilson, 1990a, 1990b, 1993 and 1995 and personal observations by the authors).

Opposite Figure 15.24 Late Pleistocene. A – A pingo rampart containing a flooded depression, Camaross, County Wexford (see Mitchell, 1971). B – Core from a pingo scar at Meenskeha, County Cork (Coxon, 1986). B1 – slumped rampart material (latter part of Younger Dryas/Nahanagan Stadial), B2 – Late-glacial/Holocene transition (10,000 ^{14}C a BP, *c.*11,700 yb2k), B3 – Early Holocene laminated muds and marl, B4 – transition into predominantly organic sedimentation ('bulk' date of 9,740 ± 150 ^{14}C BP from between the white lines), C – Rock glacier on the northern flank of Errigall, County Donegal (see Wilson, 1990). D – Protalus rampart, Gleniff, County Sligo (see Coxon, 1985), E – Periglacial patterned ground (sorted nets) on the summit of Truskmore, County Sligo (see Coxon, 1988).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for a very short period only (between 18 and 14 ^{14}C ka BP according to Lambeck, 1996; or possibly as late as 12.5 ^{14}C ka BP, Brooks *et al.*, 2008) which was a time of cold climate. It is unlikely that many plants and animals survived the maximum of the Midlandian in Ireland or that any other landbridge was possible after 12.5 ^{14}C ka BP. Such a connection to Britain was thus only present in cold-climate conditions, and plants and animals must have migrated into Ireland after it was cut off by the sea in the Midlandian Late-glacial (Woodgrange Interstadial) and in the early Holocene. However, it appears that in the Holocene even terrestrial molluscs managed to cross this barrier with relative ease (Preece *et al.*, 1986).

By 10 ^{14}C ka BP the Polar front had regained its position close to the coast of Greenland and much evidence suggests that the climate around the North Atlantic warmed quickly and dramatically (Troelstra *et al.*, 1995). The climate of Ireland ameliorated rapidly at the onset of the Holocene (some 11,700 years ago) and incredibly the YD/Holocene transition took less than a decade (Rasmussen *et al.*, 2006).