PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Records of Sea Levels During the Late Devensian

F. M. Synge

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Records of sea levels during the Late Devensian

By F. M. Synge

Geological Survey of Ireland, 14 Hume Street, Dublin 2, Ireland

Shorelines of both eustatic and isostatic type record sea-level changes over the last hundred thousand years. Marine cut rock platforms at roughly 25–40 m, 6–13 m, and just below mean sea level, appear to represent successive interglacials. Since the culmination of the Last Glaciation, the steady rise of sea level from below −100 m has been punctuated by rapid eustatic surges, notably at 16000–15000, 13000–12000, shortly after 10000, and round about 9000 a B.P.

Retardation of crustal recovery due to ice-loading about 15000–14000 a B.P. in Scotland parallels that which occurred in Scandinavia about 11000–10000 a B.P. In each case a localized transgression of considerable magnitude took place. The ensuing deglaciation resulted in the very rapid phases of uplift that led to the low marine levels recorded at *ca.* 10500 in Scotland, and *ca.* 8000 a B.P. in Scandinavia.

Introduction

Evidence for sea-level change is widespread throughout the coasts of the world. Marine deposits and the traces of former coastlines occur both above and below present sea level. Such changes of level can be explained in three different ways: *eustatic*, in response to the growth or melting of ice sheets; *isostatic*, caused by crustal deformation due to loading or unloading by ice or water; and *tectonic*, as a result of rapid earth movements that displaced crustal blocks.

Eustatic movements, by their very nature, are worldwide, so that theoretically they should provide a reliable basis for correlation. Isostatically and tectonically affected areas are particularly important, as they provide visible evidence of earlier sea-level changes which elsewhere may be drowned beneath the waters of the sea. These movements indicate a gradual general fall of sea level throughout the Quaternary era, but interrupted by temporary and rapid regressions of some 70–100 m during the main glacial episodes. At the outset of the Last Cold Period the level of the oceans started to fall well below its former stand a few metres above their present level. At the time of the greatest expansion of the ice sheets of this period a level of about 100 m below present datum was reached.

With ensuing deglaciation sea level again rose, but because the marginal areas of the great ice sheets did not immediately respond to isostatic rebound, they were submerged. Once crustal rebound gained momentum the formerly drowned peripheral areas started to emerge from the sea. But as sea level continued to rise, some of these marginal areas were again submerged, while new land was emerging rapidly in territory closer to the former ice centres. It has been suggested that this simple pattern has been interrupted at certain times by a very rapid downwarp close to the shrinking margins of decaying ice sheets (Wright 1937). The difficulty of explaining such a phenomenon and, indeed, finding good evidence of it, has led to the general abandonment of this idea. Yet, considerably more evidence has now come to light suggesting that marine transgressions did occur in such areas, quite unrelated to eustatic movements.

Once isostatic recovery was complete or considerably slowed down, the very rapid rise of sea level caused by the final melting of ice sheets all over the world led to a major transgression, which is represented in most places by a very clear shoreline. This event, which coincided with a marked climatic amelioration – the climatic optimum – culminated shortly after 7000 a B.P. and can be used as a convenient termination to the story of sea-level changes outlined in this paper.

Dating methods

Numerous methods have been evolved in order to date the various phases of sea-level change, and thus to establish a reliable chronology. Of these methods that of the radiocarbon (^{14}C) dating of organic material, such as peat or wood, bracketing or embedded within a marine sequence, has proved most effective. Thus a transgression can be dated by establishing the age of the upper layers of the underlying peat and that of the basal layers of the overlying one. But care must be taken to establish the altimetric height of the transgression by measuring the level of the actual shore notch, which could be considerably above the level of the tidal flats on which the upper peat later developed. This method has been used successfully in Britain, Ireland and Scandinavia to date land/sea-level changes during the past 9000 years.

Early archaeological sites can prove useful when they are closely associated with the coastline. But care is necessary to establish the exact level of the sea while the site was used. One ingenious method involves the determination of the phosphatic contamination of the soil caused by effluent from kitchen middens. A sharp lower limit to the contaminated soil fixes precisely the position of high water mark while the midden was being used (Simonsen 1968).

For earlier periods, the date of deglaciation has been established from ^{14}C determinations of marine shells derived from the basal layers of marine sequences deposited in front of a retreating icefront. In a falling sea-level sequence such dates refer to the marine limit. Correlation between age and sea level is particularly exact when the shells occur in clay layers interbedded in fluvio-glacial deltas. Further, the faunal characteristics of the shells may indicate the nature of the climate at the time. Generally the shells are absent from the actual shore deposits, probably because of subsequent weathering. Moraines representing oscillations of the icefront commonly contain lenses and masses of shelly marine clay. In Norway the dating of such shells have been found to date glacial advances and the associated sea level (Andersen 1968; Mangerud 1970). When such datings are incorporated in a shoreline diagram – i.e. a diagram of shoreline heights projected on to a base line running normal to the isobases – a dated uplift curve can be constructed to show the relation between sea level and time at a particular locality.

When it is possible to tie a dated glacial event to a 'varve chronology', the exact duration of ice recession and rate of fall of sea level can be measured in years. In this context it must be noted that a varve represents the annual load of sediment deposited on the sea floor each summer near the edge of the ice sheet. As the ice margin recedes, each annual varve is deposited overlapping that of the year before in the wake of the shrinking ice sheet.

In Greenland, Svalbard and Arctic Canada ^{14}C datings of driftwood and whalebone have proved very effective. It should be noted, however, that certain anomalous dates can be explained through the process of redeposition, either by man or a subsequent transgression of the sea. In Britain and Ireland driftwood does not seem to have survived the ravages of man or the weather from glacial times.

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The oldest shorelines

Such is the effectiveness of glacial erosion that the survival of pre-existing marine features cut in bedrock, such as cliffs and shore platforms, within the areas covered by the Last Glaciation, is not usually expected. Yet in Scotland, in areas exhibiting signs of considerable glacial erosion, a marine cliff and platform with a notch at 25–40 m has survived in the Inner Hebrides (Wright 1937; McCann 1968). These features occur on the west side of areas of high relief, protected from the full force of glaciation from the east. In some cases till overlies the platform.

Much lower cliffs with a platform, or platforms extending from present sea level up to 14 m have a much wider distribution. Such features are specially noticeable outside the limits of the Last Glaciation along the south coasts of England and Ireland. Recently the very well developed platform associated with a cliff notch at 10 m at Oban in Scotland has been considered to belong to a late interglacial phase; the former correlation of this shoreline with the Main Postglacial Beach (Wright 1937) cannot be upheld, as the former tilts westward at a much greater gradient (0.15 m/km) than the latter (0.07 m/km), according to detailed levelling (Gray 1974*a*). The freshness of this feature, and its accordance in level with a buried gravel beach in the Forth dated about 10500 B.P., suggest that it may have formed during cold conditions prevailing during the last advance of the Scottish glaciers between 10800 and 10300 a B.P. (Sissons 1974). On the other hand the short time available for its formation, and the presence of ice moulding and striae that predated the latest advance of the glaciers, on the platform, argue for a much earlier age (Synge 1966; Gray 1974*a*).

The glacial shorelines

Many of the shorelines associated with deglaciation tend to be poorly developed compared to those of the present day, because of the short time available for their formation. Certain ones, however, stand out more clearly; either because they mark significant stillstands of sea level, or because they represent active transgressional phases. Such shore marks are most clearly developed in soft materials, and only very rarely occur in bedrock. The highest effects of marine wave action – the marine limit – can be represented by a very minor feature that may lie many metres above the highest obvious shoreline. Indeed the presence of marine clay above what was formerly regarded as the marine limit has been documented (Armstrong, Paterson & Browne 1975). The recognition and mapping of such washing limits is common practice in Scandinavia. Such minor features are associated with the upper limit of 'washed drift', represented by a metre thick layer of coarse sand and gravel which blankets the drift. The limit can also be located as the lower limit of channelled ablation moraine, braided channels on deltas, and perched blocks (figures 1 and 2).

These shorelines commonly occur above sharp fresh kettle holes, showing conclusively that the lowest kettle rims do not necessarily denote the marine limit, although they commonly accord with the level of a distinctive shoreline. Also perfectly sharp esker crests may have originally formed beneath sea level, and survive uplift without being bevelled by wave action. In one particular example observed in south Finland uplift was so rapid that the crest of the esker passed through the wave zone of the Baltic in the space of three years (figure 1). This might explain why the drift slopes which we may observe round many reservoirs in Britain today are notched by a clear cliff notch, while no similar feature can be found on the

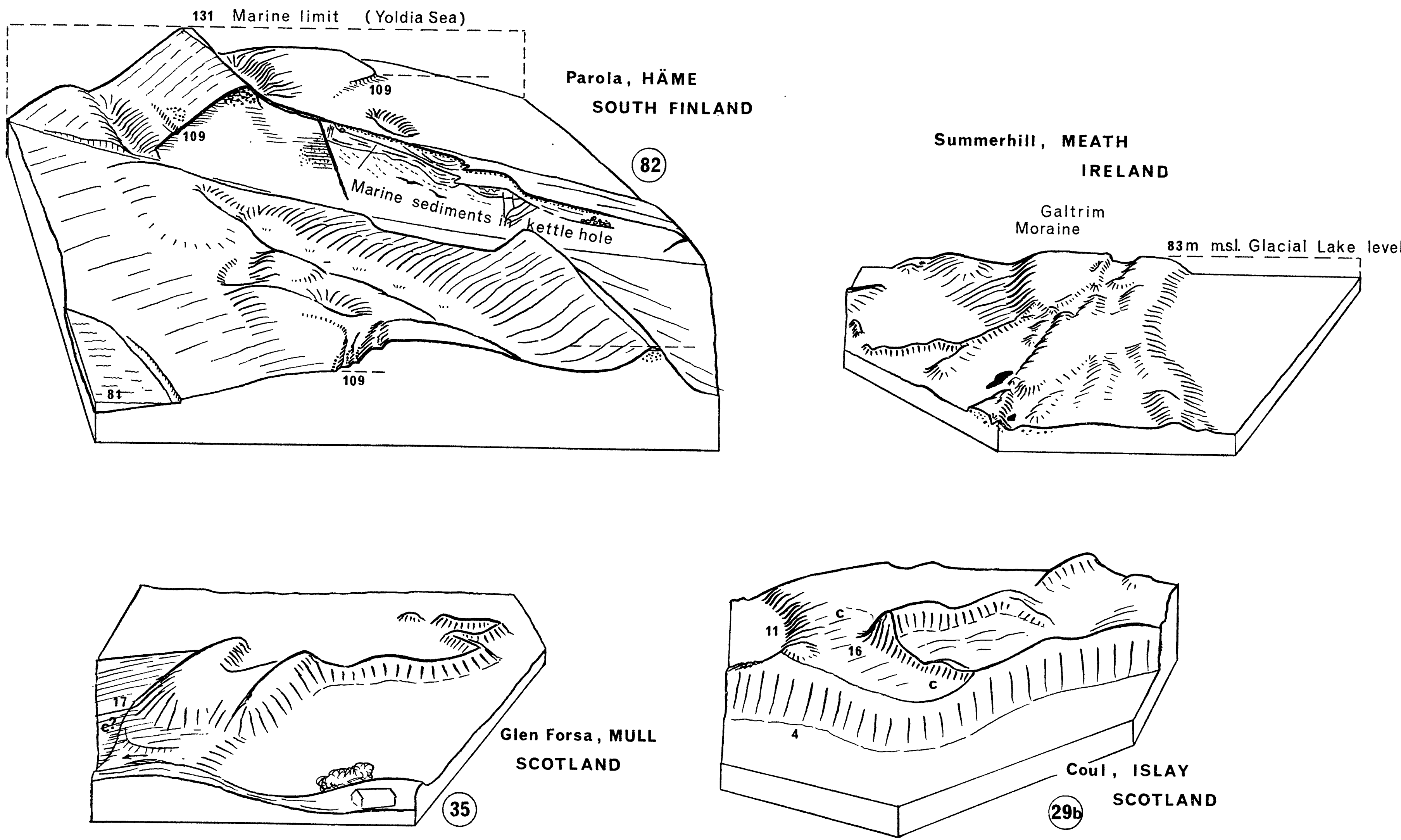

FIGURE 1. Deformation of eskers by wave erosion. Top left (82): parts of the crest of the Hattula esker, in south Finland, are bevelled by wave erosion at the washing limit (131 m). Open kettle holes and sharp drift forms occur below this level because of the continued presence of buried blocks of ice and the rapidity of uplift – namely, about 20 m per century. During the later stand of sea level at 109 m kettle holes were filled with littoral sediments and the drift hillocks were cliffed or removed by wave action (based on field observations by the writer). Top right: typical drift landforms associated with esker terminating in an ice-marginal delta moraine. Bottom left (35): esker truncated by later glacifluvial or marine action in Glen Forsa, Isle of Mull. Bottom right (29b): esker cliffed by wave erosion in an exposed location at the marine limit (16 m) on Islay.

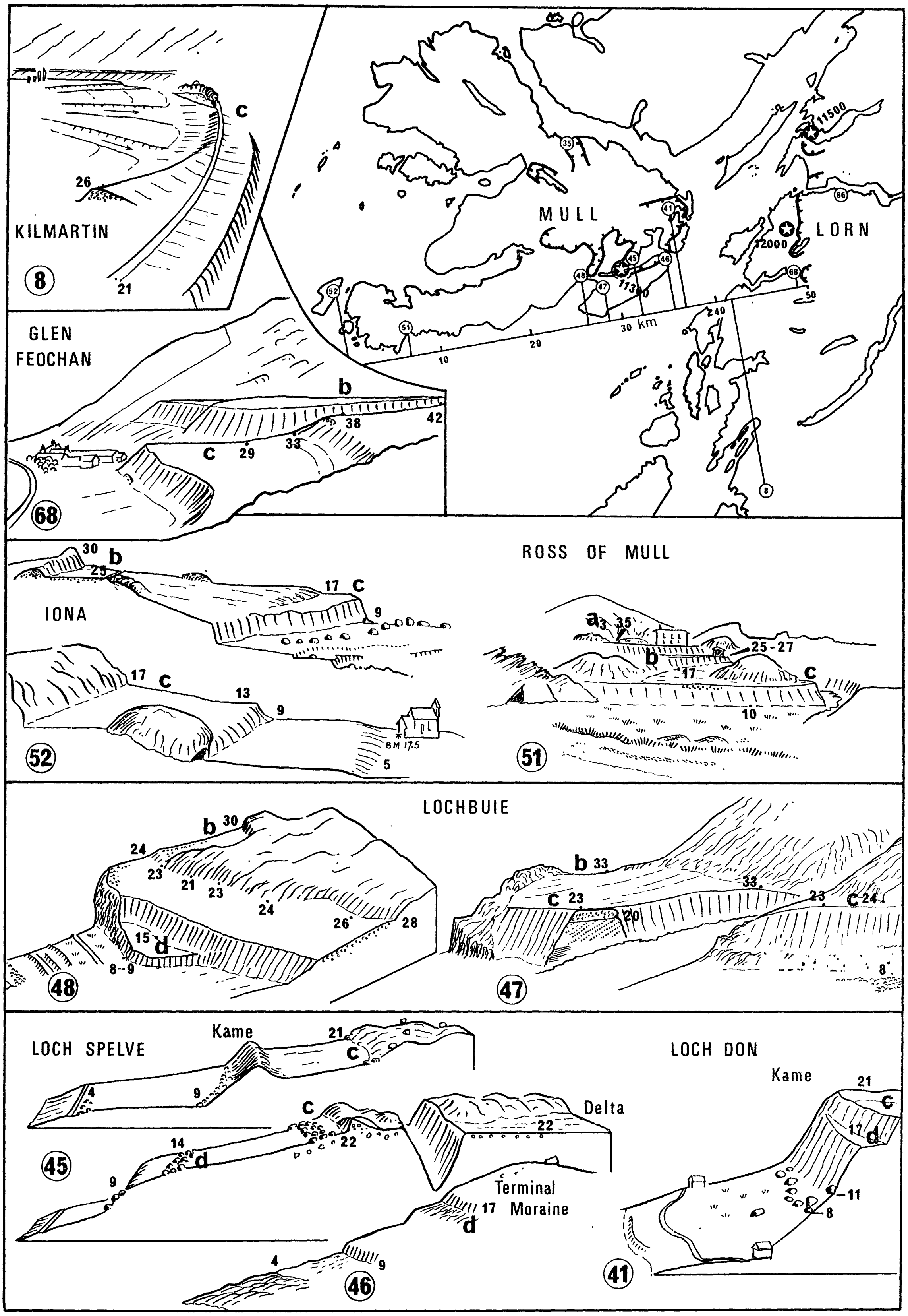

FIGURE 2. Morphological form of the raised shorelines in Mull and Lorn, West Scotland. Level 'b', equivalent to the Main Perth Shoreline, is the most prominent upper shoreline on the Isle of Mull. In exposed locations this feature occurs as a massive terrace or shingle ridge (51, 52); in more sheltered places, as a shelving gravel bench (47, 48); but only as delta deposits close to the mainland ice margin (68). A lower shoreline 'c' can be recognized as an erosional terrace in exposed locations (51, 52), as deltas close to the ice margin (47, 68), as a beach ridge sealing the braided channels on a delta plain (8), but less clearly (?) within the Mull readvance moraines (41, 45). The lowest of this series, 'd', believed equivalent to the Main Late-glacial Shoreline of the Forth, is well developed in the area of the higher isobases, but generally has been removed by subsequent marine erosion (48); and survives as a washing limit within the Mull readvance moraines (?41, 45, 46).

sea coast; clearly the reservoirs have endured for a longer time than many of the glacial sea levels!

Isostatic shorelines may be analysed by plotting them graphically on a height/distance diagram across the isobases. The older ones are invariably tilted more than the younger ones. As the broken nature of most terrain disrupts the continuity of any particular shoreline, some method has to be used to identify different portions of the same feature. This is established by the longitudinal tilt of the shoreline across the isobases. Each particular line will have its own particular tilt. In this way a system of shorelines can be built up. If some are dated, the age of the others can be determined graphically.

The accuracy of a shoreline diagram depends very much on the classification and identity of the features that are levelled. Very often such diagrams are also constructed on the assumption that uplift was regular, without the occurrence of local tilting and block faulting. For this reason some investigators prefer to analyse their data by the 'proportional height' method. According to this principle the main shorelines can be individually identified by their proportional height, one to the other. Thus a shoreline in this kind of diagram is not necessarily drawn to pass through the greatest number of measured points.

Shorelines that can be followed continuously for many kilometres give the best reference levels for determining the true isostatic tilt. The very important work of this nature initiated in the valley of the Forth in Scotland by Sissons underlined the need and value of precise levelling in an estuarine environment. This work, along with detailed stratigraphic information from numerous boreholes, still continues, and provides data for the most comprehensive and reliable dated uplift curve for Scotland (Sissons & Smith 1965).

Ten years ago, following on the work of Donner (1963), efforts were made to assemble the Scottish and Irish data on the glacial raised beaches in a shoreline relation diagram, using new measurements from widely scattered localities in the west of Scotland (Synge & Stephens 1966). Using the Main Postglacial Beach as datum, the older glacial beaches were found to lie in clearly marked zones. Each shoreline zone was related to a particular stage of deglaciation, from the oldest or 'a' series, dating from the time when the ice sheet was very extensive, to the youngest or 'f' series, from the time when the glaciers had already shrunk into the Highland glens of Scotland. At the time considerable doubt was expressed on the value of such diagrams, constructed from such widely scattered points where beach levels were measured approximately.

Although subsequent work round Inverness (Synge 1977), and in Skye (von Weymarn 1970), appears to confirm the correctness of the pattern of beaches identified in that work, certain conclusions appear to be erroneous. The writer's earlier suggestion that the Main Perth Shoreline of Sissons is not a true shoreline is not correct; it now seems apparent that one of the best developed glacial shorelines in the west of Scotland corresponds to that feature. But evidence that this shoreline tilts more steeply in the Forth than in the west of Scotland seems valid.

Another error, which should be corrected, was the assumption that the heights of the Main Postglacial Beach throughout are always in proportion to those of the older beaches. There is now sufficient evidence to show that this is not so.

Owing to the different environmental conditions present in the Forth compared with those in the west of Scotland, there are considerable difficulties in correlating the older shorelines of these two regions. Many of the 'beaches' in the Forth have developed as estuarine infill, so that each successive level only occurs as a prominent feature where glacial outwash merged into the firth (Sissons 1974). The present writer has defined beaches in a different way – i.e. as levels at which wave action was sufficiently prolonged to produce beach bars and cliffs in drift deposits. In this case, therefore, the prominence of any particular beach does not depend on the volume of glacial outwash, but rather depends on the duration of the stand of sea at a particular level.

Along the rocky coasts of the west of Scotland the raised beaches commonly occur as shelving deposits of shingle and gravel between irregular bosses of rock; in such instances the main beach levels may not be represented by either terrace flats or cliff notches, but only by the upper level of infill. In many places the sloping banks of beach material lie against steep rock faces simulating cliff notches (figure 2). Thus levelling such features to determine former stands of sea level requires special techniques.

Some of the above considerations may explain why recent studies in Mull and Lorn have failed to establish any clear pattern of glacial strandlines by a programme of detailed levelling of terrace flats and notches, in spite of the fact that clear evidence of consistent marine levels at '100 feet' and '75 feet' occur in the immediate neighbourhood, according to the observations of Bailey *et al.* (1924). This detailed investigation did, however, establish very accurately the heights and distribution of postglacial shorelines (Gray 1974*b*). The problem of relating sea-level changes to the glacial history of this fascinating area will be discussed later.

In this paper it is hoped to demonstrate the importance of mapping in some detail the morphology of strandline systems on a large scale, in order to establish the levels at which significant stands of the sea occurred. This kind of work was first undertaken in 1967 in the Varanger district of Norway, in collaboration with J. Rose and J. Smith with considerable success. Suitable areas for this kind of work occur also in Scotland, for example beside the Moray Firth from Elgin to Dornoch (Ogilvie 1923) and on the Ayrshire coast. But as yet this type of investigation has not been undertaken.

Sea level during the maximum of the last glaciation

Hitherto sea level during the maximum advance of the ice of the last glaciation has always been assumed to lie at levels well below that of the present time. But there is now some suggestion that this level did not lie far below present sea level. This is suggested by the disposition of the lateral moraine of the Irish Sea glacier along the Irish coast. These morainic deposits descend from 280 m on the Dublin Hills to 150 m some 20 km further south, but thereafter these maintain an upper limit at about 100 m for the next 90 km until the terminal moraine is reached at Kilmorequay on the south coast of Wexford. Such a horizontal ice margin suggests that this part of the glacier was afloat as shelf ice in the southern part of the Irish Sea basin. A similar distribution of glacial till of the same age in east Lincoln suggests an analogous situation in the southern part of the North Sea basin (figure 3).

The youngest marine shell dates of 30000–29000 a B.P. from the younger Irish Sea till on the west coast of Wales (John 1967), and the presence of organic beds dated 30655 and 36340 a B.P. in fluvial sediments beneath the terminal zone of the same till sequence in Staffordshire (Shotton 1967), give a maximal date for the glacial advance. This may suggest that the maximum ice advance in Britain and Ireland occurred some 9000 a before an important second re-advance. The latter is identified by a much more prominent end-moraine with no evidence of a high sea level. At that time the Irish Sea glacier was much less dominant so that the ice failed to extend much beyond the Lleyn Peninsula (Synge 1963).

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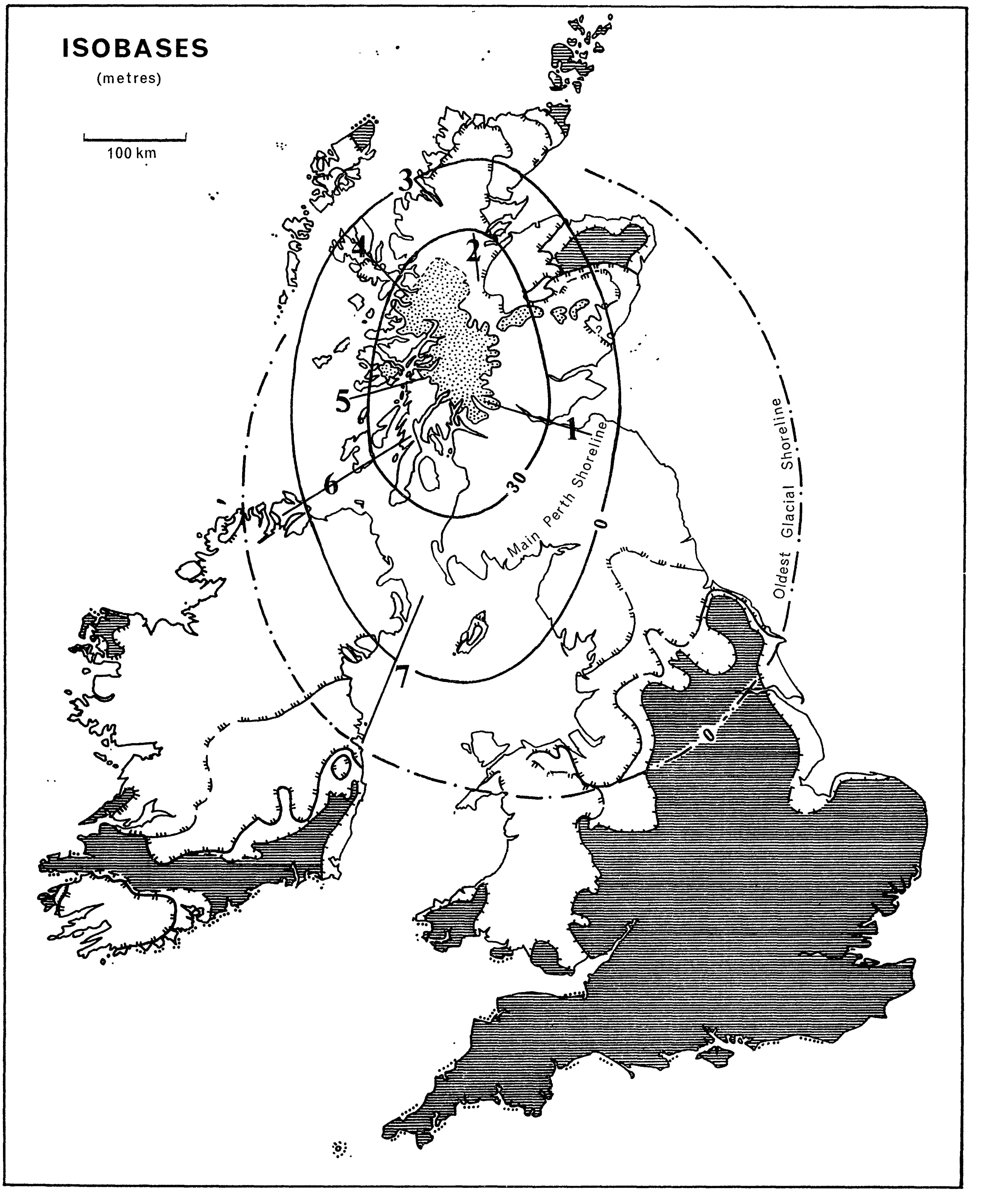

FIGURE 3. Relation between isobases and glacial limits. Unglaciated areas are heavily shaded, while that covered by the ice of the last readvance is stippled. Three isobases are shown: 0 m line of the oldest glacial, or 'a_1' shoreline; 0 m line and 30 m line of the '*b*' or Main Perth Shoreline. Base lines used in the construction of the isobases are numbered 1–7.

Oldest Late-glacial shorelines

The oldest Late-glacial shorelines occur well within the limits of the former ice sheet. The highest and oldest shore marks occur outside the limits of a very clear and prominent end-moraine on the east coast of Ireland – the Drumlin or Dunleer Readvance (McCabe 1973; Stephens, Creighton & Hannon 1975). This shoreline is very clearly displayed on Clogher Head, as a zone of bare rock from which the drift has been removed by wave action up to 19 m m.s.l. To the south the waves scoured a broad platform in drift about 1 km wide. South of the Boyne this shoreline is associated with a gravel beach ridge and cliff notch, that had been traced for 25 km along a gradient of 0.24 m/km.

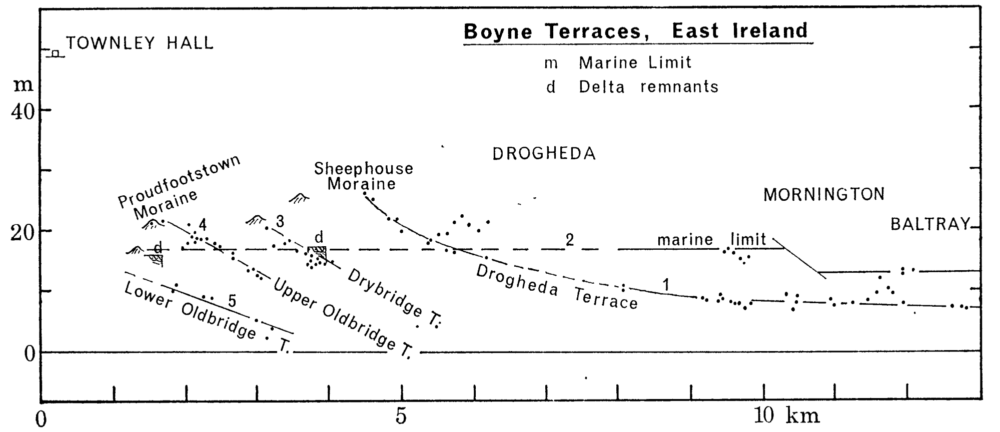

Figure 4. Relation between the oldest glacial shoreline ('a_1') and glacial outwash terraces in the Lower Boyne, Ireland. (1) *The Drogheda terrace*, outwash from the Sheephouse Moraine, deposited when sea level stood at about 7 m m.s.l. (2) *Marine limit* at about 16–17 m m.s.l. represented by the dissected fragments of a large delta between Proudfootstown and Drybridge (d). (3) *Drybridge* outwash terrace, deposited during a time of low sea level. (4) *Upper Oldbridge* outwash terrace. (5) *Lower Oldbridge* terrace, deposited after the area became ice-free.

In the Boyne valley the sea transgressed deltaic outwash by 10 m. This rise of level is represented by fragments of a large delta at 16–18 m m.s.l. constructed as the ice margin shifted some 4 km further upstream. As sea level fell a series of outwash terraces cut down through the former delta surface (figure 4).

Before this transgression occurred, or rather reached its maximum, Irish Sea ice readvanced up the Boyne valley. Glacio-marine deposits containing shells near the limit of this readvance, and originally regarded as a marine sequence *in situ* from an earlier glacial period (Colhoun & McCabe 1973), may in fact have been transported as an erratic at this time. If this is so the age of this transgression could be determined by a radiocarbon date from these shells.

The relation between this transgressive shoreline 'a_1' and those further north cannot be determined exactly. In the diagram the writer suggests that the high Boyne beach is older than the highest one near Carlingford. Both shorelines are truncated by readvance moraines. The older moraines immediately postdate shoreline 'a_1' and correspond with the moraine that encircles the Carlingford Mountains and the Mournes. The same moraine in the Isle of Man is dated as older than 18900 a B.P. This date was obtained from organic material from a kettle hole in the above morainic belt (Shotton & Williams 1971). The probable age of this first Late-glacial transgression is therefore older; probably by a few centuries. The apparent

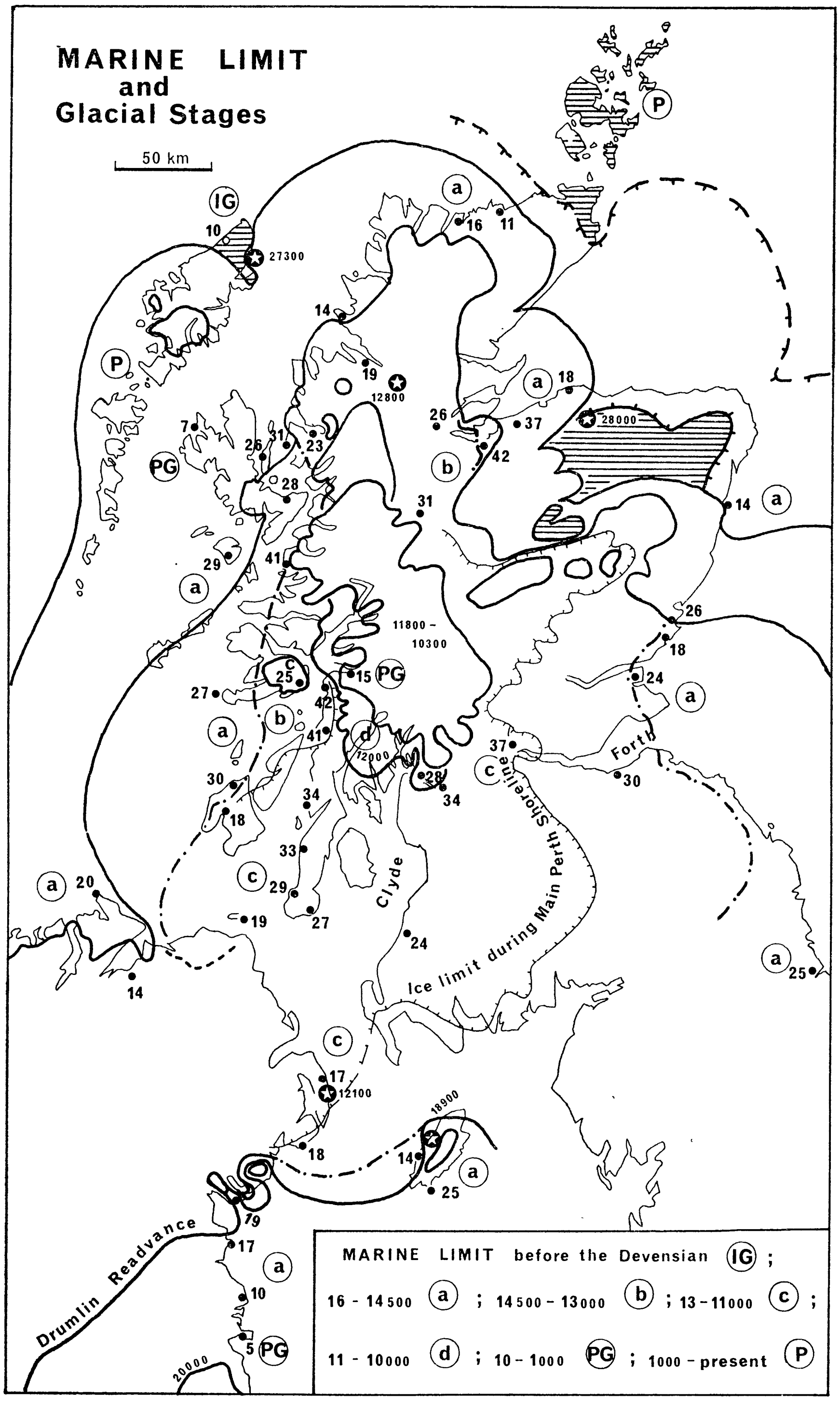

FIGURE 5. Height in metres and approximate age of the marine limit in Scotland and Ireland. The shaded areas (North Lewis, most of Orkney, Buchan and the Cairngorms) are regarded as being ice-free during the Last Glaciation. Star symbols refer to the oldest ^{14}C dated organic horizon at or near the drift surface; those in Scotland are based on Donner (1970) and Sissons (1976). Corrigendum: the number 28000 in the upper right of the figure should read 28100.

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continuation of a marine limit up the east coast of the Isle of Man and into the highest outwash terraces of the Bride moraine would support this view. At Peel the marine limit is 10 m lower, suggesting that ice still lay against the west coast while the east coast was free of ice (figure 5).

The relation between the raised beaches and end-moraines in the northern part of the Irish Sea basin is shown in table 1.

TABLE 1

shorelines	South Louth and Boyne valley, Ireland	Carlingford, Ireland	Isle of Man (terminology after Mitchell 1965)
	Gilltown formation Sea level *low*	Windy Gap Moraine	Orrisdale series (kettle hole open *ca.* 18900)
	Sheephouse moraine; 7–8 m	?	?
a_1	Proudsfootstown delta; 17 m		
		19 m beach	21–5 m washing limit, on east coast
a_2	Dunany Readvance Moraine	Rathcor I/ Cooley Pt. Moraine	Jurby Ridge and Upper Ballateare till
	10 m beach	Rathcor II/ Cooley Pt. Moraine; 13 m beach	Crawyn sand plain and 15 m beach
a_3	Port beach 8 m	Greenore Moraine; 10–11 m beach	14 m marine limit at Peel

The highest beach, 'a_1', also seems to occur in northern England, where it has been noted at 25 m round the Tees estuary (Agar 1954). Near Liverpool a marine limit has been recorded at *ca.* 5 m as the 'Hillhouse shoreline' (Gresswell 1957) and originally regarded as postglacial; but now proved much older (Tooley 1974). In Inishowen in north Donegal the marine limit is very prominent, typified by large ridges of shingle up to 22 m m.s.l.; the bedding in these ridges has been heavily disturbed by frost-heaving (Stephens & Synge 1965).

Closely spaced ice-marginal stages, each associated with a particular outwash terrace and beach terrace, typify the withdrawal of the ice from the important Drumlin or Dunany Readvance limit (figure 3). Analogous ice-marginal sequences were noted at Carlingford and Inishowen in Ireland; at the north end of the Isle of Man; and in East Fife and Inverness in Scotland.

THE PERTH SHORELINES – 'B' SERIES

Before 14000 a B.P. deglaciation appears to have occurred with great rapidity, particularly in the east of Scotland. This is apparent because of the presence of high level marine clays at 40–46 m near Crieff some 5–6 m above the very prominent Main Perth Shoreline, believed to have been formed about 13500–13000 a B.P. This suggests that isostatic response was at first slow, but then increased until it was again checked, possibly by an ice mass lingering in the Western Highlands and the Lower Clyde. During the ensuing transgression the decaying ice sheet still completely filled the North Channel and Firth of Clyde.

Such a prominent feature as the Main Perth Shoreline, which is tilted at 0.43 m/km in the Forth, should be recognizable throughout Scotland. The very manner in which it terminates

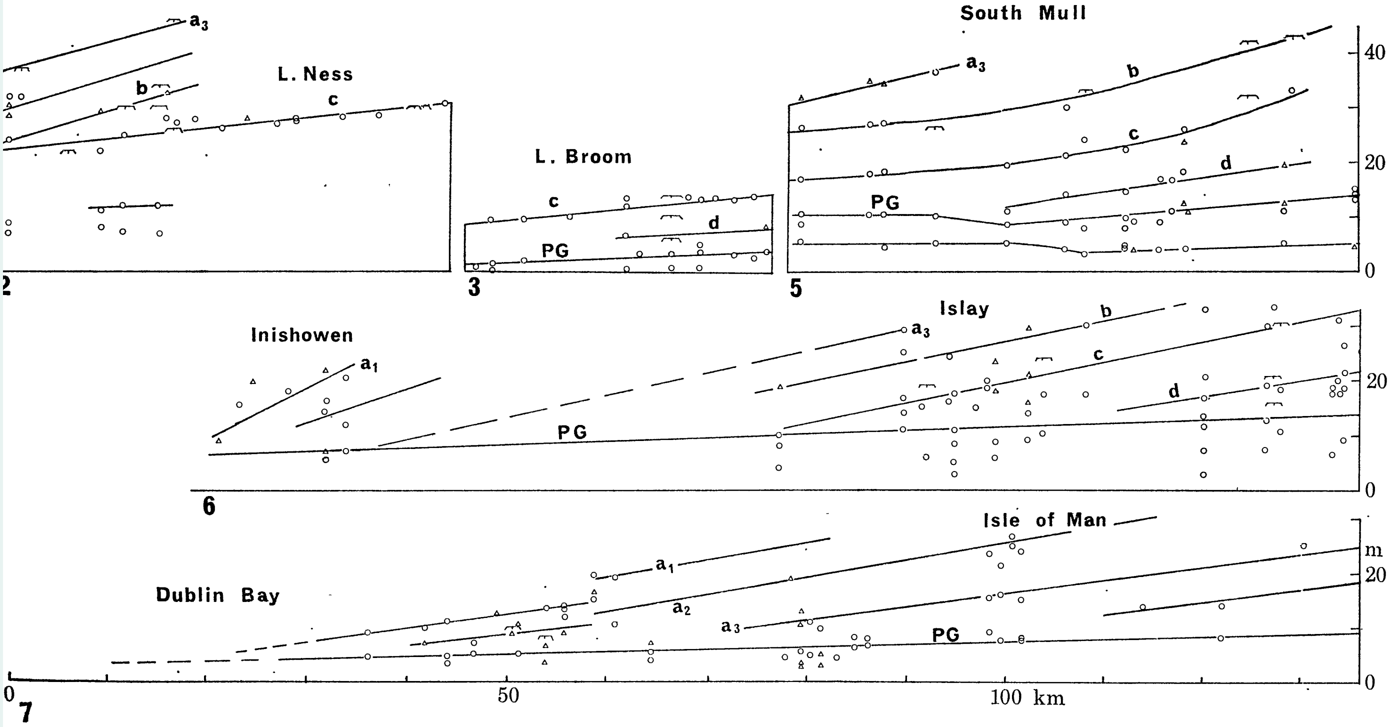

FIGURE 6. Shoreline diagrams from base lines 2, 3, 5, 6 and 7 in figure 3. The main reference levels are 'a_1' (Highest Glacial Shoreline), 'b' (Main Perth Shoreline) and 'PG' (highest Postglacial shorelines). The diagrams 2 and 7 are based on instrumental levellings; those numbered 3, 5, 6 are based on the hand-levelled data in Synge & Stephens 1966. In the diagrams, circles indicate shore notches; and triangles indicate beach ridges.

TABLE 2

	Ullapool	Coul, Islay	Inverness	Iona	Oban	(Sissons 1974) Plean, Forth
'b'	—	29 m, 0.23 m/km	—	25 m, 0.22 m/km	43 m, 0.75 m/km	35 m, 0.43 m/km Main Perth Shoreline
'c'	15 m, 0.15 m/km	—	24 m, 0.13 m/km	—	—	—
PG	5 m, 0.06 m/km	8 m, 0.03 m/km	10 m, ?	10 m, 0.07 m/km	13 m, 0.07 m/km	13 m, 0.08 m/ km Main Postglacial Shoreline

at the head of the Forth in a large fluvioglacial delta, that precedes a sudden drop of the marine limit by about 20 m at Stirling, should make identification easy. This supposition would seem to be correct; in many parts of the west of Scotland the only well developed shoreline above that of the Main Postglacial level would appear to be this very feature.

Previously the writer failed to make such a correlation because no allowance was made for variations in tilt from area to area. This is because isobases are not everywhere the same distance apart from one another. Once these clear upper shorelines are regarded as one and the same feature, a convincing isobase map could be constructed, which clearly shows that the focus of the ice cap was now shifting to the Western Highlands from a position further south (figures 3 and 6) (table 2).

Sea level between 13000 and 11800 a B.P.

After the sea receded from the Main Perth Shoreline lower shorelines were formed. The remnants of the former ice sheet melted rapidly in the Firth of Clyde, as the centre of dispersal shifted to the Western Highlands. At the same time waters with a boreal fauna were displacing the ice in the firth, as the marine limit was steadily falling owing to isostatic rebound. By 12600 B.P. the entire firth was ice-free, as shown by the presence of a shelly fauna in the marine clays of the Glasgow basin (Peacock 1971), associated with the marine limit at 34 m (Rose 1975). Generally it has been assumed that the sea connection was through the Lochwinnoch Gap, with a clearance of only a few metres. This seems most unlikely, for the obvious access route would have been up the Clyde. Therefore it is suggested that the upper red till further downstream represents a readvance of the L. Lomond glacier that later cut off the sea connection. This event could have occurred shortly before 11800 a B.P., the age of the shelly marine clay associated with a marine limit of 28 m along this part of the Clyde.

The transgressive nature of shoreline 'c' is clearly demonstrated in the Ness valley near Inverness, where the sea flooded open kettle holes. These are readily distinguished from those at higher levels by their less abrupt contours. The same shoreline also cut across the lower end of a fluvial terrace that was formed by the outlet of the youngest Glacial L. Ness; in this case the Ness river was graded to a level below that of Shoreline 'c'.

Although no obvious moraines are associated with the readvance postulated above, the sudden drop of the marine limit observed further west, in Loch Long, Glendaruel and near Otter Ferry in Loch Fyne suggests a significant halt of the ice margin (Sissons 1974). Barnacles *in situ* at 20.5 m at Glen Cruitten, dated *ca.* 12000 B.P. (Shotton & Williams 1973) pre-date a similar drop in level at Oban.

Sea level between 11800 and 10800 a B.P.

At this time, roughly corresponding to the milder climatic conditions represented by Pollen Zone II, or Allerød period, the significant *Shoreline 'd'* was formed. Near Oban it was observed as a clear notch on the distal side of a morainic deposit at 19–21 m. Previously the writer claimed that a higher shore – the equivalent of Bailey's '75 foot' level on Mull – occurred within the limits of the glacial readvance so clearly visible on that island (Synge 1966), as washing limits. The subsequent dating of marine shells collected from the terminal moraine at Kinlochspelve to *ca.* 11300 a B.P. was believed to prove that the readvance occurred during the Late-glacial climatic deterioration, *ca.* 10800–10300 a B.P. (Gray & Brooks 1972). As sea level during this latter period was below 15 m the presence of higher raised beaches of this date is impossible.

Critical examination of the evidence suggests alternative explanations. For example, the terminal moraines on Mull are quite unlike their supposed counterparts on the mainland. Instead of producing large outwash fans graded to a low sea level, they straddle their respective valleys – L. Don, L. Spelve and L. Bà – as narrow steep-sided ridges, rather typical of subaquatic moraines. Also, it should be noted, that the L. Don moraine is composed of sand, not gravel or till and blocks. Evidence of higher sea levels – 'b' level at 30–35 m and 'c' level at 21–25 m – lie immediately adjacent to these moraines, unlike those of the mainland bordering Loch Linnhe and the Firth of Lorn.

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Bailey considered that the L. Don moraine was formed while the sea still stood at the 23 m ('75 foot') level, because the outer face of this feature is notched at that level. Gray (1975) confirmed the presence of a bench or notch beneath thick peat, but did not offer any explanation as to its origin. The writer also visited Wright's classical site in Glen Forsa, where an esker was interpreted as terminating in a fan that extends down to the level of the Main Postglacial Shoreline. This evidence shows that sea level was already low while ice still stood in the glen. Gray (1975) confirmed the fan form of the feature below the esker and pointed out the channels developed on its surface.

Although the writer would accept the idea that dead ice lingered in the glen as sea level fell, he points out that the notch cutting across the end of the esker at *ca.* 17 m (not 23 m as previously stated (Synge 1966)) is quite atypical of esker fans. Furthermore, the coincidence of this level with that of the 'c' shoreline is striking. This evidence, coupled with identification of an upper washing limit at a comparable level in L. Don and L. Spelve, suggests that after the readvance the ice cap went dead, and the glaciers occupying the sea lochs melted away very rapidly before sea level fell. As uplift continued dead ice remained in the valleys for a long time.

Additional evidence of the presence of the sea at the 'c' level during the advance of the Mull glaciers is furnished by the occurrence of fluvioglacial delta bedding adjoining the moraine at Kinlochspelve. Bailey attributed this to the presence of an ice-dammed lake on the site of the present L. Uisg, although no outlet channel was named. The level of this feature appears to be so close to that of the L. Spelve washing limits that the sea, rather than a lake, most probably occupied the valley at the time.

The ^{14}C dates obtained from marine shells caught up in the readvance moraines of the mainland valleys are all grouped around 11800 a B.P. (Peacock 1971). Therefore the readvance cannot have occurred before that date, but was it much later? Although the palynological and radiocarbon record points to a major readvance between 10800 and 10300 a B.P., the occurrence of other earlier ones remain a possibility. The total absence of dates between 11800 or 11300 and 10800 a B.P. is striking. This suggests that, between those dates, a marine fauna was unable to enter the inner sea lochs. This can best be explained by the continued presence of glacier ice.

The above situation exactly parallels that experienced in North Norway. Here, within the terminal zone of the Late-glacial readvance moraines, earlier ones beneath the moraines have been dated 11800 and 11300 a B.P., the very same dates that were obtained in connection with the moraines mentioned above. This indeed suggests that the milder conditions of the Allerød period was reflected by an increase in precipitation of snow in the West Highlands. This caused a rapid build up of snowfields which caused an advance of the mainland glaciers *ca.* 11800 a B.P. and a maximum advance of the Mull glaciers *ca.* 11300 a B.P. During the later colder conditions between 10800 and 10300 a B.P., the mainland glaciers advanced further than before, and built their outwash into a much lower sea level. Further east the drier and warmer summers of the Allerød was unfavourable to the survival of glaciers (Sissons 1974).

The suggested correlation between sea-level change and glacial advance is suggested in table 3.

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Table 3

	Lorn	SE Mull	L. Lomond	
'b'	41–45 m outwash deltas			13000 B.P.
	?		34 m readvance max.	12000
'c'	first advance		28 m second advance	11800
	28–33 m Oban Moraine	20–24 m readvance		11300
'd'	18–20 m	15–16 m		10500
	12–14 m L. Etive Moraines		main readvance	10800/ 10300

Sea level during the Loch Lomond Readvance, between 10800 and 10300 a B.P.

In the Forth, deposits of a gravel beach beneath postglacial estuarine muds and peats denote a stable phase of marine activity at *ca.* 10500 a B.P. (Sissons 1974). This beach, now named the Main Late-glacial Shoreline, has been identified with the rock-cut cliff and main rock platform standing at 10 m at Oban. Reasons have already been given to suggest that the low level rock-cut shore features were originally fashioned much earlier (Gray 1974*a*).

At a few places near Oban, a very well developed shoreline cut in drift was observed some 5–6 m above the Main Postglacial Shoreline. In most localities this beach had been destroyed by later marine erosion. The clarity of this feature – shoreline 'd' according to the writer's classification – as the only obvious raised shore above the level of the postglacial series, suggests that it may be the correlative of the buried gravel layer of the Forth. This beach appears to correspond with Gray's LS2 line, inclined at 0.3 m/km, the only obvious zone of shore marks observed above the postglacial series near Oban (Gray 1974*b*).

Sea level after the Loch Lomond Readvance

Because of the general low sea levels recorded after the last significant advance of the glaciers, little information is available for the thousand or so years after 10300 a B.P. In the Forth a transgression has been recorded, for outwash from the Menteith Moraine is overlain by marine silt at 12 m, some 7 m above the estimated level of the buried gravel layer. Afterwards the level of the sea fell.

Conclusion

This investigation of sea-level change throughout the Last Cold Period has shown at least four phases of stillstand. If the data from Great Britain and Ireland are plotted on time/elevation graphs, and compared with graphs from Finland, Norway, Svalbard and Arctic Canada against a standard eustatic curve, the shorelines caused by significant rises of the oceans can be isolated (figure 7). Three of these appear to be eustatic, 'a_3' at *ca.* 16000–15000 a B.P.; 'c' at *ca.* 11800–11300 a B.P. (Allerød interval); and 'd' at *ca.* 10500 a B.P. (Late-glacial).

Very significantly the 'b' shoreline (Main Perth) is not eustatic, but represents an ice marginal downwarp that postdated the Drumlin Readvance of Ireland, in much the same way that Portlandia transgressions in Scandinavia followed the Late-glacial Readvance. According

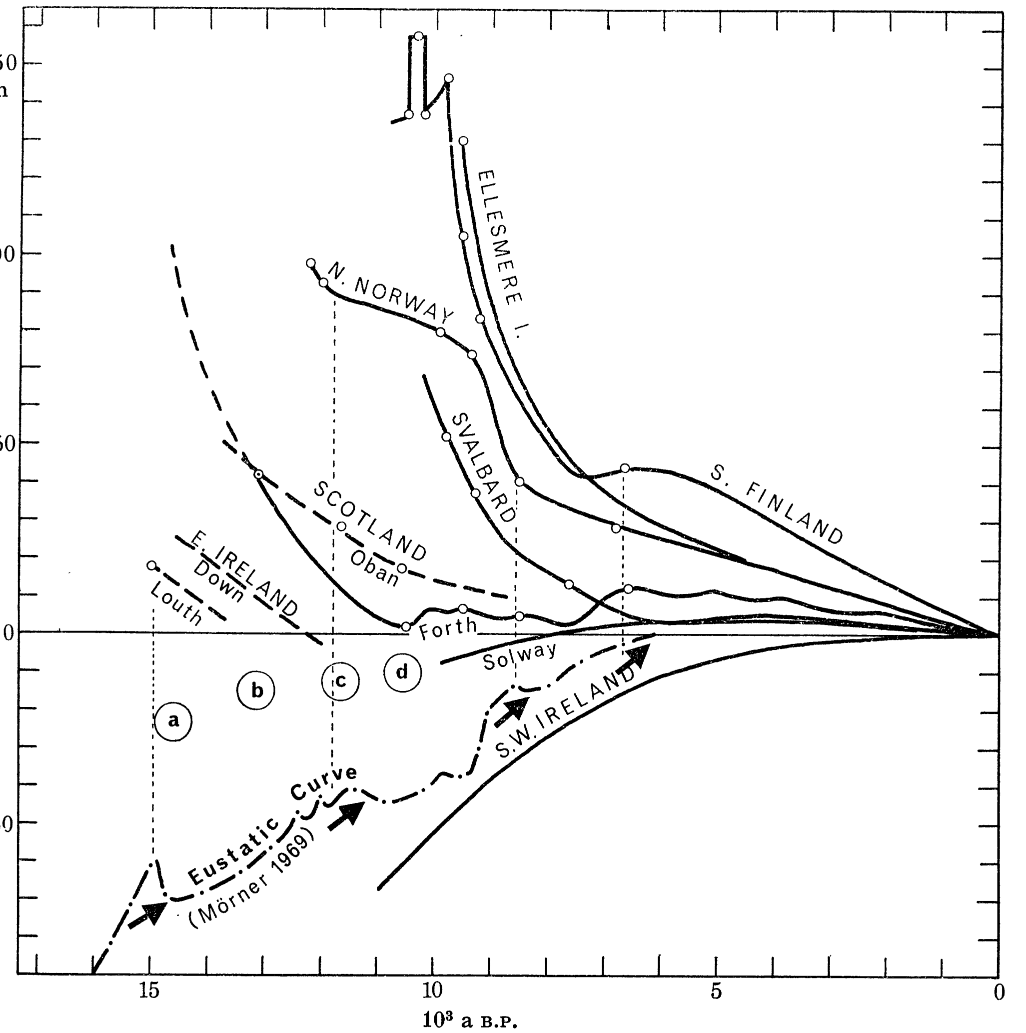

FIGURE 7. Time-elevation diagrams for stations round the North Atlantic. For comparison, Mörner's 1969 eustatic curve has been added. Data for *Ellesmere Island*, Arctic Canada, from Blake 1975; for *south Finland*, from the writer's field observations in association with Donner 1964; for *North Norway*, from the writer's field observations in association with Andersen 1968; for *Svalbard*, from Feyling-Hanssen & Olsson 1959; for *Scotland*, the *Forth* from Sissons 1974; *Oban* and *Lorn*, from the writer's field observations; the *Solway*, from Jardine 1975; and for *Ireland*, *Down*, from Synge & Stephens 1966; *Louth* from the writer's observations; and *south west Ireland* from Stillman 1968. The main eustatic surges coincide with shorelines 'a_1' (Highest Glacial Shoreline) at *ca.* 15000 a B.P. and 'c' at *ca.* 12000 a B.P. Shorelines 'b' (Main Perth Shoreline), 13500–13000 a B.P., and 'd' (Main Late-glacial) *ca.* 10500 a B.P. in Scotland seem to be isostatically controlled. Likewise retardation of uplift, and even downwarping, has produced significant shorelines at *ca.* 10300 and *ca.* 9800 in Scandinavia, that seem to coincide with a eustatic rise.

to some authorities this sinking occurred up to five hundred or so years after the readvance had taken place.

There are some indications that the Late-glacial raised beach that is so prominent in North Norway, indicates a combination of eustatic rise and crustal sinking. The sinking being a response to a lengthy halt in glacial recession, namely from *ca.* 12000 a B.P. to 10300 a B.P.

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