Late Devensian marine deposits (Errol Clay Formation) at the Gallowflat Claypit, eastern Scotland: new evidence for the timing of ice recession in the Tay Estuary

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Synopsis

The Late Devensian arctic marine deposits (Errol Clay Formation) at the Gallowflat Claypit between Perth and Dundee are correlated with the type succession at nearby Inchcoonans, but include an expanded basal glaciomarine unit with rhythms interpreted as symmict varves. Laminated silt–clay couplets are thought to be tidal. Conditions were fully marine by 13.8 ka BP (based on new radiocarbon dates and a 400 a reservoir age). Following recession of the Tay–Forth glacier from its advanced Late Devensian position at the Wee Bankie Terminal Moraine, it is inferred that deglaciation of the middle Tay estuary some 100 km to the west took place between 14.5 and 14 ka BP. The possibility that there was a readvance of ice in the Tay and Forth estuaries during or close to the Heinrich iceberg discharge event H1 is briefly discussed.

Introduction

Late Devensian raised marine strata on the shores of the Firth of Tay have been the subject of a number of studies during the last 70 years (Davidson 1932; McManus 1972; Paterson *et al.* 1981; Armstrong *et al.* 1985; Duck 1990; Peacock, 1999). These deposits include the Errol Clay Formation (ECF) and its offshore equivalent the St. Abbs Formation (Gatliff *et al.* 1994), both of which were laid down in an arctic environment following the retreat of the Scottish Late Devensian ice-sheet from the Wee Bankie Terminal Moraine complex at the entrance to the Firth of Forth (Fig. 1), probably before 12.8–13.0 ka BP (Peacock & Browne 1998). Good exposures are scarce in the ECF, and most workers since the mid-nineteenth century have relied on sections in a few, now largely abandoned claypits. Of these, the pits at Gallowflat and Inchcoonans (Fig. 2) are important reference sites for the ECF (Sutherland 1993). The significance of the claypits is further emphasized by their position relative to the retreating Scottish ice-sheet before 13 ka BP (and thus the dating of recession), and to the timing of the influx of fully marine water into the western part of the North Sea in the Late Devensian period. The former is of particular interest because of the proposal that there was a major readvance of the British–Irish Ice Sheet about 14 ka BP, a readvance that coincided with the Heinrich iceberg discharge event H1 (McCabe *et al.* 1998). This account examines the changing palaeoenvironments at Gallowflat, the correlation of the sediments with those at the Inchcoonans reference site, the timing of ice recession in the middle Tay Estuary, and the possibility of a readvance coeval with H1 having occurred in the Tay and Forth estuaries. Dates are based on the uncalibrated radiocarbon timescale, except where otherwise indicated.

The Gallowflat Claypit is situated on an almost flat, possibly planated area at about +20 m OD (Ordnance Datum), bounded by a poorly developed feature trending west to east, close to the north face of the pit (Fig. 3). The feature is at or near the level of the Main Perth Shoreline (see below). Until 1995, the deposits here had yielded only a sparse, species-poor fauna (Peacock 1999), and had attracted less attention than those at the Inchcoonans pit. The present work stems from *ad hoc* visits to the pit by Dr. M. Armstrong and myself between 1995 and 2000, initially to collect macrofaunal remains. The fieldwork was supplemented by laboratory examination of sediment samples, including a few from the east face of the Gallowflat '1970' pit preserved at the British Geological Survey, Edinburgh. Samples of about 1 kg (for macrofauna) and 200 g (for microfauna) were dried, weighed and washed through a 125 μm sieve, the faunal remains were picked from the weighed residues, and material was selected for radiocarbon dating.

It has been suggested by Paterson *et al.* (1981) and Armstrong *et al.* (1985) that the threefold lithological succession established by these workers at Inchcoonans (Divisions A–C of the ECF) can be applied to most of the arctic marine strata in the Tay Estuary between Perth and Dundee (Fig. 2; Table 1). The divisions are believed to be chronostratigraphic as well as lithostratigraphic, whether or not the colours of the sediments relate to the source (Paterson *et al.* 1981) or to variations in marine productivity and to low concentrations of reactive organic matter, particularly in Division A (Stevens 1987; Peacock 1999). However, the new investigations, detailed below, demonstrate that the lowermost, probably proximal glaciomarine strata at Gallowflat (lower part of Division A) are poorly represented at Inchcoonans, which otherwise has the most complete development known for the ECF (Paterson *et al.* 1981; Browne *et al.*

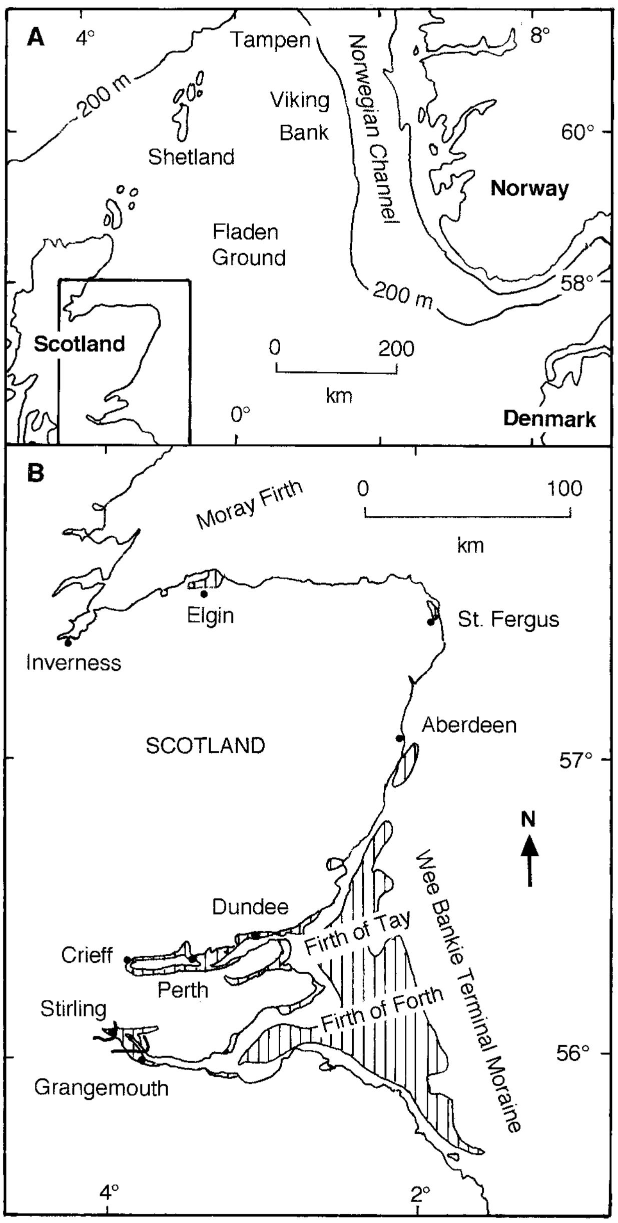

FIG. 1. Location maps. (**A**) Scotland and northern North Sea. (**B**) Eastern Scotland. The ornament shows the extent of the Errol Clay Formation onshore adjacent to the firths of Forth and Tay, its correlatives in NE Scotland, and the St. Abbs Formation offshore. Ice-front positions linked to the Main Perth Shoreline are indicated for Grangemouth and Stirling.

1995). At Gallowflat, the lower part of Division A, which overlies a basal till, occupies or occupied much of the pit, whereas representatives of Divisions B and C are (or were) confined to a small area, and have probably been preserved in a kettlehole.

Gallowflat Claypit: marine sediments and fauna

Excavation of the older part of the Gallowflat Claypit (Gallowflat '1970', Fig. 3), continued into the early 1970s, but it is now completely infilled. The newer part (Gallowflat '1999' and '2000') has since been used as a landfill site. The colour of the marine deposit above the basal till (Table 1) is closer to that of the basal Division A at the type site of Inchcoonans, rather than that of Division C as was wrongly suggested by Peacock (1999). Ramifying black tubes with cross-sections about 1–2 mm across, which are particularly numerous immediately above the till, were compared by Peacock (1999) to inorganic structures in modern glaciomarine sediments. However, further examination indicates that the tubes are partly open, are locally surrounded by carbonate-cemented clay and silt, and penetrate decayed fossils. They thus post-date the compaction of the clay, and are almost certainly the remains of tree rootlets. Their presence implies that the permanent water table at Gallowflat is, or has been close to the base of the marine deposit, i.e. a depth of about 5 m, whereas the principal zone of weathering and decalcification in the area as a whole is only some 1–1.5 m deep. It is also likely that the high degree of consolidation of the clay, which resulted in a reduction in porosity from *c.* 80% to *c.* 40% (Duck 1990), is the result of partial drying out as well as consolidation under load.

Division A at Gallowflat has yielded a sparse macrofauna consisting almost exclusively of the bivalve *Portlandia arctica* (represented by variably decayed valves and periostraca): the specimens of *Cyclopecten greenlandicus* mistakenly reported from Gallowflat '1970' by Peacock (1999) were from Inchcoonans. A single specimen of the carnivorous gastropod *Retusa obtusa* was recovered from a shelly lens 0.3 m long and 0.02 m thick, *c.* 1 m above the clay–till boundary at Locality 4 in Gallowflat '2000' (Fig. 3), but the fauna in the lens is otherwise composed of an almost complete range of slightly decayed juvenile ('spat') to adult valves of *P. arctica*, some of which are paired. The microfauna between 1.5 and 4.5 m depth on the east face of Gallowflat '1970' consists of very sparse *Elphidium clavatum* and the ostracode *Cytheropteron pseudomontrosiense* (Fig. 4). Similar assemblages have been found in samples taken from Localities 4 and 5, and in a newly opened successor claypit nearby. The shelly lens referred to above yielded only a few valves of *C. pseudomontrosiense* and *Polycope* sp.

Divisions B and C

Strata attributed to Divisions B and C were exposed for only a very short period in the claypit (possibly a few weeks) between Localities 1 and 3 (Peacock 1999). Their probable former extent (in a kettlehole, see below) is shown in Figure 3. Unfortunately, the contacts with the underlying Division A were not visible during the investigations.

At Locality 2, a basin-like structure was seen in 1996 in a re-entrant (Fig. 5), and steep dips (>70°) were observed a few metres to the north. The nose of a possible slump fold occurs in units (6) and (7), but the relationship of these units to unit (5) is unclear. Unit (8) is correlated on the basis of colour with Division B at Locality 3, and the overlying strata with Division C. Elsewhere in the re-entrant, units (1)–(5) have an irregular base and appear to have subsided into the underlying

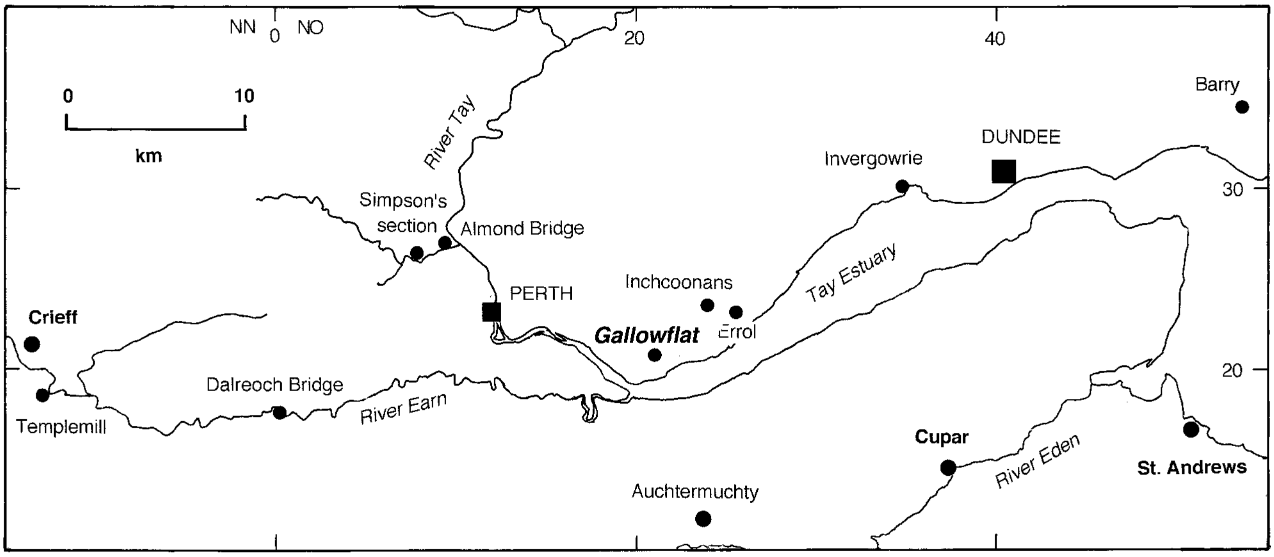

FIG. 2. Map of the middle Tay estuary showing sites mentioned in the text.

TABLE 1
Stratigraphy of the ECF at the Gallowflat Claypit

Division C (formerly termed 'brown')
2. Sand, silt and clay, crudely laminated.
1. Clay, silty and silt, clayey, moderate yellowish brown (10YR 5/4, The Rock-Color Chart Committee 1948), locally fossiliferous, in part almost unbedded, in part uneven, non-graded laminae of clayey silt 1–4 mm thick separated by coatings of clay. Calcareous, but decalcified to 1–1.5 m below soil.
Division B (formerly termed 'blue')
As 1 above, but moderate to dark yellowish brown (10YR 5/4 to 10YR 4/2), fossiliferous, calcareous.
Division A (formerly termed 'red', correlated with the lowest part of Division A at Inchcoonans)
Gallowflat '2000'. Silt, clayey and clayey silt, sandy, weakly reddish brown overall (5YR 5/4 to 7.5YR 4/3), sparsely fossiliferous. Well-scattered gravel and boulders. Calcareous, but decalcified below soil, with calcareous concretions mainly in lower metre of deposit (Duck 1990; Rowan *et al.*, 2001). Rhythmic colour banding 20–40 mm from silt (pale) to silty clay (reddish brown). Considerable sub-horizontal bioturbation. In Gallowflat '1970', McManus (1972) noted rhythmically colour banded silt and clay with sandy partings in repeated sequences at 100–350 mm intervals, and sparsely distributed boulders up to 1.3 m in diameter.
Till
Sandy, bright reddish or reddish brown (Armstrong *et al.* 1985)

clay. Overall, the arrangement of the strata in Figure 5 suggests progressively greater deformation from top to bottom, a picture consistent with the decay of an underlying buried mass of ice. The basin is therefore interpreted as part of a kettlehole in which Divisions B and C are preserved (Fig. 3). The silty clay and clayey silt of Division C at Locality 3 (Fig. 3) is capped by 0.3 m of sand, silt and clay, similar to that of units (1) and (2) at Locality 2 (above), and is underlain by 0.6 m of silty clay of Division B (Table 1).

For Division B at Gallowflat, the high-arctic, low-diversity (nine species) macrofauna is dominated by *Portlandia arctica* and *Cyclopecten greenlandicus* (Peacock 1999), and close sampling at Locality 3 yielded three different ostracode assemblages, all of arctic character (Table 2, Nos. 2–4). At Locality 2, the ostracode assemblage from the lowest part of Division C (Table 2, No. 5) is from a bed that yielded a numerically rich macrofauna dominated by the shallow-water, weed-loving species *Musculus discors* var. *substriatus* together with *Cylichna occulta*, cf. *Cryptonatica affinis*, *Cyclopecten greenlandicus* and *Portlandia arctica* (Peacock 1999).

Correlation with strata at Inchcoonans

In general terms, the mollusc and ostracode taxa at Gallowflat are similar to those in Divisions A, B and C at Inchcoonans (Brady *et al.* 1874; Davidson 1932; E. Robinson in Paterson *et al.* 1981; Browne *et al.* 1995; Peacock 1999). There is a broad correlation in terms of the ostracode species present in Division B at Gallowflat and Inchcoonans (Tables 2 and 3; Figs 4 and 6), but the species-rich ostracode assemblages themselves differ in detail. This is unsurprising in view of the variable bottom conditions and faunas in small areas of sea floor at the present day (Erwin 1983). The molluscan data are incomplete, and cannot be used in correlation, but the distribution of the *Cytheropteron pseudomontrosiense* assemblage at the two claypits indicates that only the lowest part of Division A is present at Gallowflat (Fig. 6). These strata, which are over 5 m thick in some parts of the Gallowflat pit, are represented by less than 0.5 m of deposit at the type site at Inchcoonans. The occurrence of at least part of Divisions B and C in the probable kettlehole indicates that such strata may have once been present more widely at Gallowflat, but were

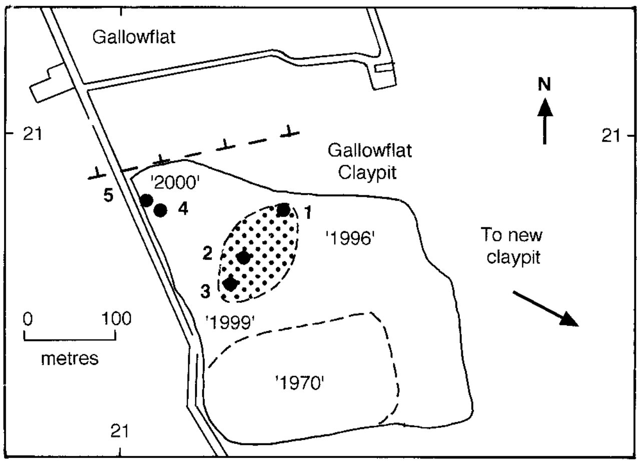

FIG. 3. Gallowflat Claypit showing localities mentioned in the text. The ornament shows the approximate extent of Divisions B and C, and the area of the probable kettle-hole. The thicker pecked line indicates the approximate position of the southward-facing feature of the presumed Main Perth Shoreline.

removed by subsequent erosion, perhaps in part at the time of formation of the widespread Main Perth Shoreline (see above).

Radiocarbon dating

The ECF with its arctic fauna is thought to have been laid down before *c.* 13 ka BP (Paterson *et al.* 1981; Peacock 1999), but the comparability of marine and terrestrial radiocarbon ages before this date is subject to uncertainties in the reservoir age of contemporary 'polar' water (to be subtracted from the reported age; Table 4). A further uncertainty stems from the radiocarbon 'plateau' at 12.5 or 12.6 ka BP, which apparently represents about 1000 calibrated years (Stuiver *et al.* 1998; Van der Plicht 2002). For the Tay Estuary, the radiocarbon 'plateau' is apparently close to 12.7 ka BP in the marine environment (Peacock 2003), indicating that the reservoir age for 'atlantic' water may have then been between 400 and 600 a. This agrees in general terms with a reservoir age for 'atlantic' water in the 13–11 ka BP period of *c.* 400 a (Peacock & Harkness 1990; Bondevik *et al.* 1999). In contrast, values for 'polar' water of 1180 ± 630 a and 1800 ± 750 a have been suggested for the North Atlantic at 15 cal ka BP (*c.* 12.5 ka BP) (Waelbrook *et al.* 2001), and between 1600 and 400 a more generally for glacial episodes (Voelker *et al.* 1998). The 400 a figure is for the thoroughly mixed water column of the ice-free Norwegian Sea, and agrees with the dating of episodes within the 15–13 ka BP interval in the Bay of Biscay and off the west coast of Britain and Ireland using planktonic foraminifera and a 400 a reservoir age (Elliot *et al.* 1998; Zaragosi *et al.* 2001). For the following account, therefore, I have retained the standard 400 a reservoir age adjustment for dates between 15 and 13 ka BP, but with the proviso that this may be too low, particularly well before 13 ka BP (Table 4).

It has proved difficult to obtain reliable radiocarbon ages for the ECF because of the generally decayed or partly decayed state of the macrofauna (Peacock 1999), even where the shell carbonate is apparently pristine. For Gallowflat, three new dates are available from Division B at Locality 3, 0.6 m below the sharp junction with Division C (Fig. 4; Table 4). One such date, from an apparently undecayed fragment of the bivalve *Cyclopecten greenlandicus* (AA-37788, 13.3 ka BP, adjusted) agrees in general terms with dates of 13.2 and 13.3 ka BP obtained on shell periostraca and seaweed from the upper part of Division A and the base of Division B at Inchcoonans, some 4 km to the NE (Beta-111507 and -8). The latter have hitherto been taken as reliable, being in order of deposition (Peacock 1999). However, recent work indicates that radiocarbon dates obtained from periostraca of *Portlandia arctica* elsewhere are too low (Björck *et al.* 2001), possibly because of susceptibility to contamination by 'young' carbon. Thus Beta-111508, if not the seaweed date Beta-111507, must be considered suspect.

AA-37787 and CAMS-77192, which were taken from the same Gallowflat clay residue, are some 500 a older than AA-37788. The analysed material in this instance was shell carbonate from undecayed benthonic foraminiferal tests and from ostracode valves on which every detail of the complex shell ornament is preserved. Some doubt applies to radiocarbon dating of microfauna in shallow water because of reworking of older sediments (Spjeldnaes 1978) but, at Gallowflat, reworked macrofauna is absent or extremely sparse (Peacock 1999), and no apparently reworked microfauna has been detected. Contamination by reworked microfauna is thus highly unlikely. I therefore suggest that the two microfaunal ages are to be preferred because of the excellent preservation of the dated tests, and because there is agreement to within 1σ between analyses on differing phyla from the same clay sample. It follows that, in the ECF, the carbonate from the analysed macrofauna has probably been slightly decomposed and replaced, even where apparently undecayed. Thus the dates from such samples in Table 4 must be regarded as minima, including those from Gallowflat (Beta-111509) and Barry (OxA-1704) (see Peacock 1999), which have hitherto been considered reliable.

The radiocarbon dates at Gallowflat and Inchcoonans may be compared with a uranium-series age of 14.2 ± 0.9 ka BP on carbonate concretions collected from near the base of Division A at Gallowflat (Rowan *et al.* 2001). This date (equivalent to an uncalibrated radiocarbon date of *c.* 12.2 ka BP), falls well within the Windermere Interstadial (WI), and only overlaps with the lower, suspect ages in Table 4. It is considerably younger than would be expected from the context of the ECF (Peacock & Browne 1998), even allowing for the probability, discussed above, that the reservoir age during the deposition of Division B may be somewhat greater than 400 a. The reasons for this are unclear, but might stem from the possibility either that the concretions were not chemically closed systems until some time

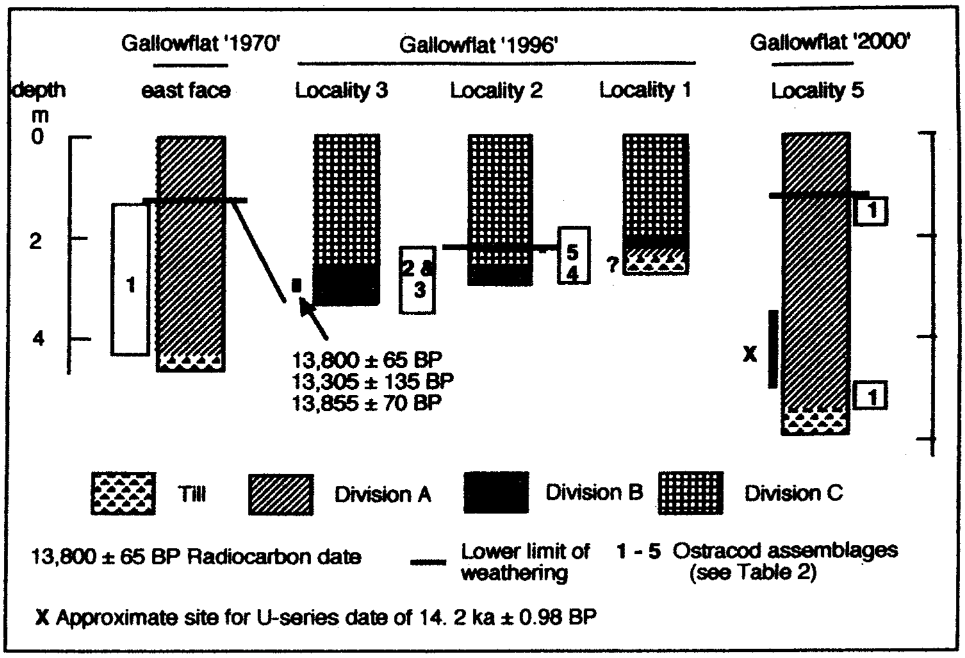

FIG. 4. Lithologies and ostracode assemblages in the Gallowflat Claypit. (For 1–5, see Table 2.) U-series date on concretions from Rowan *et al.* (2001).

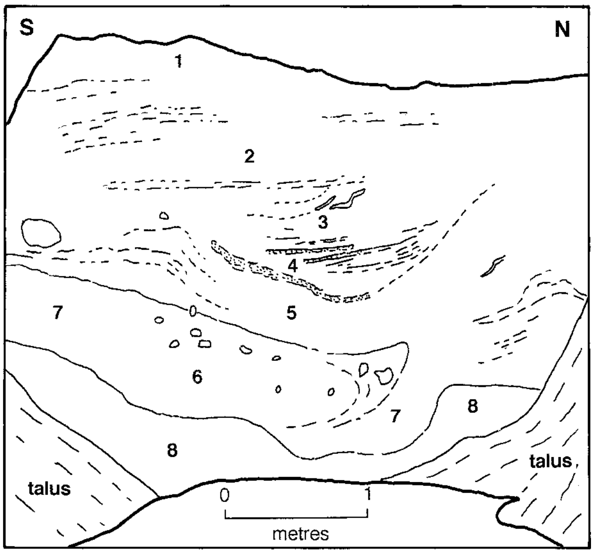

FIG. 5. Basin-like structure at Locality 2 in the Gallowflat Claypit (see Figs 3 and 5). Vertical scale equals horizontal scale. 1, Crudely laminated to thinly banded yellowish brown silt with clay and fine-grained sand, locally pebbly; 2, silty clay with scattered stones; 3, slightly contorted silty clay; 4, brownish yellow sand; 5, silty clay with pebbles, local sandy and gravelly lenticles, and a boulder some 25 cm by 15 cm; 6, yellowish brown silty clay with a few calcareous concretions and decayed shells (Division C); 7, matrix-supported, stony silty clay with scattered bivalves (*Portlandia arctica* and *Musculus discors*) (Division C); 8, greyish brown silty clay, stone-free, with slickensides on irregular joint surfaces (Division B).

after their formation, or they are not synsedimentary and are therefore later diagenetic features.

Palaeoenvironment

The very low diversity faunas in Division A at Gallowflat invite comparison with assemblages dominated by *Portlandia arctica*, *Cytheropteron pseudomontrosiense* and sparse foraminifera reported from the former late glacial to early Holocene Champlain Sea of eastern Canada. These, collected in part from rhythmically bedded sediments, have been taken as evidence for a low-salinity, partly glaciomarine environment (Rodriguez 1992) that agrees with the occurrence of the probable symmict varves discussed below. Division A at Gallowflat and the lowest part of Division A at Inchcoonans are therefore interpreted as glaciomarine deposits laid down when the ice-front of the retreating Tay glacier lay upstream, perhaps close to Perth (Fig. 2). On the other hand, the upper part of Division A at Inchcoonans and at other sites such as Invergowrie Railway Station (Fig. 2) have yielded significant proportions (>5% to >20%) of the ostracode genus *Krithe*, and as such are likely to have been deposited under conditions of near-normal marine salinity (Van Morkhoven 1963; Robinson in Paterson *et al.* 1981).

For Divisions B and C at Gallowflat the fauna as a whole is that of a shallow, subtidal, arctic marine environment, with indications of still shallower water in Division C (Peacock 1999). It is thus consistent with the marine limit for the area of about +40 m OD (Paterson *et al.* 1981). With some exceptions (see below), a wide range of ostracode adult sizes and juvenile moult stages is normally preserved, as in the assemblages in Table 2, suggesting that there has been little or no reworking by bottom currents (although significant bioturbation is not excluded). The occurrences of the bivalve *Cyclopecten greenlandicus* and the ostracode genus *Krithe* support the view that Division B and part of Division C at Gallowflat, as at Inchcoonans, were laid down under conditions of normal or near-normal marine salinity. This almost fully marine water seems to have penetrated nearly as far west as Crieff, as *C. greenlandicus* has been

TABLE 2

Ostracode assemblages 1–5 from Gallowflat (Fig. 4)

1. *Cytheropteron pseudomontrosiense*
2. *Sarsicytheridea punctillata*, *Acanthocythereis dunelmensis*, *Rabilimis mirabilis* (16 spp.)
3. *S. punctillata*, *Robertsonites tuberculatus*, *Heterocyprideis sorbyana*, *Cytheropteron dimlingtonensis* [*A. dunelmensis*, *Cythere lutea*] (13 spp.)
4. *Cytheropteron arcuatum*, *Krithe* spp., *Rabilimis mirabilis*, *Cytheropteron biconvexa* (11 spp.)
5. *S. punctillata*, *R. tuberculatus*, *H. sorbyana*, *C. dimlingtonensis* (13 spp.)

Number 1 from Gallowflat '1970' east face, Division A (Paterson *et al.* 1981, fig. 15), revised by J. D. Peacock, together with additional samples. Numbers 2, 3 and 4 from Locality 3, Division B, identified by J. E. Robinson, 0.6 m below contact with Division C. Number 5 from Locality 2, Division C, identified by J. D. Peacock. *Musculus* bed immediately above contact with Division B.

TABLE 3

Ostracode assemblages from Gallowflat '1970', east face, and from Inchcoonans Auger Hole B (Robinson in Paterson *et al.* 1981)

i. *Cytheropteron pseudomontrosiense* (in Table 2)
ii. *Rabilimis mirabilis*, *Krithe glacialis*, *C. montrosiense*, *C. simplex*
iii. *R. mirabilis*, *Sarsicytheridea punctillata*, *K. glacialis*, *Heterocyprideis sorbyana*, *C. arcuatum*
iv. *R.mirabilis*, *S. punctillata*, *C. arcuatum*, *Acanthocythereis dunelmensis*
v. *R. mirabilis*, *C. arcuatum*, *C. montrosiense*, *S. punctillata*, *C. paralatissimum*
vi. Sparse ostracodes dominated by *S. punctillata*

Inchcoonans locations are shown in Figure 6. Robinson included *C. pseudomontrosiense* in *C. montrosiense.* The following species have been re-identified in Auger Hole B: *Cytheropteron simplex* for *C. testudo*; *C. paralatissimum* for *C.* sp.

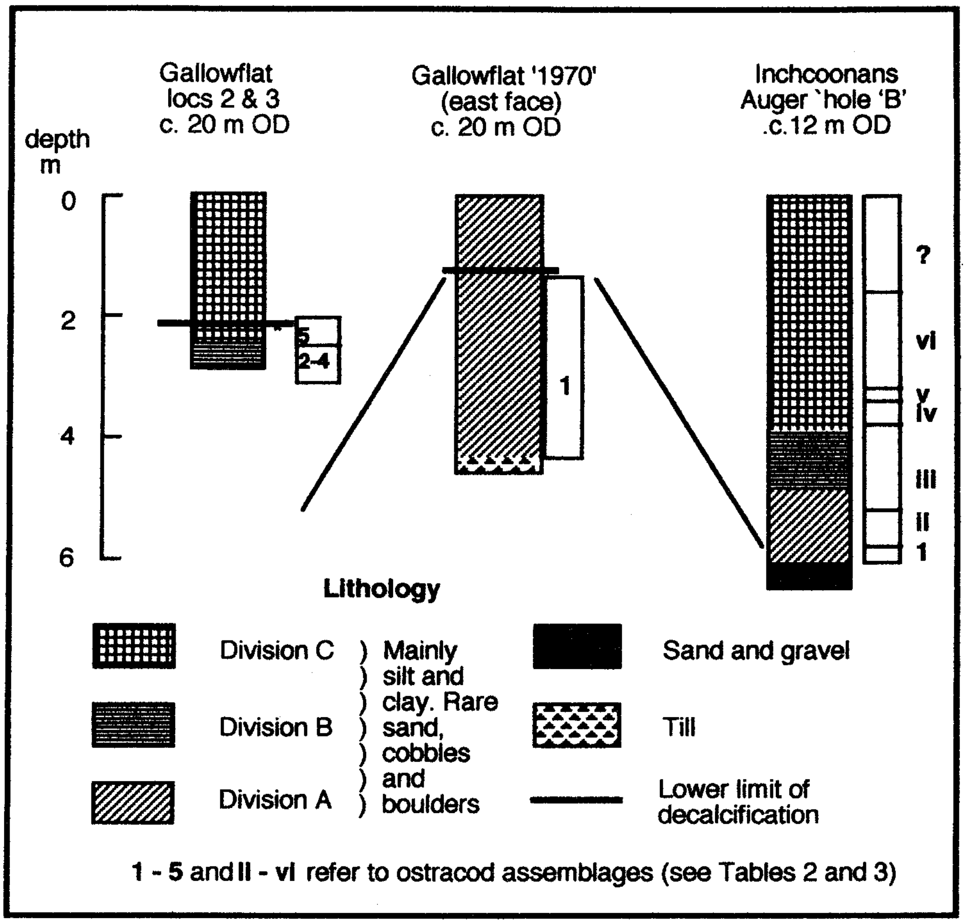

FIG. 6. Comparison of lithologies and ostracode assemblages from the Gallowflat and the Inchcoonans claypits.

recovered from reddish brown clay at Templemill, and *Krithe glacialis* has been recorded from a low-diversity (nine species) ostracode fauna collected from a borehole at Dalreoch Bridge (Fig. 2; Browne 1980; BGS unpublished records).

Although McManus (1972) suggested that the 100–350 mm rhythms in Gallowflat '1970' were not sufficiently well defined to permit interpretation as varves (annual layers), the thinner couplets in Gallowflat '2000' (20–50 mm) resemble those of symmict varves; that is,

TABLE 4
Radiocarbon dates from Gallowflat, Inchcoonans and Barry

Locality	Species	Laboratory no.	$\delta^{13}C$ PDB (‰)	Reported age (a BP + 1σ)	Adjusted age (a BP + 1σ)
Gallowflat[1] [NO 212 209]	*Balanus balanus*	Beta-111509	+0.9	13 340 ± 60	12 935 ± 70
Gallowflat, [NO 2112 2083] Locality 3, 3.2 m depth Division B	*Rabilimis mirabilis* and *Heterocyprideis sorbyana*	AA-37787	− 1.4	14 205 ± 50	13 800 ± 65
Gallowflat, [NO 2112 2083] Locality 3, 3.2 m depth Division B	Benthonic foraminifera	CAMS-77912	− 2.3	14 260 ± 60	13 855 ± 70
Gallowflat, [NO 2112 2083] Locality 3, 3.2 m depth Division B	*Cyclopecten greenlandicus*	AA-37788	+1.3	13 710 ± 130	13 305 ± 135
Inchcoonans,[1] Errol [NO 241 234]	*Cyclopecten greenlandicus*	OxA-1703	[2]	13 090 ± 140	12 685 ± 145
Inchcoonans SNH No. 3 Borehole [NO 242 334] Division B, base 7.3–7.4 m depth	Seaweed	Beta-111507	− 23.9	13 650 ± 70	13 245 ± 80
Division A, top 7.9–8.0 m depth	*Portlandia arctica* (periostraca)	Beta-111508	− 19.1	13 710 ± 80	13 305 ± 90
Barry[1] [NO 547 347]	*Balanus* sp.	OxA-1704	[2]	14 350 ± 170	13 950 ± 175

[1]Not precisely located.
[2]$\delta^{13}C$ is zero (assumed). Adjusted ages based on an apparent age of 405 ± 40 a for seawater (Harkness 1983). AA-1703, AA-1704 and CAMS-77192 were prepared to graphite in East Kilbride and analysed at the University of Arizona NSF-AMS dating facility (the first two samples) and the University of California Center for Accelerator Mass Spectrometry (the last sample). OxA-1703 and -1704 were prepared and analysed at the Oxford AMS dating laboratory. Support provided by NERC Scientific Services and Facilities is hereby gratefully acknowledged. Beta-111507 to -9 were funded by the British Geological Survey.

varves deposited in saline water rather than the more clearly marked diatactic varves of fresh water (Sauramo 1923; De Geer 1950, fig. 3B). Similar silt–clay couplets averaging 55 mm in width from SW Sweden have been interpreted as symmict varves laid down under glaciomarine conditions (Stevens 1985). The rhythms at Gallowflat '2000' suggest that a thickness of 5 m of marine deposit was laid down in 125–250 a. However, the presence of a shelly lens in Division A at Locality 4 about 1 m above the till (see above) suggests that this type of sedimentation was locally interrupted, perhaps by debris flows or slumping, and these figures should be regarded as no more than a rough guide.

Some of the rhythms elsewhere in the ECF may be varves, such as those reported from all three divisions of the ECF at Inchcoonans (Browne *et al*. 1995) and from an exposure near Almond Bridge west of Perth (Fig. 2; Simpson 1933). Although Paterson (1974) believed that the rhythms (10–50 mm) at the latter locality resulted from deltaic sedimentation, it is possible that the 7.2 m succession here is indeed varved and was laid down in a few hundred years. This sedimentation was not necessarily in a glaciomarine environment, as similar rhythms have been reported from marine deposits of WI age in the Firth of Tay (Paterson *et al*. 1981; Peacock 2002). However, at the nearby Almond Bridge Borehole (Fig. 2), much of the deposit is finely laminated (see below), rather than in varve-type rhythms, and a much higher depositional rate would have been possible as material from the valley side was reworked into the now largely infilled channel of the River Almond (Paterson *et al*. 1981).

The finely laminated deposits present in Divisions B and C at Gallowflat Locality 2 were probably laid down very rapidly. The sharp differentiation of the silt and clay couplets indicates little or no mixing by bioturbation. Further, the ostracode valves from one sample are chiefly juvenile instars with few adults, and are almost certainly redeposited. The sedimentology of the couplets is thus consistent with reworking and redeposition by weak currents in a subtidal environment, with the clay coatings being deposited and consolidated in the slack water between tidal cycles (Edge & Sills 1989; Barras & Paul 1999). Locally very high depositional rates (perhaps 1–2 m a^{-1}) can be surmised, although in this instance these were probably sustained only over short periods, perhaps a matter of weeks. Finely laminated silts and clays that were probably formed in a similar fashion, and with implied very high rates of deposition, are known elsewhere in the Errol Clay

TABLE 5
Events close to, or possibly associated with, Heinrich iceberg event H1

Event	Source	Peak (ka BP)	Range (ka BP)
1. Killard Point Stadial (readvance)	McCabe *et al.* 1988	13.8, 14.0	<14.7, >12.7
2. St. Kilda, formation of inner morainal bank	Peacock *et al.* 1992	–	<15.2, >13.5
3. St. Fergus Silt Formation, predating readvance of Moray Firth glacier	Hall & Jarvis 1989; Peacock 1997; Peacock *et al.* 2000	–	<14.3, <14.9
4. Glaciomarine sediments 15 m thick, Fladen Ground	Sejrup *et al.* 1994	14.5–14.2	<15, >14
5. Tampen Readvance, retreat of ice to Norwegian coast	Birks *et al.* 1994; Sejrup *et al.* 1994	–	<18.9, >15.1
6. Denmark, Young Baltic Readvance	Lagerlund & Houmark-Nielsen (1993)		>14.2–14.1
7. Barra Fan, peak of H1 ice-rafted basaltic debris	Knutz *et al.* 2001	*c.* 14	–

Formation; for instance, in boreholes at Dalreoch Bridge, in Division B in the BGS Almond Bridge Borehole (where finely laminated sediments are >4 m thick), and at two localities near Auchtermuchty (Fig. 2; M. A. E. Browne, personal communication, 2001). As such, they may account in part for the great thicknesses of the Errol Clay Formation at some localities, particularly in channels (where up to 40 m of deposit has been recorded; Paterson *et al.* 1981).

Deglaciation of the middle Tay Estuary

The two radiocarbon dates of about 13.8 ka BP for Division B at Gallowflat are clearly minima for ice recession at Gallowflat. To the 125–250 a postulated for the deposition of Division A here (see above), there must be added an unquantified period for the deposition (at Inchcoonans) of the upper part of Division A plus part of Division B. Allowance must also be made for a possible condensed sequence or non-depositional interval at the base of the marine deposit. Thus, on the basis of a 400 a reservoir age, a date of deglaciation between 14 and 14.5 ka BP seems likely for the middle Tay Estuary. This relates to the continual recession of the Tay–Forth lobe of the Scottish ice-sheet from the Wee Bankie Terminal Moraine at the mouth of the Firth of Forth (Fig. 1), there being no evidence for a significant readvance before its retreat into the hills west of Crieff (Paterson *et al.* 1981).

Discussion

The dating of deglaciation in the middle Tay Estuary to 14.5–14 ka BP bears on the glacial history of the Tay–Forth region as a whole, particularly in view of ice retreats and readvances that have been proposed for the British Isles and neighbouring areas during the 18–13 ka BP period, including the Heinrich iceberg discharge event H1 at 14 ka BP (Table 5). Possible ice-front positions in the Tay and Forth are linked by the Main Perth Shoreline (MPS; Sissons 1976; Figs 1 and 7), which some

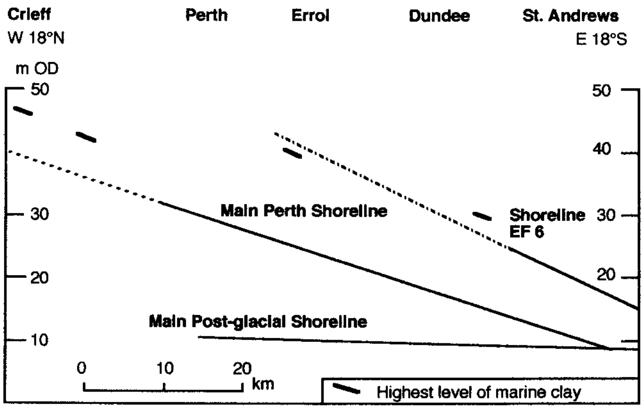

FIG. 7. Shoreline diagram for the Tay (from Paterson *et al.* 1981, fig. 4).

workers believe to have been formed during a temporary balance between glacio-isostatic uplift and eustatic sea-level rise, either during a readvance (the 'Perth Readvance' of Sissons & Smith 1965), or during the rapid climatic amelioration at the opening of the WI (Paterson 1974) at *c.* 13 ka BP. Another view is that the MPS resulted from the spreading of abundant sediment from nearby glaciers during this amelioration (Peacock 1999). For the Tay–Earn area there is a possible readvance limit or pinning position near Crieff, where gravel terraces grade to the MPS (Browne 1980; Figs 2 and 7). This limit lies some 15 km west of, and within the disproved maximum position of the 'Perth Readvance' at its type site (Paterson 1974; Sissons 1976). For the Forth Estuary, the MPS was contemporary with an ice-front attributed to the 'Perth Readvance' near Grangemouth (Fig. 1; Sissons & Smith 1965).

The Gallowflat dates suggest that marine deposition following ice recession here began before 14 ka BP, but it is unclear at present whether this was only a little before 14 ka BP or several hundred years earlier. In the first case the Tay glacier would have been receding close to 14 ka BP, i.e. during H1, and it could be inferred that the climatic signal for this event in the Firths of Forth and

Tay was weak, as may have been the case elsewhere in the North Sea area (Table 5). However, if deglaciation were in progress nearer 14.5 ka BP, time would be available for ice recession into the Scottish Highlands before a readvance coeval with the MPS peaking at 14 ka BP. For the Forth Estuary a date for the MPS of 14 ka BP would imply not only that the ice-front positions of Sissons & Smith (1965) near Grangemouth correlate with H1, but also that the high-arctic marine fauna that existed close to the ice-front as it receded westwards from Grangemouth to Stirling reflected marine conditions more generally, and not merely a local glaciomarine environment as suggested by Peacock (1999).

Conclusions

The threefold succession of the ECF at Gallowflat is composed of a lower, widespread, glaciomarine unit, and locally developed middle and upper units laid down under conditions of near-normal or normal marine salinity in a shallowing environment. Here and at the type site at Inchcoonans, the stratigraphical successions are incomplete. Rhythmically banded sediments at Gallowflat and elsewhere in the ECF are interpreted as varved, and the laminated silt–clay couplets as tidal. Radiocarbon ages for the middle unit of the ECF of *c*. 13.8 ka BP suggest that deglaciation was in progress in the middle Tay Estuary between 14 and 14.5 ka BP, the former being a time when readvances of ice coinciding with, or close to Heinrich event H1 have been proposed. Alternative scenarios are suggested: first, that the Tay glacier was retreating during H1; second, that ice-front positions associated with H1 may be located west of Crieff in the Tay–Earn area, and near Grangemouth in the Forth Estuary. However, the discussion demonstrates the need for caution in assigning all glacial readvances in the 18–13 ka BP interval to the same event (see also Table 5). It also underlines the requirement for further careful radiocarbon dating of the ECF and its offshore equivalent, the St. Abbs Formation, as well as continuing assessment of the reservoir age or ages applied to such dates.

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