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SPECIAL

A revised model for the last deglaciation of eastern Scotland

A. M. MCCABE[1], P. U. CLARK[2], D. E. SMITH[3] & P. DUNLOP[1]

[1]*School of Environmental Science, University of Ulster, Coleraine BT52 1SA, UK (e-mail: m.mccabe@ulster.ac.uk)*
[2]*Department of Geosciences, Oregon State University, Corvallis, OR 97331, USA*
[3]*Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, UK*

Accelerator mass spectrometry ^{14}C ages on monospecific marine microfauna from raised mud record initial deglaciation of the eastern coast of Scotland before 21.0 cal ka bp. Two subsequent ice-margin readvances occurred prior to the Loch Lomond Advance and are identified from ice-contact deposits overlying marine mud. The Lunan Bay Readvance dates to <20.2 cal ka bp, and possibly <18.2 cal ka bp. The younger Perth Readvance occurred between *c*. 17.5 cal ka bp and 14.5 ^{10}Be ka. Within dating uncertainties, these readvances are similar in age to ice-margin fluctuations documented from the Irish Sea Basin and northwestern Ireland and record three near-synchronous fluctuations of much of the British–Irish Ice Sheet margin during the last deglaciation, suggesting a common response to regional climate forcing.

Early models for the last deglaciation of eastern Scotland suggested that the ice-sheet margin readvanced at least twice in this region following the Last Glacial Maximum (LGM): once during the Perth Readvance, and again during the subsequent Younger Dryas-age Loch Lomond Advance. Simpson (1933) first recognized evidence for the Perth Readvance from coarse-grained outwash overlying marine silts in the Tay valley near Perth. Later Sissons (1963, 1964, 1967) mapped the limits of this event more widely in central Scotland. Other workers argued that the last deglaciation was characterized by continuous ice-margin retreat until the re-formation of the Scottish ice cap during the Loch Lomond Advance (Clapperton & Sugden 1972; Paterson 1974; Sugden & Clapperton 1975; Browne 1980; Sutherland 1984; Boulton *et al*. 2003). More recently, Clapperton (1997) suggested that the Scottish ice sheet periodically readvanced during deglaciation in response to North Atlantic climate changes but did not provide a radiocarbon chronology.

Here we propose a revision to the deglacial chronology of east–central Scotland based on four new accelerator mass spectrometry (AMS) ^{14}C dates obtained from *in situ* monospecific samples of the foram *Elphidium clavatum* contained in raised marine mud and a re-evaluation of critical stratigraphic sections. Our new ages first demonstrate that initial deglaciation of eastern Scotland occurred before 17 720 ± 50 ^{14}C years bp (21 130 ± 90 cal years bp) or distinctly earlier than previously considered (14 920 ± 200 ^{14}C years bp) (Hall & Jarvis 1989; Sejrup *et al*. 1994). Moreover, stratigraphical relationships between dated marine mud and overlying ice-contact deposits indicate that early retreat was followed by two regional readvances prior to the Loch Lomond Advance (Younger Dryas).

Early deglaciation and the Lunan Bay Readvance. Radiocarbon ages on fossiliferous marine mud and the unconformable relationship between the mud and overlying ice-contact gravel in the Lunan Bay area (Fig. 1) (Rice 1960) indicate early deglaciation and subsequent ice-margin readvance. Marine mud up to 10 m thick mantles the area around Lunan Bay to at least 22 m Ordnance Datum (O.D.) (Rice 1960). Two AMS ^{14}C ages from marine microfauna obtained from this mud indicate that the ice margin had retreated from its maximum limit offshore to a position west of the Lunan valley before 17 720 ± 50 ^{14}C years bp (21 130 ± 90 cal years bp) (Table 1). This age for initial deglaciation is much earlier than that previously considered for eastern Scotland (Hall & Jarvis 1989; Sejrup *et al*. 1994), but is similar to the age of deglaciation of the coast of northwestern Ireland (>17 140 ± 110 ^{14}C years bp; 20 300 ± 80 cal years bp) (McCabe & Clark 2003) and of the Irish Sea Basin (21 400 ± 1300 ^{36}Cl years) (Bowen *et al*. 2002).

Because the microfauna record full marine conditions and the mud contains little evidence of ice rafting we infer that a hiatus occurred between initial marine conditions and subsequent deposition of the overlying ice-contact gravel, thus suggesting an ice-margin readvance. Although no tills have been recorded overlying the muds the pattern of numerous, deep kettle holes is sufficient to demonstrate ice-contact deposition within the valley. The presence of a hiatus is further supported by the absence of raised marine deltas and the lack of marine modification of ice-contact ridges and kettle holes in the Lunan valley. Moreover, the absence of shoreline features in the valley indicates that relative sea level must have fallen prior to this ice-margin readvance, and that any isostatic depression associated with readvance was insufficient to raise relative sea level to an altitude where coastal processes could modify the ice-contact deposits.

The continuity of the ice-contact topography across the Strathmore–Lunan watershed and erratics from the eastern Grampians (Synge 1956; Rice 1960) records the decay of an ice steam that readvanced southeastwards and whose eastern limit may be located where the marine mud has been glaciotectonically disturbed at Red Castle in the lower Lunan valley (Fig. 1) (Rice 1960).

The Perth Readvance. The field relations originally described by Howden (1870) and Simpson (1933) at two sites west and north of the Firth of Forth in support of the Perth Readvance, and subsequently disputed by Paterson (1974), are best explained by a readvance. In Figure 2, we describe an exposure at Bertha Park, along the River Almond, that is typical of the stratigraphy previously described in the area (Simpson 1933; Paterson 1974; Peacock 1999). The lower section is composed of *c*. 10 m of till that records deposition by ice that moved eastwards into the North Sea (Figs 1 and 2). The overlying silty sands (80%) and mud (15%) include three horizontal beds of finely laminated mud. Although we were unable to recover any marine fossils from this unit, it is in the same stratigraphic position as previously described marine mud containing Foraminifera, ostracodes and paired valves of *Portlandica arctica* (Paterson 1974; Peacock 1999), and is correlative with the Errol Clay Formation, which is widespread around the firths of Tay and Forth (Peacock

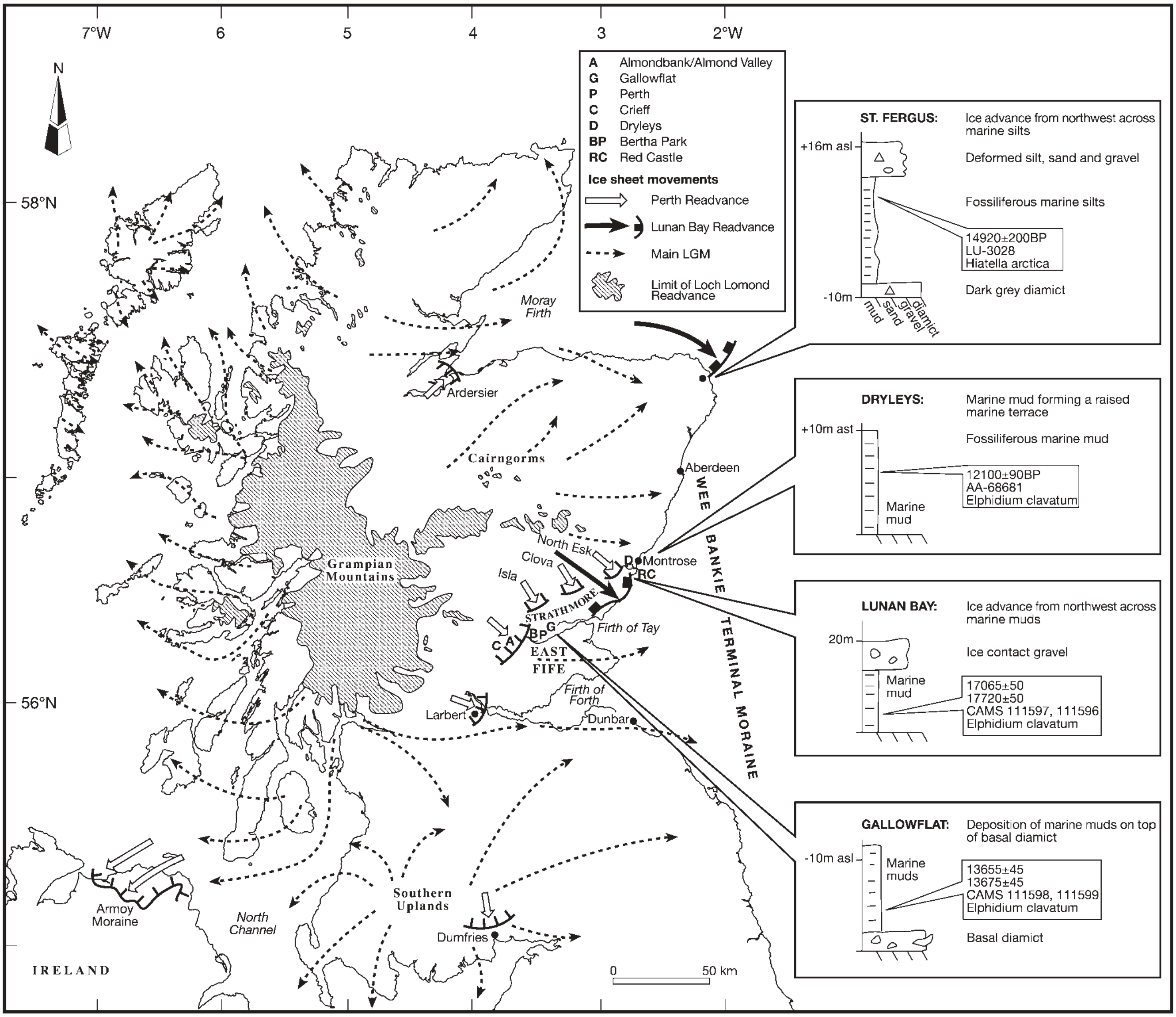

Fig. 1. Summary of main ice flow lines in Scotland and suggested correlations for readvance limits discussed in the text. Redrawn and modified from Peacock (1999, 2003) and Boulton *et al*. (2003).

1999). These marine beds are overlain by *c*. 20 m of poorly sorted boulder gravel (80%) interbedded with thin, discontinuous beds (10–15 cm thick) of pebble gravel (20%). The gravels form kettled topography on the north side of the River Almond, and thus record ice-contact deposition.

The key argument that Paterson (1974) made against the Perth Readvance was that the kettles along the River Almond formed as a result of melting of stagnant ice masses left during the last retreat of the ice sheet and subsequently buried by marine deposits (Errol Clays) and then by outwash gravel. This *ad hoc* argument is not supported by the field relations, which show that where ice-contact gravel occurs above the marine beds only the gravel spread contains kettle holes. Indeed, none of the marine beds of the inner Firth of Tay show deformation related to buried ice (Peacock 1999). Therefore the kettled gravels record an ice margin associated with a deglacial readvance from the eastern Grampians across marine deposits in the Tay area, as originally recognized by Simpson (1933).

Similar evidence for the Perth Readvance occurs in Strathmore, where kettled ice-contact deposits are found at the mouths of several Highland glens, marking the limit of outlet glaciers originating from the eastern Grampians (Sissons 1964; Maizels 1983) (Fig. 1). In this area Howden (1870) reported that marine clays underlie the ice-contact deposits, 11 km inland from Montrose.

Although none of the marine beds in the two exposures at Bertha Park and Montrose is dated, the age of the Errol Clay Formation is constrained elsewhere by ^{14}C ages on marine fossils. We have obtained two new ^{14}C ages on monospecific samples of *E. clavatum* from marine mud 1 m above till at the base of a new pit (11 m O.D.) at Gallowflat (Fig. 1, Table 1). These ages are in agreement with previously published ^{14}C ages on macrofauna and benthonic Foraminifera from nearby exposures (Peacock 2003). Allowing for some time to deposit sediments below those dated at the Gallowflat pits, Peacock (2003) argued that deposition of the Errol Clay Formation began

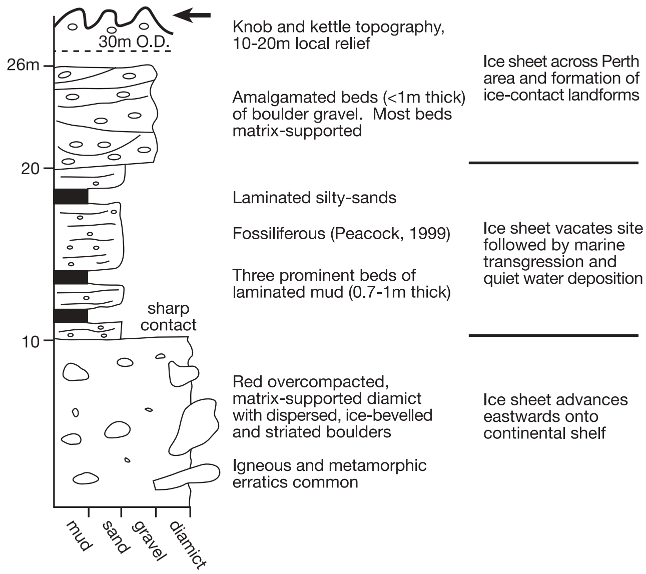

Fig. 2. Schematic log from Bertha Park river section, Perth, eastern Scotland (see Fig. 1 for location).

at 14.0–14.5 ^{14}C ka bp (*c*. 16.8–17.6 cal ka bp), providing a maximum age for the Perth Readvance. The timing of the termination of the Perth Readvance is suggested from ^{10}Be ages on moraines from the Cairngorm Mountains, which indicate that deglaciation of the eastern Highlands occurred at *c*. 14.0–14.5 ^{10}Be ka (Everest & Kubik 2006). These constraints on the age of the Perth Readvance suggest that it is correlative with the Killard Point Stadial identified in Ireland, which occurred between *c*. 17 cal ka bp (McCabe *et al*. 2005) and 14.7 ± 0.3 ^{10}Be ka (Clark *et al*. 2006). These dates also imply that the ice sheet remained near its terminal limits for at least 1000 years.

Additional support for the timing of the Perth Readvance may come from a site near St. Fergus, where Hall & Jarvis (1989) described morainic topography deposited by ice advancing east from the Moray Firth overlying the glaciomarine silts that dated to 14 920 ± 200 ^{14}C years bp (18 235 ± 280 cal years bp) (Fig. 1). Given that the age of the mud is greater than the oldest estimated age of the Errol Clay Formation (Peacock 2003), it is possible that the readvance recorded at St. Fergus is equivalent to the Lunan Bay Readvance. If so, then the Lunan Bay Readvance preceded the Perth Readvance by only centuries, in which case it may be equivalent to a readvance by the Irish ice sheet margin that occurred sometime between 15.0 and 14.2 ^{14}C ka bp (18.3 and 17.2 cal ka bp) (McCabe *et al*. 2007).

In addition to raised marine mud, the other major sea-level indicator that developed around this time is the Main Perth raised shoreline (Sissons & Smith 1965; Sissons *et al*. 1966; Smith *et al*. 1969; Cullingford 1977). This shoreline formed during the Perth Readvance, as suggested by the areal extent of the shoreline in the Forth and Tay estuaries and its close association with outwash terraces that end up-valley in ice-contact deposits. The lowest member of the earlier East Fife shorelines on the outer coast, 40 km to the east of Perth, has a similar slope to the Main Perth shoreline in the Forth valley, indicating that while ice stood at the Perth Readvance limit there was either a decrease in the rate of isostatic uplift or renewed isostatic depression in response to ice build-up during the Perth Readvance (Smith 1965).

The evidence for high relative sea levels during the Perth Readvance contrasts with the absence of similar evidence during the earlier Lunan Bay Readvance. Sea surface levels during the interval bracketing these two readvances (21.0–14.5 cal ka bp) rose from *c*. 130 to 100 m below the present level (Yokoyama *et al*. 2000). Accordingly, the Lunan Bay Readvance may have isostatically loaded the crust as much as the Perth Readvance, but it occurred when sea surface levels were lower, resulting in a lower relative sea level. Alternatively, the isostatic response associated with the Lunan Bay Readvance was less than during the Perth Readvance, either because of a lesser ice load or because there was less time for the isostatic response to approach equilibrium. Further information on the relative sea-level history of the region is required to constrain these possibilities, but the present constraints on the differing relative sea levels associated with the two advances provide independent confirmation that they are of differing age.

Conclusions. Our new AMS ^{14}C ages and examination of critical stratigraphical relations between marine mud and overlying ice-contact gravel require a major revision to the existing model of the last deglaciation of eastern Scotland. Initial deglaciation from the coast of eastern Scotland occurred before 17 720 ± 50 ^{14}C years bp (21 130 ± 90 cal years bp), or distinctly earlier than the previous estimates. Similar ages for early initial deglaciation have also been documented from the Irish Sea Basin (Bowen *et al*. 2002) and northwestern Ireland (McCabe & Clark 2003).

We also describe evidence for two subsequent readvances. Stratigraphical relations clearly distinguish the older Lunan Bay Readvance from the Perth Readvance. The Lunan Bay Readvance occurred after 17 065 ± 50 years bp (20 250 ± 40 cal years bp), and perhaps after 14 920 ± 200 ^{14}C years bp (18 235 ± 280 cal years bp), or the age of marine mud at St. Fergus. If the age of the readvance is associated with the younger age at St. Fergus, then it is probably correlative with a readvance in the north Irish Sea Basin that occurred between 15.0 and 14.2 ^{14}C ka bp (McCabe *et al*. 2007). The Perth Readvance is supported by stratigraphic evidence from the sections along the River Almond

Table 1. *AMS ^{14}C ages from monospecific samples of* in situ Elphidium clavatum *corrected for an assumed reservoir age of 400 years*

Location/description/comments	Laboratory number	Radiocarbon age (years bp ± 1σ)	Calibrated age* (years bp ± 1σ)
Gallowflat: from laminated mud 1 m above glacial diamict on new pit floor	CAMS111598	13 655 ± 45	16 355 ± 130
	CAMS111599	13 675 ± 40	16 385 ± 125
Lunan Bay: from raised marine mud on the south margin of the bay; mud is overlain by ice-contact gravel elsewhere in area; dates marine incursion associated with early deglaciation of the east coast of Scotland after ice withdrew west from the Wee Bankie Moraine	CAMS111597	17 065 ± 50	20 250 ± 40
	CAMS111596	17 720 ± 50	21 130 ± 90

*Calibrated using the Fairbanks 0805 calibration curve (Fairbanks *et al*. 2005).

and can be correlated with the Killard Point Readvance from the northern Irish Sea Basin (McCabe *et al*. 2005).

The final readvance of the British–Irish Ice Sheet, associated with its partial regrowth during the Loch Lomond Stadial, occurred in the highlands of Scotland (Sissons 1964) and Ireland (Bowen *et al*. 2002). Within the existing dating uncertainties, the good agreement between the deglacial history derived here for eastern Scotland and that from Ireland (Bowen *et al*. 2002; McCabe & Clark 2003) thus indicates three near-synchronous fluctuations of much of the British–Irish Ice Sheet margin during the last deglaciation, suggesting a common response to regional climate forcing rather than internal dynamic controls on deglaciation.

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