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Radiocarbon dating of historic mudflat sediments at Airth in the Inner Forth Estuary and the impact on the estuary of 19th century agricultural improvements

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ABSTRACT

The results of sediment-stratigraphic, diatom and pollen analyses, and AMS ^{14}C dating of mudflat and salt marsh sediments at Higgin's Neuk, Airth in the inner Forth estuary are reported. Engineering borehole records of abundant peat within mudflat sediments encouraged work to establish rates of mudflat accretion over the last several centuries, and thus to establish the feasibility of early 16th century naval works in this highly turbid part of the estuary. However, six ^{14}C assays on peat closely associated with buried archaeological structures of likely 18th century age record later prehistoric and early historic age-estimates. The assays are thought to be correct. The peat is not *in situ*. It probably originated from the well-documented, extensive late 18th and early 19th century clearance of raised mosses in the River Forth for agriculture. The sediment-stratigraphic evidence is important because it confirms the scale of the impacts of peat clearance on the inner estuary derived from contemporary documents. The peat may act as a marker horizon in mudflat and salt marsh sediments from which rates of post-18th century mudflat accretion can be derived. At Higgin's Neuk these were probably very high, given uncertainties in dating controls, around 0.8 cm/yr (1.2 yrs/cm) for the last ca. 150 years.

KEYWORDS

Forth Estuary, radiocarbon dating, estuarine sediment, archaeology, agricultural improvement, peat clearance

Introduction

The commissioning by James IV (r. 1488-1513) of very large ships such as the *Margaret* (ca. 600 tons) in 1502 and the *Michael* (ca. 1000 tons) in 1505, the largest European vessel at the time, necessitated construction of a new dockyard at Newhaven on the south shore of the Forth Estuary east of Edinburgh, and a second, "clearly of considerable size" (MacDougall, 2015, p. 235) to refit these and other ships near an existing harbour up-estuary near Airth. Precisely where this dockyard was located is unknown. Reid (2002) used toponymic, documentary and cartographic sources to suggest the location to be on a headland today called Higgin's Neuk (Figure 1). Archaeological work between 2016 and 2018 aimed to uncover material evidence for the dockyard (Graham et al., 2018, 2019).

Parallel sediment-stratigraphic, diatom and pollen analyses, and AMS ^{14}C dating of mudflat and salt marsh sediments, were also undertaken because the growth over time of these will have affected the siting and success of the dockyard: commentaries of the time demonstrate that silting was a serious problem (Accounts of the Lord High Treasurer of Scotland iv, p. 336; Exchequer Rolls VII, p. 522; Sibbald (1710) in Cadell, 1913; Morris, 1919-20). This paper reports on those analyses, which provide insight into the sources of sediment deposited at Higgin's Neuk and, possibly, rates of historic mudflat accumulation.

The Forth estuary penetrates central Scotland for nearly 100 km from the North Sea to its present tidal limit west of the city of Stirling. The inner Forth estuary from Stirling to Alloa (Figure 1) is best described as a tidal river (Webb & Metcalfe, 1987). The channel is glacially deepened. Devensian and Holocene sea level change and sedimentation have shaped the estuary (Smith et al., 2010). Rising sea level in the early-mid Holocene led to the highest postglacial relative sea level by ca. 4700 cal BC. This helped form extensive salt marshes that now, with agricultural improvement, form the coastal plain, a clay-rich silt locally called 'carse'. Two younger shorelines can be mapped by lower carse surfaces, less well dated at ca. 2700 cal BC and around the BC-AD boundary. Present sea level was established thereafter.

Estuarine sediments filling the glacially deepened channel are clay-rich silts with laminations of fine or medium-fine sand, overlain by olive black silty clay with silty fine sand laminae and small shell fragments (Gostelow & Browne, 1986). At Bothkennar, 2 km south of Higgin's Neuk (Figure 1), Paul et al. (1995) and Barras and Paul (1999) defined and ^{14}C dated four sediment-stratigraphic units of Holocene age above the basal Bothkennar Gravel Formation, of Devensian Lateglacial age. The Claret Formation, black to very dark grey silts and clays, extending at Bothkennar to -16.5 m OD, was ^{14}C dated by marine shells at that depth to 4043-3662 cal BC. It rises to ca. +1 m OD, marine shells between -4 and -1 m OD (there is some confusion as to the precise altitude between publications) dated to 2620-1900 cal BC. This evidence supports that from sea level change (Smith et al., 2010) in suggesting a water surface close to the present in the last two-three millennia. Claret Formation sediment at Bothkennar was later eroded by a channel of the Forth which was then filled with the Grangemouth Docks Member, laminated black to dark grey clay-rich silt with thin sandy bands interpreted as intertidal estuarine mud and dated by marine shells at its base (-4.2 m

OD) to 2872-2340 cal BC. Marine shells at -1.44 m OD were dated to 1392-933 cal BC. The base of the overlying Skinflats Member, around 1 m of dark grey clayey silts, is dated by marine shells to 1494-1053 BC. The most recent sediment, the Saltgreens Member, very dark greyish-brown structureless clay-rich silts between ca. +2.2 m OD and the ground surface at ca. +3.1 m OD, is not dated.

Some 75 % of the freshwater input to the estuary is from the headwater Rivers Teith and Forth but tidal forces propel suspended sediment upstream, resulting in maximal turbidity near Airth, accentuated by the estuary narrowing here (Webb and Metcalfe, 1987; Figure 1). Sand and mudbanks in this reach give rise today to constantly changing channel bathymetry. Table 1 gives modern tidal data (Admiralty Hydrographic Department, 1996) for Alloa, 5 km upriver from Higgin's Neuk.

Higgin's Neuk is on the south shore of the Forth channel. The Forth channel here is around 350 m wide and 3.5 m deep at its deepest but it rapidly shallows immediately upstream to large mudbanks in mid-channel as well as fringing mudflats and salt marshes. The channel is not constrained by bedrock, Higgin's Neuk itself being underlain by carse ca. 15 m thick. Carse forms an extensive surface on the headland and inland at ca. +5 m OD to Airth, ^{14}C dated by marine shells at different localities to between ca. 3100 and ca. 1200 cal BC (Smith et al., 2010). Between the headland and the Forth channel is mature, fully vegetated salt marsh with a surface consistently at ca. +3 m OD. A sea wall protecting the headland and cutting across a shallow embayment west of Higgin's Neuk (Figure 2) is the only visible archaeology away from the headland.

Methods

Cartographic analyses (Table 2) defined elements of local coastal evolution over recent centuries. Engineering boreholes were examined on-line (BGS Onshore Geoindex: http://mapapps2.bgs.ac.uk/geoindex/home.html) from the salt marsh surface out into the Forth channel along and near the lines of the 1936 Kincardine Bridge and the Clackmannan Bridge, opened in 2008, to understand the sediment stratigraphy to depths deeper than hand-sunk cores could be made. Seventy-seven Eijelkamp peat-gouge boreholes of 3.0 cm diameter were sunk across the salt marsh surface, surveyed to OD (Figure 2), to describe in detail the upper part of the sediment stratigraphy and to explore spatial variations. Boreholes are clustered in the south east of Figure 2, partly to define the line of a ca. 40 m long, ca. 5 m wide artificial stone linear structure entirely buried by sediment, recognized subsequently from excavation to be a stone pier or more likely a jetty (Graham et al., 2018). Sediment descriptions were made in the field: laminae are sediment bands <2 mm thick; beds are >2 mm thick. Diatom analyses defined the depositional environment of sediments beneath a ground surface at +2.95 m OD at Borehole 30a beside the jetty. Sixteen ca. 1 cm thick sediment slices were sampled between +1.85 m OD and +0.25 m OD from the centre of a 7.5 cm diameter Eijelkamp peat-gouge sediment core, prepared by standard techniques (Renberg, 1990) and counted on a stereo microscope at magnification x1000 to ca. 300 valves. Pollen analyses were made to define more closely the depositional environment of the sediment from 10 x ca. 1 cm thick sediment slices at two depth intervals (+1.13-0.97 m OD; +0.64-0.24 m OD) in the same sediment core, prepared by standard techniques (Moore et al., 1991) and counted to ca. 300 land pollen grains (tlp). The humic acid fractions of six samples of peat within the sediment (in the absence of single entity samples) were ^{14}C dated by AMS techniques (Dunbar et al., 2016) and calibrated using OxCal v4.3.2 r5 (Bronk Ramsey, 2017) applying the Intcal13 atmospheric curve (Reimer et al., 2013) to establish a chronology of salt marsh accretion. Relevant results from archaeological excavation (Graham et al., 2018) are incorporated in the discussion.

Results

Cartographic evidence (Table 2) suggests that the Forth channel has moved progressively northward from the southern shore over recent centuries, allowing a wedge of sediment to accumulate. Maps by Pont (1583-1614) and, much later, by Adair (1730) depict, though imprecisely, the south bank of the Forth channel lying close in to Airth. Roy (1747-1755) depicts the south bank of the Forth channel further north. Bailey's (1990) reconstruction of successive land claim sea walls north east of Airth from AD1726 to AD1814 probably reflect this process. In AD1828 the *Plan showing line of proposed embankment* shows the southern bank of the Forth channel ca. 200 m north of Higgin's Neuk. The Admiralty Chart of 1860 is the first to differentiate between salt marsh and mudflat though it is only the 1941 Admiralty Chart that shows salt marsh at Higgin's Neuk.

Civil engineering boreholes consistently record peat at depth below salt marsh and mudflat surfaces. Most are thin layers or pockets not measured in detail by engineers but some logs, notably along the line of the Clackmannan Bridge show thick peat beds (Table 3). Peat is confined to boreholes on the southern shore. The deepest recorded peat is at ca. -11 m OD in borehole 2358/1. Figure 3 depicts by dashed lines the thicknesses of the main peat-rich units below the salt marsh surface at Higgin’s Neuk in boreholes on the line of the Clackmannan Bridge (boreholes /291 to /701). These define a ca. 2 m deep peat-filled channel of the Forth, close inshore, from -4.5 m OD in borehole 483, spreading laterally across the contemporary mudflat at around -2.5 m OD and rising close to +1 m OD. Laminae of peat rise in some engineering boreholes to +1.4 m OD. The salt marsh surface at Higgin’s Neuk is at +2.9 ± 0.1 m OD.

Boreholes sunk by hand with Eijelkamp peat-gouges reached different depths, the deepest to -3.95 m OD; eight of the 77 penetrated to > -2 m OD. Stone at around -0.25 m OD was also struck in boreholes at the edge of the sea wall, interpreted as wall foundations (Figure 3). Figure 4 combines descriptions from all 77 hand-sunk boreholes to synthesise trends with altitude in five sedimentological characteristics. The sediment is overwhelmingly a pale to dark grey clayey silt or silty clay. Sand is common between +1 and -0.75 m OD (Figure 4a), mostly as laminae or single-grain layers but also in bands between 2 and 10 cm thick, thicker below -1 m OD. Black mineral sediment, silty clay with high amorphous organic matter, is common in subsurface sediment below +2.5 m OD (Figure 4b). Peat is common below ca. +1 m OD, always herbaceous. Roots penetrating into underlying mineral sediment were rare below the surface mat. The frequency of laterally continuous peat laminae and beds in boreholes along and either side of the jetty is schematically shown in Figure 3 where peat beds were also recorded in boreholes directly on its surface. Peat was black or more rarely brown; brown peat was more common below ca. +1.25 m OD. It occurred as very thin laminae of organic matter, with sharp boundaries within mineral sediment (Figure 4d) and beds >2 cm thick (Figure 4e). Beds >30 cm thick were recorded only below -1 m OD and beds >50 cm only between +0.25 and -0.75 m OD, but exceptionally beds >1 m were recorded. Although most boreholes were focused on and near the line of the buried jetty (Figure 2), peat was concentrated in this part of the mudflat. Wood was recorded in two boreholes directly next to the sea wall and close to the jetty at ca. +0.5 m OD, with much cereal chaff.

Diatom analyses (Figure 5) defined the depositional environment of the mudflat as it over-topped the jetty. The sediment is a mid-grey silt, laminated except structureless between +1.95-1.69 and +1.09-0.95 m OD and with laminae of peat below +0.58 m OD. The surface of the jetty at Borehole 30 is at +0.89 m OD. Diatom preservation was poor. The diagram is dominated by marine to marine-brackish and marine-brackish taxa, *Paralia sulcata* and *Raphoneis amphiceros*. The appearance of brackish and freshwater-brackish taxa above +0.95 m OD might suggest slight freshening of the water column, but this waned above +1.3 m OD.

Pollen analyses (Figure 6) from (a) mid-grey structureless silt and (b) more organic laminated silt with dark brown peat laminae are not dissimilar. Pollen preservation was not recorded but grains were well preserved. Tree pollen is abundant, largely from deciduous trees and shrubs (*Alnus glutinosa*, *Corylus avellana*-type) but *Pinus sylvestris* is also well-represented. *Calluna* pollen is common, as is *Vaccinium*-type, which increases up-profile in Figure 6b, the only clear trend in the spectra. Herbs are rare. Most taxa represent a terrestrial, well-wooded environment, with heath. Grains of Chenopodiaceae and *Plantago maritima* are representative of salt marsh environments.

The six ^{14}C assays are shown in Table 4. Three assays (SUERC-73733, -73729 and -73734) were on thin peat bands directly overlying the stonework of the jetty, obtained at a time when the stonework had yet to be excavated, because these assays could define a time immediately after the stonework was constructed. Assay -71395 is beyond the end, and north east of the jetty at Borehole 1 (Figures 2, 3), and deeper, dated to establish the chronology of salt marsh accretion away from the stonework, as were assays -71397 and -71396, unrelated to archaeological structures (Figure 3). The radiocarbon assays themselves present a confusing picture. There is great consistency between the middle four estimates, but not in the end members. Age estimates do not become progressively younger with rising altitude.

Discussion

The most recent mudflat sediments at Higgin's Neuk do not look like those at nearby Bothkennar (Barras and Paul, 1999). They differ in colour, the amounts of sand, the rarity of shells, and particularly in the abundance of peat. In situ peat within carse clay or their sub-estuarine equivalents in the Forth estuary has not been recorded before (Sissons, 1969; Gostelow & Browne, 1986; Barras and Paul, 1999; Smith et al., 2010). Present-day salt marshes in Britain are entirely minerogenic because they have formed under conditions of relative sea level fall (Allen, 1990) but very high turbidity and sediment flux in the inner estuary might, it was thought, preserve thin peats. Sediments in hand-sunk boreholes compare closely with records of engineering boreholes beneath both the Kincardine and Clackmannan Bridges (Figure 3). The latter extend much deeper and show that thick peat beds are found filling a channel close inshore to -4.5 m OD. The peat beds and laminae recorded in hand-sunk boreholes represent lateral equivalents. Rare vertical roots within minerogenic mudflat sediments suggest *in sit*u formation but the laminae are best seen to represent drapes of organic matter deposited at slack water across the mudflat. Diatom analyses show the sediments formed in a brackish-marine environment close to that which characterises the inner estuary today (Webb and Metcalfe, 1987).

The pollen data, however, are not representative of mudflat or salt marsh environments from comparable sediments in the Forth valley (Sissons and Brooks, 1971). Although single grains of Chenopodiaceae and *Plantago maritima* are recorded, grasses (Poaceae) and sedges

(Cyperaceae) are far from abundant. The proportions of *Pinus* (Scot's pine) pollen may be inflated in wave-driven environments, but the bulk of the pollen is from terrestrial environments with deciduous trees and *Calluna* (ling) heath. The $\delta^{13}C$ values of ^{14}C assays (Table 4) are also representative of organic matter from terrestrial rather than estuarine environments, values of organic matter in salt marshes lying between -22 and -16 ‰ (Haines, 1976; Ember et al., 1987; Fogel et al., 1989). Four of the radiocarbon age-estimates (Table 4) are in good agreement that the mudflat at Higgin's Neuk between -0.1 and +0.9 m OD formed in the later Iron Age: these broadly agree with Barras and Paul's (1999) chronology (above). These include the three assays (SUERC-73733, -73729 and -73734: Table 4) dating peat bands directly overlying the jetty (Figure 3). The jetty is not directly dated. A plank of *Pinus* wood found in excavation beneath stonework where the jetty was connected to the sea wall was ^{14}C dated but was too young to allow calibration (Graham et al., 2018, 122-3): the wood probably post-dates the 18th century AD. The stonework itself (Figure 7) is not of prehistoric date. The top course is of tooled ashlar blocks and though typological dating is problematic (Hume, 1976, p. 34-35) the closest parallels in the inner Forth estuary are 18th century examples (Graham, 1969). The jetty uncovered by coring and subsequent excavation is precisely aligned with what was defined on a detailed plan of 1828 (Table 2: RHP4298) as an 'Old Stone Pier', visible for around 15m above the mudflat surface.

The dated peat beds have much older radiocarbon ages than the jetty they rest on. The apparent relation to ^{14}C dated sediments at Bothkennar (above: Barras and Paul, 1999) is coincidental, or the marine shells at Bothkennar are not in life position. The ^{14}C assays may have an ageing error but the dating of humic acid fractions ensures no contamination from sources like coal dust: hard water error from plants photosynthesising in carbon-rich water is possible but the pollen analyses and $\delta^{13}C$ values suggest a terrestrial, not aquatic, source for the peat. The age estimates of the ^{14}C assays are probably correct. But the peat is not *in situ* despite its sheer abundance and strong stratification.

The terrestrial environment defined by *Calluna* pollen (Figure 6) is heathland. Near Higgin's Neuk, this habitat would be found on raised mosses throughout their accumulation. Raised mosses once bordered vary large expanses of the inner Forth estuary east and west of Stirling, such as Dunmore, Wester Moss and the Flanders Mosses (Figure 1). The arboreal component in the pollen assemblages is from trees on dry ground around them. If the assemblages can be used as chrono-stratigraphic indicators, the paucity of *Quercus*, the abundance of *Corylus avellana*-type and the occurrence of open-ground, usually agrarian herbs would suggest a later Holocene landscape, though one lost by the Roman Iron Age (Turner, 1965; Dumayne-Peaty, 1998).

There are two probable origins of the reworked or re-deposited raised moss peat. One is the delivery in streams of liquefied peat in bog-bursts but given the overwhelming input of freshwater from the Rivers Forth and Teith to the estuary (Webb and Metcalfe, 1987) the more likely origin is from raised mosses cleared in agricultural improvement in the mid-late 18th and early-mid 19th centuries. Mosses east of Stirling beginning to be cleared are shown on Roy's Military Survey ca. AD1750 but those west of Stirling were cleared from the late 18th century (Cadell, 1913; Harrison, 2009; Smout and Stewart, 2012, p. 128). Enormous amounts of peat in deep raised mosses, several millions of cubic metres (Sloan, 1997; Smout and Stewart, 2012, p. 128), were removed in what was one of Europe's most remarkable agricultural improvements. Peat at Blairdrummond, one of the Flanders Mosses, was floated in artificial channels, propelled after 1787 by water pushed from the River Teith by a 'great wheel' to the River Forth and down the estuary (Cadell, 1913, pp. 262-83). Floated peat was observed east of Higgin's Neuk. At Carriden (Figure 1), "Sometimes, considerable quantities of peat moss in large coherent masses or in a pulpy state are deposited on the shore, which has floated down the river in the process of clearing the extensive moss fields at Blair Drummond and other places in the vicinity” (NSA, 1845, p. 56) and the northern shore around Alloa was reported as “frequently … covered to a considerable depth with the moss thrown into the water at Blair Drummond” (NSA, 1845, p. 231). The earliest Admiralty Chart (1860) maps ‘drifted peat’ on the north shore at Culross. Floated peat has been blamed for the decline in fishing in the estuary (McLusky, 1978; Sloan, 1987; Smout and Stewart, 2012, p. 48). The salt marsh at Higgin’s Neuk retains one of the last remaining and best physical proofs of the scale of the moss clearances upstream and of their environmental impacts downstream.

Why, though, should the radiocarbon assays (Table 4) yield later prehistoric and early historic ages, with four clustered in the later Iron Age, when raised mosses spread across carse from ca. 4700 cal BC (Smith et al., 2010)? The assays probably represent the mixing of peat from the oldest to still-forming peat: the average age of mixed peat would be around 1500 cal BC, as, perhaps coincidentally, in assays SUERC-71397 and -71396 (Table 4) but not those between 350 cal BC and cal AD22 in other assays. Not all the peat was introduced to the River Forth at the same time although the rapidity of clearance indicates no significant lag. But Cadell (1913) recorded that deeper peats were cast and dried for fuel, not floated.

If the origin of the peat is accepted and an age around AD1800, roughly the age of the jetty from architectural typology (above), assumed for its earliest deposition, the peat may be used as a synchronous marker horizon for recent mudflat sedimentation at Higgin’s Neuk and, perhaps elsewhere in the inner Forth estuary. There are caveats in assuming this age for the first deposition of reworked peat because moss clearance west of Stirling occurred over a long time from the late-18th to the mid-19th centuries, not in a single event, and because reworked peat in the estuary east of Stirling is not noted until the mid-19th century. The chronology we adopt is partly testable. The foundations of the sea wall at Higgin's Neuk, at around -0.25 m OD, are retrodicted to have been constructed around AD1835-40: the sea wall is first mapped on the 1828 Plan RHP4298. No in situ sediment-stratigraphic evidence before ca. AD1800 could be demonstrated for salt marsh sediment. The cereal chaff recovered at ca. +0.5 m OD next to the sea wall (above) is younger: it was not ^{14}C dated. Chaff was also found in a test pit sunk at the jetty (Graham et al., 2018, pp. 122, 124) where it was presumed to have been spilled during corn milling: a mill at Higgin's Neuk is first recorded in AD1597 but archaeological remains are of 19th century age. The earliest inferred sediment-stratigraphic event, dated loosely to ca. AD1800, was the filling with reworked peat of a channel just offshore of Higgin's Neuk, with a base at -4.5 m OD (Figure 3): the age and origin of peat at greater depths ca. -11 m OD are unknown. Engineering borehole 700 (Table 3) records below the base of the channel a 'dressed' post, suggesting earlier anthropogenic activity on the mudflat although this is below present MLWS (Table 1; Figure 3). This channel has been preserved through subsequent channel avulsion. A mudflat surface at -2.5 m OD, close to present MLWS, was then covered with a veneer of peat (Figure 3). Some 5.5 m of mudflat and salt marsh may have accumulated at Higgin's Neuk since ca. AD1800, riding at an average rate of around 0.4 cm/yr (2.5 yrs/cm). The sharp reduction in frequency of peat laminae/beds at +1 m OD (Figure 4c, d) might mark the cessation of peat flotation in the Flanders Mosses or cessation of peat delivered downstream, maybe ca. AD1860, implying a doubling of the rate to ca. 0.8 cm/yr (1.2 yrs/cm) for the last 150 or so years. These are very rapid rates of salt marsh accretion. They are not supported by data at Bothkennar (Barras and Paul 1999) but recently accumulating mudflat sediment there was not dated, the 7.3 m of sediment younger than ca. 2600 cal BC years ago accumulating at ca. 0.16 cm/yr (6.0 yrs/cm). The Bothkennar site lacks the abundance of peat that Higgin's Neuk has, though, possibly because all sediments examined lay protected from sediment deposition behind an

18th century sea wall. Boyd and Sommerfield (2016) found that organic matter accumulation determined the high accretion rates (up to 0.54 cm/yr) in recent anthropogenically altered salt marshes in New England.

Estimates of historic salt marsh accretion are comparatively few. This review is not exhaustive, but a number of studies report long-term salt marsh or mudflat accretion rates not dissimilar to those proposed from less than precise proxies at Higgin's Neuk and in some places in not intensively agrarian and increasingly industrialised a landscape, suggesting that more studies should be undertaken. Allen and Rae (1988), for instance, reported in the isostatically subsiding Severn estuary, accretion rates since ca. AD1250 of around 0.14 cm/yr, accelerating after AD1845 to ca. 0.4 cm/yr, and around 1.3 cm/yr from the early 20th century (Allen et al. 1993). Using historical marker-horizons, Oenema and DeLaune (1988) suggested accretion rates in Dutch marshes over the last ca. 200 years between 0.4 and 1.5 cm/yr. Estimates using radionuclides extend in time only a century or so, with ^{210}Pb, but over this short timescale, Cundy and Croudace (1996) recorded rates of salt marsh or mudflat accretion of 0.4-0.8 cm/yr, also comparable to those suggested at Higgin's Neuk although in isostatically subsiding southern England.

Finally, the study has not generated independent evidence for sediment deposition in the inner estuary in the 16th century when the dockyard at Airth was constructed (above). It has identified a deep channel of the Forth close inshore, to -4.5 m OD, that pre-dates the deposition of reworked peat, but the age of this is unknown. It may be that such channels, on the south shore of the estuary, allowed large ships to dock somewhere. Archaeological excavation also did not identify evidence for the 16th century dockyard: the evidence reaches in time only to the 18th century (Graham et al., 2018, 2019).

Conclusion

Radiocarbon dating of peat-rich mudflat sediments at Higgin's Neuk appears to indicate a later prehistoric age for mudflat growth but this interpretation is falsified by the relation of the dated peat to an 18th century buried jetty. The peat is reworked and very probably originated in the spectacular 19th century moss clearances west of Stirling, one of Europe's great landscape transformations. Nevertheless, it is possible that this sediment-stratigraphic marker horizon might allow the peat to be used as a chrono-stratigraphic marker of rapid recent estuarine sedimentation.

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Figure and Table Captions

Figure 1. The location of the inner Forth estuary in Scotland showing places named in the text and (inset) the Higgin's Neuk headland, the Kincardine and Clackmannan Bridges and present mudbanks and salt marsh (pale brown).

Figure 2. Map of the carse surface (pale green) and the salt marsh surface (in yellow) at Higgin's Neuk showing the sea wall running north west by BH16, the locations of engineering boreholes 291, 481-483 inc., 754, 700 and 701 on the line of the Clackmannan Bridge, and of hand-sunk boreholes. Boreholes referred to in the text are numbered: dated boreholes are also differentiated. *(OS MasterMap© Topography Layer [TIFF geospatial data], Scale 1:2000, Tiles: ns9187, ns9287, Updated: 11 June 2015, Ordnance Survey (GB), Using: Edina Digimap Ordnance Survey Service https://digimap.edina.ac.uk, Downloaded: 2016-01-14 15:22:10.809)*

Figure 3. (a) synthesis of archaeological and sedimentological data on a ca. 150m long cross-section from the southerly edge of the present-day salt marsh at Higgin's Neuk to the Forth channel plotted against depth in m from +3.0 m to -5.0 m OD, showing the jetty, traced north for some 40m beneath the salt marsh surface, the depth of the sea wall demonstrated by excavation and coring to around -0.25 m OD, approximate depths of peat layers and beds from hand-sunk boreholes on and around the jetty, peat recorded in civil engineering boreholes (Table 3) within the dashed-line envelope, and the present-day tidal range (MHWS: mean high water spring tides; mean tide; MLWS: mean low water spring tides). Stars mark the locations of radiocarbon dated peat layers described in Table 2.

Figure 4. Schematic generalised sediment stratigraphy of the salt marsh presented as mean percentages of five consistently defined sediment characteristics in the 77 hand-sunk boreholes from the peat surface to -2.0 m OD.

Figure 5. Percentage-based diatom taxa at Borehole 30a between 1.85 m OD and 0.25 m OD. Sediments are variously laminated silts, below 0.10 m OD with clay, with one peat band at + 1.25 m OD.

Figure 6. Two short percentage-based (%tp) pollen diagrams from (a) herb peat at 1.13-0.97 m OD and (b) from silt at 0.64-0.24 m OD at Borehole 30a.

Figure 7. Photograph of three upper courses of stonework exposed in excavation on the east-facing wall of the jetty where it is connected to the sea wall to the left. Mudflat sediments with rubble are to the right.

Table 1. Tidal data at Alloa.

Table 2. Cartographic sources.

Table 3. Descriptions of peat units in civil engineering boreholes along the lines of the Kincardine and Clackmannan Bridges arranged from the southernmost boreholes towards the Forth channel.

Table 4. AMS ^{14}C assays on samples of herb peat within mudflat sediments arranged by altitude.