Field Guide

IGCP 495 (UK Working Group)
and INQUA Coastal and Marine Processes
(NW Europe Working Group)

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S Dawson and A Dawson 2007

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Finally much of the research discussed in this Guide and field trip is the product of the meticulous research undertaken by Robin Cullingford. We acknowledged the quality of his research and point out that much of the material described in this report is due to his outstanding work

Field Excursion

The field excursion will visit sites across eastern Fife and Tayside that, with a few exceptions, have not been studied for over 25 years. We will make the point that the area is ideal for new research since detailed baseline field mapping that has already been completed provides an exceptional platform on which new work can be undertaken. Day 1 will focus on landforms, sediments and methodology. The excursion will visit several locations across eastern Fife. On Day 2 the excursion will move to consider aspects of former relative sea level changes in the Tay area. Broader issues relevant to former changes in relative sea level across Scotland as a whole will also be discussed.

DAY 1

Stop 1

Kincraig Point: We will visit a flight of raised depositional and erosional shoreline features that present a spectacular view over the Outer Forth estuary. The area was one of the first areas of eastern Scotland to undergo deglaciation and as a consequence the raised features are generally interpreted as having formed ca. 16-17 kyr. The landforms provide an opportunity to discuss the methodology used in the identification and measurement of raised shoreline features. In particular, it provides the opportunity to consider the interrelationship between raised shoreline features, the determination of the altitude of individual shoreline fragments and the construction of shoreline height distance diagrams.

Stop 2

Cocklemill Burn: The Holocene stratigraphy of the Cocklemill Burn sediments is presently the subject of considerable discussion. We will visit the key sections that have formed the basis of studies by Tooley and Smith and Robinson et al. Attention will focus on inferred patterns of relative sea level change for the Holocene as well as on the identification of tsunami deposits within the sediment sequence.

Stop 3

Strathkinness: The stop represents a panorama viewpoint demonstrating the field relations between the glacial and glacifluvial sediment sequences and the raised shorelines across an area extending from St Andrews to Tentsmuir. The stop will provide an opportunity to review previous research ranging from Geikie to the present day.

Stop 4

Bruce Embankment and Step Rocks: The stop provides an opportunity to investigate the foreshore stratigraphy of the St Andrews area. The discussion will focus on the status of possible interglacial shore platforms, competing hypotheses as well as relationships with younger raised marine and aeolian sediments.

Stop 5

East Kincaple Farm: The stop provides the opportunity to investigate the stratigraphic and morphological relationships between the older red clays and the younger Holocene carse sediments. From the stop location the field relations between the raised carse sediments and Holocene aeolian sediments.

Stop 6

Eden Valley: We will show the morphological relationships between Lateglacial and Holocene raised marine landforms. The Holocene stratigraphy will also be shown – based on hand coring and riverbank sequences.

DAY 2

Stop 7

Gallowflats Claypit: The party will investigate the stratigraphy of the Gallowflats Claypit in order to a) understand the field relations between the earlier (Lateglacial) and younger (Holocene) raised marine sediments. The laminated clay sequences at Gallowflats will be described as well as relationships to underlying glacigenic sediments and the (higher) marine limit.

Stop 8

Newburgh and Carse of Gowrie: The stop will consider the field relationships between the raised marine strata along the southern and northern sides of the Tay and described within the context of previous research.

Figure 1 Map of Eastern Fife and Tayside – showing stop locations.

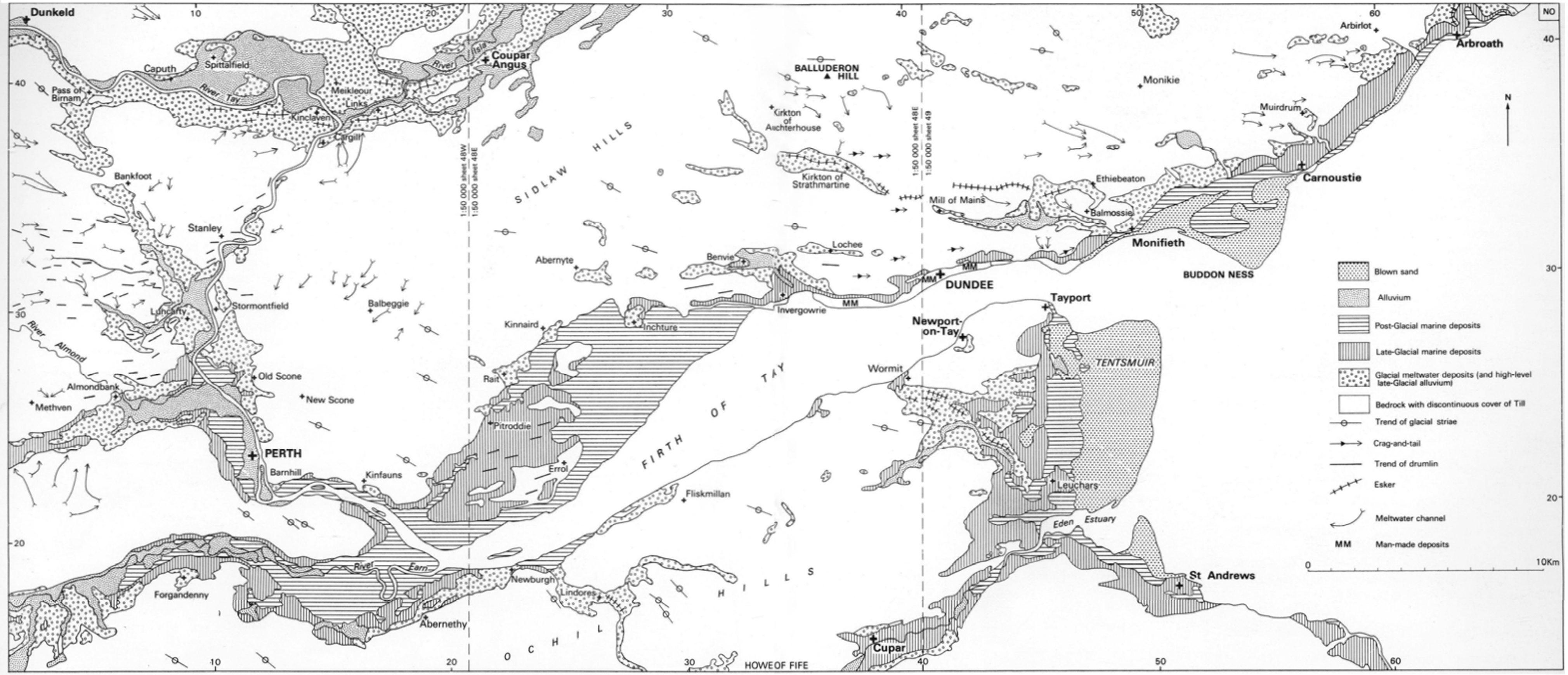


Figure 2 Distribution of Quaternary features and deposits (excepting till) (after Paterson et al. 1985).

IGCP 495: Fife and Tayside 2007

Introduction

The purpose of this field excursion is to examine the field evidence for the nature of former changes in relative sea level that took place in Eastern Fife and Tayside during the Lateglacial and Holocene. The majority of the detailed field research that has been undertaken for this part of Scotland was undertaken during a 20-year period between 1960 and 1980. For the most part this work was directed by J B Sissons and undertaken by R A Cullingford and D E Smith. Important stratigraphic investigations on the Lateglacial marine succession have also been undertaken during recent decades by J D Peacock. Together these studies that are based on a combination of geomorphological and stratigraphic studies in conjunction with radiometric dating have provided fascinating insights into the nature of relative sea level changes that have taken place over the last ca. 14,000 years.

In recent years, our knowledge of former sea level changes for Scotland has been greatly aided by the analyses of Shennan et al. for the Arisaig area of western Scotland. These detailed studies of former sea level changes have used a research methodology using isolation basins that has not been used elsewhere in Scotland. By contrast the classic studies of Smith and Cullingford are based on detailed geomorphological mapping coupled with lithostratigraphic studies. The majority of the areas in which this methodology has been used have been in estuarine lowlands (e.g. the Forth and Tay valleys) as well as in former marine inlets.

The reconstruction of the patterns of relative sea level change for west and east Scotland highlight several important issues. First, the reconstructed trends in relative sea level for west and east do not appear to be in agreement for certain key time intervals. Second, the contrasting methodologies do not easily replicate between east and west for two reasons:

- there are no obvious isolation basin sequences in eastern Scotland that could be used in a future study analogous to the research of Shennan et al. for the Arisaig region.

- there are no large estuarine sediment sequences in western Scotland that are comparable to those of the Forth and Tay

The purpose of the field excursion is therefore to describe the detailed research of earlier researchers, in particular those of Cullingford, Smith and Peacock. In doing so at attempt will be made to highlight the key conclusions arising from these studies and consider how new research and dating methods might be employed to provide answers to many unsolved questions regarding the nature, pattern and timing of relative sea level changes for the Lateglacial and Holocene. Part of the problem, therefore, arises from dating issues. Clearly the accuracy of radiocarbon dates obtained during the 1970s and 1980s are not comparable with modern AMS radiocarbon dates. There is also the key issues of radiocarbon date calibration, radiocarbon plateaux, apparent ages etc. Thus in drafting this report we have been acutely aware that the "old" sets of radiocarbon dates may have considerable limitations of accuracy although the broad trends in past relative sea level changes may have some degree of accuracy and should not be discounted out of hand.

Background

The pattern of Lateglacial and Holocene relative sea level changes across Eastern Fife and Tayside reflects partly the extent, timing and patterns of regional glaciation and deglaciation. The scale of Late Devensian glaciation across eastern Scotland is the subject of considerable disagreement although there is a consensus that the area was entirely ice covered and associated within a general east to west flow towards and across the North Sea. Not surprisingly no evidence exists for episodes of glaciation prior to the Late Devensian nor have any interglacial deposits been recognised.

During regional deglaciation, localised melting of stagnating ice resulted in the production of extensive areas of fluvioglacial sediments that are generally draped over till. The melting ice also led to the discharge of large volumes of glacigenic sediments into the Lateglacial sea where they were subject to extensive reworking and renewed sedimentation. Subsequent changes in relative sea level led to highly complex patterns of coastal sedimentation and the development of a wide range of emerged and submerged coastal landforms.

The Glacio-Isostaic and Regional Eustastic Context

In areas such as Fife and Tayside, and by analogy with other areas subject to significant glacio-isostatic rebound, the pattern of Lateglacial and Holocene relative sea level changes can be broadly grouped into three distinct episodes.

First an initial phase of deglaciation appears to have been associated with the submergence of coastal landscapes. This process is generally considered as having been due to the coincidence of low regional eustatic sea levels and a glacio-isostatically depressed land surface. Progressive ice thinning and melting led to accelerated glacio-isostatic rebound that outpaced the rate of rise of glacio-eustatic sea level (due to increased ocean water volumes) that resulted in a long-term lowering of relative sea level. Whilst this simplified statement conceals some intricate and complex relative movements of land and sea the dominant trend in relative sea level during the Lateglacial was characteristic by a fall from the Lateglacial marine limit to low levels generally thought to have occurred near the end of the Lateglacial and the beginning of the Holocene.

The second phase was of a sustained and progressive rise in relative sea level. This appears to have been due to the rate of regional glacio-eustatic sea level rise (increased ocean volumes) having exceeded the (decreasing) rate of glacio-isostatic uplift. This period of time broadly coincides with the period of extensive melting of the last ice sheets across the northern hemisphere. This phase of rapidly increasing ocean volume appears to come have come to an end after the disappearance of the last vestiges of the Laurentide ice sheet. This period of time, therefore, appears to have been dominated by a relative rise in sea level.

The final phase represents the remainder of the Holocene when continued glacio-isostatic rebound, albeit at greatly reduced rates, in conjunction with much smaller scale changes in ocean volume, led to a relative sea level fall and the production of Holocene raised beaches in the present coastal landscape.

During the field excursion we will see examples of coastal landscape responses to these three drivers of relative sea level change. We will also consider field evidence demonstrating that such a simplified scheme of change conceals important fluctuations. In considering the field evidence important differences and similarities between the pattern of relative sea level change for this area will be made through comparison with those known for western Scotland.

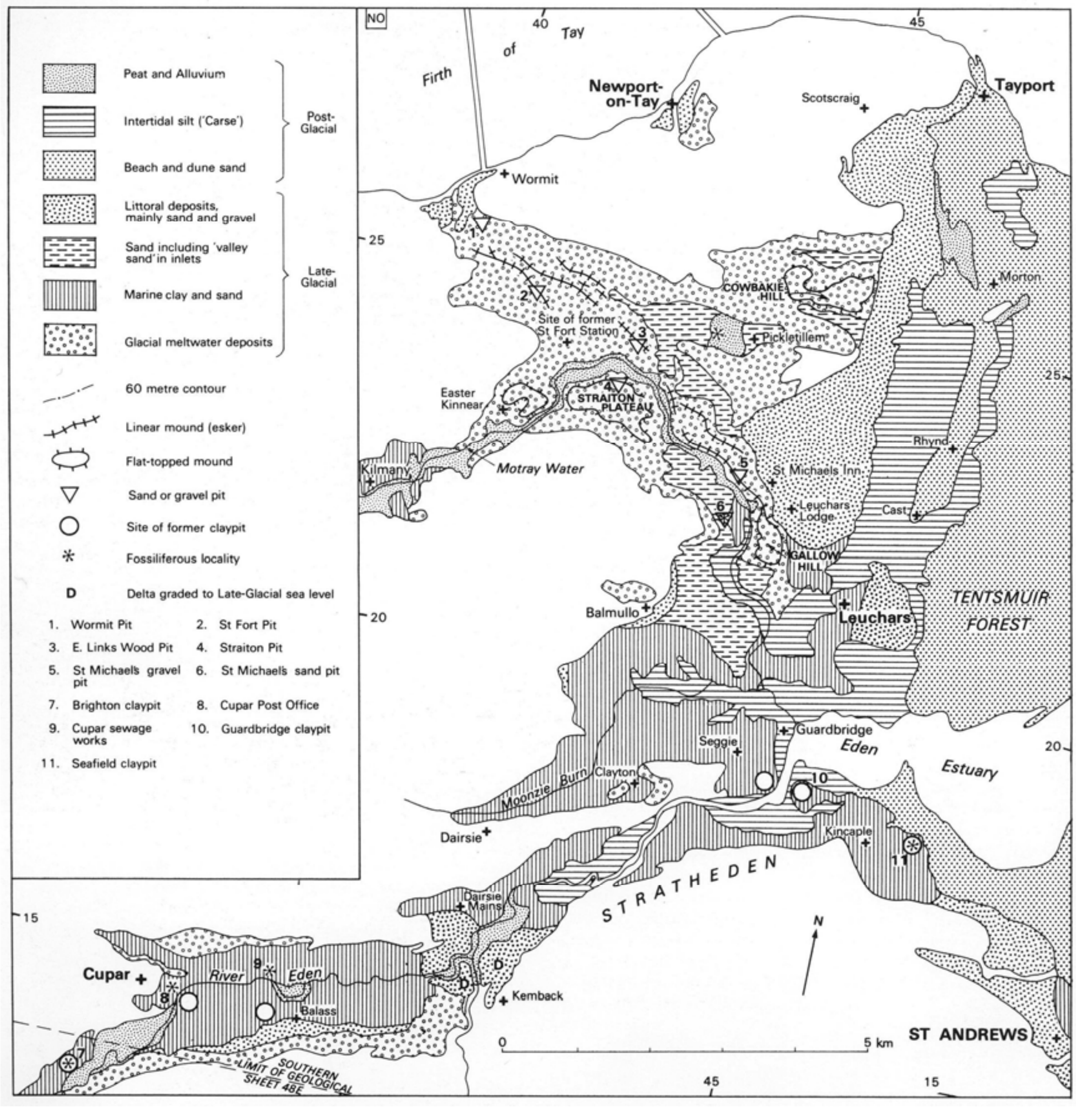


Figure 3 Shoreline height-distance diagram for eastern Fife and Tayside (after Cullingford, 1971; Cullingford and Smith 1966; Cullingford and Smith 1980; Paterson et al. 1985). Note that relative sea level fell from position of Main Perth Shoreline to Main Lateglacial Shoreline before rising to the level of the Main and Low Buried beaches.

Deglaciation and relative sea level change

Two key papers consider the early stages of regional deglaciation across Fife and the coastal areas to the north. In a classic paper, Andrews and Dugdale (1970) attempted to estimate for Fife the ages of the highest and oldest raised shoreline features based a methodology developed by him to construct shoreline relations diagrams for the Canadian Arctic. Based on the use of this method he estimated that the earliest raised shorelines in eastern Fife were produced ca. 17 kyr BP. More recently McCabe (2007) have proposed the occurrence of an episode of ice readvance at Lunan Bay near Montrose between ca. 20 – 18 kyr based on AMS dating of marine microfauna from marine mud sequences that rest beneath fluviogacial gravels.

The continued recession, thinning and stagnation of the last (Late Devensian) ice sheet was associated with the development of dead-ice features across many low-lying areas the most conspicuous of which are those north of Monifeith and in the Leuchars-Wormit areas. Early research by Rice (1961) and Chisholm (1966) demonstrated how dead ice persisted in many coastal areas long after the ice margin had retreated to inland. For example at St Michael's north of Leuchars, the most regionally well-developed shoreline, the Main Perth Shoreline, is pitted by kettle holes demonstrating that dead ice remained in this area close to former sea level when the margin of the ice sheet lay ca. 50 km farther west near Perth. Near Wormit, raised estuarine sands (the Brackmont Sands) containing *Corophium* burrows occur beneath glacifluvial sands and gravels suggesting deglaciation having taken place in association with a high-level (ca. 17 m OD) palaeoestuary (Buller and McManus 1972).

As the ice retreated westwards inland, the Lateglacial sea began to penetrate across low-lying coastal areas. Marine and estuarine sedimentation was dominated by the deposition of laminated pink clays and silts, collectively known as the Errol Beds. The fauna of the Errol Beds has been extensively studied by Peacock who has shown that sedimentation was associated with an arctic marine fauna. Raised marine sediments of a similar age also occur in areas of western Scotland where they are associated with a fauna indicative of slightly warmer, yet still cold, marine conditions.

The Errol Beds of eastern Scotland are generally regarded to predate the Windermere Interstadial (ca. 13-11 kyr). In the Tay valley they extend as far westwards as Almondbank near Perth where they are overlain by kettled fluvioglacial sands and gravels. Simpson (1933) interpreted this sediment succession as indicative of glacial readvance, known as the Perth Readvance, later adopted by Sissons (e.g. Sissons 1967). In a later paper Paterson (1974) argued that the Almondbank succession did not demonstrate the former occurrence of an ice advance and proposed that the sand and gravel sequence simply represented sediments deposited as part of a prograding delta. Thereafter the concept of a Perth Readvance was abandoned. More recently, McCabe et al. (2007) have again proposed the former occurrence of an ice readvance near Perth (but disputed by Peacock et al.).

The arguments for and against the former occurrence of a Perth Readvance is complex and is not discussed here in detail. Dating of the fossilferous Errol clays at Gallowflat Claypit in the Tay estuary by Peacock (2003) point to fully marine sedimentation by 13.8 kyr with the additional inference that deglaciation of the middle Tay estuary took place around ca. 14.5 –14.0 kyr. Whereas McCabe et al. (2007) maintain that the Perth Readvance advocated by them represents part of a more widespread glacial advance across the British Isles possibly linked to Heinrich (H1) iceberg discharge event, Peacock (2003) expresses considerable doubts.

The resolution of this area of uncertainty is extremely important in respect of understanding patterns of Lateglacial relative sea level change across Scotland. Whereas the concept of a Perth Readvance has been debated for over 70 years, the evidence for a contemporary ice readvance across western Scotland is equally unclear although Robinson and Ballantyne have presented morphological evidence for a glacial readvance in Wester Ross that is thought to have interrupted regional deglaciation. In addition the reconstruction of Lateglacial sea level changes for the Arisaig area by Shennan et al. (19xx) shows no sign of any significant fluctuation in relative across this time interval – instead relative sea level appears to have undergone a progressive and sustained fall throughout the Lateglacial until the Younger Dryas.

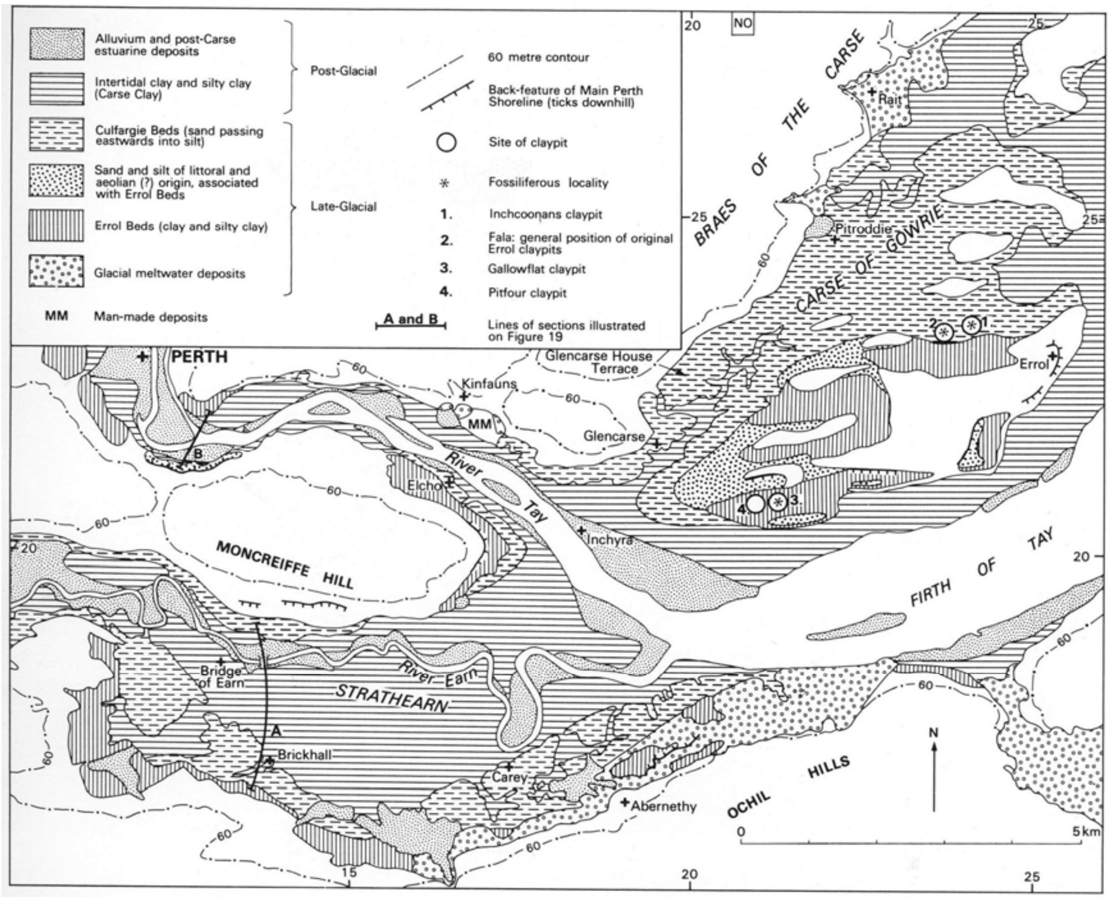


Figure 4 Quaternary deposits of Stratheden and St Fort areas (after Cullingford 1971 and Paterson 1985).

Younger Dryas and early Holocene

The nature and pattern of relative sea level changes for Younger Dryas and early Holocene in eastern Scotland is mostly based on research undertaken by Sissons and co-workers for the Forth valley. Studies of the buried stratigraphy were interpreted to indicate a fall in relative sea level that culminated in the production of a widely-developed buried erosional surface (the Buried gravel layer) considered to have been produced during the cold climate of the Younger Dryas. Sissons (1974) proposed that the Buried Gravel Layer is of the same approximate age as a well-developed raised rock platform and cliff (the Main Rock Platform) in western Scotland (e.g. Gray 1974) and that both shorelines should be referred to as the Main Lateglacial Shoreline. The key arguments used in support of a Younger Dryas age for the features are:

- that the regional glacio-isostatic tilt of both the Main Rock Platform and Buried Gravel layer are broadly similar (between ca. 0.13-0.16 m/km).

- that neither feature shows any evidence of having been overridden by glacier ice

- that both features are restricted in their occurrence to areas outside the limit of Younger Dryas glaciers. In the case of the Buried Gravel layer in the Forth valley, the shoreline can be traced eastwards as far the Menteith moraine where it grades into outwash from the Younger Dryas outlet glacier

- that both features indicate the former occurrence of marine planation in areas of restricted fetch, phenomena generally explained as the result of cold climate erosional processes.

Although the Buried Gravel layer has not been extensively mapped across Tayside and eastern Fife as a buried feature, Armstrong et al. (1985; Figure 15) describe the feature as declining in altitude broadly from W 18^0N to E 18^0S across the area. In the coastal area offshore St Andrews the shoreline is plotted as a submerged feature at ca. –10 m OD (Armstrong et al. 1985). Thus the general view is that during the Younger Dryas, relative sea level had fallen sufficiently low resulting in the production of new land areas now submerged. The shoreline isobases also indicate that the Main Lateglacial Shoreline across eastern Scotland is a buried feature with a significant glacio-isostatic tilt from approximately W (highest) to east (lowest).

In the Forth valley, the Buried Gravel Layer is overlain by a series of two buried beaches – the Main and Low Buried beaches that appear demonstrate a relative marine transgression over and across the Buried Gravel layer (Main Buried Beach) followed by a relative marine regression (Low Buried Beach). Both buried shorelines are considered to be Early Holocene in age with the Low Buried beach considered to be the younger of the two. In the Tay estuary, however, Cullingford et al. (1980) identified a buried beach beneath basal peat at Carey, lower Strathearn that they equated with the onset of organic sedimentation on top of the Main Buried beach (Main Buried Shoreline). Basal peat dates of 9640 +/- 140 C^{14} yrs BP and 9524 +/- 67 C^{14} yr BP were considered consistent with an inferred age of ca. 9600 C^{14} yr BP for the Main Buried beach in the Forth valley. Cullingford et al. (1980) also showed that at nearby Innernethy, an 80 cm-thick peat bed rests on top of silty sand of an inferred buried estuarine flat. The surface of the silty sand is considered to be cut into and at a lower altitude than the adjacent Main Buried Beach while dating of the basal peat resting on top of the silty sand surface give consistently younger ages obtained at Carey (8555 +/- 60 C^{14} yr BP and 8505 +/- 50 C^{14} yr BP) (Cullingford et al. 1980). The latter authors thus regarded that the Low Buried Beach in lower Strathearn was abandoned due to falling relative sea levels around ca. 8.6 –8.5 C^{14} kyr BP but there is no information available to demonstrate how low relative sea level fell before again rising.

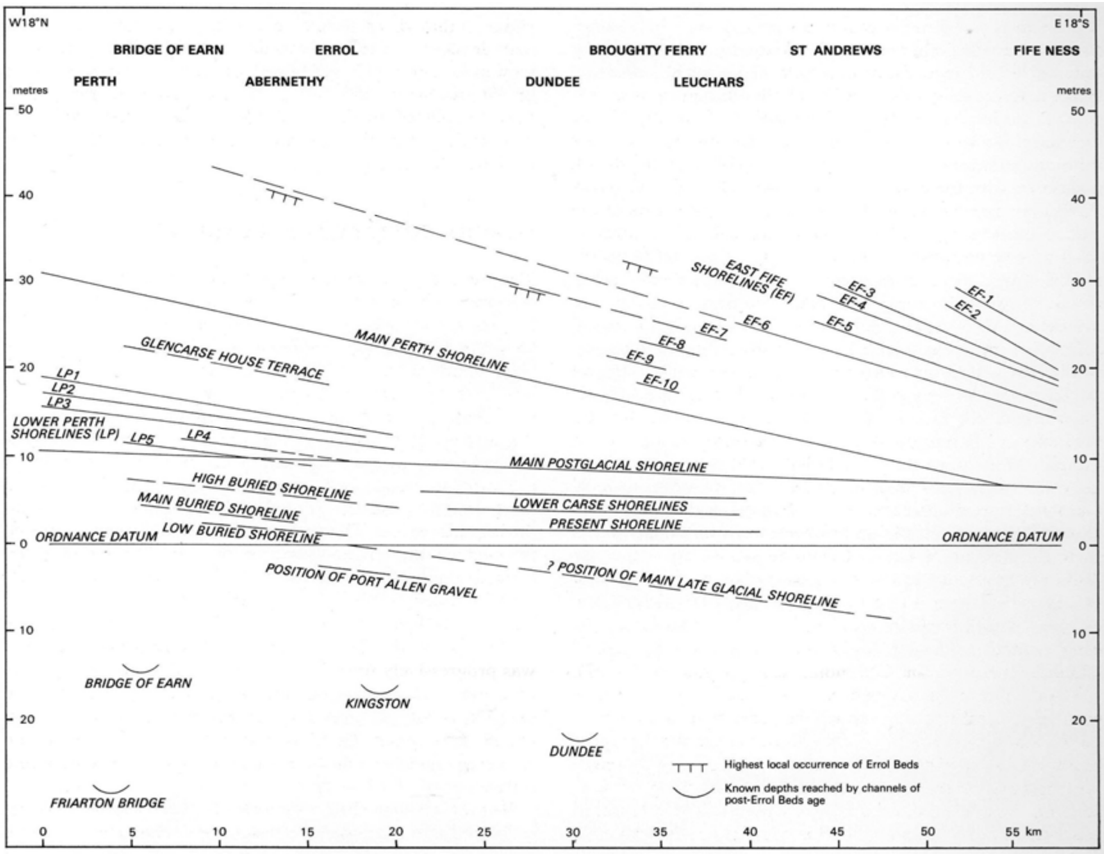
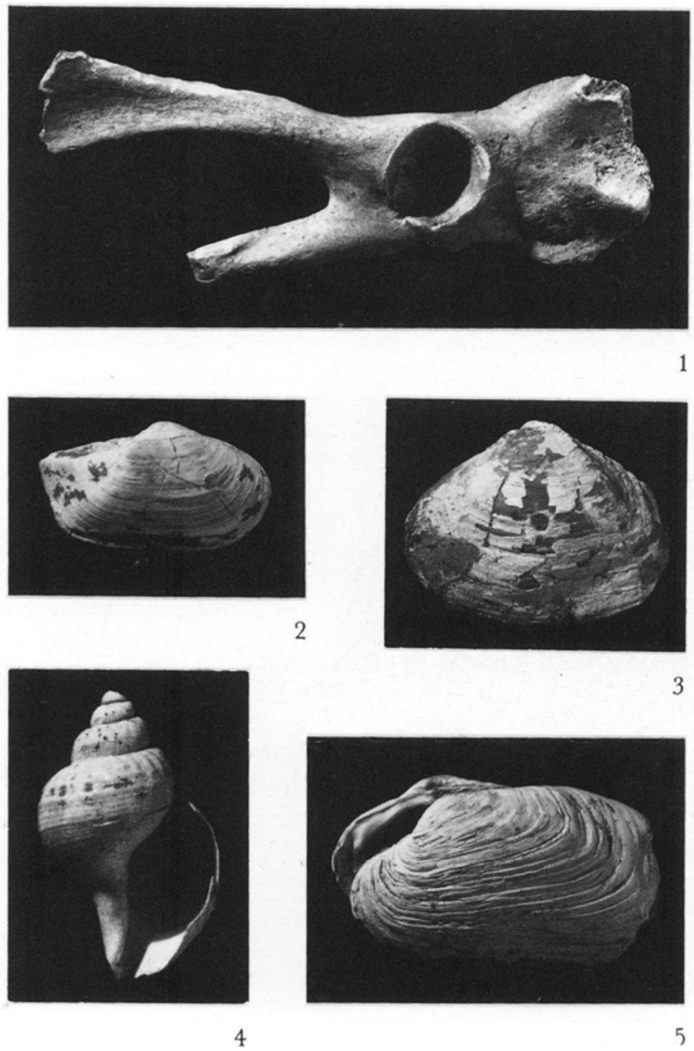


Figure 5 Quaternary deposits in lower Strathearn and the western part of the Carse of Gowrie. Note location of Errol (and adjacent Gallowflats – not shown) (after Cullingford 1971 and Paterson et al. 1985).

The buried peat that rests on both the Main and Low Buried beaches is everywhere overlain by considerable thicknesses of estuarine silts and clays, known as carse deposits that reach up to well over 10 m in thickness. The carseland surface in lower Strathearn generally occurs between +9.8 – 10.2 m OD. Across eastern Scotland the most widely developed carse surface has been mapped and described as the Main Postglacial Shoreline. The shoreline exhibits glacio-isostatic tilting and broadly declines in altitude from west to east with a regional gradient of ca. 0.06 – 0.08m/km. The morphology of the carse landscape also shows that several carse surfaces exist each cut into the other as staircases. Conventionally, the highest carse surface has been interpretetd as the oldest. For example, Cullingford et al. (1980) maintained that the principal carselands of the Tay estuary date to between ca. 7200 –5900 C^{14} yr BP.

However, for certain areas of Scotland, this view is now being challenged with younger carse sediments considered as having been deposited upon older carse sediments as a result of relative marine transgression later during the Holocene).



1 *Phoca vittulina* Linné, bone of, × 0.7, 1981.37.1
2 *Portlandia arctica* Gray, × 2,,1981.37.17
3 *Thracia* cf. *serpentrionalis* Jeffreys, × 2, 1981.37.18
4 *Buccinum cyaneum* Brugière, × 2, 1981.37.2
5 *Hiatella arctica* (Linné), × 1.4, 1981.37.12
All specimens in the Davidson Collection, Museum and Art Gallery, Perth

Figure 6 Macrofauna from Inchoonans Claypit (Errol Beds) (adjacent to Errol and Gallowflats Claypit) (after Paterson et al. 1985; for detailed information refer to Peacock 1999; 2003).

Middle to late Holocene

Sea level changes during the middle Holocene are more clearly understood and well documented for this area. Extensive carseland deposits attest to the volumes of sediment available during the early to middle Holocene. These are seen to the north of St Andrews around Tensmuir Forest and will be also be examined at the carse of

Gowrie, between Dundee and Perth (Field day 2). Holocene caves and a cliffed shoreline are present on the southern coast of Fife, one of the clearest seen to the east of Anstruther at Caiplie (see figure below).

Photo: S.Dawson

Caiplie Caves, nr Anstruther, Fife.

At the Earn-Tay confluence on Tayside, the Holocene evolution has been determined by Cullingford et al. 1980). Sub-surface deposits exposed in riverbank section sand extensive boreholes, coupled with a comprehensive dating program to create the only relative sea level curve for the Tay area (see enclosed paper).

Details of the Holocene stratigraphy for Fife has been determined from Silver Moss, St Michael's Wood, to the north of St Andrews (Chisholm, 1971; Morrison et al., 1981; Smith, in Gordon and Sutherland, 1993). Studies concerning the development of the Main Postglacial Shoreline, formed at the maximum of the Main Postglacial Transgression are well preserved within small peat mosses which occupy former gullies which are thought to have formed sheltered embayments when sea level stood at the Main Postglacial Shorleline. Extensive areas of raised estuarine silt, clay and sands extend toward the Tay Estuary and south to St Andrews. The Shoreline, located at 7- 9m OD lies at the inland limit of the deposits at the break of slope. Chisholm (1971) obtained radiocarbon dates on samples of peat (15cm thick) which enclose the silts and clays within the gully and gave 5830±110 BP above and 7605±130 BP below. Further dating and extensive stratigraphic work undertaken by Morrison et al. (1981) traced a tapering wedge of silt and clay to their inland limit within the peat. A distinctive tapering sand unit was also mapped, dated to 7555±110 and 7050±100 BP and attributed to extreme marine incursion, later identified as the Second Storegga Slide Tsunami (see review in Smith et al., 2004). The base of the surface peat was dated to 5890±5 BP (Morrison et al. 1981) corroborating Chisholm's earlier date of

5830±110 BP. Thus, the deposits within St Michael's Wood record the culmination of the Main Postglacial Transgression.

Further sites around the Eden estuary in Fife record many stratigraphic sections and boreholes undertaken by Chisholm (1971) attest to the evolution of the Holocene relative sea level in the area. Lack of radiocarbon dates to constrain the age of these widespread deposits again hinder the understanding of broad areas of former coastline in the Eden estuary area. Many of the sites described by Chisholm are under investigation at present by the authors (S Dawson and AG Dawson) and palaeoenvironmental reconstruction coupled with AMS dating over the next few years will allow the limited dates available for Fife to be placed in their wider context. We will examine the stratigraphy of some of these sites within the Eden Estuary during the Field meeting.

Holocene dunes are also extensively developed at St Andrews Links, where a cuspate foreland is developed and will be visited during Field Day 1 (see figure below). However, lack of detailed study and a robust chronology hinder understanding of the coastal evolution of this area.

Photo: S.Dawson

View to N of St Andrews and links.

Widespread dune formation is also seen at Tensmuir Forest where forestry commission planting in the 1920s make the interpretation of the dune suites more difficult and lack of radiocarbon dates make evolution speculative.

Wider comparisons

The only detailed curve of relative sea level change that has been constructed for eastern Scotland outside of the Forth valley is that of Cullingford et al. (1980) (Figure xxx). The curve, that does not include any Lateglacial data, shows a progressive yet slight decline in relative sea level through the periods of formation of the Main and Low Buried beaches. After relative sea level had fallen after the formation of the Low Buried beach to an altitude low enough (but by an unknown amount of fall) to permit the accumulation of peat, relative sea level began to rise. Dating of the timing of the rise at different locations is dependent on the altitude of the junction between the top of the buried peat and the base of the overlying carse. Considered together, these dates demonstrates the former occurrence of an exceptionally rapid rise in relative sea level that , according to Cullingford et al. (1980) led to a rise of over 9 m within a relatively short period of time.

The Shennan et al. (1996) reconstruction of Lateglacial and Holocene sea level change for the Arisaig area of western Scotland show some important differences with studies of past changes in relative sea level for eastern Scotland that, to date, have never been discussed:

- The Arisaig analysis shows no indication of the existence for the early Holocene of a Buried Beach sequence similar to that described for the Tay (and Forth) estuaries.
- The low point of relative sea level occurs much earlier at Arisaig than in Tayside – although this difference may in part relate to improvements in dating methods over the last 20 years
- There appears to be no trace in the Arisaig stratigraphy of a relative marine transgression during the Younger Dryas. Yet the formation of the Buried Gravel layer in the Forth valley during the Younger Dryas has always been considered to have been a relative marine transgression, or at the very least a period of relative sea level stability during which widespread marine planation could take place (note that this part of the chronology has never investigated for the Tay and Earn areas).

Tsunami Deposits

At a number of locations along the east coast of Scotland, a deposit of silty fine sand occurs "sandwiched" within carse sediments while elsewhere it is enclosed within peat. The stratigraphic unit at some location is as thick as 50 cm while elsewhere it is no thicker 0.5 mm with a typically massive structure with only rare indications of sedimentary bedding or lamination. The unit has everwhere been shown to contain marine diatoms dominated by the species *Paralia sulcata* the majority of which are fractured and indicative of deposition under high energy conditions. (Dawson et al. 1996). The stratigraphic boundary between the base of the deposit and the top of the underlying sediments is always represented by an unconformity with local shear structures. In addition, intraclasts derived from the underlying sediments (sands, silts, clays and/or peat) frequently occur within the high-energy deposit. The sedimentary unit has been dated most commonly dated by radiocarbon assay and most recently by optically stimulated luminescence (OSL) dating (see Robinson, this volume) (for summary see Smith et al. 2004). Whereas dating of the top of the basal peat has proved notoriously unreliable due to the presence of an unconformity, the dates that have mostly been used to date this extreme event have been for the base of the overlying peat (for most locations where the deposit occurs within carse clays dating has been by OSL). The majority of these point to a conventional C^{14} age of 7200 yrs BP, equivalent to a calibrated age of ca. 8000 yrs BP (Bondevik et al. 2003; Bondevik et al. 2005).

The sedimentary unit was originally considered as the product of a major storm surge (Smith et al. 1985) but later interpreted as due to a large tsunami generated by one of the world's largest underwater sediment slides, the Storegga Slide , that took place at this time on the continental slope west of Norway (Dawson et al. 1988). Support for this view is provided by by the occurrence of similar deposits of the same approximate age having been recognised along most coastlines bordering the Norwegian Sea, northern North Atlantic and North Sea (Bondevik et al. 2005; Smith et al. 2005). For Tayside and eastern Fife, the most well-known site where the tsunami horizon can be observed is at Montrose (Smith et al. 2004). Additional locations include St Michael's Wood at Tentsmuir (Haggart 19780, the Hole of Clien (Tay estuary) (Smith et al. 1985b; Smith 1993), lower Strathearn (Cullingford et al. 1989; Dawson et al. 1989) and Cocklemill Burn (see Robinson (this volume) and Tooley and Smith (2005) (also this volume).

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APPENDIX

Kincraig and the Cocklemill Burn

D.E.Smith and M.J.Tooley

Introduction

The area around Kincraig Hill and the Cocklemill Burn has been a focus of interest in coastal and sea level change in Scotland for over 150 years. The profile of Kincraig Point, with its terraces (Figure 1), is a well-known feature of the coastal landscape of Fife, while the many sections along the left bank of the Cocklemill Burn and along the adjacent coast disclose records of sedimentary environments extending at intervals from the Late Devensian to the present. This is an area in which relative sea level changes may be identified from both morphological and stratigraphical evidence.

Geology and setting

The reader is referred to the attached paper by Tooley and Smith (2005) for a summary map of the location of the features and deposits which will be visited in this area. The area is dominated by the 1.5km long ridge of Kincraig Hill, rising to over 200m OD. Kincraig Hill is a volcanic neck of Upper Carboniferous or Permian age composed of bedded tuffs and agglomerates including blocks of basalt and with two feeder channels marked by basaltic intrusions and masses of basaltic breccia, viewed in section along the steep cliffs and rock platform to the south. To the north, the solid geology consists of calacreous sandstones, also of Carboniferous age and with a basaltic intrusion at Ruddons Point (Forsyth and Chisholm, 1977). The area is marked by Late Devensian and Holocene terraces, largely of marine origin, surrounded and partially overlain by areas of blown sand, probably of late Holocene origin.

Morphology: the terraces

The terraces on Kincraig Hill were interpreted as belonging to the 25-foot, 50-foot and 100-foot "raised beaches", favoured in early Geological Survey maps, by Geikie (1902). More recently, the area was examined by Smith (1965), who identified the terraces shown in Figure 2 of Tooley and Smith (ibid.). These features were interpreted as erosional features. Measured at their inner margins, their altitudes are respectively 24.5m, 21.9m, 10.6-11.6m and 3.7-4.0m Ordnance Datum Newlyn (OD). To the south of Kincraig Hill, an inter-tidal rock platform occurs, although the altitude of this has not been measured. Mean High Water Spring Tides at the nearest tidal station, Anstruther, is at 2.9m OD.

Cullingford and Smith (1966) correlated the highest two terraces on Kincraig Hill with the most recent shorelines of their Late Devensian sequence, shorelines EF 5 (at 24.5m) and EF6 (at 21.9m), but did not base their terrace sequence on these terraces, preferring to correlate only clearly depositional features. Later, Cullingford and Smith (1980) correlated EF5 and EF6 with their Angus-Kincardine shoreline sequence, equating EF5 with DS5 and EF6 with DS6. Andrews and Dugdale (1970) estimated the age of the full shoreline sequence of Cullingford and Smith (ibid.) at 18,250 to 15,100 BP, but Sissons (1976) later revised the age estimate to 17,600 to 14,750 BP (it is not stated in these accounts whether these estimates are in radiocarbon years or sidereal (calendar) years BP). Cullingford and Smith (1966; 1980) maintained that the terrace sequence was developed in association with a westwards-retreating ice margin, and recently McCabe et al. (2007) have maintained that to the North-East of the area here, at Lunan Bay, there is evidence of a readvance of ice sometime between 20,200 and 17,500 sidereal years BP. Given that the shoreline sequences of Cullingford and Smith were developed at a time of progressive deglaciation and continuous uplift, it seems that the ages of the two upper terraces on Kincraig Point are later than that of the Lunan Bay Readvance.

Smith et al. (1969) correlated the third terrace (10.6-11.6m OD) with their Main Perth Shoreline. The Main Perth Shoreline was correlated with the Perth Readvance limit at Stirling by Sissons and Smith (1965), but the status of the Perth Readvance was called into question by Patterson (1974) and the concept abandoned by Sissons (1974). However, the concept of the Perth Readvance has recently been reasserted by McCabe et al. (2007), and an age of sometime between 17,500 and 14,500 calendar years BP maintained. If this is correct, the third terrace at Kincraig may have been developed and abandoned around that time. The rock platform and lowest terrace around Kincraig Hill have not been correlated with any shoreline: the terrace (at 3.7-4.0m OD) because it is erosional; but it seems likely that this belongs to the Holocene Blairdrummond Shoreline of Smith et al. (2006), on the basis of Gaussian trend surface analysis and dated at 4500-5800 sidereal years BP.

Stratigraphy: the Cocklemill Burn

Description. The sections along the Cocklemill Burn have long attracted attention (e.g. Brown, 1867; Etheridge, 1881; Bell, 1890, 1892; Geikie, 1902). Here, *limus* occasionally exposed at an intertidal level, is overlain by a sequence of Holocene estuarine/marine sands and by blown sand. At intervals along the burn a purple clay with shells, probably of Late Devensian age, is exposed. The clay probably underlies the peat and its fauna is of a high arctic environment. Within the marine/estuarine sands, the fauna is of a temperate environment. The full details of the Holocene fauna, determined by Professor David Keen, are given in Tooley and Smith (2005).

The detailed stratigraphy from a 7 metre exposure is described by Tooley and Smith (ibid.), and that paper should be referred to for a full description. The description here is a summary only. Thus a basal sand of at least 0.27m is overlain by 0.38m of *limus,* in turn overlain by fine to coarse sand, the base containing intraclasts of organic material. Above the fine to coarse sand, an horizon of coarse sand and gravel with re-deposited shells and shell fragments together with intraclasts of organic material (Figure 2) is in turn overlain by bioturbated horizons and stratified shelly sand beds. Table 1 summarises the radiocarbon dates obtained from this section.

Table 1 Radiocarbon dates from the Cocklemill Burn Section

Lab. Code	Material	Altitude, OD	^{14}C age, BP	Calibrated age, BP, 2σ
Beta 179976	Shell	+6.69	5090±80	5600-5280
Beta 179975	Shell	+4.46 to +4.44	7620±60	8180-7940
Beta 169869	Shell	+2.49 to +2.44	7820±80	8360-8180
Beta 179974	*Limus*	+1.08 to +1.07	7970±40	9000-8640
Beta 179973	*Limus*	+0.81 to + 0.77	8750±40	9570-9900

Interpretation. At the base of the sequence, the sand was probably gradually replaced after circa 9700 sidereal years BP by a *limus* , which then continued to develop until circa 8800 BP, when it was eroded and sands began to accumulate at the site. During this accumulation, a high energy deposit (shown in Figure 2) was laid down. The shells from this deposit, clearly re-deposited, must pre-date the event in age. Their ages should have 405±40 radiocarbon years subtracted to accommodate the marine reservoir effect, and an age for this event of circa 7215 radiocarbon years BP (circa 8120 sidereal years BP) is suggested. It seems likely that this deposit may have accumulated during the Holocene Storegga Slide tsunami (Smith et al., 2004) in the area. The top stratum at the site, dated at 5090±80 (subtracting 405±40 gives 4685±120, thus 5652-4998 sidereal years BP) was probably deposited at the time of the Blairdrummond shoreline.

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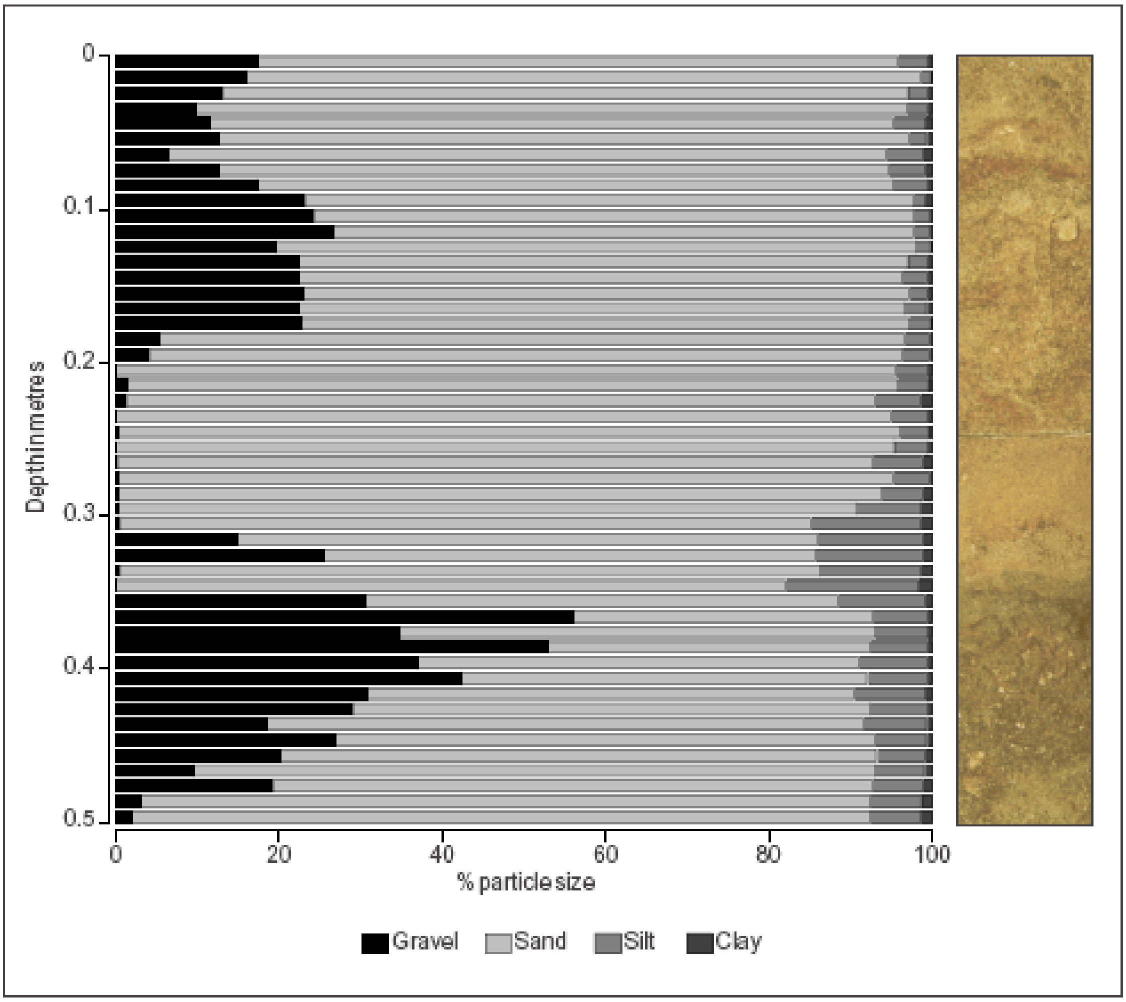


0
0.1
0.2
0.3
0.4
0.5
Depth in metres
0
20
40
60
80
100
% particle size
Gravel
Sand
Silt
Clay

Cocklemill Burn

OSL chronology of Holocene shallow marine and raised shoreline deposits at Cockle Mill Burn, East Fife

This is a short introduction to OSL and ^{14}C unpublished dating work conducted at the University of St Andrews by Katie Overshott (in an undergraduate dissertation) with Ruth Robinson and Jack Jarvis. Bill Austin and Margaret Donaldson collaborated on the palaeoenvironmental analyses of pollen from a peat horizon and foraminiferal assemblages in sediments. We acknowledge the helpful and fruitful discussions with Barbara Mauz at Liverpool who has conducted a similar OSL dating project.

Our chronology (OSL and ^{14}C) is not compatible with recent work by Tooley and Smith (2005). We present our dates (and theirs) for comparison.

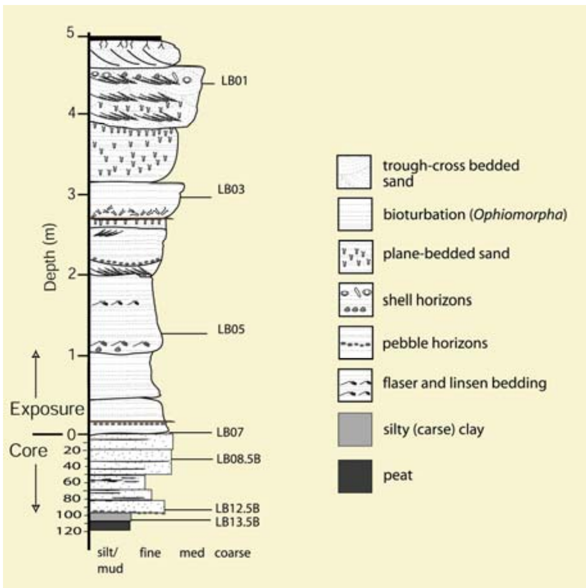


Figure 1. Cocklemill Burn exposure and core site. Schematic sedimentary log with facies descriptions.

Methods

The section analysed, measured and sampled contains 4.8 m of exposed sand directly overlying a 1.3m core (photo and schematic sedimentary log provided). Twenty-six samples were collected for grain-size analysis and seven samples have been dated using OSL. Additionally, one sample from the top 1cm of the basal peat (see log) was separated and *Menyanthes* seeds were extracted for ^{14}C AMS dating. Nine pollen samples were analysed from the peat and seven sediment samples from the core were analysed to identify foraminiferal size and assemblages. All analyses, including OSL dating, were conducted at the University of St Andrews.

Palynology and foramineral analyses

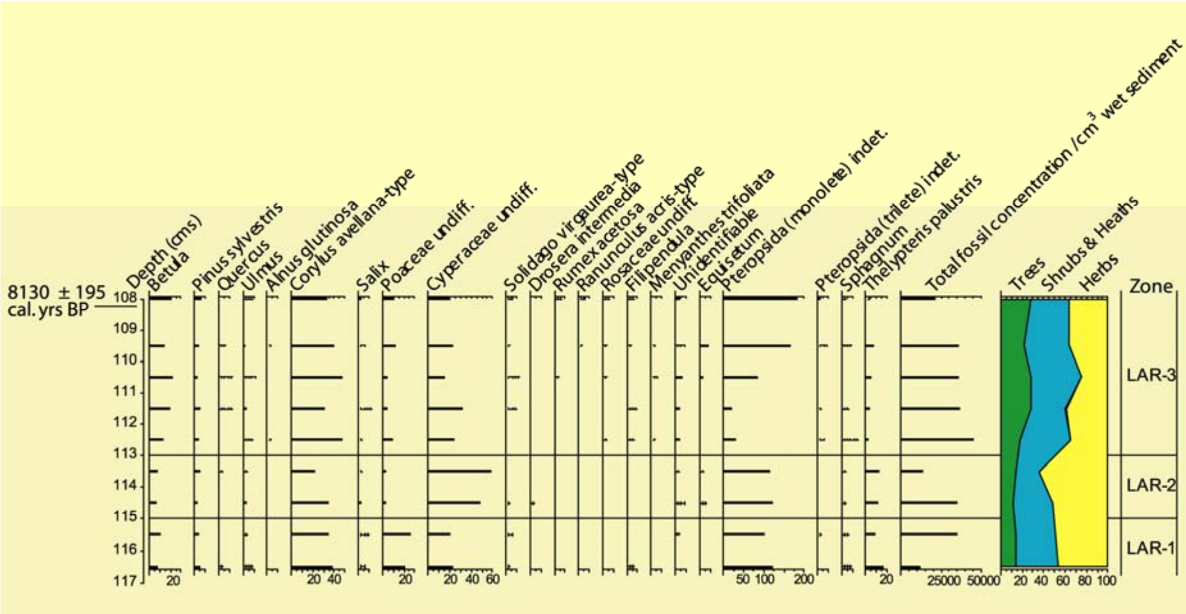


Figure 2. Palynology of basal peat (9cm): AMS ^{14}C date from top 1 cm slice of peat

Figure 2 is a Pollen diagram for nine 1 cm slices of peat extracted from the core and a species/palaeoenvironmental interpretation of the data. The AMS ^{14}C radiocarbon date of 8130±195 cal. yrs BP is from ANU and is of *Menyanthes* seeds extracted from the top 1cm of the peat.

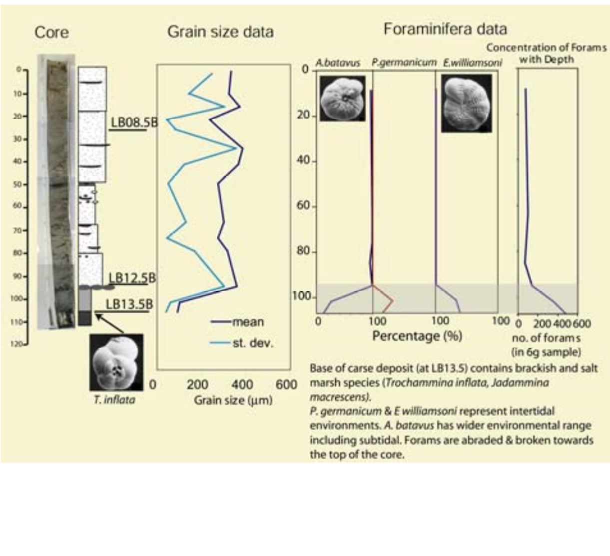
Palaeoenvironmental Interpetation

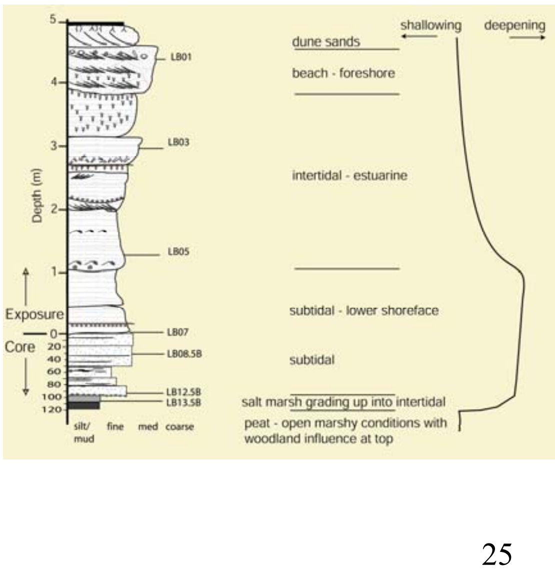
The peat contains three phases distinguished from the pollen assemblages;

LAR-3 Hazel & birch increase relative to herbaceous and pollen concentrations double. Both marshy and sandier drier species present.

LAR-2 No grasses, sedges expand and hazel declines towards top. First occurrence of elm (8300-8400BP)

LAR-1 Open marshy conditions with adjacent woodland





The carse deposit overlying the peat contains brackish and salt marsh species (*T. inflata and J. macrescens*), as well as intertidal species *P. germanicum* and *E. williamsoni* at its base, but these species are replaced by *A. batavus* which has wider environmental range, including subtidal. We conclude that the core sequence shows a transgression from peat, to marsh and brackish environments followed by intertidal and finally subtidal environments.
Based on the sedimentary facies and grain size, the exposed sequence has been interpreted in terms of depositional environment. We suggest that the base of the exposed section (at ~2.8m OD, if visible on the trip), represents peak transgression and the remaining top of the section represents an overall shallowing coarsening upwards sequence from subtidal (lower shoreface), intertidal-estuarine and beach or foreshore settings. The sequence is capped by dune sands.

OSL Chronology

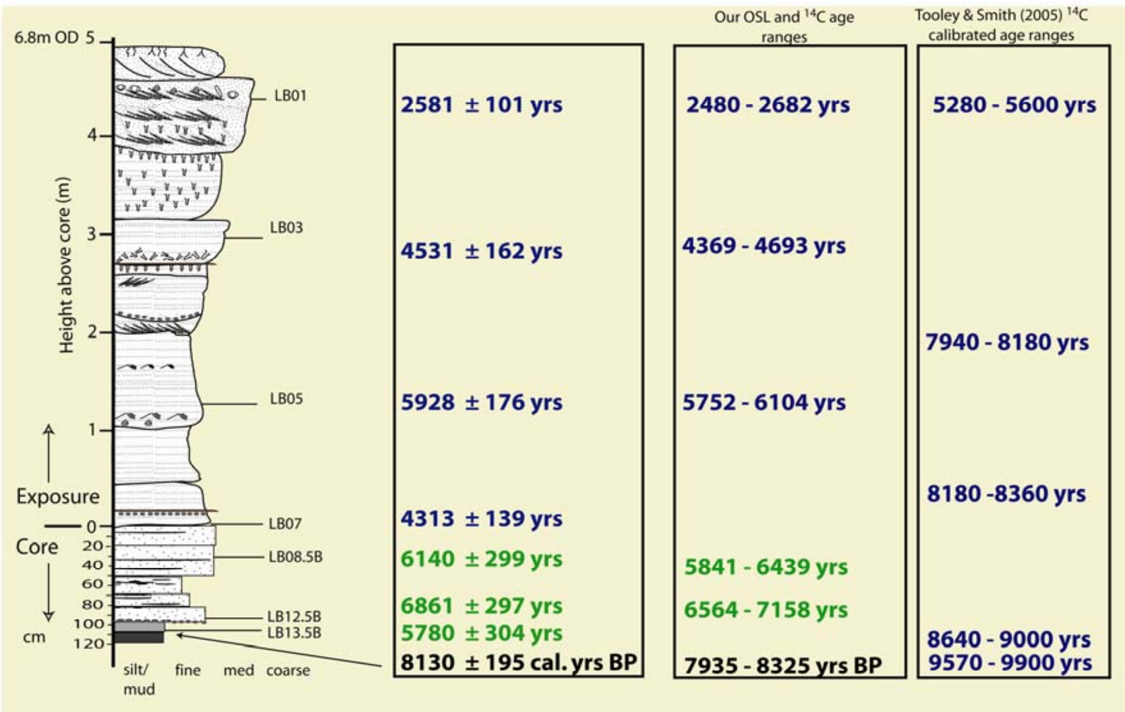


Figure 4. OSL and ^{14}C ages for core and exposed section for our unpublished work and a comparison to the calibrated ages published in Table 2 of Tooley and Smith (2005).

OSL methods are not discussed in detail here (e.g., Murray and Wintle, 2006). We used the single aliquot regeneration protocol on 180-212mm quartz fractions and standard aliquots (~5mm diameter).

Chronology:
^{14}C - the Early-Mid Holocene peat underlying carse clays (grey unit in sedimentary log o Fig. 4) is found at other coastal sites in Fife (e.g., Tooley & Smith 2005). Our age range of 7935-8325 cal. yrs BP from seeds extracted from the top of the peat is younger than the ^{14}C AMS ages of Tooley and Smith (2005). The 8130±195 cal. Yrs BP age constrains the onset of transgression (an index point).
OSL – There are two OSL ages that represent stratigraphic reversals in this section. Sample LB13.5B (5780±304 yrs) was collected just above the peat (possible

dosimetry effects) and sample LB07 (4313±139 yrs) is located at the base of the exposure (possible variable water content effects). The five remaining samples range in age from 6861±297 yrs to 2581±101 yrs and the ranges for each sample are given in Figure 4; they are also all younger than the dates presented by Tooley and Smith (2005). We therefore interpret our anayses and dates indicate that transgression started at 8130±195 cal. Yrs BP, that peak transgression occurred at ~6ka, that two unconformities exist in the section (one c. 6ka and a second between 4.5 and 2.5 ka), and that marine deposits overlie the second unconformity.

Reference

Tooley, M.J. and Smith, D.E. (2005). Relative sea-level change and evidence for the Holocene Storegga Slide tsunami from a high-energy coastal environment: Cocklemill Burn, Fife, Scotland, UK. Quaternary International, 133-134, 107-119.

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Early Flandrian land and sea-level changes in Lower Strathearn

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The morphological and stratigraphic studies reported here relate to early Flandrian relative sea-level changes in the carselands, or Postglacial raised estuarine flats, of Lower Strathearn. These data coupled with the study and dating of associated environmental changes by pollen and diatom analysis and radiocarbon assay, have enabled graphs of relative sea-level changes and land uplift to be constructed.

The carselands are backed by the Main Postglacial raised shoreline, whose local altitude is 9.8–10.2 m OD (ref. 1), and whose ^{14}C age has been determined elsewhere in east-central Scotland to be in the range 5,900–7,200 yr BP (refs 2–4). The carse deposits, consisting of estuarine silt and clay, vary in thickness from a thin veneer to well over 10 m, and are extensively underlain by a bed of terrestrial peat, which in turn rests on sandy estuarine deposits. The surface of the latter is shown by more than 250 boreholes sunk by the authors to form a staircase of buried steps separated from each other by distinct bluffs, the foot of each bluff representing a buried raised shoreline.

These morphological and stratigraphic relationships, which are broadly similar to those established in the Forth carselands[5,6], suggest the following sequence. A Lateglacial and early Flandrian phase of generally falling relative sea level was punctuated by stillstands and/or transgressive episodes resulting in the formation of what are now buried raised estuarine flats in descending order of age and altitude, the abandonment of the flats being followed by the growth of vegetation, including peat. Later, relative sea level rose again, causing the progressive burial of the peat-covered flats, in ascending order, by the carse deposits, and culminating in the formation of the extensive carseland surface visible today.

The 15 ^{14}C dates from six sites used in constructing the relative sea-level and land uplift curves (Figs 2 and 3) are listed in Table 1, and the locations of the sites are shown in Fig. 1. The data include two ^{14}C dates relating to the culmination of the Main Postglacial transgression at Glencarse[7] (site 6), in the Carse of Gowrie, as this site is close to, and lies on the same Main Postglacial Shoreline isobase as, the Carey–Cordon area[1].

At Carey (site 1, Fig. 1) a 59 cm-thick bed of highly-compressed peat rests on medium sand, and is overlain by >6 m of carse deposits. The pollen record established by analysis of samples at 1–2 cm intervals throughout the peat and the upper 7 cm and lower 6 cm of underlying and overlying estuarine sediments contains no suggestion of any gaps in the depositional record. Although few unambiguous indicators of a salt-marsh environment are present, a reed-swamp succession may be suggested, especially at the basal transition, by the high frequencies of Gramineae pollen (up to 70% of 500 total land pollen). These are interpreted as reflecting the presence of *Phragmites*, of which there is also macroscopic evidence. The diatom assemblage of the basal 12 cm of carse deposits is dominated by several species of *Fragilaria*, averaging >70% of the total count (1,000 valves). In common with sites 2–5, diatoms are abundant only within and above the peat-carse transition, and the buried estuarine deposits contain only small numbers, which include both marine and brackish-water taxa. The base of the peat (altitude 3.2 m OD) at two different places along the same exposure has been dated at 9,640 ± 140 yr BP (I-2796)[1,9] and 9,524 ± 67 yr BP (SRR-72)[8], giving the approximate date of initiation of peat growth following the withdrawal of estuarine conditions (point 1a, Fig. 2). Pollen evidence confirms this date, with *Betula*, *Juniperus* and *Filipendula* all

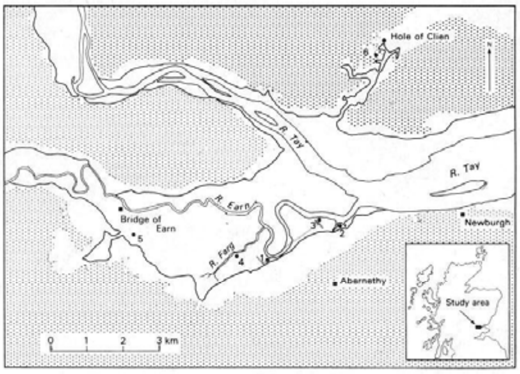

Fig. 1 Location of sites: 1, Carey; 2, Innernethy; 3, Cordon; 4, Culfargie; 5, Kintillo; 6, Glencarse. The heavy, continuous line represents the Main Postglacial Shoreline, marking the inner edge of the carselands. Land above 15 m OD is stippled.

present in the basal peat samples, as has been found at Main Buried Beach sites in the Forth valley[10,11]. As the Carey exposure is located close to the buried shoreline (altitude 3.2 m OD) the ^{14}C dates must relate closely to the abandonment of the latter, especially the one derived from the basal 1 cm of peat (I-2796). The Carey buried shoreline is believed to correlate with the Main Buried Shoreline of the Forth valley[5,6], which has been similarly dated at about 9,600 yr BP. (J. B. Sissons, personal communication). The top of the peat at Carey (present altitude 3.8 m OD) gave radiocarbon ages of 7,605 ± 180 yr BP (NPL-127)[1,9] and 7,778 ± 55 yr BP (SRR-71)[8], dating the onset of peat burial beneath the carse deposits (1b, Fig. 2). (Note that in ref. 9, the I-2796 date was erroneously recorded in yr BC instead of yr BP.)

At Innernethy (site 2) an 80 cm-thick peat bed rests on the silty sand of an extensive buried estuarine flat. The latter is next below the Carey feature in the staircase of buried flats, and site 2 is located adjacent to the buried shoreline (altitude 2.8 m OD). A 1 cm-thick peat band that occurs within the buried estuarine deposits, 18 cm below the base of the main peat bed, demonstrates that the buried shoreline was formed at the culmination of a transgression. The ^{14}C ages of this thin peat band (2a, Fig. 2; altitude 2.7 m OD) and the base of the main peat bed (2b; altitude 2.8 m OD) date this culmination to between 8,555 ± 60 (SRR – 1399) and 8,505 ± 50 yr BP (SRR-1398). These dates are statistically indistinguishable at the 95% level from the only published date of 8,690 ± 140 yr BP (I-1839)[4,6,10] relating to the Low Buried Beach in the Forth valley, with which the Innernethy buried flat should correlate by morphological analogy. This may imply that the Low Buried Shoreline was abandoned about 8,500 or 8,600 ^{14}C yr ago, rather than the 8,800 yr usually quoted[6,13], a possibility that is reinforced by the basal peat date at site 3. Apart from a brief appearance of Chenopodiaceae corresponding to the thin peat band within the buried estuarine deposits, the only apparent vegetational succession is at the peat–carse boundary, where a sequence of freshwater environments may be indicated before the onset of carse deposition (2c; present altitude 3.6 m OD) at about 7,530 ± 50 yr BP (SRR-1397). The diatom record in the carse deposits suggests marine and brackish water conditions, as indicated by *Paralia sulcata* (Ehrenberg) Cleve, *Rhaphoneis surirella* (Ehrenberg) Grunow ex Van Heurck and *R. amphiceros* (Ehrenberg) Ehrenberg[12].

At Cordon (site 3) a riverbank exposure at the front of the same buried flat on which site 2 is located shows a similar stratigraphy to that at site 1 (ref. 1). At both transitions the appearance of Compositae, Chenopodiaceae, *Plantago* sp., *Filipendula*, Rosaceae, *Typha angustifolia* and Lemnaceae may

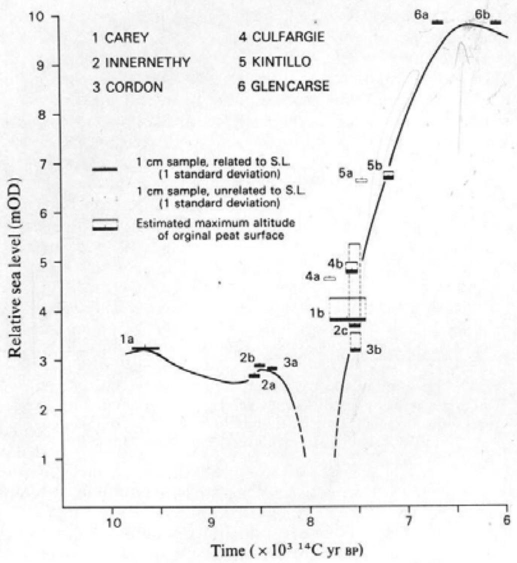

Fig. 2 Early Flandrian relative sea-level changes in the Carey–Cordon area, Lower Strathearn. Horizontal bars extend one standard deviation either side of the ^{14}C dates.

indicate a succession of salt-marsh and freshwater communities as suggested in the Forth valley[11]. Marine and brackish water diatoms are prevalent within the basal carse assemblage with *Paralia sulcata* and *Rhaphoneis surirella* averaging over 50%. The basal peat date (3a, Fig. 2; altitude 2.8 m OD) is 8,370 ± 45 yr BP (SRR-1147), suggesting the removal of estuarine conditions slightly later than at site 2. This indicates abandonment of the frontal edge of the estuarine flat at a measurably later date than that of the shoreline 1 km to landward. The reappearance of estuarine conditions and initiation of peat burial (3b, Fig. 2; present altitude 3.2 m OD) occurred about 7,525 ± 50 yr BP (SRR-1394).

The basal peat dates at sites 1–3 all relate closely to the abandonment of two now-buried estuarine flats, the older and higher of which is the Carey flat. Three distinct buried steps occur above the Carey feature, and the rather thin peat on two of them has been dated at sites 4 and 5 (Fig. 1, Table 1). These higher buried steps are necessarily older than the lower ones already considered, yet the basal peat dates are much younger than at sites 1–3, and in fact differ little from the ages of the topmost peat layer at the latter sites. This suggests a lengthy hiatus between abandonment of the flats and the start of peat growth, and that the latter was a response to the rising ground-water level associated with the Main Postglacial transgression. The basal peat dates (4a and 5a, Fig. 2), although associated with marine transgression, cannot therefore be related to specific relative sea levels, and the higher buried flats remain undated.

Thin compacted peat at Culfargie (site 4) and Kintillo (site 5), 19 cm and 8 cm thick respectively, rests on fine sand and is overlain by 1.6 m and 3.5 m respectively of carse silty clay. Increased evidence of aquatic taxa is evident in the carse deposits at both sites and at Kintillo a sequence of freshwater and salt-marsh communities is suggested similar to that found at Cordon. Marine influence in the carse is also indicated by the abundance of *Paralia sulcata*. The basal peat dates at Culfargie (4a, Fig. 2; present altitude 4.6 m OD) and Kintillo (5a, present altitude 6.6 m OD), of 7,780 ± 50 yr BP (SRR-1396) and 7,465 ± 55 yr BP (SRR-1401) respectively, are verified by the high values for *Corylus*/*Myrica* pollen. Transgression of the peat surface occurred around 7,555 ± 50 yr BP (SRR-1395) at Culfargie (4b, Fig. 2; present altitude 4.8 m OD) and 7,180 ± 55 yr BP (SRR–1400) at Kintillo (5b, Fig. 2; present altitude 6.7 m OD).

In using peat-top dates to construct a relative sea-level curve account must be taken of the peat compaction that accompanied and followed burial by the carse deposits (compaction of the sandy sub-peat materials is assumed to have been negligible). Peat compaction at sites 1, 2 and 4 was estimated by comparing the mean dry bulk density value for an uncompacted monocotyledonous peat at Hole of Clien (NO 2034 2291), in the Carse of Gowrie, with similarly derived values for the buried peats in Lower Strathearn, on the assumption that the fossil peats, before burial, had a comparable bulk density to the surface peat, and that the amount of subsequent compaction is directly proportional to the increase in bulk density. To allow for variations

Table 1 Summary of details of radiocarbon-dated sites in Lower Strathearn

Point no.	Site	Nat. grid ref.	Sample location	Altitude (m OD)	^{14}C age (yr BP) (uncorrected)	Lab. ref.
1a	Carey*	NO 1717 1710	Base of buried peat	3.19	9,640 ± 140	I-2796
1a		NO 1747 1703	Base of buried peat	3.19	9,524 ± 67‡	SRR-72
1b		NO 1717 1710	Top of buried peat	3.78	7,605 ± 180	NPL-127
1b		NO 1747 1703	Top of buried peat	3.78	7,778 ± 55‡	SRR-71
2a	Innernethy†	NO 1899 1783	Thin peat layer in silty sand beneath buried peat	2.66	8,555 ± 60	SRR-1399
2b		NO 1899 1783	Base of buried peat	2.84	8,505 ± 50	SRR-1398
2c		NO 1899 1783	Top of buried peat	3.64	7,530 ± 50	SRR-1397
3a	Cordon*	NO 1845 1813	Base of buried peat	2.80	8,370 ± 45	SRR-1147
3b		NO 1845 1813	Top of buried peat	3.16	7,525 ± 50	SRR-1394
4a	Culfargie*	NO 1625 1717	Base of buried peat	4.60	7,780 ± 50	SRR-1396
4b		NO 1625 1717	Top of buried peat	4.79	7,555 ± 50	SRR-1395
5a	Kintillo†	NO 1348 1766	Base of buried peat	6.60	7,465 ± 55	SRR-1401
5b		NO 1348 1766	Top of buried peat	6.68	7,180 ± 55	SRR-1400
6a	Glencarse†	NO 2022 2256	Top of buried peat	9.52	6,679 ± 40	SRR-1150
6b		NO 2022 2256	Base of surface peat	9.82	6,083 ± 40	SRR-1151

* Riverbank exposure.
† Temporary excavation.
‡ These dates are not plotted in Fig. 2 because they were obtained on rather thick (4-cm) samples, and therefore relate less closely to the lithostratigraphic boundaries than the other dates, which were obtained from 1-cm thick samples.

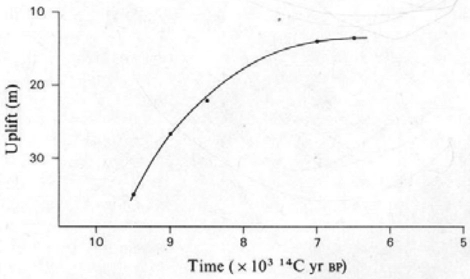

Fig. 3 Land uplift in the Carey–Cordon area between 9,500 and 6,500 yr BP. The graph shows total land uplift between each date and the present.

in bulk density within the peat, the mean value for each site was derived from measurements carried out at vertical intervals of 1–4 cm through the peat. The estimated values for compaction at sites 1, 2 and 4 range from 40 to 68%, and in the absence of direct measurements at sites 3 and 5, an overall mean value of 52% was used at those sites. The estimated original altitudes of the peat surfaces at the time they were transgressed by the sea are shown in Fig. 2.

The age and altitude of the Main Postglacial Shoreline, marking the culmination of a major transgression, have been measured at Glencarse (site 6), where a 30 cm-thick layer of carse deposits is underlain and overlain by peat. The buried peat was transgressed (6a, Fig. 2) about 6,679 ± 40 yr BP (SRR-1150), and peat growth on the abandoned surface of the carse deposits (6b; altitude 9.8 m OD) was under way at 6,083 ± 40 yr BP (SRR-1151)[7].

Two characteristics of the relative sea-level curve (Fig. 2) as yet unexplained are the transgressive nature depicted for the Carey buried shoreline (point 1a) and the fall of relative sea level between points 3a and 3b. The former is in line with the transgressive nature suggested for the correlative Main Buried Shoreline in the Forth area[6,14]. The latter is suggested by a buried channel excavated to a few metres below OD near the present River Earn[1,15]. This low point on the curve occurs between 8,370 ± 45 and 7,525 ± 50 yr BP, whereas the equivalent trough in the Forth curve is dated to between 8,690 ± 140 and 8,270 ± 160 yr BP (ref. 4). However, the discrepancy may be negligible when account is taken of the wider timespan delimited for this event by the available Lower Strathearn dates, and the possibility that the low relative sea level occupied a very brief timespan after 8,370 ± 45 yr BP.

The relative sea-level curve (Fig. 2) is primarily the net result of isostatic land uplift and eustatic sea level changes. A curve of land uplift (Fig. 3) for the period 9,500–6,500 yr BP was constructed by a similar method to that of Sissons and Brooks[4]. Land uplift at 500-yr intervals was calculated by adding the amount by which world sea level was below the present level at each date, according to a particular published eustatic curve, to the contemporary relative sea level in Lower Strathearn as shown in Fig. 2, and subtracting 2 m to compensate for the fact that the data in Fig. 2 relate to former estuarine shorelines and therefore to high water mark. Curves were drawn for all eight eustatic curves[16–23] not rejected as unsuitable according to the criteria used by Sissons and Brooks, and the results averaged to produce Fig. 3. The form of the curve is strikingly similar to the Forth uplift curve, the magnitude of uplift being less in Lower Strathearn because of the greater distance from the centre of uplift.

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