Chapter 2

GLACIAL LAKE ORIGINS
ICY HISTORIES

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SUMMARY

It has been over 11,000 years since a glacier last existed on the island of Ireland. Nevertheless, the impact of former glaciations on our lakes is inescapable and almost every lake in Ireland has a glacial legacy. During the last glaciation, ice covered the entire island. As the ice retreated onshore, vast quantities of meltwater were released, forming lakes along the ice margin wherever bedrock, ice or moraines formed a barrier. Some of these lakes have vanished completely, but many remain. Glacial lakes with dams formed largely of bedrock continue to exist in both upland and lowland glaciated landscapes today, whereas lakes dammed by moraines and ice drained more easily and have mostly disappeared or are much smaller than in the past. As the last ice sheet melted, the meltwater carried sediments from the glacier that were then deposited in the lakes and these glacial lake deposits continue to affect our environment and society today. Sand and gravel deposited where meltwater streams entered the glacial lake form groundwater aquifers in many areas, while the finer silt and clay carried further into deeper parts of the lake basins controls local hydrology by acting as an impermeable seal, causing waterlogging and the growth of peat in raised bogs across lowland Ireland. Glacial lake sediments can provide a record of meltwater discharge and ice sheet retreat, useful for understanding future retreat patterns in modern ice sheets. Deltas and outwash fans deposited in glacial lakes are an important source of aggregates for the construction industry. This chapter examines the glacial origins of modern and ancient lakes in Ireland.

Keywords ice-dammed lake, palaeolake, varve, moraine-dammed lake, corrie lake, trough lake

WHAT IS A GLACIAL LAKE?

Defining modern glacial lakes is relatively straightforward. A glacial lake, also termed a pro-glacial lake, is one that receives glacially derived meltwater, i.e., melt from a glacier, ice cap or ice sheet (Ashley, 2002; Carrivick and Tweed, 2013). A further division can be made between those lakes that are in direct contact with the glacier or ice sheet (i.e., the ice margin terminates in water), known as ice-proximal, ice-contact or ice-marginal lakes, and those that are not in direct contact but are fed by water from a glacial system, known as ice-distal lakes (Ashley, 2002). This classification is useful because there are significant differences in lake characteristics, including sediment input and water circulation, depending on the presence or absence of an ice margin. Other classifications refer to the type of barrier that holds the lake in place. This can be one or a combination of ice, bedrock, glacial moraine, or landslide debris (Carrivick and Tweed, 2013). This latter classification is useful because ice, moraine and landslide barriers are much more likely to fail, causing sudden lake drainage and often catastrophic floods downstream (Carrivick and Tweed, 2016).

Definition and classification are a little less straightforward for former glacial lakes, including Ireland's lakes. As for modern lakes, classifying former lakes based on how glacially derived meltwater arrived in the lake can be done, but the division into ice-proximal and ice-distal lakes is not helpful, as in a formerly glaciated area such as Ireland all lakes will have moved from an ice-proximal to an ice-distal position as the glacier or ice cap retreated.

There are several other ways to classify former glacial lakes. One approach is to consider how the lake basin formed. Using this approach, it is possible to identify three main ways these lakes were created. These are: lake basins formed primarily by glacial erosion, such as corrie lakes or lakes in glacial troughs and glacial overdeepenings; lakes formed primarily due to glacial deposition, such as lakes formed between drumlins or ribbed moraine, in hollows left by buried ice melting (kettle holes), or between glacial moraines; and lakes formed within a pre-glacial basin that was occupied by ice and then a glacial lake during ice retreat. The latter are often modified by glacial erosion and deposition but retain evidence that indicates a lake probably existed prior to the start of the Quaternary period (2.6 million years). Lakes in this last group can be very large in area but are often surprisingly shallow compared to their size.

Another way to classify former glacial lakes is to consider the type of barrier or dam that creates, or created, the glacial lake basin, and the time span for which that barrier existed. There are three basic types of dams, although all three commonly form part of a glacial lake margin at some point during its existence. These are bedrock dams, unconsolidated glacial debris or moraine dams, and the ice itself. Of these, a bedrock dam is the most stable, although the elevation of the dam can shift through time due to the rebounding of the Earth's surface after the weight of ice has been removed and rock channels can be cut and deepened by streams discharging from the lake, slowly altering the lake level. Dams formed of unconsolidated material are much less stable and can be breached easily and in modern lakes often result in glacial lake outburst floods (Carrivick and Tweed, 2016).

In all cases, as ice retreats across a lake basin, the ice margin forms at least one margin of the lake, damming the lake water. As with moraines, this ice barrier can be breached relatively easily, especially as it thins due to melting (e.g. Veh et al., 2023). As the ice barrier retreats, water escapes from the lake as lower outlets emerge, from under the ice sheet, and water levels in the lake fall. The lake may shrink considerably or disappear completely as the ice retreats further and the water can escape from the basin created by the ice dam.

A further consideration when classifying former glacial lakes is time. In many cases, ice-dammed lakes are ephemeral in nature. In modern glacial settings some lakes form and disappear within a few years (e.g. Rick et al., 2022). Records from formerly glaciated areas indicate that other lakes can last for much longer periods (100s-1000s years), before disappearing completely (e.g. Dyke, 2004; Hughes et al., 2016; Davies et al., 2020). Ancient lakes that have disappeared completely, or that have a much smaller modern equivalent are referred to as palaeolakes and there are many examples of such lakes in Ireland.

Finally, glacial lakes can also be formed indirectly by ice, where the weight of the ice cap presses down on the Earth's surface, forming a depression below the ice cap. As the ice sheet melts, the ice cap retreats into the depression created by its weight and a glacial lake forms around the margin, ponded by the ice and higher ground outside the depression. Even after the ice has completely melted, the depression remains for many thousands of years, as does the lake. Through time, the Earth's surface slowly rebounds, gradually lifting the depression and reducing the lake size. In Ireland, ice was thickest in the north of the island and thinned southward, so the north of the island is rebounding more than the south. This means that large lakes in Ireland are still changing in size many thousands of years after the removal of the last ice sheet, as the northern end of the lake closest to the centre of the ice sheet rebounds more quickly compared to the end far from the ice sheet centre (e.g. Delaney, 2022).

These lake types are discussed further below. However, before that, it is worth considering two things: the unique characteristics of glacial lakes; and the evidence used to identify former glacial lakes.

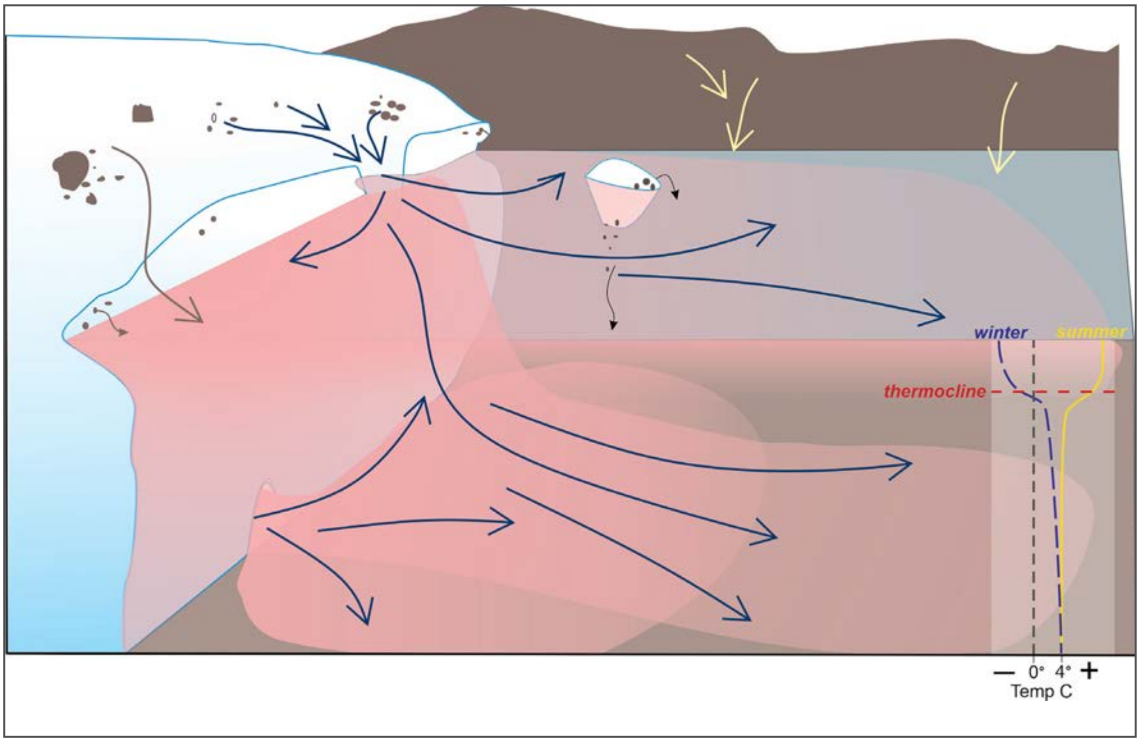
GLACIAL LAKE LIMNOLOGY

Modern glacial lakes have several distinct limnological characteristics that impact on the sediments and landforms left behind, so can also be identified in palaeolake deposits and landforms in Ireland.

Lake water stratification and circulation

In modern glacial lakes, well-developed vertical stratification of the water column is a common feature (Figure 2.1; Smith and Ashley, 1985; Ashley, 2002). This can be both temperature (see Chapter 1) and sediment-driven density stratification, as its development reflects vertical and seasonal changes in both temperature and suspended sediment concentrations in the lake water.

Figure 2.1 Schematic block diagram showing thermal stratification and interflows in an ice-contact glacial lake.



Thermal stratification is controlled by both solar radiation and meltwater input (e.g. Smith and Ashley, 1985; Sugiyama et al., 2016). Solar radiation in summer creates a less dense, warmer layer at the top of the lake water column, overlying a colder, denser bottom layer. These two layers are separated by the thermocline, an area of rapid temperature change (Figure 2.1). In autumn, as temperatures drop, the cooling surface waters become increasingly dense and as they reach 4°C (H_2O is at its densest at 4°C), the thermocline breaks down and vertical mixing (overturning) occurs. Thermal stratification then re-establishes with the warmest water (4°C) now at the base of the water column and colder water above. In spring, as waters warm, overturning occurs again, and re-establishes the summer stratification. Such lakes are termed 'dimictic' and are often ice-covered throughout the winter, effectively creating a closed system.

Density stratification also occurs due to the input of cold meltwater and suspended sediment. In ice-contact lakes, water temperatures near the ice margin are often very low, as meltwater near 0°C in temperature is discharged from the ice sheet/glacier into the lake and icebergs calve from the ice margin and add further meltwater. This water sinks to the bottom. Away from the ice margin or in ice-distal lakes, temperatures rise and may be above 4°C throughout the water column (Sugiyama et al., 2016 and references therein). However, the water columns of such lakes are still commonly stratified because sediment carried in suspension increases the density of the inflowing water (e.g. Gustavson, 1975a, b; Smith and Ashley, 1985; Gilbert and Desloges, 1987). These dense inflows sink downward on entry into the lake, forming underflows and increasing the density of the bottom lake waters further. Meltwater discharges with lower sediment content tend to form overflows at the lake water surface or move down toward the thermocline, forming interflows (Figure 2.1). These occur in summer but cease in winter as the lake surface freezes over.

Not all glacial lakes are dimictic, and polymictic (mixing occurs several times a year), monomictic (mixing occurs once a year) and non-stratified lakes also occur, depending on water temperatures and bathymetry. A further control on lake stratification is wind. Strong, katabatic winds are a common feature of ice sheets and glaciers, as cold, dense air formed above the ice cap moves downward and outward toward the ice margin; these winds are often funnelled down glacial troughs. Wind-driven circulation of the surface waters of a glacial lake mixes the surface layer and increases its thickness (e.g. Smith, 1978). In shallow lakes, the entire water body may be mixed, removing stratification. Wind can also drive overflows across the lake, changing where sediment is deposited.

Sedimentation in glacial lakes

The patterns of water circulation and stratification in glacially fed lakes have a profound influence on sediment deposition within the lake. Firstly, seasonal variation in sediment input is marked. In winter, meltwater and sediment input to the lake is almost non-existent, as ice cover forms in the autumn and seals the lake surface. In contrast, large amounts of meltwater and sediment are input in the relatively short summer period (Smith and Ashley, 1985). Initially, sediment transport is by melt from snow. Later in the season, glacial melt becomes more important. Rainfall events during summer also contribute to sediment movement, both from land and adjacent ice (e.g. Cockburn and Lamoureux, 2007). Most of this sediment (both bedload and suspended load) is rapidly deposited close to the discharge point, as the dense inflow sinks downward, forming a rapidly thinning wedge of sediment. Where sediment builds up to the level of the lake water surface, a delta forms. This is termed an ice-contact delta, or glaciodelta, when the discharge is directly from the ice. Deltas formed in this way are commonly Gilbert-type deltas, exhibiting a tripartite sedimentary sequence of flat or gently dipping bottomset beds composed of sand and silt, deposited distal to the sediment discharge point, overlain by steeply dipping foresets that have aggraded across the bottomsets as sediment is added, and then by topsets, consisting of fluvial sediments deposited on the delta surface (Figure 2.2A). Sometimes at the ice margin, discharges from the base of the ice do not build up to the surface and instead form a fan of sediment, termed a subaqueous outwash fan (Delaney, 2019; Figure 2.2B), that decreases in particle size rapidly down the fan surface. These deposits are important for identifying past glacial lakes and reconstructing past ice margins.

Further away from discharge points, toward the centre of the lake basin, finer-grained sediment, mostly silt and clay, is deposited (Figure 2.2C, D). In these areas, the silt grains are deposited quite quickly, as the inflowing water spreads out across the lake. This means that silt deposition primarily occurs in summer when meltwater is entering the lake. However, due to both their very small size and platy shape, many clay grains remain auto-suspended toward the top of the lake water column throughout the summer, kept in motion by surface winds currents. It is only when full mixing occurs in the autumn that these very small grains are transported downward. Once the lake surface

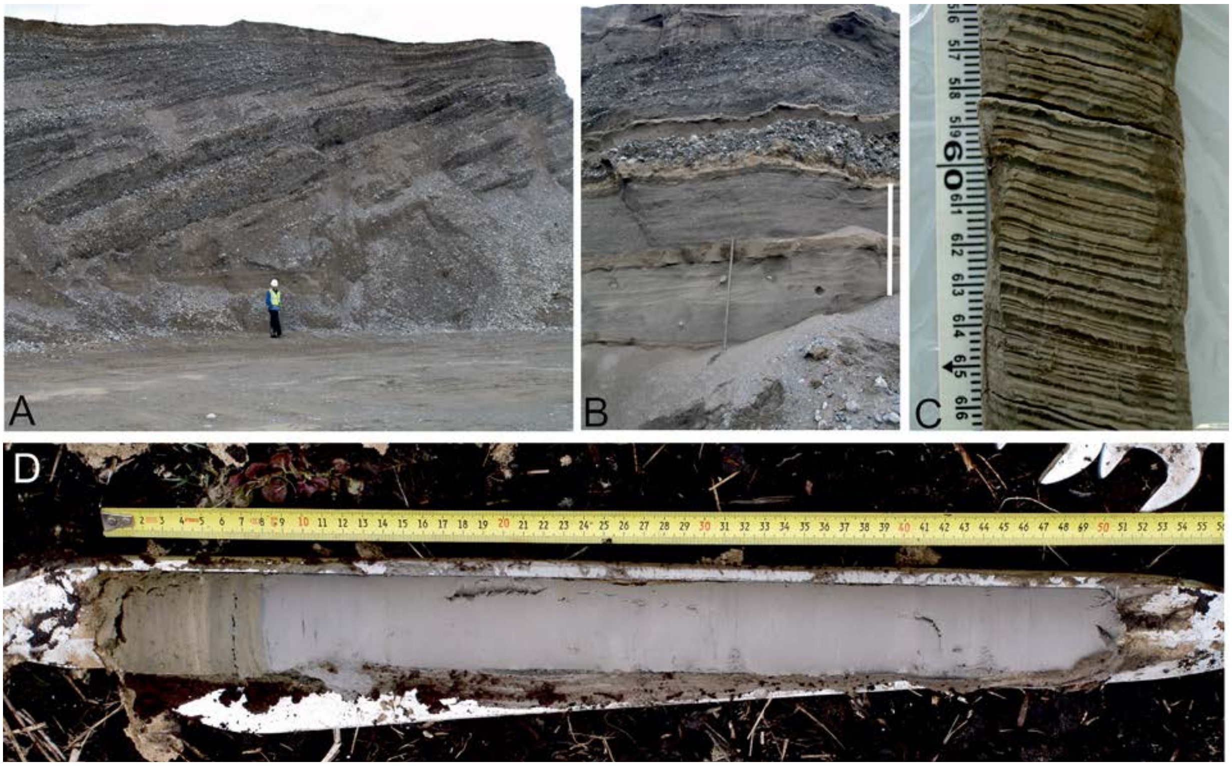


Figure 2.2 A. Blackwood glaciodelta, Co. Offaly, person for scale. The tilted foresets were formed by material avalanching down the delta front. B. Birr outwash fan. Beds of sand and gravel deposited rapidly from high energy underflows are separated by drapes of fine sand and silt deposited at low flow. C. Dried core from Carriganachtan bog, south of Athlone, Co. Roscommon, containing glacial varves. The paler layers are coarse to fine silt deposited in summer; the darker layers are fine silt and clay deposited when the lake is frozen in winter. D. Fresh core from Carriganachtan Bog, Co. Roscommon, showing an abrupt transition from glaciolacustrine silt and clay on the right to organic Holocene (after 11,700 BP) lake sediments (left). The glacial lake sediments appear massive (homogeneous), but when dried the fine laminations visible in photo C appear.

waters are frozen, the still water allows the deposition of a very fine silt and clay layer during winter (Smith and Ashley, 1985).

This highly seasonal variation in sedimentation in stratified glacial lakes leads to distinctive laminated patterns in the resulting deposits (Figure 2.2C). The pattern is rhythmic, in that it is repeated from year to year, and consists of a lower layer composed of one or more silt-dominated laminae, representing the summer/melt season, capped by a distinct lamination of clay and very fine silt deposited from suspension when the lake surface is frozen in winter.

The winter lamination is commonly graded, with the finest particles at the top. The coarse-fine rhythmite formed in this way is called a varve. Varve is a Swedish word applied by Gerhard De Geer at the end of the nineteenth century to annually laminated sediments deposited in Swedish palaeolakes during deglaciation (De Geer, 1940).

The formation of clastic varves, composed of mineral sediments, in glacial lakes is a hugely important feature for palaeo-environmental reconstruction in formerly glaciated areas like Ireland. By measuring varve thickness, sequences of varves can be matched across long distances, allowing stratigraphic correlation of lake sediments across vast areas, provided suitable sediments fed by the same ice sheet can be found. Where large palaeolakes formed along the ice margin, varve-matching in the direction of ice retreat has been used to reconstruct the retreat rate of the ice margin (De Geer, 1940; Ridge et al., 2012). Varved sediments also provide a continuous, high-resolution record that can be used to examine changes in climate-related parameters including temperature and rainfall, as well as records of changing ice margin position and meltwater discharge (e.g. Loso et al., 2006; Palmer et al., 2012). These records also formed during the last glaciation in Ireland.

GLACIAL LAKES IN IRELAND: ICE-DAMMED PALAEOLAKES

The recession of the last major ice sheets was marked by the development of large ice-contact lakes along their margins during retreat (Dyke, 2004; Murton and Murton, 2012; Hughes et al., 2016; Davies et al., 2020). That such lakes also formed along the margins of the last Irish ice sheet has been known since the 1920s (Charlesworth, 1928, Farrington, 1934). Despite this, the number and extent of ice-dammed palaeolakes in Ireland is unknown, and the existence or extent of many of these lakes is debated. Palaeolakes continue to be identified (e.g. Synge, 1950; Van der Meer and Warren, 1997; Meehan, 1999) and it is likely that evidence for further, as yet unidentified, ice-dammed lakes will be found in the future, and the size and extent of those already known will continue to be revised. The location of ice-contact palaeolakes is shown in Figure 2.3 (letters in blue) and named in the text. While some palaeolakes have entirely disappeared, in other cases a modern remnant exists. Modern lakes in glacially formed basins are numbered in red in Figure 2.3. Evidence for ice-dammed palaeolakes can be recognised from a combination of erosional and depositional features in the Irish landscape.

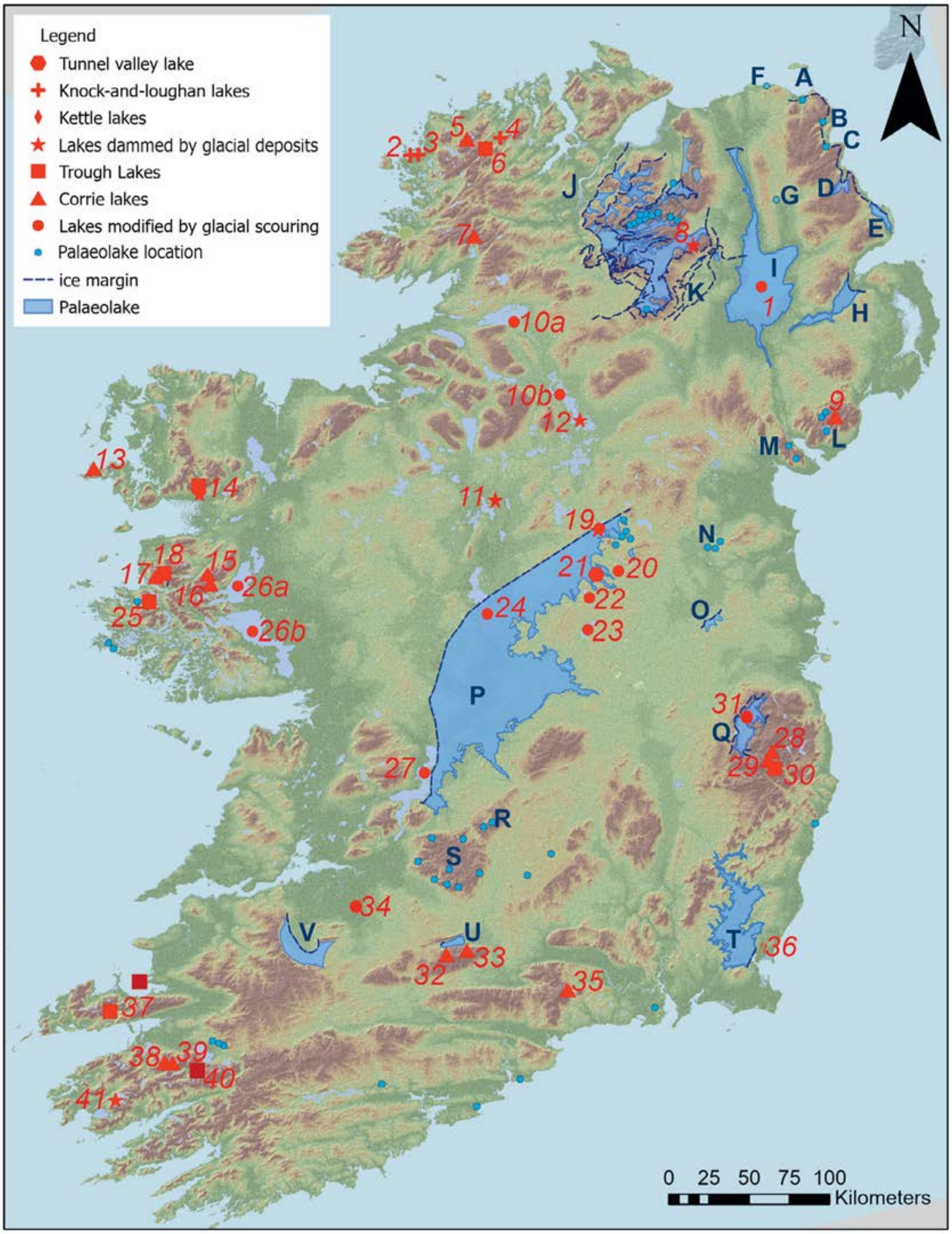


Figure 2.3 Glacial lakes in Ireland. Palaeolake locations, where the lake has disappeared or only a remnant remains, are shown as blue dots where the lake is too small or the evidence too little to show extent. Paleolakes named in the text are indicated by a blue letter. Lakes in glacially formed basins are numbered in red.

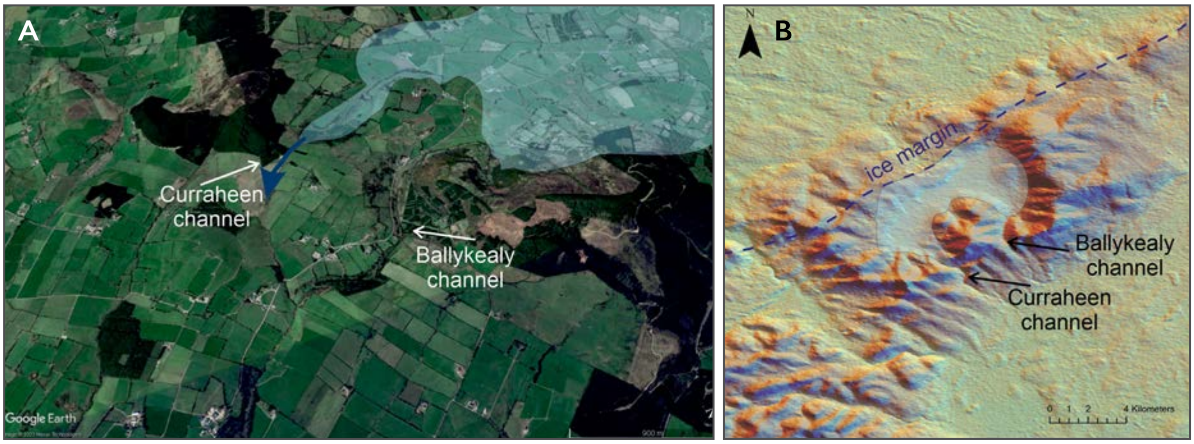


Figure 2.4 A. Google Earth image showing the meltwater channels at Curraheen and Ballykealy, Co. Tipperary, formed by outflows from ice-dammed palaeolake Ollatrim (R; Figure 2.3). The area shaded blue shows the likely extent of the lake when water was exiting through the Curraheen channel. B. 12.5 m resolution hillshaded digital elevation model (DEM) created from radar (ALOS-PALSAR) showing a reconstruction of Palaeolake Ollatrim and the meltwater channels pictured in 2.4A.

Erosional Features

The most commonly found erosional features are the outflow channels through which the former lakes drained. These are usually perched on the watershed across which the lake drained, away from the ice margin. They are often (but not always) without a modern stream and may terminate at a fan of sediment deposited by the outflowing meltwater. The elevation of the channel floor indicates the water level height of the lake when the outflow was active.

Examples of such channels can be seen around the Devil's Bit Mountains in Co. Tipperary. Here, the last ice sheet margin receded westward; once across the NE-SW oriented Devil's Bit ridge, water was ponded on the reverse slope between the ice and the ridge, forming Palaeolake Ollatrim (R on Figure 2.3; Charlesworth, 1928). Two major outlet channels developed, one at c. 245 m above sea level at Ballykealy and a lower channel at Curraheen as the ice retreated further across the Ollatrim river basin (Figure 2.4). Once the ice margin retreated beyond the northwest margin of the ridge, the lake drained westward down the path of the modern Ollatrim River.

Less commonly identified features are wave-cut shoreline notches and wave-planed surfaces, formed by erosion of bedrock and previously deposited glacial features. Such features can only develop when the palaeolake was large enough

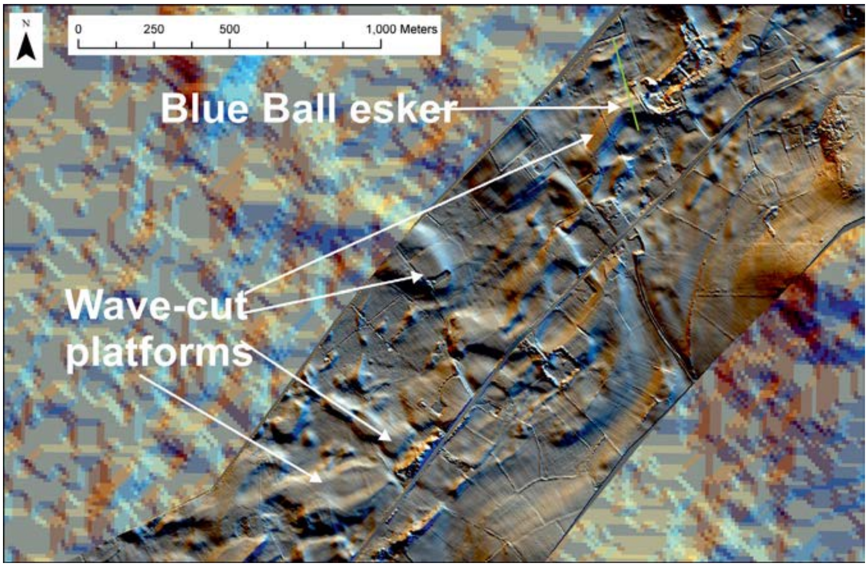


Figure 2.5 Hillshaded digital elevation model created from 1 m resolution airborne LiDAR (data from Transport Ireland, available for download through GSI.ie), showing terraces cut by wave erosion in Palaeolake Riada (P) into the Blue Ball-Kilcormac esker, Co. Offaly. Reprinted from Delaney (2022).

to have a significant wave fetch. A good example of a wave-planed surface can be seen along the northwestern margin of the Blue Ball-Kilcormac esker in Co. Offaly, where the northern side of the esker and adjacent glaciofluvial features have been truncated to form a flat surface, cut by wave erosion in Palaeolake Riada (P; Figure 2.5; Delaney, 2022). Terraces and shoreline notches are also recorded at several locations in Co. Tyrone, formed by extensive lakes ponded on south central Ulster between multiple ice lobes during the final stages of ice sheet decay (K; Doughty and Enlander, 2019).

Depositional features

Many palaeolake depositional features are relatively common and easily identified. Most important are ice-contact subaqueous outwash fans and deltas, formed at a point discharge into the former lake, either at the ice margin (where they are often at the downstream end of eskers) or at inflows from the surrounding land. Their flat surfaces are similar in appearance to wave-cut terraces, but they often have shallow channels cut into their surface, as seen in the Blackwood delta west of Tullamore (Figure 2.6). Ice-contact deltas were first described in Ireland in Co. Meath, where they formed in now-vanished Palaeolake Summerhill (O) at the mouth of a

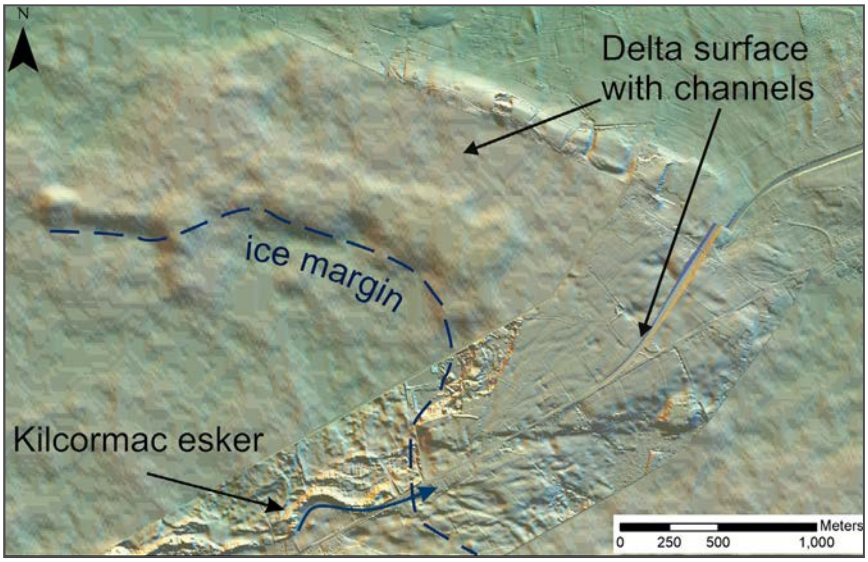


Figure 2.6 Hillshaded digital elevation model created from combined 1 m resolution airborne LiDAR (Transport Ireland) and 12.5 m radar data (ALOS-PALSAR) showing the Screggan-Blackwood delta complex at the north end of the Blue Ball esker, Co. Offaly. A faint network of braided channels can still be seen in the 1 m resolution image on the upper part of the fan. The Kilcormac esker marks the path of the subglacial stream that fed the delta. Image reprinted from Delaney (2019).

tunnel in the ice sheet through which meltwater discharged each summer; as the ice margin retreated each year, a new delta formed (Synge, 1950).

Ice-contact deltas can reach a considerable size and, in many cases, act as an important source of building aggregates. One of the largest examples in Ireland lies north of Blessington, Co. Wicklow, where a delta complex formed in Palaeolake Blessington (Q) covering over 10 km^2 and reaching vertical thicknesses of over 80 m, has been used as a source of aggregates for building for over 40 years (Philcox, 2019). The delta was fed by meltwater streams discharging from an ice margin that lay against the Slievethoul bedrock ridge to the northwest of the delta. Sedimentary sequences indicate multiple changes in water level during the existence of the ice-dammed lake; at its highest level the lake surface was over 100 m above modern Lake Blessington

Shoreline deposits have rarely been described in relation to palaeolakes in Ireland. However, some evidence of beach and shoreface deposition is found on top of deltas that formed in the largest known ice-contact lake, Palaeolake Riada (P; see below and Delaney, 2022). Around smaller lakes in mountainous areas, boulder shorelines may be found, such as that described around the modern Lough Nahanagan, Co. Wicklow (number 29 on Figure 2.3), associated with a wavecut notch indicating a higher past water level at the end of the last glaciation (Colhoun and Synge, 1980). More shoreline sediments will likely be recognised in the future, as palaeolakes are more closely investigated.

One of the most widespread, but least described, indicators of the existence of glacial palaeolakes in Ireland are deposits of fine-grained silt and clay (Figure 2.2 C, D). These are very widespread in the central lowlands, where they underlie many of the extensive raised bogs (Van der Meer and Warren, 1997; Delaney, 2007, 2022) and can create a considerable challenge for road and bridge construction (Long, 2020). They also commonly underlie Holocene sediments in both lowland and upland lakes throughout Ireland (see Chapter 3). As these deposits are generally overlain by Holocene wetland and lake sediments, they are hard to spot. Nevertheless, significant thicknesses of glacial lake sediments associated with the larger palaeolakes have been identified in borehole records and exposures. For example, north of Lake Ennell, Co. Westmeath (23), a series of boreholes drilled to support construction of the Joe Dolan Bridge revealed more than 14 m of glacial lake sediments that were originally deposited in Palaeolake Riada (P; Long, 2020).

While sedimentary records extending into the Late Glacial (Younger Dryas) cold period (12,900-11,700 BP (Before Present)) have been studied at multiple sites, the underlying glacial sediments are rarely studied, as such studies tend to focus on bio-indicators and geochemistry rather than physical sediment characteristics. This is a pity, as varved (annually laminated) deposits are known to occur, although they are difficult to recognise without drying core samples (see Figure 2.2 C, D). Such high-resolution sediments are useful for examining rapid changes in climate and environment, such as happened during the last glacial termination.

Varves in glacial lake sediments can also shed light on the duration of a glacial lake's existence. Modern glacial lakes are very variable in age. At modern, rapidly retreating ice margins, ice-dammed lakes can appear, expand, and then drain completely in less than ten years (e.g. Rick et al., 2022). This timescale order is likely to apply to many smaller former lakes, as minor shifts in the margin are likely to have resulted in new outflows opening. However, some lakes can persist over 100s and even 1,000s of years. Attempts have been made to estimate the duration of just two ice-dammed palaeolakes, using the record of varved sediments. Charlesworth (1938) counted 137 varves from glaciolacustrine sediments associated with Palaeolake Lagan (H), which formed in inner Belfast Lough and the Lagan Valley during the latter stages of ice retreat across Ireland, dammed by ice from Scotland. However, it is unclear how much of the glaciolacustrine deposit was exposed, so this is a minimum estimate.

In central Ireland, varve counts for Palaeolake Riada (P) from sites west of the River Shannon give a minimum age of 262 years for the palaeolake's existence (Delaney, 2007 and unpublished data). As the varve sites are located close to the most westerly, and youngest, ice margin position, this is a minimum estimate of the lake duration and, given the extent of the lake to the east, suggests that a duration of more than 1,000 years is not unlikely. Similar extensive lowland lakes are also likely to have existed for several 100 years.

The longest varved record comes from modern Lough Nagirra at Tory Hill, Co. Limerick (34), where partly varved glacial lake silt and clay underlies Late-Glacial and Holocene lake sediments (O'Connell et al., 1999). Counting of varved clays, combined with interpolation of the sediment accumulation rate for unlaminated sections, indicates that cold conditions continued at the site for c. 1,870 years after ice was initially removed from the basin.

DISTRIBUTION OF PALAEOLAKES

Ice-dammed lakes from the last glaciation (and probably older glaciations) formed in a wide variety of settings (Figure 2.3). A division is made here into upland and lowland lakes, as these tend to have somewhat different characteristics. However, in reality, a continuum exists, depending on the height and steepness of the bedrock against which the lake was dammed. Where the ground rose steeply and reached significant heights, relatively small, deep lakes formed that rapidly changed configuration and dropped in level as minor ice margin retreat allowed water to escape. Where the ground surface sloped gently toward the ice margin, then larger, but shallower, lakes formed that existed for longer periods.

Upland ice-dammed lakes generally formed in relation to regional ice retreat away from higher ground, rather than the recession of local glaciers that originated within the upland area. This is because local glaciers receded to higher areas, whereas regional ice retreated downslope, damming water between the ice margin and the bedrock. For many upland areas, the result was the damming of multiple small lakes in valleys and lower areas within the upland area. These lakes tended to evolve rapidly as the ice retreated and new outlet routes were exposed, dropping in height and merging with adjacent lakes. Evidence for such lakes has been found around the Antrim Plateau (A-H on Figure 2.3), the Sperrin Mountains (J, K), the Mourne Mountains and Cooley Peninsula (L, M), Wicklow Mountains (Q), the Keeper Hills (S), and associated Devils Bit Ridge (R), and on the northern margin of the Galtee Mountains (U), but similar lakes almost certainly formed around other mountains and hills, especially where upland ridges were elongated across the path of ice flow.

A particularly large cluster of such lakes occurred during ice retreat from the Sperrin Mountains in Cos. Tyrone and Londonderry (J; Charlesworth, 1921; Dardis, 1986a; McCarron, 2013). This is because, during the last deglaciation, the ice retreated from both the northwest and southeast side of the mountains. Initially, the entire upland area was covered by ice. Ice retreated more quickly on the northern side first, so that lakes formed on the southern side of the watershed and drained north and northwestward across the cols (saddle between two ridges), leaving delta terraces and outflow channels suspended above the modern drainage system when the ice retreated. As ice thinned vertically, these lakes merged into larger lakes to the north and south of the mountains, the largest of which was probably Palaeolake Gortin (K), which covered almost 52 km^2 and was over 150 m deep (Charlesworth, 1921). As the ice receded into lowland areas the ice cap broke down into multiple separate domes, damming more water, although the exact configuration of the lake is unknown. Today, the only lake in the area is the 0.47 km2 Lough Fea (8).

One of the largest examples of a lake dammed against an upland massif (or group of mountains) is Palaeolake Blessington (Q; Charlesworth, 1928; Farrington, 1934; 1957, Synge et al., 1975; Warren, 1993; Philcox, 2019). This palaeolake formed in the upper part of the Liffey valley in the Blessington basin, in and around the area occupied by the modern Blessington Lake (31; currently dammed at a lower level than the original glacial lake by the Pollaphuca dam), as ice retreated from the western and northern slopes of the Wicklow massif.

The outflows from Palaeolake Blessington lie south of the modern outlet from the Blessington Reservoir at Pollaphuca and consist of a group of meltwater channels around Hollywood, West Wicklow. Some of these meltwater channels have undulating long profiles, indicating that initially, water flowed out of the lake through the ice sheet, flowing upslope across the underlying bedrock, under pressure from the weight of ice above (Farrington and Mitchell, 1973; Synge et al., 1975). As the ice sheet thinned, channels developed at lower levels down the hillside, forming between the ice margin and the bedrock. In modern glacial systems, lakes with similar subglacial outlets often drain suddenly, as the ice dam tends to lift when water pressure against it is higher, releasing water in an outburst flood (e.g. Roberts et al., 2005). South of Palaeolake Blessington, coarse gravels exposed at the base of the Whitestown terrace are thought to have been deposited by these outburst floods (Farrington and Mitchell, 1973; Philcox, 2019).

Lowland ice-dammed lakes were widespread during retreat of the last ice sheet and included the largest palaeolakes by area, although many much smaller lakes also existed. These lakes developed in relatively shallow depressions, many of which were probably pre-glacial in origin, but were modified by glacial erosion during the Quaternary. The largest known examples include Palaeolake Newcastlewest in Co. Limerick (V), Palaeolake Mulmontry in Co. Wexford (T), Palaeolake Riada, which extended across parts of Counties Offaly, Westmeath, Tipperary and Longford and included modern Loughs Sheelin (19), Derravaragh, Owel, Ennell, Ree (21-24 on Figure 2.3) and part of Derg (27) and areas between (P), Palaeolake Summerhill in Co. Meath (O), and Palaeolake Neagh (I), whose surface lay approximately 30 m above modern Lough Neagh (Dardis, 1986b). Other large modern lakes, including Corrib, Mask (26) and the upper and lower Lough Ernes (10), are also likely to have been larger during the last glacial period.

Where detailed mapping has been undertaken, many smaller lakes have also been identified. For example, Meehan (1999) has mapped multiple small lakes in Cos. Meath and Cavan, that shifted position and drained as the ice margin retreated downslope to the northwest (N).

The largest of the ice-contact lakes was Palaeolake Riada, which reached over 2,300 km2 in size (P; Figure 2.3) greatly exceeding Ireland's largest modern lake, Lough Neagh, at 383 km2 (see Chapter 12). The westward and north-westward retreat of ice across the Irish midlands north of the Slieve Bloom massif caused damming of meltwater between the ice margin, the Slieve Blooms, and the rising topography to the east prevented water from escaping. The lake outflow position changed as the ice margin retreated northwest and west toward the Shannon River. Initially, the lake drained eastward into the Barrow catchment, but then the outflow switched to the northern end of the Inny River catchment between Derravaragh and Lene

(21, 20), draining into the Boyne catchment. Finally, as ice retreated west beyond the western margin of the Slieve Bloom mountains, the lake drained into the lower Shannon through an outlet south of Nenagh, Co. Tipperary. As ice retreated west, the modern drainage path through the Shannon Gorge at the base of Lough Derg (27) was established. This gorge may have initially formed subglacially and been subsequently modified by glacial meltwater discharge or may date from earlier glaciations.

EROSIONAL GLACIAL LAKES

Subglacial erosion has played an important part in creating lake basins in Ireland. The largest lake basins, including Neagh, Upper and Lower Erne (10), Ree (24), Derg (27), Corrib (26), and Owel and Ennell (22, 23; Figures 2.3, 2.7), are all thought to have been partly eroded by glaciers and contain evidence of glacial action, including rock drumlins, channels and overdeepenings in their bed. However, many much smaller lakes on bedrock throughout Ireland also owe their origin to glacial erosion. This is because the processes of glacial erosion tend to create an irregular surface, even where the topography is relatively flat. Minor irregularities, often reflecting bedrock structures such as bedding planes, cause minor changes in subglacial pressure as ice moves across the landscape, and this, in turn, leads to variable erosion and the creation of ridges and hollows. The hollows then become areas of low pressure where water tends to accumulate beneath the ice, enhancing weathering and breakdown of bedrock. The resulting basins vary considerably in size, depending on the interaction between ice and variable bedrock lithology. Very small lakes are widespread on areas of formerly glaciated bedrock known as knock-and-lochan topography. Examples include the lakes explored by Fossitt (1994) and Watson et al. (2010) in Co. Donegal, Loughs Mullaghalan and Altar Lough (2, 3), and Lough Nadourcan (4) which contain glacial lake sediments deposited before 14,500-13,100 BP, indicating that they filled with water as ice retreated. Many examples of similar lake basins exist.

In mountainous areas, larger glacial erosion features such as corries and glacial troughs are thought to have formed over several glacial cycles and the lakes that presently occur in these features have likely reformed in multiple interglacials, of which the modern lakes in these basins are just the latest examples. Different types of basins, including some compound forms, are described below.

Cirque lakes

In mountainous areas during glaciations, snow accumulates in depressions on north- and east-facing slopes, where it is protected from solar radiation. Melting and refreezing of the snow enhances the weathering of bedrock below so that depressions expand due to periglacial frost action. As these depressions deepen, the perennial snow infill thickens and is transformed into ice, eventually deforming under its own weight and moving, becoming a glacier. These glaciers erode by quarrying and plucking bedrock; the rotational movement of the ice body within the hollow causes overdeepening of the hollow and forms a rock lip at the ice terminus where erosion is reduced, forming the amphitheatre morphology characteristic of cirques (or corries, as they are termed in Ireland; Figure 2.7A). There are hundreds of such corries in the Irish mountains (Geological Survey of Ireland, 2021), many of which contain lakes, or wetland areas underlain by lake sediments. Well-known examples include Callee and Alohart in the Macgillycuddy's Reeks, Co. Kerry (38, 39); Coumshingaun in the Comeragh Mountains, Co. Waterford (35), Curra and Muskry in the Galtee Mountains, Co. Tipperary (32, 33), Bellawaum in the Mweelrea Mountains (17; Figure 2.7), Glenawough and Loch na Deirce Móire in the Partry Mountains (15, 16), and Acorrymore on Achill Island, Co. Mayo (13), Belshade in the Bluestack Mountains and Feeane in the Derryveagh Mountains, Co. Donegal (7, 5), Shannagh in the Mourne Mountains, Co. Down (9), and Ouler and Nahanagan in the Wicklow Mountains (28, 29).

Dating of the most recent phase of lake formation relies on two approaches: dating the moraines damming the lake, which formed during the last stage of glaciation; and dating sediments deposited within the lakes, which can give the age of lake formation after ice left the basin. Such dates do not give the age at which the corrie started to form, but rather the end of the last phase of glacial activity. Dating of glacial moraines commonly relies on surface exposure dating of glacial boulders on the moraines, using terrestrial cosmogenic nuclides such as 10Be or 36Cl, produced within crystals in the rock by exposure to cosmic rays (see Davies, 2023 for further explanation). The concentration of nuclides depends on the duration of exposure to light, so an age can be derived for the uncovering of the boulder. A few corries containing lakes have been dated in Ireland, and indicate that most corries were exposed, and presumably lakes formed, as ice retreated after the most recent glacial maximum. For example, at Lough Alohart in the Macgillycuddy's Reeks, Co. Kerry (39) terrestrial cosmogenic nuclide dates suggest that moraines formed

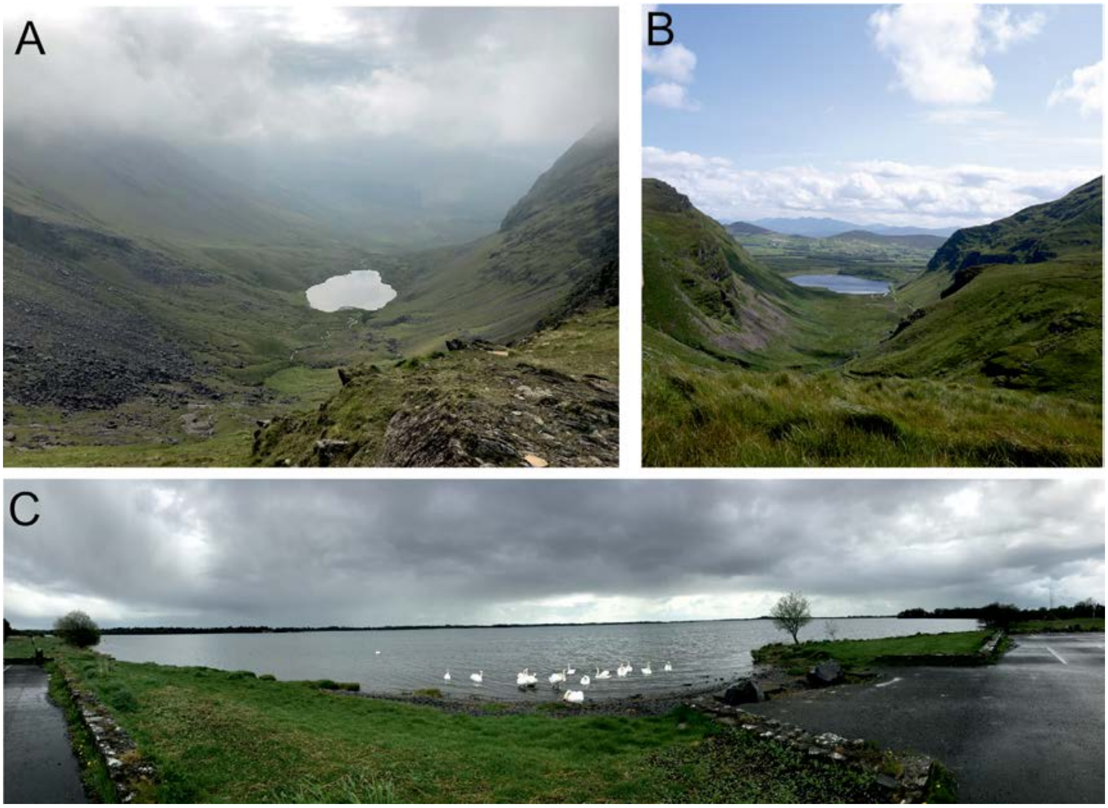


Figure 2.7 Types of erosional glacial lakes. A. Corrie lake: Lough Bellawaum, Mweelrea Mountain, Co. Mayo (17). Photo taken from back wall of corrie. The lake is primarily dammed by the bedrock lip of the corrie beyond the far edge of the lake, on top of which moraines are visible. B. Glacial Trough lake: Lough Annascaul, Dingle Peninsula, Co. Kerry (37), looking south from above the trough. The lake extends to the lowland beyond the glacial trough, where it is dammed by terminal moraines. C. Basin overdeepened by glacial erosion: Lough Ennell, Co. Westmeath (23).

at the mouth of the corrie lake at around 20,400 BP, during the early stages of ice retreat (Barth et al., 2018).

One corrie lake, Lough Nahanagan in Co. Wicklow, is of particular interest as it is the typesite for the Younger Dryas stadial within Ireland, known as the Nahanagan stadial (27; Watts et al., 1977; Colhoun and Synge, 1980). This was a short cold period, lasting c. 1,000 years, that occurred after the initial climate warming at the end of the last glaciation. At Lough Nahanagan, this climate warming led to the melting of ice and formation of a lake in which organic sediments were deposited. After this, a return to cold conditions led to the reforming of a small glacier in the corrie, partly displacing the lake. The ice ploughed up the lake sediments, which were incorporated into small moraine ridges within the corrie. These moraine ridges are visible today because the surface of the lake lies approximately 38 m below its natural elevation, exposed by partial drainage of the lake to drive the turbines of the Turlough hydroelectric power scheme. It is likely that similar moraines and disturbed lake sediment lie within other corrie lakes in upland areas but have not yet been identified.

Glacial trough lakes

During multiple glaciations, selective linear erosion occurred along pre-existing valleys in Ireland, resulting in the creation of glacial troughs (Figure 2.7B). These large valleys commonly have undulating long profiles, as overdeepenings developed where ice discharge through the trough is relatively high, for example at the junction with tributary valleys (Benn and Evans, 2010). As the ice retreated, moraines formed at the glacier terminus, creating further barriers to water movement, and the overdeepenings filled with water, forming elongated lakes. Dramatic, classic examples of such lakes exist in many of the longer glaciated valleys in upland areas. These include Glendalough in the Wicklow Mountains (Upper and Lower lakes; 30), Black Valley/Cummeenduff Glen in the Magillycuddy's Reeks (Reagh and upper and lower parts of Cummeenduff; 40), Kylemore Valley in the Twelve Bens Mountains (Kylemore, Pollacappul and Maladrolaun; 25), Doolough Valley, Mweelrea Mountains (Glenullin, Doo, and Fin; 18), Glenveagh in the Derryveagh mountains (Beagh and Glen; 6), and Silent Valley, Mourne Mountains (L).

Lakes in glacial meltwater features

As the last ice sheet melted it generated a large amount of meltwater, which drained either along the margins of the ice sheet or flowed downward to the ice sheet bed and then toward the margin, flowing under pressure. This pressurized subglacial meltwater cut channels into the ice sheet bed that, on a reverse slope, led upward toward the ice margin, against the slope gradient. Often the path of these subglacial tunnel channels undulated. Today, many such tunnel channels contain small lakes. An exceptionally large example is Lough Derravaragh (21), the southern end of which lies within a tunnel channel which drained subglacially through the Knockeyon chert and limestone ridge.

LAKES FORMED BY GLACIAL DEPOSITS

Many of the lakes lying within corrie and trough basins in mountainous areas of Ireland are dammed partly by glacial moraines, in addition to bedrock. These moraines formed at the glacier terminus at a time when the ice margin was relatively stable. Today many of these moraines do not form a part of the lake dam, as the outflow channel through the moraine has usually cut down to bedrock in the thousands of years since the lake first formed. However, when the ice extended beyond the trough or corrie to lowland areas beyond, very large moraines are often present that continue to form part of the lake barrier. Examples of such lakes include Lough Namona on the Iveragh Peninsula (41) and Lough Annascaul on the Dingle Peninsula (37; Figure 2.7B), both in Co. Kerry.

Other large lakes are partly or fully dammed by glacial deposits, particularly subglacially formed landforms such as ribbed moraines and drumlins. Both these landforms are a major glacial feature of the northern half of the island. Drumlins are small hills (500-4000 m in length, generally around 10 m high) that are elongated parallel to the direction of former ice flow. Ribbed moraine are much larger ridges (up to 70 km long), that are aligned at right angles to the direction of ice flow. The surfaces of ribbed moraine are reshaped into drumlins, so lakes dammed by these ridges often appear to be drumlin-dammed lakes. Lakes where ribbed moraines form part or all of the dams include Loughs Feeagh and Furnace in Co. Mayo (14), dammed by ribbed moraine that form part of the Clew Bay drumlin field, and the complex of lakes that include Loughs Oughter, Corglass, Inchin and Farnham (12) in Co. Cavan. Lakes dammed solely by drumlins are much smaller. An example is the cluster of small lakes north of Drumod, Co. Leitrim, that includes Gubagraffy, Roosky, Cloonturk, Bog and Cloonboniagh Loughs (11). These lakes are all less than 500 m in length.

The smallest lakes in glacial depositional settings are kettle hole lakes that occur in kame-and-kettle topography. Kettle holes form when ice buried within glacial sediments melts, leaving a depression that infills with water, while kames are elevated mounds. Kettle hole lakes occur very commonly in deposits that formed at or near the ice margin, where sediment is often moved onto the glacier surface by upward ice flow, or by water transport, burying the glacier ice, which later melts. The best-known examples are the many very small lakes and ponds found between Curracloe and Blackwater, Co. Wexford, which formed within the Screen Hills kame-and-kettle moraine during the retreat of ice up the Irish Sea Basin. These are almost entirely unnamed and are mostly less than 5000 m^2 in area and less than 100 m in width, although larger examples occur, including Lough Ballyroe, Lough Na Beist and Doo Lough (36; Mitchell, 1950; Heuff, 1984). They are usually steep-sided and can be surprisingly deep; for example, Lough Na Beist is less than 200 m long, but has a maximum depth of 15 m (Heuff, 1984), while cores from Doo Lough show that over 12 m of sediments have infilled the basin since its formation (Mitchell, 1950).

CONCLUSIONS

The history of almost all lakes in Ireland includes a significant phase of glacial activity, and this is reflected in both lake basin morphology, including size, shape, and bathymetry, and the deposits underlying these lakes. The geomorphology and depositional record from these lakes are of considerable use in reconstructing the last glacial period but also mask evidence of the pre-glacial history of many lakes. In many cases, it is difficult to distinguish between the impact of ice and of other erosional processes, particularly in coastal and limestone areas where solution has played a role in lake basin development.

The impact of now-vanished glacial palaeolakes on many aspects of modern Irish landscape development is almost certainly underestimated. In the Irish lowlands, there are many areas where the former existence of glacial lakes is indicated by the presence of blue-grey silt and clay deposits underlying raised bogs, and by sand and gravel mounds underlain by deltaic deposits. Given the extent of raised bogs through the Irish midlands these unmapped lakes may have been very large, on a similar scale to Palaeolake Riada.

These glacial lake deposits have the potential to provide highly detailed information on glacial retreat patterns and meltwater discharge and interactions between the last Irish ice sheet and climate during ice sheet retreat, information that contributes to understanding how modern ice sheets will react to the ongoing climate crisis.

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