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Reconstructing late holocene sea-level changes in the Forth Valley, Scotland (UK)

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Master of Research

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Abstract

The research contributes to the understanding of late Holocene environmental changes in the Forth valley. Scotland has been greatly affected by differential glacio-isostatic uplift after the demise of the last British-Irish ice sheet. This has been one of the main causes for fluctuations in sea-level during the Holocene as recorded previously from the Forth lowland. Previous studies have attempted to determine late Holocene sea-level changes in the Forth lowland on the basis of archaeological evidence (e.g. Smith *et al*. 2010). However, little is known about these changes in the Forth valley.

A high resolution study using stratigraphical and diatom analysis has been completed from a sediment core near the upper tidal limit of the Forth valley. A radiocarbon date of 2761±45 BP (2862±94 *cal*. BP) was established in the lower peat layer. Evidence of peat moss clearance and other anthropogenic activity is present throughout the core. Furthermore, an indication of relative sea-level rise was found subsequent to the radiocarbon date. However, further work needs to be completed further downstream and collaborated with the findings in this study to be sure of this brief and minor transgressional phase. The environment remained predominantly riverine with a slight marine to marine-brackish influence.

In addition to the possible change in relative sea-level, the results have been indicative of a dynamic riverine system. The stratigraphical evidence suggests multiple changes in the river course as organic material has accumulated in certain sections of the core. The diatom assemblage indicates the formation of a wetland prior to the river Forth migrating back. During the progression of terrestrialisation, marine to marine-brackish diatoms were present but low in abundance.

Key words: Scotland, Late Holocene, Diatoms, Stratigraphy, Sea-level.

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Chapter 1. Introduction

1.1. Introduction

Scotland has been established as a site of interest for past sea-level studies as its history in glacial activity has and still is modifying the landscape. The preservation of landforms related to sea-level changes has been well preserved in south-east Scotland (Smith *et al*. 2010; Sissons 1983). Furthermore, morphological studies on changes in the Forth valley during the late Holocene are scarce as pre-historic archaeological evidence has been used to determine these changes (e.g. Smith *et al*. 2010). The systematic clearance of peat, to expose the underlying fertile carselands in the eighteenth century, has made late Holocene environmental reconstructions difficult in south-east Scotland (Tipping, Smith and Jordan 2013). Therefore, this study looks to contribute stratigraphical and microbiological evidence on late Holocene relative sea-level changes in the Forth valley.

1.2. Aims and Objectives

The main aim of this research is:

- To reconstruct the environment of the river Forth at the upper tidal limit during the late Holocene

In order to achieve this aim, the objectives are as follows:

- To record the stratigraphy from a borehole collected at the upper tidal limit of the Forth valley.
- To utilise the radiocarbon date documented for the lower peat section of the borehole.
- To produce a high-resolution dataset using diatom analysis for environmental interpretation of lifeform, salinity, pH and trophic classification.

- To combine these methods and determine the environment of the Forth valley during the late Holocene.
- To include a summary diagram, demonstrating how sea-level has changed during the late Holocene.

1.3. Summary

This thesis will examine and improve knowledge on late Holocene environmental changes in the Forth valley. In addition, the structure of this dissertation will follow a review of the literature in Chapter 2, discussing the origin of the complex processes that occur in south-east Scotland. Furthermore, a site description of the area and why it has been selected to distinguish late Holocene changes in the Forth valley is described in Chapter 3. Chapter 4 is the presentation of results with the following discussion in Chapter 5. Chapter 6 summarises the conclusions of the research with recommendations for future work.

Chapter 2. Literature Review

2.1. Introduction

Sea-level changes in the Forth valley are complex. At least eleven different levels of shoreline terraces have been recognised from previous studies as a result of sediment supply from rivers, land uplift, and sea-level movements (Smith 1965; Sissons *et al*. 1966). The most extensive research on relative sea-level in Scotland has been in the south-east, as a result of the well preserved late Quaternary landforms in the lowlands (Sissons, 1983). However, little is known about relative sea-level in the Forth valley during the late Holocene (Smith *et al*. 2010). The overall aim of this research paper is to reconstruct the environment of the Forth valley during the late Holocene.

2.2. Glacio-isostasy and Glacio-eustasy in Context with Past Scottish Sea-Level Studies

Critical to an understanding of sea-level change and coastal response in the Forth valley is to consider the nature of interplay between glacial-isostasy and glacio-eustasy (Gray 1985). Isostasy is the equilibrium of the Earth's lithosphere, essentially floating on the asthenosphere (Fairbanks 1983). Eustasy applies to the equal balance of sea-level with the geoid whereby sea-level can be affected by a change in water volume (glacio-eustasy) or shape of the basin (tectnoeustatic) (Fairbanks 1983). Isostasy and eustasy are two elements that cannot be measured apart as they are both substantial to relative sea-level changes in glacially affected areas (Fairbanks 1983).

In Edinburgh, Maclaren (1842) first developed the concept of glacio-eustasy where the growth and demise of ice sheets affects global sea-level. As ice sheets melt, eustatic sea-level rise causes transgressional events (Gray 1985). Subsequently, isostatic uplift occurs

Fig. 2.2.1. Rate of relative land-level change 1 ka to the present day in the British Isles (mm^{-1}) (Shennan, Milne and Bradley 2012).

differentially, with most movement occurring at the centre of the past ice-sheet and the least movement at the periphery (Gray 1985). Shennan, Milne and Bradley (2012) collated data to illustrate the rate of relative land-level change for the last 1000 years to the present (Fig. 2.2.1). Positive values show land uplift whereas negative values show subsidence. The last British-Irish ice sheet has caused glacio-isostatic uplift where it was once present and land subsidence at the periphery (Shennan, Milne and Bradley 2012).

Jamieson (1865) first demonstrated evidence of interactions between sea-level change and land uplift in the Forth valley, developing the theory of glacio-isostasy. He distinguished a period of high sea-level, followed by a regression, allowing peat to accumulate down to present sea-level and another transgressional phase as estuarine silts and clays overlay the peat. This coincides with earlier research by Blackadder (1842) and Fleming (1830), whom discovered evidence of lower sea-levels from buried peat in the Forth. Additionally, Wright (1914; 1934), along the west coast of Scotland, developed the isokinetic theory, whereby time-transgressive shorelines develop in a glacio-isostatically uplifted area. This occurs when isostatic uplift is equal to the rate of sea-level rise. The Main Postglacial shoreline is an example of a better produced shoreline through this process (Gray 1983). Furthermore, diachronous (time-transgressive) shorelines develop where the oldest shoreline is towards the centre of uplift and the younger is towards the periphery as illustrated in Fig. 2.2.2 (Smith *et al*. 2012; Gray 1985). However, Andrews (1970:76) observed similar behavioural patterns to Wright's (1914; 1934) isokinetic theory in most of Arctic Canada where shorelines were poorly developed. Therefore, suggesting this theory may only apply to shorelines in Scotland.

Raised shorelines are indicative of a fall in eustatic sea-level or land uplift whilst buried beaches are distinguished by land subsidence or sea-level rise (Lambeck 2001). Sissons (1963) revolutionised relative sea-level studies by producing the first detailed surveys of

Fig. 2.2.2. Cross section from the centre of isostatic rebound to an area beyond influence of glacio-isostasy showing the interplay of eustatic and isostatic movements and creation of shorelines (Gray 1985).

shoreline altitudes using instrumental levelling. Sissons (1962; 1963a) contributed to Jamieson's theory and discovered raised shorelines in Scotland were differentially uplifted. The altitudes of raised beaches were originally used as early efforts to model glacio-isostatic uplift in Scotland (Smith *et al*. 2006). Sissons (1972) research in the western part of the Forth valley was the first demonstration of dislocated shorelines in Scotland (Smith *et al*. 2010). However, studies to date have failed to discover a way to measure diachronous shorelines in the Forth Lowland (Smith *et al*. 2010). The effect of differential uplift from crustal adjustment determines why records of relative sea-level movement cannot be applied throughout Scotland (Gray 1985).

2.3. Late Devensian and Transition into the Holocene

Since the first detailed accounts of the last glaciation in Scotland, from Jamieson (1865) and Geikie (1874; 1865), research has transformed into detailed localised studies. Research by Simpson (1933) and Sissons (1963b) demonstrated evidence of two significant stages of the decay of the last British-Irish ice sheet, the Perth Stage and the Loch Lomond Stadial, in the Forth Lowland. The timing of the Last Glacial Maximum, where sea-level was at a lowstand of 130m, has been debated (Clark *et al*. 2012). The British-Irish Ice Sheet in the Late Devensian is said to have, reached its maximum between 22000 *cal*. BP - 18000 *cal*. BP as evident from the GRIP ice core $\delta^{18}O$ record (Bradwell *et al*., 2008; Bowen *et al*., 2002). Additionally, Mix, Bard and Schneider (2001) suggested the Last Glacial Maximum occurred between 24000 *cal*. - 18000 *cal*. BP. However, Peltier and Fairbanks (2006) indicate the event to be earlier at 26000 *cal*. BP - 21000 *cal*. BP corresponding with Clark *et al*.'s (2012) evidence. Rannoch, immediately west of the Forth valley, is identified as the centre of the British ice sheet in the Last Glacial Maximum, suggesting that this particular area would have and still is experiencing rapid uplift from glacio-isostasy (Clark et al., 2012; Smith *et al*. 2000; Lambeck 1993b).

Bradwell *et al*. (2008) stated that the ice sheet over northern Britain has been poorly defined and therefore, causes modelling of both past and future glacio-isostatic activity difficult. Additionally, various sections of the British-Irish ice sheet behaved differently in space and time, suggesting accurate modelling of the Last Glacial Maximum is complex (Hughes *et al*. 2013). It is important to define whether the Fennoscandian ice sheet was connected to the British-Irish ice sheet as it affects glacio-isostatic uplift on the north-east coast of Britain and more significantly the Forth valley (Terferle *et al*. 2009). In Fig. 2.3.1**,** Clark *et al*. (2012) indicate a connection with the Fennoscandian ice sheet in their model for the extent of the Last Glacial Maximum, disagreeing with traditional views. Clark *et al*. (2012) believes there is strong evidence offshore that suggests the two ice masses were connected, as demonstrated in Fig. 2.3.1 and Fig. 2.3.2, but not enough to critically analyse. They recognise difficulties in modelling the British-Irish ice sheet as submarine areas were not fully examined due the lack of data availability for the Irish and North seas (Hughes *et al*. 2013). In terms of the demise

Fig. 2.3.1. Maximum extent of the British-Irish ice sheet with the smaller dashed line representing the 'traditional' view from assessing Bowen *et al* (1986). Larger solid line distinguished as the Last Glacial Maximum by strong evidence of landforms and ice-rafted debris from the continental shelf (Clark *et al*. 2012).

of the Last Glacial Maximum, Clark *et al*. (2012) presented two scenarios (Fig. 2.3.2) for the retreat of the British-Irish ice sheet in an attempt to avoid contradicting data. However, demonstrating evidence in two separate scenarios still presents ambiguity and assumptions that ignore the data that disagrees for each scenario. Scenario one disputes deglaciation dates

Fig. 2.3.2. Isochrones of the ice retreat of the British-Irish ice sheet with successive margin positions in years ka BP. (Clark *et al*. 2013).

recorded from Lake Windermere and the Yorkshire Dales, suggesting northern England was ice free before 17000 BP (Ballantyne *et al*. 2009; Telfer *et al*. 2009). Additionally, no evidence for the remaining ice cover over the southern North Sea was found in scenario two (Carr 2004).

Coastal landforms in Scotland developed during the Devensian and the Holocene (Smith 1997). The earliest evidence of shorelines indicating sea-levels connected with ice-sheet decay can be found between Stonehaven and the Firth of Forth (Smith 1997). Cullingford and Smith (1980) identified eight narrow sand and gravel raised shorelines up to 40m eastward. The tilt in shorelines indicate crustal recovery as glacio-isostatic uplift will be additional at the centre of previous ice loading and less at the periphery (Sissons 1983). In addition, three shorelines between Stirling and Perth relate to former ice limits where the highest shoreline occurs as far west as Kincardine (Sissons, Cullingford and Smith 1966). Relative sea-level in the Forth valley fell from 38m (altitude of the second shoreline) to 20m (altitude of the lowest) as the land recovered from ice loading (Sissons, Cullingford and Smith 1966). However, in an attempt to prove these shorelines were climatically related, using foraminifera, there was no supporting evidence as to whether the samples were autochthonous (Browne *et al*. 1981). Therefore, these theories look doubtful (Smith and Cullingford 1982).

It has been argued that the Loch Lomond Stadial, ice limits illustrated in Fig. 2.3.3, created further crustal depression (Firth, 1986; Sutherland, 1984). Many investigations into vegetational change in western Scotland (e.g. Loch Ashik) have provided evidence of climatic warming at the beginning of the Lateglacial interstadial to cooling in the Loch Lomond Stadial, from the presence of arctic-like vegetation (Brooks *et al*., 2012). This readvance in ice is identified in Greenland ice core records between 12900 *cal*. BP - 11700 *cal*. BP (Björck *et al*. 1998; Ramussen *et al*. 2006; Lowe *et al*. 2008). However, limitations with radiocarbon dating methods in correlation to ice core records has led Muscheler *et al*. (2008) to believe it may have occurred 300 years later. Although the Loch Lomond Stadial was short in duration, Stuvier, Grootes and Brazunias (1995) found temperatures were equal to the coldest parts of the Late Devensian. Lambeck (1993a) modelled crustal uplift of up to 1m - 2m associated with this event alone. The transition from the Loch Lomond Stadial into the Holocene is established by sediment accumulation in rising sea-levels (Smith 1997). Sissons, Cullingford and Smith (1966) and Sissons (1983) define these events in the western Forth valley where they distinguished the accumulation of estuarine sediments across outwash from the Menteith Moraine (Loch Lomond Stadial limit) at the head of the Forth Lowland.

Sissons, Cullingford and Smith (1966) distinguished the alignment of all raised shorelines in south-east Scotland (Fig. 2.3.4). Additionally, Sissons (1984) provided a morphological and

Fig. 2.3.3. Loch Lomond Stadial limits throughout Scotland as interpreted from geological evidence and numerical modelling (Golledge 2010).

Fig. 2.3.4. Younger Dryas and Holocene shoreline diagram for the Forth lowland (Smith 2005).

Fig. 2.3.5. Representation of morphology, buried morphology and stratigraphy at the head of the Firth of Forth with numbers indicating shoreline sequence (Sissons 1984).

stratigraphical map of all eleven shorelines at the Firth of Forth in Fig. 2.3.5, although not all of them can be found alligned at the same location. The High Buried Beach (10300±200 ^{14}C BP), between 9.2m - 12.5m Ordnance Datum (OD), was formed as sea-level rose and marine erosion stopped across the outwash deposits down valley from the Menteith moraine, signifying the end of the transition into the Holocene (Sissons 1966; Sissons, Cullingford and Smith 1966; Sissons 1983). The Main Buried Beach below, between 6.5m - 11.8m OD, distinguishes a fall in sea-level (Sissons, Cullingford and Smith 1966; Sissons, 1983; Smith *et al*. 2010). However, Smith *et al*. (2010) defined this regressive period to have occurred between 11200 *cal*. BP - 10000 *cal*. BP in the Forth Lowland. The Main Buried Beach, using two contact points had been dated between 10700 ^{14}C BP - 10570 ^{14}C BP at the rear and 9922 ^{14}C BP - 10241 ^{14}C BP at the front edge, indicative of a time-transgressive shoreline (Sissons 1983). Therefore, indicating the formation of the High Buried Beach and the transition into the Holocene was earlier than 10300±200 ^{14}C BP. This correlates with the Greenland ice core data, suggesting 11700 *cal*. BP as the start of the Holocene (Lowe *et al*. 2008). A continued fall in sea-level is established by the Low Buried Beach occurring at 8m (Sisson, Cullingford and Smith 1966). Robinson (1993), using microbiological indicators, dated the Main Buried Beach at 9300 *cal*. BP - 9600 *cal*. BP and the Low Buried Beach at 8800 *cal*. BP. However, recent work from Smith *et al*. (2010) dated the less extensive Low Buried Beach at 9537 *cal*. BP - 9881 *cal*. BP positioned between 5.2m - 7.4m OD. Sea-level withdrew during the early Holocene forming buried beaches, also known as estuarine terraces, and eventually became covered in peat (Smith *et al*. 2010). Sea-level reconstructions of the Scottish west coast, from Shennan and Horton (2002), do not recognise this early Holocene transgression, suggesting localised processes occurred on the east coast. Additionally, the buried beaches identified in south-east Scotland are indicative of early Holocene marine regression and have not been found elsewhere in Scotland (Sisson, 1983). The upper Forth and Lower Teith valleys experienced flooding from high relative sea-level across the outwash deposits after the termination of the Loch Lomond Stadial (Smith *et al*. 2010).

2.4. Holocene Sea-Level Change in Scotland with Reference to the Forth Valley

Modern sea-level studies combine morphological and stratigraphical evidence in order to determine past environments (Smith, 1993). Reconstructions of past sea-level are based on indicative meaning, whereby, geological estimates are dependent on linking present-day relationships to make assumptions for the past (Shennan, Milne and Bradley, 2012). According to previous studies, the Forth valley is close to the centre of glacio-isostatic uplift in Scotland (Lambeck 1993b; Smith *et al*. 2000). Relative sea-level can be studied in detail from exposed coastal locations in east Scotland (Tooley and Smith 2005). Owing to the complex nature of glacio-isostasy and glacio-eustasy, sea-level changes in Scotland should be considered relative (Smith, 1993). The Forth valley is a low energy environment that has preserved environmental evidence for past relative sea-level change in detail from its shoreline terraces and underlying deposits (Smith *et al*., 2010).

Smith *et al*. (2010) produced a relative sea-level graph west of Stirling from the two uplifted blocks where shoreline dislocation occurred, defined in Sissons (1972) (Fig. 2.4.1 and Fig. 2.4.2). The shorelines in this area slope eastwards towards the centre of glacio-isostatic uplift (Smith *et al*. 2010). One of the dislocated points, Point A in Fig. 2.4.1, is located westerly near the Loch Lomond Advance Limit, suggesting uplift was caused by crustal recovery from this particular Stadial (Sissons 1984). The second dislocation point corresponds to the Abbey Craig fault reiterating how sensitive south-east Scotland is to neotectonics (Sissons 1972). Smith *et al*. (2010) suggested this process of block uplift occurred until sea-level withdrew from the Blairdrummond Shoreline at approximately 4700 *cal*. BP. The gradient of each dislocated shoreline is similar, indicating that block uplift occurred at the same rate (Fig. 2.4.1) (Smith *et al*. 2010). These carselands are representative of an estaurine environment as evident from faunal and microfossil data, mainly silt composition and consistent altitudes (Robinson 1993; Barras and Paul 1999). The early Holocene sea-level fall and subsequent rise between 9500 *cal*. BP - 9000 *cal*. BP is observed later at other sites in Scotland as the Forth valley is closer to centre of glacio-isostatic uplift (Smith *et al*. 2010; Smith 2005).

Fig. 2.4.1. Deformation of the Main Postglacial Shoreline (upper line) and the Main Buried Shoreline in part of the Forth valley illustrating two dislocations (Sissons 1984)

Fig. 2.4.2. Combined relative sea-level graphs around West Flanders Moss and east of the Menteith moraine where block uplift occurred (Smith *et al*. 2010).

The Main Postglacial Transgression has been recorded in this area between 9500 *cal*. BP – 7800 *cal*. BP, evident from the rapid rise in relative sea-level (Sissons and Brooks 1971; Sissons, 1974; Robinson 1993). The mean rate of sea-level rise during the Main Postglacial Transgression was 3.94mm/yr in the western Forth valley and 5.11mm/yr east of Stirling (Smith, Firth and Cullingford 2002). During this period, estuarine sediments of the carselands accumulated and overlay the early Holocene peat (Smith 1997). In addition, Smith *et al*. (2010) suggested sea-level rise fluctuated at approximately 8300 *cal*. BP, evident in the regressive and transgressive overlaps discovered at Woodlane between 8192 *cal*. BP – 8447 *cal*. BP. This agrees with previous research by Robinson (1993). Additionally, peat was found beneath marine sediments in Fife, east of Stirling, dated to the early Holocene (Tooley and Smith 2005). This period indicates sea-level outpacing glacio-isostatic uplift or the Main Postglacial Transgression. It could be argued that this was a local episode, yet these events have occurred at other carse sites, such as the Cree Estuary and the Ythan estuary (Smith *et al*. 2003; Smith *et al*. 1999). Additionally, Clark (1942) suggested that the sixteen whale skeletons excavated during the eighteenth and nineteenth centuries in the carselands became trapped by the tide in the low energy environment at deposition (Morris 1892; Lothian 1864; Drummond 1824; Blackadder 1824). They were found between 1.2m - 4m below the carseland and overlay peat (Smith *et al*. 2010). Beds of shells that occur in some parts of the carseland and the whale skeletons are indicative of deposition during relative sea-level rise events during the Holocene (Smith *et al*. 2010).

The Main Postglacial Shoreline developed (indicating the end of the Main Postglacial Transgression) at approximately 7800 *cal*. BP when Mean High Water Spring Tides (MHWS) ranged between 14.6m - 16.5m OD (Smith *et al*. 2010; Sissons 1983). This is higher than Lambeck's (1991; 1993b) results from Glacial Isostatic Adjustment modelling which suggested MHWS values were between 14.35m - 14.7m OD at approximately 7700 BP. Smith, Cullingford and Brooks (1983) suggest the age of the exposed 40m shoreline varies a few hundred years as it is time-transgressive. The Main Postglacial shoreline, underlying the Main Buried Beach in the Forth Lowland (Fig. 2.4.1), demonstrates a metre-scale dislocation in two places owing to two events of uplift in the last 9600 years (Sissons 1983). Studies have not yet been able to define the duration of sea-level to produce the Main Postglacial Shoreline (Smith *et al*. 2010). The emergence of peat directly overlying the carse is evidence of sea-level withdrawing after the formation of this shoreline (Smith *et al*. 2010). West of Stirling, the accumulation of peat formed the West Flanders Moss and East Flanders

Moss at the head of the Forth valley (Sissons and Smith 1965; Sissons, Smith and Cullingford 1966; Robinson 1993; Smith *et al.* 2010).

Additionally, Smith *et al.* (2010) have identified the Storegga Tsunami in Fig. 2.4.2. Evidence of the Storegga Tsunami was first found in the carse of the Forth lowland by Sissons and Smith (1965) as a distinctive layer of sand which was initially considered to be indicative of a coastal flood event (Smith *et al.* 2004; Smith *et al.* 1985). Dawson *et al.* (1988) defined this event as a tsunami after evidence of the Storegga Slide was found on the continental slope off western Norway. Additionally, this sand horizon occurs shortly before the deposition of the Main Postglacial Shoreline, creating possible variations in dates for the Main Postglacial Transgression (Smith *et al.* 2010). The fine or fine to medium sand morphology can be found across 600km of the British coast from Shetland to northeast England (Smith *et al.* 2004). Smith *et al.* (2010) dated the tsunami horizon between 7570 *cal.* BP - 7790 *cal.* BP (Fig. 2.4.2), contradicting Smith *et al.*'s (2004) estimate at 7900 *cal.* BP. However, Weninger *et al.* (2004), indicate older dates at approximately 8100 *cal.* BP. It has been suggested that the contacts used to date the Storegga tsunami by Smith *et al.* (2010) had been contaminated by rootlet intrusion as it lies directly below the carse, therefore, 8100 *cal.* BP is considered to be the more reliable date. Despite Gehrels (2010) acknowledgement of the lack of data for relative sea-level during the Holocene on the east coast of Scotland, Smith *et al.* (2010) provided comprehensive research of the environment in the Forth lowland during the early to mid Holocene.

Shennan and Horton (2002) created a sea-level graph for the Forth valley using GIA models, radiocarbon dates and evidence from Robinson (1993). However, Gehrels *et al.* (2011) argue that the intercalated index points, such as those used in Fig. 2.4.3, taken from coastal peat are unreliable for radiocarbon dating methods, owing to the vertical displacement

Fig. 2.4.3. Relative sea-level graph for the Forth valley. The solid line is the best estimate for late Holocene sea-level (Shennan and Horton 2002).

causing sediment consolidation. Shennan and Horton (2002) state that this does not apply to most sites in Scotland as the samples are collected on hard substrate, such as, sand. Furthermore, the mid-Holocene highstand is not as high in altitude as in Fig. 2.4.2 (by approximately 2.5m). Once again the solid line included by Shennan and Horton (2002) distinguishes the lack of late Holocene sea-level data in the Forth valley. This estimation attempt is inappropriate as it creates assumptions for how sea-level fell between approximately 5000 BP to the present. Analysis of observations on land- and sea-level change is still the most accurate method of determining past environments as modelling still needs developing in accuracy and include other processes, such as, neotectonics which occur in the Forth (Smith *et al*., 2012; Shennan and Horton, 2002).

Patterns of glacio-isostatic uplift and altitudes of shorelines are typically depicted in isobase maps (Fig. 2.4.4). Isobase maps, such as Fig. 2.4.4, generalise patterns of uplift and the

Fig. 2.4.4. A) Patterns of uplift for the Main Postglacial, Blairdrummond and Wigtown Shorelines B) displaying where each is a visible feature compared with a model of present day relative sea-level change (Smith *et al*. 2012).

approximate location of shorelines as such data is not available in all parts of Scotland, suggesting how complex uplift patterns are (Sissons, 1983). In the Bannockburn area, the highest level carseland at 12.1m - 12.09m OD is related to the Blairdrummond Shoreline where dates for withdrawal were given at 4290 *cal*. BP - 5260 *cal*. BP (Smith *et al*. 2012; Tipping, Smith and Jordan 2013). This agrees with Smith *et al*. (2010) where relative sea-level was established to have withdrawn by 4700 *cal*. BP. As sea-level fall stabilised after the Main Postglacial Shoreline developed, the coast was liable to flooding (Smith *et al*. 2010). The index points used by Smith *et al*. (2010) distinguished the Blairdrummond shoreline from an area 5km in length in the western Forth lowland, occurring 2m - 3m above the Main Postglacial Shoreline. As the altitude of the Blairdrummond shoreline and the Main Postglacial shoreline are close, perplexing dates were recorded by Mackie (1972), Robinson (1993) and Ashmore and Hall (1997) for north and south of the Forth, ranging from 5950 *cal*. BP - 6780 *cal*. BP to 3860 *cal*. BP - 4520 *cal*. BP. The first date establishes the fall in relative sea-level from the Main Postglacial Shoreline, as the latter correlates with dates for the Blairdrummond shoreline (Smith *et al*. 2010). It has been suggested that the formation of the Blairdrummond shoreline had transgressed over the buried peat that would have accumulated on the carseland and eroded it away, hence why buried peat has not been found around the carseland area merging to the surface peat (Tipping, Smith and Jordan 2013).

The second carseland level at 8.3m - 10.1m OD has been loosely dated to the Wigtown shoreline (Fig. 2.4.4) approximately 3900 *cal*. BP or possibly later due to the end of the shell midden accumulation in Grangemouth (Smith *et al*. 2010; Tipping, Smith and Jordan 2013). Two possible shorelines have been identified East of Stirling that lie below the Blairdrummond shoreline, providing possible relative sea-level changes (Smith *et al*. 2010). A terrace in the area with a break in slope just north of the Abbey Craig Fault at an altitude between 7.9m - 9.8m OD is an alleged shoreline (Smith *et al*. 2010). This has been dated between 4200 *cal*. BP - 3100 *cal*. BP as a result of dates investigated at Grangemouth by Robinson (1993) and Sloan (1993). Furthermore, a slope between 6.7m - 7m OD has been identified below in the Alloa area (Smith *et al*. 2010). The third level may have been dated to around 3000 *cal*. BP (Smith *et al*. 2010). The former base of a raft of peat, marked by silty clay, may be from a buried shoreline terrace dated 9528 *cal*. BP - 9656 *cal*. BP which is close to the age of the surface of the Low Buried Shoreline (Tipping, Smith and Jordan 2013; Smith *et al*. 2010; 2012). As sea-level continued to fall west of Stirling from the 3900 BP shoreline, raised moss developed as exposed carseland occurred east of Stirling (Smith *et al*. 2010). Little is known about relative sea-level changes in the Forth valley during the late Holocene and how the present coastline has been reached (Smith et al., 2010).

Sea-level fall after the mid-Holocene highstand fluctuated to reveal the carselands as former estuarine mudflats where peat accumulated (Smith 1968). The Forth channel became established in the floodplain areas when sea-level withdrew from the lowest carseland in the Stirling area (Tipping, Smith and Jordan 2013). Isostatic uplift occurred in this area, causing a tidal stream to erode the lowest carseland level, thus forming the Forth channel (Tipping, Smith and Jordan 2013). Smith (1978) recorded the altitude of the flood plain along the river Teith and the river Forth, 2km west of Stirling, lying between 5.0 - 5.1m OD. Additionally, estuarine waters would have dominated the flood plain north-east of Cambuskenneth prior to the effect of glacio-isostatic uplift at approximately 2500 BP where the tidal limit lay near Netherton (Tipping, Smith and Jordan 2013).

Scottish river catchments have experienced changes in vegetation and land use during the Holocene due to climatic changes, glacio-isostatic uplift and anthropogenic influences (McEwen, 1997). The fall in relative sea-level as a result of glacio-isostatic uplift would have led to changes in hydrology during the late Holocene. Changes in the thalweg after the alleged formation of the Wigtown shoreline would have caused the river Forth to change course (Fig. 2.4.5) (Tipping, Smith and Jordan 2013). Hypothetically, it could have flowed from Forthside past Abbey Craig before passing through Cambuskenneth to Bolfornaught then to Fallin and the river Devon mouth (Tipping, Smith and Jordan 2013). Eventually, the bend at Bolfornaught became less acute and finally became straighter due to the construction of an embankment in the 18th century (Tipping, Smith and Jordan 2013). A majority of these embankments have not been dated along the river Forth, making reconstructions of the environment difficult as they would have modified its natural course. Tipping, Smith and Jordan (2013) recorded a series of radiocarbon samples from fill in the valley including Netherton (the study site for this project). Macklin and Lewin (1993) consider the British Holocene fluvial record to be 'culturally blurred', affecting attempts of past reconstructions based purely on climatic and glacio-isostatic changes.

It had been assumed that the development of peatlands covered the majority of the estuarine clay as sea-level fell, yet the Carse of Stirling has been overlain by the sporadic development

Fig. 2.4.5. Hypothetical changes in thalweg at the river Forth after the lowest level carseland was abandoned (Tipping, Smith and Jordan 2013).

of peatlands, wetlands and mineral soils (Harrison 2003). It has been suggested that the exposed carse was never covered by moss south of Stirling (e.g. Gargunnock and Kippen) (Harrison 2003). As a result of increased demand for agricultural land, forestry, horticultural and energy properties, peatlands have been subject to clearance for centuries (Holden, Chapman and Labadz 2004). Most of the surface peat was removed in the eighteenth and nineteenth centuries, limiting the amount of collectable data available for the late Holocene (Cadell 1913). However, anthropogenic removal of the peat occurred before clearance in the 19th century, but not as extensively, for fuel sources and was deposited into the river Forth through the process of flotation (Harrison 2003). This practice stopped as the Salmon Fisheries Scotland Act 1862 was implemented to prevent river pollution from moss clearance

(Harrison 2003). Work on environmental changes of the river Forth during the late Holocene is scarce. Therefore, archaeological and environmental reconstruction projects (e.g. Tipping, Smith and Jordan 2013) have been completed to determine historical elements of the river Forth, such as, the Battle of Bannockburn. MacLagan (1872) stated the possibility of the carse of Stirling or the Forth valley to be an unhabitable swamp 1000-2000 years ago. However, the fall in relative sea-level from the 3900 *cal*. BP shoreline led to improved drainage in the Forth valley allowing settlements to expand on cultivation activity (Smith *et al*. 2010). Additionally, tidal values have reduced greatly from the Main Postglacial Transgression and are presented in Table 2.4.1. Therefore, this study will provide proxy evidence for late Holocene environmental changes in the Forth valley to determine hydrological changes of the river Forth at Netherton.

Table 2.4.1. Tidal values relative to Ordnance Datum (Admiralty Tide Tables 1996).

2.5. Medieval archaeology from the Late Holocene

A Bronze Age wheel has been recovered from the Forth Lowland as evidence of one of the first types of wheeled transport in Britain and Ireland (Hedges *et al*., 1993). In addition six log boats have been excavated in Cambuskenneth with only one dated at 800 *cal*. BP - 1057 *cal*. BP (Smith et al. 2010). These discoveries indicate the distribution of people in the Forth valley and former sea-levels or cultural changes that took place during the late Holocene, although little is known about this relationship (Smith *et al*., 2010). The archaeological sites studied by Smith *et al*. (2010) had evidence dated from 1600 *cal*. BP and earlier. Rideout

(1996) undertook excavations in 1982, 1984 and 1985 in the Lower Greenyards and Bannockburn, finding remains mainly from the Iron Age. Although it has been argued that the buildings excavated may have been used for domestic use rather than a defensive purpose, a medieval promontory fort and a palisaded homestead were found (Rideout 1996). Additionally, cartographic artefacts have been dismissed as inaccurate portrayals of the peat mosses surrounding Stirling during the 18th century (Harrison 2003). Therefore, archaeological evidence found around the Forth valley does not provide a detailed representation of the environment or enough evidence to be sure of settlement activity during the late Holocene, especially prehistoric.

2.6. Summary

Scotland has undergone a complexity of land and sea-level changes throughout the Late Quaternary (Gray 1985). Previous research in the Forth valley has been used as an analogue for Holocene sea-level studies in Scotland (Smith 1997). This thesis will contribute to the literature in both a geomorphological and historical aspect for Scotland. Furthermore, it is evident that there is a lack of late Holocene sea-level data for the Forth valley. However, land clearances in the eighteenth and nineteenth centuries will prove to be a limitation in data collection for this specific time period.

Chapter 3. Site Description

3.1. Introduction

The river Forth is located in south-east Scotland draining the eastern side of the mountainous Trossachs, west of Stirling, into the Firth of Forth (Fig. 3.1.1). The borehole collected is from Netherton, on the north bank of the river Forth next to the connecting river Tieth and the Allan Water tributary. The river and its tributaries were exposed as a result of glacio-isostatic uplift, eroding the lower carseland level (Tipping, Smith and Jordan 2013).

Fig. 3.1.1. Map of Scotland indicating the location of the study site (adapted from Smith *et al*. 2003).

3.2. Site Description

The theory development of glacio-isostasy was demonstrated in detail by Jamieson (1865) in the Forth lowland with applied shoreline evidence of relative sea-level changes (Fig. 3.2.1) from Sissons (1962; 1963). Furthermore, evidence of events during the Holocene, such as, neotectonics establishing the formation of dislocated shorelines and the Storegga Tsunami, were first discovered in the Forth Lowland. Many significant archaeological discoveries in the area have been significant to interpreting late Holocene localised environmental changes (e.g. Smith *et al*. 2010), yet there is a lack of morphological studies specifically looking at this period in the Forth valley. Many of these studies have been discussed in Chapter 2 (Literature Review) with details of the research to date for the area surrounding the river Forth. Therefore, the site of interest has been fundamental to many late Quaternary studies, particularly Holocene relative sea-level studies, which have been paramount to the development of theories on glacially influenced changes in sea-level.

Fig. 3.2.1. Map of the Forth lowland with shoreline and river terraces (Tipping, Smith and Jordan 2013).

Surrounding the estuary of the river Forth are former estuarine mudflats, known as carselands, comprising of fertile silts and clays deposited from changing sea-levels, underlying areas covered in peat moss (Tipping, Smith and Jordan 2013). West Flanders Moss and East Flanders Moss, located west of Netherton, accumulated after the formation of the Main Postglacial Shoreline at the head of the Forth valley (Sissons and Smith 1965; Sissons, Smith and Cullingford 1966; Robinson 1993; Smith *et al*. 2010). However, the increasing demand for agricultural land and fuel led to the clearance of surface peat that sporadically covered south-east Scotland between the eighteenth and nineteenth centuries (Smith *et al*. 2010; Holden, Chapman and Labadz 2004). Peat removal included drainage into the river Forth, influencing the deposition of sediments downstream throughout the late Holocene (Harrison 2003).

Netherton (Fig. 3.2.1) has been chosen for this research as Tipping, Smith and Jordan (2013) found the site had the best continuation of sediment. Additionally, a pilot study was undertaken to confirm the presence of diatoms. These findings can be found in the Results chapter. The site is at 3.8m OD where the spring tidal range is 2.8m OD today at Stirling. The upper tidal limit is further downstream from Netherton, yet it has been suggested that the tidal limit was further upstream during the early stages of the late Holocene before glacio-isostatic uplift caused sea-level to fall to its current position (Tipping, Smith and Jordan 2013; Admiralty Tide Tables 1996). Although it cannot be certain that the tidal values today were persistent throughout the late Holocene, research from Shennan *et* al. (2000) in the western North Sea has shown similar conditions for the last 6000 years. The tidal range suggests periodic flooding occurs near Netherton today as it is located at the peritidal limit (Tipping, Smith and, Jordan 2013). Therefore, these hydrodynamic changes during the late Holocene in the surrounding area will be recorded in the core collected from Netherton.

3.3. Summary

This chapter shows the location of the collected borehole that will be used for stratigraphical and diatom analysis. Furthermore, the area surrounding Netherton will have significant influences on the environmental changes found in the core as the river Forth is influenced by the tidal range, upstream activities and localised adjustments. Therefore, the results will provide evidence for late Holocene relative sea-level changes of the river Forth.

Chapter 4. Methods and Techniques

4.1. Introduction

This chapter will look into the techniques used for this project and justify why they are appropriate to reconstructing the environment of the Forth valley. The methods applied include sediment coring and laboratory preparation for diatoms. Furthermore, a radiocarbon date has been provided for the lower peat section of the stratigraphy. Diatom analysis is the focal point of the methodology as this specific technique will be a crucial element of the discussion.

4.2. Diatoms

Diatoms are unicellular algae of the Bacillariophyta, occurring in almost every aquatic environment, terrestrial environment, submerged surface or open water exposed to light (Round, Crawford and Mann 1990; Lowe and Walker 1997:176; Kennington 2002; Armstrong and Brasier 2005:200; Bathurst, Zori and Byock 2010). Denys (1991/2) categorises the variety of lifeforms as euplanktonic (living in open waters), tychoplanktonic (present in the plankton but origin is from other habitats), epontic (attached to substrata or vegetation) and benthic (weakly attached to the substrata) (Serieyssol, Chatelard and Cubizolle, 2011). Additionally, diatoms can occur where water is present intermittently (Stoermer and Smol 1999). They are characterised by their 95% siliceous cell walls, consisting of two overlapping valves, forming the frustule (Lowe and Walker 1997:176; Kennington 2002; Armstrong and Brasier 2005:200). The frustule's composition of opaline silicate improves the preservation potential of diatoms as it is resistant to diagenic deterioration, even in fossil deposits (Lowe and Walker 1997:176; Stoermer and Smol 1999; Korhola 2000; Kennington 2002). Gehrels, Roe, and Charman (2001) found that diatoms had significantly greater species diversity than foraminifera and testate amoebae. The frustules distinct characteristics and broad diversity show taxonomic differentiation to species or sub-species level, providing specific knowledge of the environment (Bathurst, Zori and Byock 2010).

Past environments during the Quaternary and Holocene in particular, have been reconstructed successfully using diatoms as indicators of change (Round, Crawford and Mann 1990:48; Lowe and Walker, 1997:175; Smith *et al*. 2010). Since the nineteenth century, salinity identification of diatoms has been used to determine changes of palaeoenvironments in coastal areas (Denys and de Wolf 1999). Halden (1929) performed the earliest sea-level study using diatoms as an indicator and has since revolutionised during the 1950s through the availability of electron microscopes (Stoermer and Smol 1999). Diatoms are a sufficient microbiological indicator in establishing environmental changes as they occur in large numbers, have a high species diversity, unique specificity and good preservation potential (Palmer and Abbot 1986; Denys 1984; Battarbee 1986). Additionally, they are sensitive to physical and chemical conditions, emigrating quickly and reproducing rapidly as changes occur (Armstrong and Brasier 2005:200; Ognjanova-Rumemova 2008). They have limited environmental ranges for temperature, pH, salinity, acidity, oxygen and mineral concentrations (Kennington 2002; Armstrong and Brasier 2005: 203). However, it is difficult to define the constraints that these factors have on certain diatoms as some taxa are able to tolerate a range of conditions (Potapova and Charles 2002). Diatoms from peat have been used to determine palaeoenvironmental changes in freshwater and brackish fluvial systems (Brugram and Swain 2000; Ryu *et al*. 2008; Bathurst, Zori and Byock 2010). As an indicator of flood duration, Gehrels Roe and Charman (2001) found diatoms were more effective at indicating such events than testate ameobae and foraminifera as they respond quicker to changes in hydrology.

Their suitability for sea-level reconstruction has been repeatedly shown in studies of salt marshes as indicators of tidal inundation and salinity (Barlow *et al*. 2013; Roe *et al*. 2009). Diatom analysis has been used to indicate transgressional and regressional phases in littoral sediment sequences (Tooley and Shennan 1987; Shennan 1989; Kennington 2002). In addition to gradual sea-level changes, diatoms, combined with lithological evidence, can be used to establish storm-surge or tsunami events, such as, the Storegga tsunami (Hemphill-Haley 1995; Kennington 2002; Smith *et al*. 2010). Therefore, they can be used to determine shoreline deposition or influences of glacio-isostasy (Stabell 1985; Long and Shennan 1993; Smith *et al*. 2010).

Diatom assemblages are associated with elevation and relative tidal levels (Patterson *et al*. 2000; Gehrels, Roe and Charman 2001). Diatoms, covering a range of inter-tidal and supra-tidal environments, are better preserved than testate amoebae and are not complicated by in-faunal migration like foraminifera (Guilbault, Clague and Lapointe 1995; Gehrels, Roe and Charman 2001; Roe, Charman and Gehrels 2002; Patterson *et al*. 2005). Additionally, there is a relationship between diatom assemblages and salinity (Kolbe 1927; Hustedt 1957; Simonsen 1962; Ehrlich 1975). This relationship can identify interactions between marine and fluvial systems during the Quaternary (Denys and de Wolf 1999). Haring (1852) and Gregory (1855) studied the earliest research on marine diatoms inland, indicative of a change in the coastline position. However, when there are a range of origins in a diatom assemblage, it is important to establish autochthonous (*in-situ*) and allochthonous (positioned different from its origin by the movement of wind or water) species (Denys and de Wolf 1999; Kennington 2002). Freshwater diatoms have the potential to be windblown into marine sediments or transported over long distances through fluvial systems (Lowe and Walker 1997: 177). Therefore, it is important to use Denys' (1991/2) diatom lifeform classification to determine autochthonous and allochthonous species in samples. Simonsen (1969) suggested that benthic diatoms in a sample are representative of autochthonous species as they are less susceptible to transportation. However, this assumes that all epiphytic and planktonic diatoms are allochthonous in samples, effectively excluding information that is potentially relevant to the reconstruction of the environment (Vos and De Wolf 1988). Additionally, the presence of marine species, typically planktonic in lifeform, in non-marine sediment near the coastline represents a period of increased marine influence (Denys and De Wolf 1999).

Similarly to all microfossils, taphonomic processes can create difficulty in tracing the origin of diatom species (Denys and de Wolf 1999). Differentiation in preservation is common in coastal deposits, whereby a fraction of species that lived in brackish environments, such as, salt marshes, remain (Brockmann 1940; Sherrod, Rollins and Kennedy 1989; Denys and de Wolf 1999). Therefore, diatoms are effective at identifying changes in the upper part of the tidal range or salt marsh environment rather than tidal-flat or sub-tidal environments (Barlow *et al*. 2013). Additionally, valve morphology, including the type and quantity of silica, causes variability in abrasion, dissolution and drying of diatoms, creating variable preservation in coastal sediments (Cooper, Gaiser and Wachnicka 2010; Jordon and Stickley 2010).

Other causes of fragmentation are chemical leaching, diagenesis, compaction, heating, strong temperature fluctuations, sample pretreatment and predation (Romeyn and Bouwman 1983; Beyens and Denys 1982; Andrews 1972). Damaged or partially preserved diatoms occur in oceans and other alkaline conditions (e.g. estuaries, freshwater and brackish environments) as these environments can dissolve weakly silicified taxa (Lowe and Walker 1997: 177; Cooper 1999). Weakly silicified diatoms are typically elongated whereas centric diatoms are considered strongly silicified (Vos and De Wolf 1988). These processes have created an incomplete fossil record of marine diatoms (Hesse 1989; De Wever, Azéma and Fourcade 1994; Martin 1995; Scheiber, Krinsley and Riciputi 2000). Diatoms are easily transported from fluvial systems, as they are light, creating mixed assemblages of freshwater, brackish and marine taxa (Lowe and Walker 1997:177). In high energy environments, such as the river Forth, palaeoenvironmental interpretations can be difficult as sedimentary facies may be scoured, subjecting transported valves to reworking (Denys and De Wolf 1999). However, reworked diatoms are typically broken or partially dissolved (Lowe and Walker 1997: 177). Therefore, preservation of diatoms conveyed in the results as fragmentation would suggest that species were reworked or transported from a distance (Vos and De Wolf 1988).

Robust species, such as, *Paralia sulcata* and *Pseudopodosira westii*, can dominate diatom assemblages as they tolerate transportation through tidal currents (Hemphill-Haley 1995; Lowe and Walker 1997: 177; Denys and De Wolf 1999; Barlow *et al* 2013). This can create misleading datasets that are not representative of autochthonous assemblages as dissolution can occur in both saline and freshwater environments, creating misinterpretations (Vos and de Wolf 1988; Flower 1993; Straub 1993; Sawai 2001; Kennington 2002; Ryves *et al*. 2003; Bradshaw *et al*. 2005; Barlow *et al*. 2013). Although common abundance is considered when differentiating from autochthonous species, these robust species in particular are highly silicified, creating preferential enrichment over autochthonous species in sites susceptible to even slight marine influence (Denys 1989; 1994; Vos and De Wolf 1994; Hemphill-Haley 1995; Denys and De Wolf 1999). Additionally, *P. sulcata* are either tychoplanktonic, eptonic or benthic in origin and are typically indicative of storm events, making this particular species a poor environmental indicator (Haggart 1986; Denys 1991/2). Although bioturbation and other processes can cause sediment mixing and contamination of diatom assemblages, studies on the consequences are scarce (Barlow *et al*. 2013). On the other hand, benthic species, such as, *Navicula directa* and *Hantzschia amphioxys* bind with sediment, preventing resuspension of the matrix (Sullivan 1999).

Modern diatom datasets have been studied from sites in west and north Scotland but are scarce in east Scotland (Barlow *et al*. 2013). In terms of archaeology, diatoms can be used as an indicator of the distance between sites of brackish or marine influenced environments (Miller 1982). Additionally, interactions with human activity can change diatom assemblages and the rate or direction is indicated through community composition (Snoeijs 1999). Increased human activity promotes nutrient loading, sediment loading, and eventual eutrophication, decreasing the amount of benthic habitats that are able to maintain rich species diversity (Sullivan 1999; Weckström, Korhola and Weckström 2007). Although there are disadvantages, few microfossils can match the applications of diatom analysis, especially as a proxy for environmental changes (Battarbee 1991; Brasier and Armstrong 2005: 205). Diatom assemblages demonstrating taxa of mixed salinities (euryhalobous to polyhalobous) provides evidence for the surrounding environment (Vos and De Wolf 1988). Salt marsh sediments are a more effective method of determining relative sea-level change over the last 2000 years (Bradwell *et al*. 2013). These sediments are typically fine-grained, where diatoms are best preserved as they are damaged easily in coarse-grained sediments (Lowe and Walker 1997:176). Additionally, Gehrels, Roe and Charman (2001) proved that diatom analysis is a more accurate indicator of sea-level than testate ameobae and foraminifera as it responds rapidly to changes in hydrology (Serieyssol, Chateland and Cubizolle 2011). Therefore, diatom analysis is one of the techniques chosen for this research.

As Netherton is a predominantly freshwater environment at present, defining the trophic status and pH characteristics of highly abundant taxa will provide more details of late Holocene sea-level influence in the Forth valley. Although salinity is considered to be a significant influential factor affecting diatom composition, temporal variability (e.g. flooding, river flow fluctuations, changes in light and temperature, nutrient availability) can similarly impact assemblages (Rovira *et al*. 2012). There have been many studies proving the effectiveness of diatoms as chemical and physical bio-indicators in riverine systems (Stoermer and Smol 1999). Although paleolimnological research is typically studied on stratified sediments, such as deep lake systems, there is no reason to assume that rivers do not have a similar sedimentation structure of diatoms, even though they are poorly understood in these systems (Schönfelder and Steinberg 2002; Battarbee 1986). Furthermore, diatoms have a low resistance to abrasion and dissolution in high hydrological energy (Riberio, de Sanna and Torgan 2010). It may be difficult to determine benthic diatoms as a result of well-developed river dynamics (Schönfelder and Steinberg 2002). However, this does not make the assemblage redundant, as it can be used to infer environmental changes elsewhere, such as, sea-level and upstream influence.

4.3. Stratigraphy

Along the East end of the river Teith on the Alan Water confluence at Netherton, the floodplain contains rafted peat and fragments of wood (Tipping, Smith and Jordan 2013). A sample has been taken in a 40cm thick horizon of peat and woody material approximately 1m - 1.4m below the floodplain for diatom analysis as part of the pilot study for this research. A site description is provided in Chapter 3 of this project. Diatom analysis from these samples will determine the environmental conditions of when the riverine sediments were accumulated, despite the possibility that the peat may have been moved by the river in this high energy environment (Tipping, Smith and Jordan 2013).

Sediment used for diatom analysis was taken from a core using a Russian corer. To prevent diatoms from fracturing and drying out, cores are sealed air-tight (Lowe and Walker 1997:176). However, where other evidence may have decayed, diatoms do survive if wetting or drying of a sediment column occurs (Bathurst, Zori and Byock, 2010; Moser, Macdonald and Smol, 1996; Round, 1964). The Russian corer consists of a steel half-cylinder with a sharpened edge, on which a flat steel blade is attached and turns around the central axis of the cylinder (Pitkänen, Turunen and Simola, 2011). The narrower side of the blade fits precisely to turn inside the half-cylinder, while the broader side acts as an anchor to keep the blade in position during sampling. At the sampling depth it is turned 180° by the rod to cut and secure the sample against the blade face to reduce the loss and contamination of soil. The Russian corer is advantageous for its simplicity and is strong in soft soils and sediments (Franzén and Ljung, 2009). The stratigraphy is recorded after the core is collected and before diatom preparation is undertaken.

4.4. Radiocarbon Dating

Radiocarbon dating is a radiometric technique widely used to date Holocene sediments (Lower and Walker 1997:240). Radiocarbon calibration is essential in comparing ^{14}C ages with records when exploring rates of environmental change (Reimer *et al.*, 2009). De Vries (1958; 1959) discovered the differences in ^{14}C content between the past and present, revolutionising the techniques of radiocarbon dating. The ^{14}C age allocated to the sediment is considered to be the date of deposition (Lowe and Walker 1997:247). However, reworking of sediments can identify sections of the stratigraphy to be older than the depositional environment (Fowler, Gillespie and Hedges 1986). Radiocarbon dates are extracted using the INTCAL09 curve from the CALIB 6.0.0 software in conjunction with Stuvier and Reimer (1993) with the total range to 2σ quoted. Radiocarbon dates were initially produced by Smith, Tipping and Jordan (2013) at the Forth valley in an attempt to recover late Holocene sediments that could be used for diatom analysis. The date recorded from Netherton correlates to the late Holocene and has been calibrated using CALIB 7.0.

4.5. Diatom Preparation

Samples were extracted every 0.5cm of the sediment core to ensure a high resolution data set. Laboratory preparation, following Renberg (1990), separated diatom valves from sediment and mud particles. A total of 140 samples were taken from the site at Netherton for diatom preparation. Renberg (1990) modified the standard method, involving the oxidation of sediment samples in beakers with 100ml of hydrogen peroxide and sometimes centrifuging in order to save time and cupboard space (Olsson, 1929; Brander, 1936; Schrader, 1973). Additionally, the modified method reduces the amount of fractured diatoms throughout the preparation (Renberg 1990).

Small sub-samples (3-5mm^3) were taken and placed in glass test tubes (120x11mm), shortening the oxidation time. 1 ml of 30% H_2O_2 was added to each sample and the individual tubes were covered as sediments rich in certain metals may react vigorously with hydrogen peroxide. Using H_2O_2 to remove organic matter through oxidation will separate diatom frustules from the sediment matrix (Lowe and Walker 1997; 176). The tubes were placed in a metal test tube rack and immersed in a water bath. The water bath was heated to 85°C and the samples were left for 1 hour. Throughout the hour the samples would be checked and lightly shaken to make sure they had not dried out. After the first hour, a further 1ml 30% H_2O_2 was added and the samples were placed back into the water bath for another 1-2 hours until digestion had taken place. Following digestion, the samples were removed from the water bath, filled with distilled water and placed into a refrigerator overnight. After chilling, the supernatant was removed and the samples were refilled with distilled water. The individual tubes were shaken and the turbid sample was placed onto a circular cover slip and topped up with distilled water. The sample was then left to air dry overnight, although the duration of drying can be shortened by applying heat (Gehrels, Charman and Roe 2001).

Once dry, the sediment-covered cover slips were mounted using Naphrax, a high reflectivity mounting agent, onto a microscope slide. 300 diatoms are counted from each slide under a microscope of 1000x magnification.

A high-powered microscope is essential to examining diatom species as their taxonomic characteristics, such as the centric or pennate shape of the frustule, are crucial for correct identification (Lowe and Walker 1997:176). Hustedt’s (1957) modification of Kolbe’s (1927; 1932) classification of salinity, known as the halobian system, is used to determine the salinity preference of diatom taxa (Table 4.5.1). Similarly to Vos and de Wolf (1988), preservation counts were recorded for each sample in an attempt to distinguish allochthonous species. Additionally, the sediment matrix sampled for diatom analysis will provide an indication of the environment (Vos and de Wolf 1988). Care needs to be taken when analysing environments with fluctuating salinity regimes as diatoms will be abundant according to their ability to cope with salinity changes rather than their salinity classification (Snoeijs 1999). Metcalfe *et al*. (2000) have critiqued Denys (1991) and Vos and De Wolf (1993)'s classification system as their results are concluded from ecological conditions of a microtidal environment in the Netherlands and Belgium. Although there are limitations to these sources, as the study site is a macrotidal environment, it is the most comprehensive data for diatoms in the North Sea Quaternary coastal environment (Metcalfe *et al*. 2000).

Table 4.5.1. Salinity classifications and definitions (Hemphill-Hayley 1993).

Term	Salinity Range	Comment
Polyhalobous	> 30 ‰	Marine Species
Mesohalobous	0.2 – 30 ‰	Brackish Species
Oligohalobous	< 0.2 ‰	Freshwater Species
Halophobus		Cannot tolerate even slightly salty water
Euryhalobous		Occur over large ranges of salt concentration

4.6. Summary

This chapter provides a brief overview of diatoms in sea-level reconstruction. Furthermore, an outline of the methods and techniques used in this research to collect, prepare and analyse the diatom samples are explained. Stratigraphic and diatom analysis, combined with radiocarbon dates, will identify environmental changes in the Forth valley.

Chapter 5. Results

5.1. Introduction

The results distinguish the identification of sediment in the stratigraphy and the diatom assemblages. The results have been divided into zones according to changes in sedimentation. Diatom assemblages have been presented in 5%+ percentage counts for salinity, pH and trophic status. Furthermore, a band of peat was dated in zone 1 at 2761±45 ^{14}C BP (2862±94 *cal*. BP). It is important to outline the different characteristics (salinity, pH and trophic status) of the diatom assemblages in order to interpret the data for environmental reconstruction.

5.2. Pilot Study

A pilot study of samples taken from a peat section of a sediment core from Netherton was completed. This study established the presence and types of diatom taxa that may be found for this research project. A diatom diagram of percentage total counts has been produced for the pilot study (Fig. 5.2.1). Similar to the results found in this research, marine to marine-brackish species *Paralia sulcata* was abundant throughout the count and at certain points above 5%. Additonally, fresh-brackish species *Achnanthes linearis*, *Achnanthes lanceolota*, *Cocconeis placentula*, *Encyonema silesiacum* and freshwater species *Cymbella laevis*, *Eunotia sudetica*, *Tabellaria flocculosa* dominate the count. Brackish-fresh species *Fragilaria ulna* remains the most abundant species at between 20%-35% of the count. All these species from this pilot study, including *Paralia sulcata*, are abundant at >5% throughout the diatom assemblage in this study.

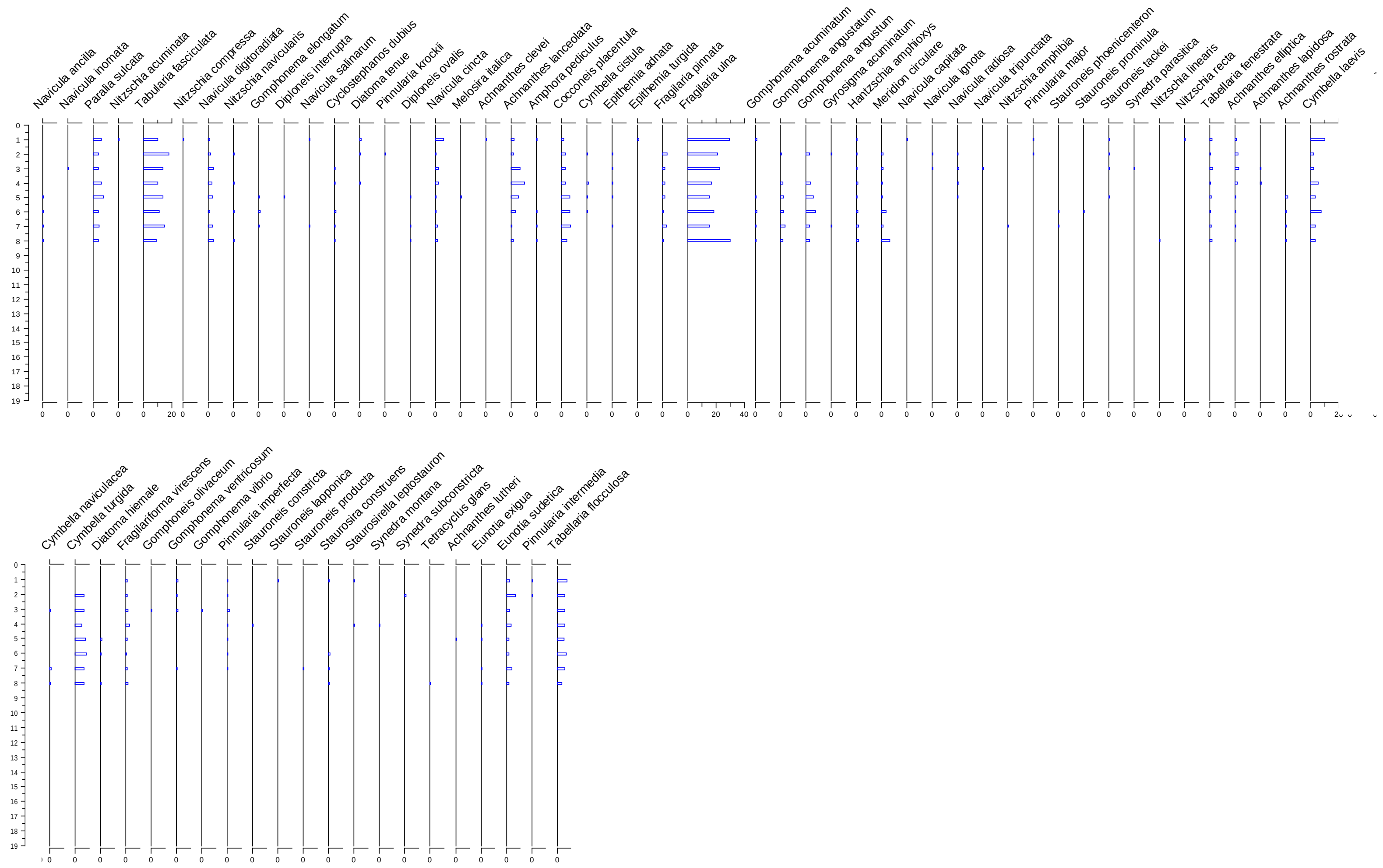

Fig. 5.2.1. Diatom assemblage for pilot study (expressed as percentage counts)

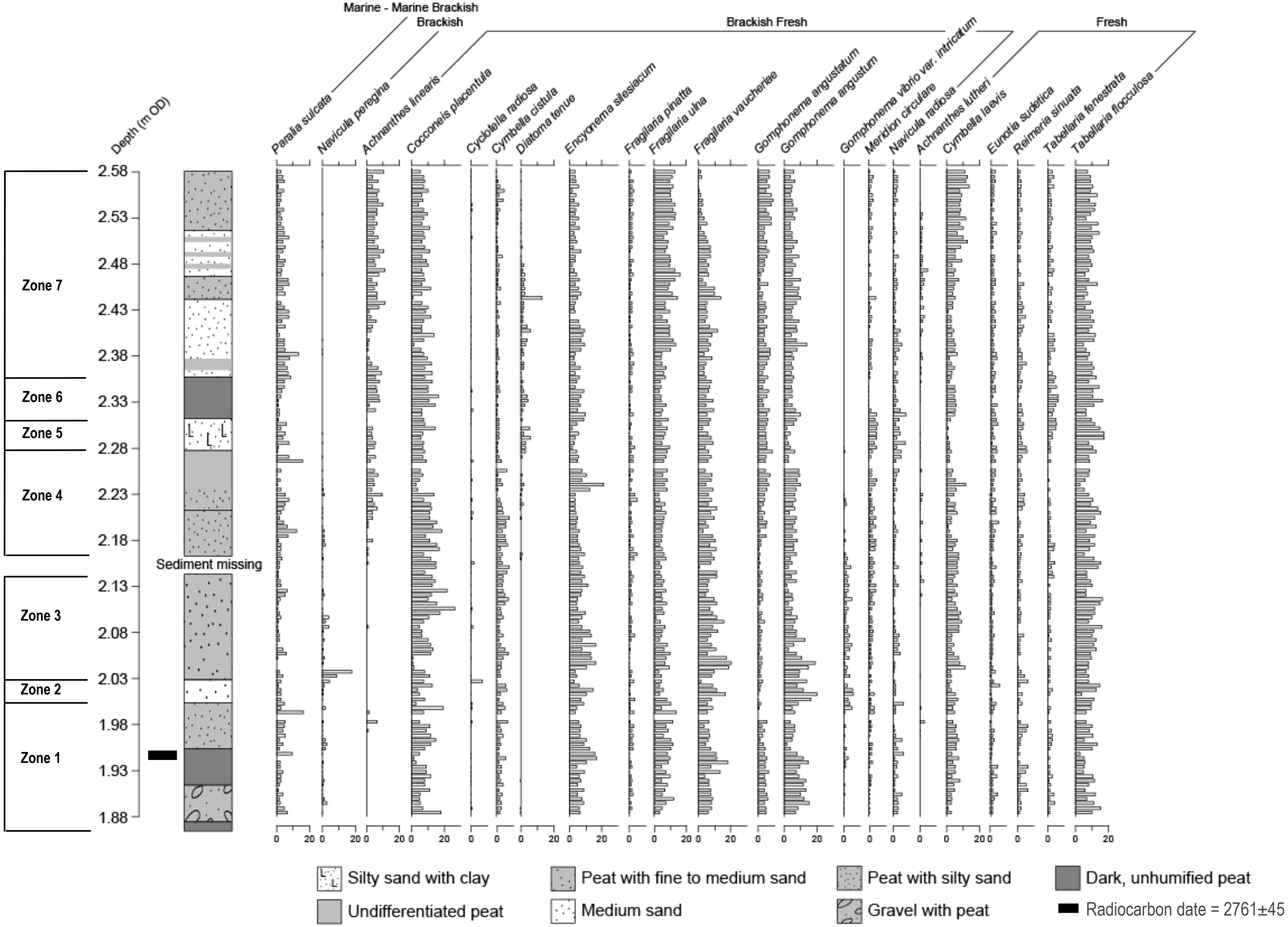

Fig. 5.3.1. Diatom percentage counts for taxa abundant at >5% (in order of salinity), stratigraphy and zones for Netherton

5.3. Stratigraphy

The stratigraphy presents sequences of deposition during the late Holocene (Fig. 5.3.1). The results have been zoned in terms of stratigraphical changes as they are significant in comparison to the diatom assemblages. Although the stratigraphy predominantly consists of peat, there are large sections intercalated with layers of sand (zone 1, 3, 4 and 7). The top of the sediment core is 2.58m OD. Additionally, there is a single section of the stratigraphy that contains peat and gravel in zone 1 between 1.87m OD – 1.91m OD with peat sections above and below. A radiocarbon date of 2761±45 ^{14}C BP (2862±94 *cal*. BP) was recorded from the top section of the peat in zone 7 and was calibrated using CALIB 7.0. This is followed by a sharp change in sedimentation to medium grained sand (zone 2). Zone 3 is comprised of peat intercalated with fine to medium grain size sand until the hiatus where a 2cm gap of sediment is missing between 2.14m OD - 2.16m OD. At zone 4 the peat section continues with finer grained sand in comparison to zone 3. Another sharp change in sedimentation occurs in zone 5 as silty sand and clay are present then changing back to a section of undifferentiated peat at zone 6. Zone 7 returns to a section of peat intercalated with silty sand, similar to zone 4 and 1.95m OD - 2m OD in zone 7.

5.4. Diatoms

A total of 158 taxa were identified from the 140 samples prepared for diatom analysis. 95 of those were categorised as brackish-fresh species. The most abundant species throughout the assemblages (>5%) were *A. linearis*, *Achnanthes lutheri*, *C. placentula*, *Cyclotella radiosa*, *Cymbella cistula*, *C. laevis*, *Diatoma tenue*, *E. silesiacum*, *Eunotia sudetica*, *Fragilaria pinatta*, *F. ulna*, *Fragilaria vaucheriae*, *Gomphonema angustatum*, *Gomphonema angustum*, *Gomphonema vibrio var. Intricatum*, *Meridion circulare*, *Navicula peregina*, *Navicula radiosa*, *P. sulcata*, *Reimeria sinuata*, *Tabellaria fenestrata* and *T. flocculosa*, as indicated in

Fig. 5.3.1. Brackish-fresh species dominated the assemblage and remained between 50.67%-80.67% of the percentage count (*A. linearis*, *C. placentula*, *C. radiosa*, *C. cistula*, *D. tenue*, *E. silesiacum*, *F. pinnata*, *F. ulna*, *F. vaucheriae*, *G. angustum*, *G. angustatum*, *G. vibrio var. intricatum*, *M. circulare*, *N. radiosa*). Typical diatom taxa of a riverine environment (*Cocconeis* spp., *Cyclotella* spp., *Encyonema* spp., *Fragilaria* spp., *Gomphonema* spp., *Navicula* spp., *Tabellaria* spp.) are abundant at >1% of the percentage count throughout the core (Medvedeva, Barinova and Semenchenko 2012; Wu, Schmalz and Fohrer 2010). Diatoms were not found at 2.27m OD and 1.97m OD. Furthermore, a section of sediment was missing between 2.14m OD – 2.16m OD. Although not all diatom taxa identified will be discussed, it is important to include them in the results, even if their abundance is below 1%. Their preferred halobian, trophic or pH classification, combined with abundant species in each sample, will assist as further evidence in the environmental reconstruction of the Forth valley.

Overall, the percentage count for salinity shows a dominant brackish-fresh to fresh assemblage with a fluctuating marine influence between 0% to 17% (Fig. 5.4.1). The most dominant marine to marine-brackish species is *P. sulcata* and in some samples the only marine to marine-brackish diatom present in the count. *P. sulcata* dominates the spikes in marine-brackish influence in sections of zones 1, 4 and 7 at >10% of the assemblage. However, at these points, fragmented marine species below 1% were identified, such as, *Diploneis smithii*, *Podosira stelligera*, *Rhaphoneis amphericos*, *Actoptychus senarius*, *Cocconeis dirupta* and *Nitzschia acuminata*. At 2.39m OD (zone 7), brackish-fresh species were at their lowest abundance at 50.67% as marine to marine-brackish species increased to 14.67% as a result of the significant rise in *Paralia sulcata* (13.67%). The abundance of brackish species remained below 5% of the assemblage throughout with the exception of zone 2, where *N. peregrina* increases to 18.3% of the count.

Marine to marine brackish species do not occur at 1.93m OD and 2.03m OD (zones 1 and 2). At these points, brackish-fresh and fresh species dominate the assemblage at 99.67% (1.93m OD) and 99% (2.03m OD). Epontic fresh-brackish species, such as, *C. cistula*, *E. silesiacum*, *F. ulna*, *F. vaucheriae*, *G. angustatum*, and *G. angustum* dominated the percentage count. Additionally, freshwater species *T. flocculosa* and *C. laevis* were above 5% of the percentage count at these points. Diatom taxa that tolerate a range of trophic conditions from eutrophic to dystrophic (*E. silesiacum* and *G. angustum*) peaked at these points (37.67% at 2.03m OD and 32.33% at 1.93m OD). This is followed by the influence of eutrophic to mesotrophic species (*C. cistula* and *F.vaucheriae*) dominating the count at 27% (2.03m OD) and 22.33% (1.93m OD). Furthermore, *C. placentula* falls below 5% at these points where it typically remains over 5% throughout the rest of the assemblage. Only 22 different marine to marine-brackish species were identified throughout the diatom assemblage.

The largest peak in freshwater species (37%) was in zone 7 where species (>1%), such as, *T. flocculosa* and *C. laevis*, *E. sudetica*, *Eunotia tenella*, *Cymbella cymbriformis* and *R. sinuata* increased in abundance. Marine to marine-brackish species *P. sulcata*, *P. stelliger*, *Diploneis Didyma* and *C. dirupta* are present at these points but remain below 6% of the count. Additionally, brackish-fresh species continue to dominate the overall assemblage at these points where increases in fresh or marine to marine-brackish species occur. The lowest abundance of freshwater species is present in zone 7, indicative of the sharp increase in brackish-fresh species as marine to marine-brackish species are low in abundance (*F. vaucheriae*, *G. Angustum* and *E. silesiacum*). Only 24 freshwater taxa were identified throughout the core. In zones where freshwater species decrease, marine to marine brackish diatoms do not necessarily increase. However, marine to marine taxa are present throughout the assemblage, even where the abundance of freshwater species increases.

The diatom assemblage indicates the environment is predominantly alkaliphilous (Fig. 5.4.2) as these specific taxa remained between 39%-60.33% of the count. 81 of the identified diatom species are alkaliphilous, consisting of (>5%) *C. placentula*, *C. radiosa*, *C. cistula*, *F. vaucheriae*, *D. tenue*, *F. pinatta*, *F. ulna*, *G. angustatum*, *M. circulare* and *N. peregrina*. When alkaliphilous species decrease, circumneutral taxa increase, specifically *E. silesiacum, T. fenestrata* or *A. linearis*. However, acidophilous taxa remain abundant throughout the diatom assemblage as taxa (>1%), such as, *E. sudetica*, *Pinnularia major*, *Psammothidium levanderi*, *Cymbella hybrida*, *E. tenella*, *Cyclotella antiqua* and *T. flocculosa* are present. *T. flocculosa* specifically remained above 3% of the percentage count throughout the core. Additionally, *T. flocculosa* and *E. sudetica* are the only acidiphilous species that occur in more than one of the samples at above 5% of the count.

Diatoms that survive in specific trophic conditions are present throughout the diatom assemblage. Diatoms that are able to tolerate a large range of trophic conditions (eutrophic to dystrophic) were present and dominant throughout the count with fluctuations in eutrophic and eutrophic to mesotrophic taxa. Species identified as tolerant of eutrophic to dystrophic conditions ranged between 10%-38.67% due to the abundance of (>1%) *A. linearis*, *E. silesiacum*, *G. angustum* and *N. radiosa*. In zone 3, eutrophic to mesotrophic taxa peaks to 38.67% (dominated by *C.placentula*, *C. cistula* and *F. vaucheriae*) whereas species that are able to tolerate a range of conditions reduces to 10% of the count, indicating specific environmental conditions. Eutrophic species (*F. ulna*, *F. pinatta* and *N. peregrina*) and mesotrophic species (*G. angustatum*) increased when eutrophic to mesotrophic taxa decreased. Oligotrophic species (*C. antiqua*, *C. laevis*, *E. sudetica, P. levanderi*) remained below 15% of the count throughout the assemblage except in zone 7 where they peaked to 20.33%. Diatom species that were indifferent to trophic conditions or were not affected by this variable remained below 10% of the count throughout the core.

5.5. Summary

The results from the stratigraphy indicated large changes in sedimentation dominated by organic matter. Therefore, the diatom counts were zoned according to significant changes in the stratigraphy. The diatom assemblage is indicative of a predominant brackish-fresh environment with a slight, but consistent, marine to marine brackish influence throughout the core. Additionally, the diatoms identified reflected a variable environment with taxa able to survive in a range of conditions and other species indicative of a specific environment. Overall, the assemblage suggested the site was alkaliphilous during the late Holocene with a significant eutrophic to mesotrophic influence.

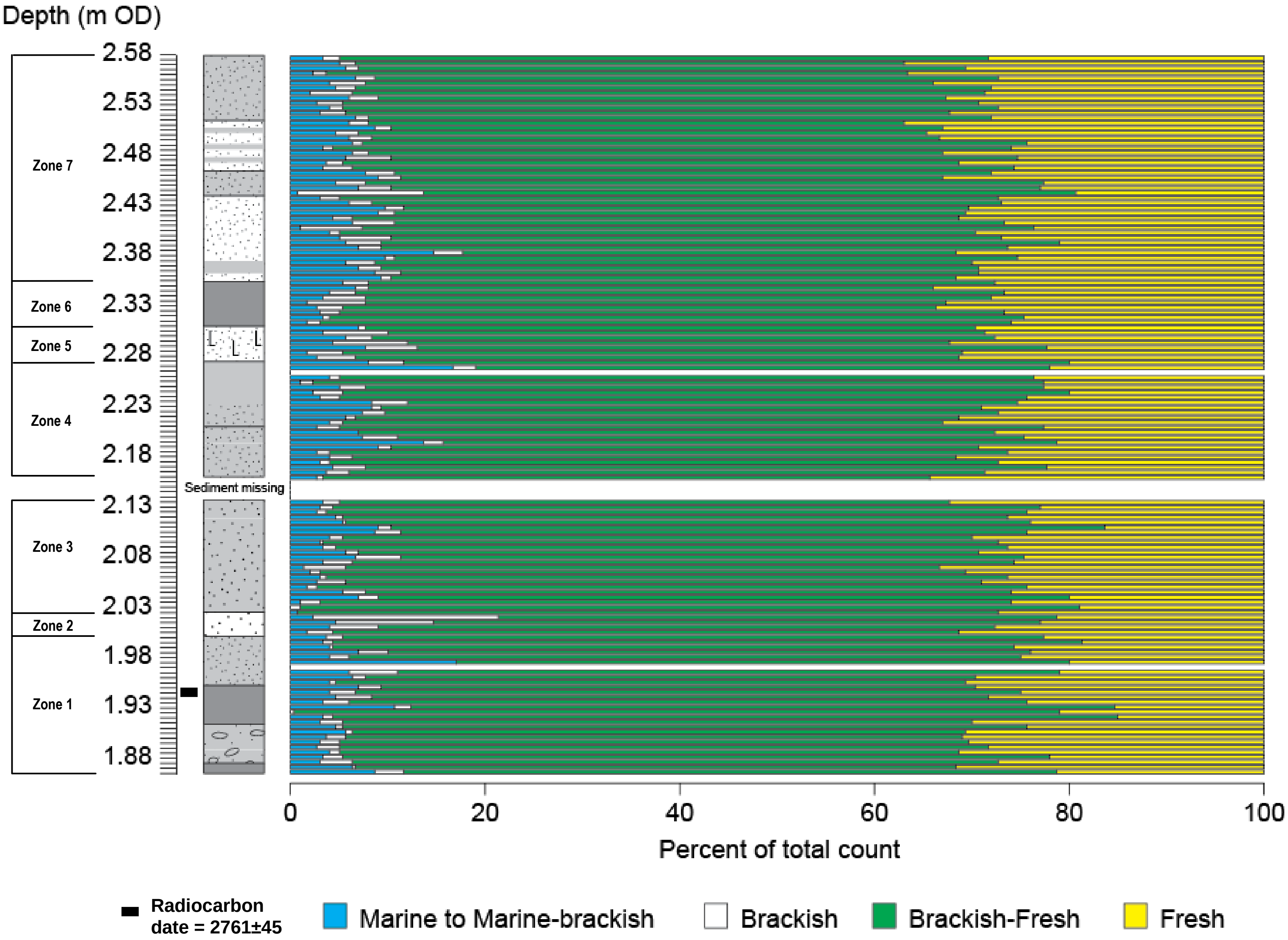

Fig. 5.4.1. Percentage of diatom counts for salinity

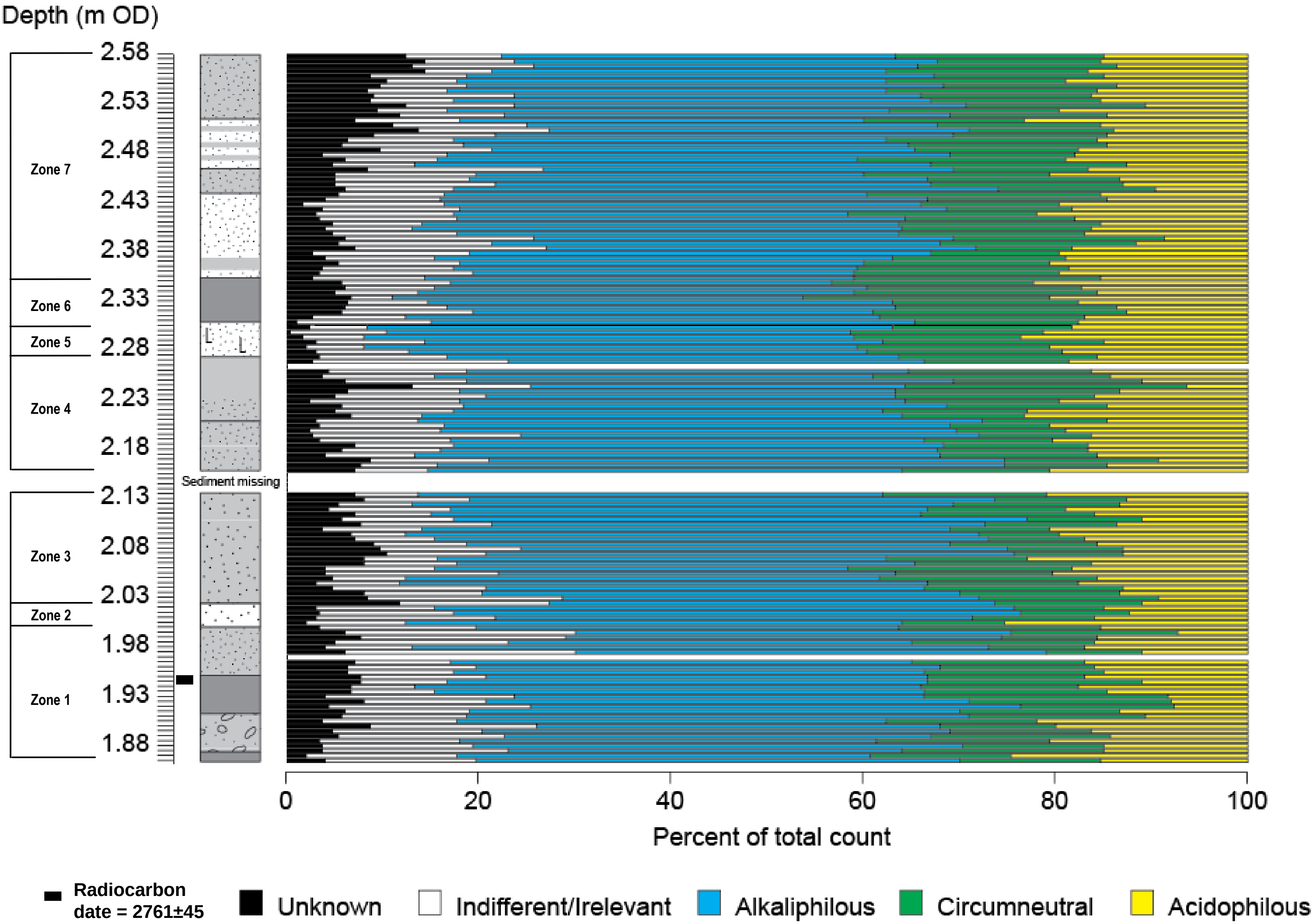

Fig. 5.4.2. Percentage of diatom counts for pH

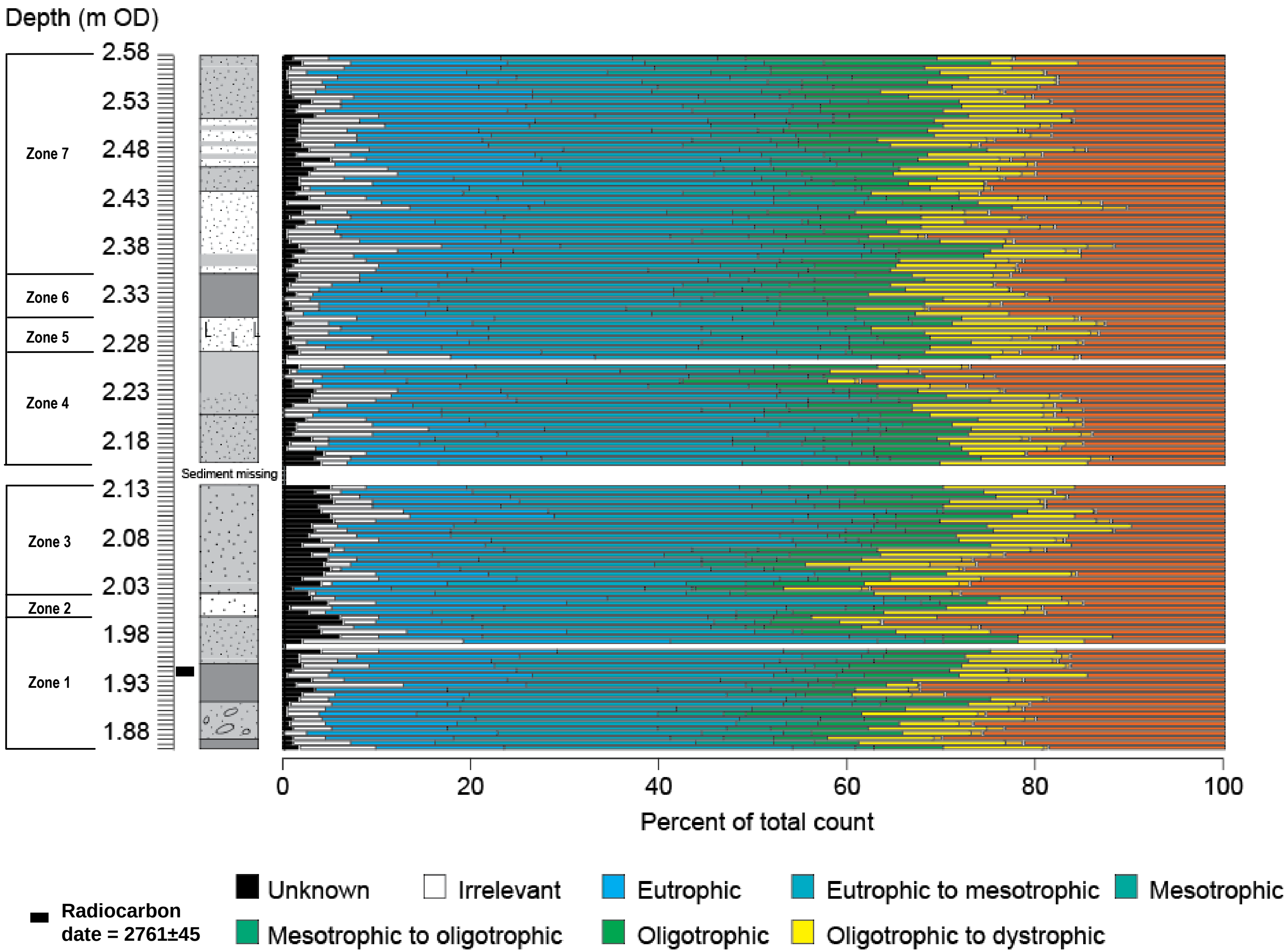

Fig. 5.4.3. Percentage of diatom counts for trophic status

Chapter 6. Discussion

6.1. Introduction

The results support other studies (e.g. Rovira *et al*. 2012) concerning the large tolerance diatoms have for changes in environmental conditions. Diatom taxa that are able to tolerate a range of trophic statuses (*Achnanthes linearis*, *Encyonema silesiacum*, *Gomphonema angustum*, *Navicula radiosa* and *Paralia sulcata*) were present throughout and at times dominated the percentage count, particularly in peat (zones 1 and 6). Therefore, the diatom assemblages throughout the sediment core suggest how changeable the environment surrounding Netherton was during the late Holocene as it was influenced by upstream activity, local hydrodynamic changes and the upper limit of the tidal range.

6.2. pH

Although the diatom assemblage throughout indicates an alkaliphilous environment, acidiphilous species remain abundant. The underlying geology is important as a controlling factor of pH in the environment (O'Driscoll *et al*. 2012). O'Driscoll *et al*. (2012) found circumneutral and alkaliphilous species present in rivers surrounded by acidic peat forest in north-west Ireland. The dominance of an alkaliphilous assemblage is indicative of the Midland Valley carboniferous rocks, underlying the Quaternary sediment, influencing the pH of the Forth valley and its surrounding tributaries (Browne *et al*. 1999). The acidic tychoplanktonic species *Tabellaria flocculosa* (>5%) is present throughout and is transported to this environment through the river Forth from peat moss erosion or removal upstream. *Eunotia* species and *Pinnularia* species, occasionally occurring above 1% of the percentage count, are indicative of low nutrient environments and are typical species found in peatlands (Kokfelt, Struyf and Randsalu 2009). Therefore, the persistent presence of this diatom and other species associated with acidic freshwater peatlands (eg. *Eunotia* spp.) is indicative of a constant flow of freshwater. Tributaries further upstream entering the river Forth, flow through acidic peat mosses before reaching Netherton, eroding the source of acidic taxa. The peat mosses are close to the study site as indicative species (e.g. *T. flocculosa*, *Eunotia sudetica*, *Psammothidium levandari*, *Pinnularia major*, *Cymbella hybrida* and *Cyclotella antiqua* abundant at >1% of the percentage count throughout the assemblage) were well preserved and not broken from the turbulence of the river. Flanders Moss is approximately 15km west of Netherton, an area of acidic peat moss that had not been cleared in the 19th century for fertile land (Harrison 2003).

Smith *et al*. (2010) completed lithostratigraphical and biostratigraphical studies of the remnants of peat mosses west of Stirling. Stratigraphic evidence from Fotheringhams, the centre of Ochtertyre moss approximately 4km west of Netherton, dated the base of the peat, overlying the carse, at 2467 *cal*. BP -2759 *cal*. BP (Ellis 2001). Smith *et al*. (2010) found a sharp rise in the acidic *Alnus* species (60%+) after 3320±80 *cal*. BP at Fotheringhams signifying a correlation with the acidic diatom taxa present at Netherton. *Alnus* species lower the soil's pH and increases nitrogen in soils, suitable for algal growth in mesotrophic and eutrophic waters (Bissonnette *et al*. 2014). Although no date has been recorded for the transition, Smith *et al*. (2010) found *Betula* and *Alnus* species increased after the 4300±70 *cal*. BP contact point in the peat lithology from Lecropt Moss (1km east of Netherton). As acidiphilous species did not dominate the count at any point, it can be assumed that these species travelled downstream from these particular sources. Additionally, studies have found (e.g. Messyasz *et al*. 2010) that periphytic and benthic species (as *T. flocculosa* is typically loosely attached to substrate in origin) are easily torn off by water velocity, affecting the composition of diatom assemblages downstream. Although peat has been transported through the river Forth, it has not dramatically decreased the overall pH of the water body.

6.3. Zone 1

Zone 1 is a section of peat with a peat and gravel intrusion between 1.87m OD - 1.91m OD. The peat layers (between 1.86m OD – 1.87m OD and 1.91m OD – 1.95m OD) are indicative of terrestrial land with a lack of riverine influence. However, the diatom assemblage is highly abundant with riverine taxa (e.g. *Cocconeis placentula*, *Encyonema silesiacum*, *Fragilaria* spp. and *Gomphonema* spp.) and marine to marine-brackish species (*Thalassiosira eccentrica*, *Rhaphoneis amphericos*, *Paralia sulcata*, *Nitzschia angustata* var. *acuta*, *Diploneis didyma*, *Cocconeis dirupta*) abundant at <10% of the count. As brackish species remain below 1.67% of the count at this point, it would be difficult to associate the sharp increase of *P. sulcata* as a slight transgressional onset. Typically, diatoms that thrive in nutrient poor environments are present in peat profiles, such as, *Pinnularia* spp., *Eunotia* spp., and *T. flocculosa* (Kokfelt, Struyf and Randsalu 2009). Therefore, the stratigraphy may indicate an accumulation of organic matter rather than the development of peatlands. The fluvial influence suggests there is a direct connection with the river Forth including a strong tidal influence pushing marine to marine-brackish diatoms into the freshwater environment.

The top section of the peat in this zone (1.95m OD) has been dated at 2862±94 *cal*. BP. This corresponds with the modelling results provided by Shennan, Milne and Bradley (2009) and Bradley *et al*. (2011) whom have implied a fall in relative sea-level at approximately 1mm/year from isostatic uplift during the late Holocene. Land uplift estimated around 2500 *cal*. BP would have reduced the estuarine influence in the area as the tidal limit lay further downstream of Netherton (Tipping, Smith and Jordan 2013). Although the diatom assemblage corresponds with the lack of estuarine influence, the tidal range is still influential in the area as evident from the abundance of marine to marine-brackish species. However, the small diversity of marine species suggests only robust marine taxa were able to preserve well in this freshwater environment. Arguably, as there are no sedimentary flood deposits in the peat sections, the diatom assemblage is possibly evident of an alkali wetland, such as a fen, which remains in constant connection with the river Forth. If the peat was typical of terrestrial land it would not contain the strong influence of riverine diatom taxa. Flooding would have hindered moss formation on the banks of the river as Harrison (2003) suggests the area would have been well drained. Therefore, the sediment changes in the stratigraphy and diatom assemblages suggest a highly dynamic and unsettled fluvial system in this zone.

The peat with riverine intercalated gravel (189cm-193cm) shows an increase in acidic species associated with peatland environments to 24.67% of the percentage count (*Pinnularia* spp., *Eunotia sudetica* and *T. flocculosa*) (Kokfelt, Struyf and Randsalu 2009). Although the presence of these taxa and organic matter in the stratigraphy may represent a bog-type environment, the assemblage is still dominated by alkaliphilous riverine species. Patrick (1997) stated if acidic peat was to enter a fluvial system, the location of deposition would immediately lower the pH of the water body. Therefore, the acidic diatom taxa and the peat layers have been transported into the site at Netherton from further upstream. Peat can be transported downstream as it is susceptible to erosion and is therefore present with riverine deposits (Warburton and Evans 2011). Peat has been transported into the environment as the river was undercutting raised mosses west of Netherton. Additionally, the presence of gravel may be indicative of eroded peat block movement, as such activity causes the deposition of gravel downstream (Crowe and Warburton 2007). The erosion of peat from a peatland catchment can contribute to sedimentation changes in river flows when deposited in wide channels (Warburton and Evans 2011). This is evident by the increase in eutrophic to mesotrophic species (*C. placentula*, *Fragilaria vaucheriae*, *Cymbella cistula*, *Achnanthes lanceolota* and *Reimeria sinuata* at >1% of the percentage count) as sediment accretion can trap allochthonous particulate organic matter, generating nitrogen for benthic algae to thrive and oxygen depletion to improve eutrophic conditions (Ruddy, Turley and Jones 1998). Abrasion of the peat blocks would have transported remnants downstream and is therefore, present, intercalated with gravel, in the stratigraphy. This could possibly argue that the clearance of peat started before 2862±94 *cal.* BP, for fuel rather than cultivation, as this practice increased the amount of organic matter recorded downstream (Harrison 2003). The stratigraphy and diatom assemblage in this section of the zone suggests the river Forth is travelling through this point until organic matter accumulates again as a result of river migration.

The diatom assemblage in the peat section between 1.91m OD – 1.95m OD peaked to a predominantly freshwater environment where the tidal influence was absent, evident by the absence of marine and marine-brackish taxa. Brackish-fresh species (*E. silesiacum, F. ulna, G. angustum* at >5% of the percentage count) are highly abundant in the absence of the marine to marine-brackish taxa. However, freshwater species are abundant at 15% suggesting the freshwater input has not pushed the upper tidal limit further downstream but sea-level has fell temporarily at this point, promoting terrestrialisation. This fall in sea-level is a result of glacio-isostatic uplift as sea-level was considered to be rising throughout the late Holocene (Peltier and Fairbanks 2006). The reduced freshwater input is further evident by the decrease in *T. flocculosa* <8.67% and *E. sudetica* <1% transporting less material from peat mosses upstream. Marine to marine-brackish species return at 1.93m OD as the sedimentation in the stratigraphy changes to peat with intercalated silty sand at 1.95m OD.

C. placentula is tolerant of different environmental states, including moderately polluted areas, whereas, *E. silesiacum* is intolerant of such conditions and has been found in typically undisturbed waters (Hofmann and Werum, Lange-Bertalot 2011; Jahn, Kusber and Romero 2009; Dohet *et al.* 2008). Periphytic diatoms, such as, *C. placentula* and *E. silesiacum*, are considered good indicators of ecological river conditions as a result of its ability to rapidly respond to changes in nutrient concentrations (Rusanov, Stanislavskaya and Acs 2009). Although Bronze age settlements were present in the area by 2900 *cal*. BP, evidenced by the Bronze Age wheel found at the base of the Blairdrummond peat moss, the high abundance of *E. silesiacum* (>10%) in the peaty section suggests these early settlements were minor as they did not pollute the river Forth (Smith *et al*. 2010). Small amounts of peat clearance surrounding the river Forth may have occurred before 2200 *cal*. BP, as Smith *et al*. (2010) found evidence of cereal cultivation at this date from pollen data at Letham moss. Furthermore, land reclamation occurred at Flanders moss until the 18th century, involving the drainage of peat through the river Forth during the late Holocene (Harrison 2003). Therefore, the occurrence of peat intercalated with riverine sediment could possibly be a result of anthropogenic activity as its clearance to expose the fertile underlying carselands would increase deposition into the river system.

6.4. Zone 2

Zone 2 is comprised of medium grained sand and its sharp contact point demonstrates the change in deposition from organic riverine sediment in between zones 1 and 3. Although the abundance of overall brackish species did not increase throughout this section, *Navicula peregrina* peaked to 18.33% of the count at 2.02m OD. The medium grain size suggests the deposition of the material was fluvial rather than aeolian. Additionally, the high abundance of brackish-fresh species (57.33%-72%) suggests this substrate is not of marine origin or indicative of coastal flooding. This is further evident by the lack of marine and brackish diatoms present. The epipsammic *Staurosirella leptostauron* is present at >1% in this zone and is typically evident of a terrestrial environment (Lowe 2011). Therefore, it is possible that a depositional sand bar was formed as part of a seasonal outlet creek. This would have entrapped water and allowed certain diatoms to increase in abundance under these conditions.

Although *N.peregrina* is a brackish epipelic diatom, it is indicative of nutrient-rich standing water (Ridgeway *et al*. 2000). Metcalfe *et al*. (2000) found *N. peregrina* was the only highly abundant brackish species present before the post-glacial transgression at the Humber estuary along with the brackish-fresh species *C. cistula* and *Fragilaria pinatta*. The environment of the Humber estuary during this period was predominantly riverine at the upper tidal limit and the diatom assemblage is indicative of an alder carr (Metcalfe *et al*. 2000). Similarly, *N. peregrina* is abundant in this section with *C. cistula* (>6.3%+) and *F. pinnatta* (>3.3%) as eutrophic (>29%) and eutrophic to mesotrophic species (33.67%) increase in abundance, further indication of still or slow moving waters. However, the diatom and pollen evidence by Metcalfe *et al*. (2000) was found in a section of peaty silt and sand and not substrate entirely composed of medium grained sand (Metcalfe *et al*. 2000). There is no pollen evidence to support this theory of localised change in the Forth valley. The closest evidence is from Fotheringhams where the section of peat after 3320±80 *cal*. BP recorded a sharp increase in *Alnus* and small spikes in *Corylus* and *Cyperceae* between 11.03m OD - 11.05m OD, indicative of an alder carr environment (Stark, Wallberg and Nylén 2006; Walker *et al*. 1998).

Although it could be argued that the environment became a freshwater wetland or swamp, the stratigraphical evidence does not correspond to the theory the diatom assemblage indicates. However, alder carr swamps are typically affected by run-off water from surrounding hill slopes, suggesting diatoms could be washed out through a seasonal outlet creek during saturation and deposited the medium sand substrate (Stark, Wallberg and Nylén 2006). The environment is still connected with a riverine source, evident by the presence of marine to marine brackish species (*P.sulcata*, *C. dirupta*, *Podosira stelligera* and *R. amphericos*), even though they remained below 4% of the overall percentage count. To find further evidence for this theory, more core samples in the surrounding area should be taken to demonstrate whether the medium sand substrate is a local feature and therefore, the surrounding organic matter corresponds with the environment of a freshwater wetland. *N. peregrina* decreases to 1% of the percentage count by 2.0m OD as brackish-fresh riverine species continue to dominate, suggesting the river resumes to its original position and washes the temporary sandbar away.

6.5. Zone 3

The riverine epilithic taxa *C. placentula* is present throughout the core and fluctuates significantly between 1.3%-26.67%. Its presence is indicative of low levels of soluble reactive phosphorous and high nitrate concentrations (Abuhatab-Aragón and Donato-Rondón 2012, Patrick 1977). To allow inference of past trophic status, a diatom transfer function must be established to calculate total phosphorous and total nitrogen concentrations. Additionally, *C. placentula* are typically highly abundant after spring floods when temperatures and organic matter are higher (Rovira *et al*. 2012). In zone 3, *C. placentula* was highly abundant (dominating 26.67% of the count at 2.09m OD), corresponding with the increase in eutrophic to mesotrophic species *C. cistula* and *F. vaucheriae*. However, it must be considered that *C. placentula* can rapidly colonise in a large range of environmental conditions and it has been found highly abundant at sites of fast flowing water and brackish waters (Rovira *et al*. 2012; Wu, Schmalz and Fohrer 2010; Kelly *et al*. 2001). Nevertheless, the high abundance of eutrophic to mesotrophic benthic diatoms compared to planktonic are indicative of a lower hydrological energy. Similarly, Messyasz *et al*. (2010) observed in the summer months of the Welna and Nielba river in Poland that *C. placentula*, *Cyclotella meneghiniana* and

Gomphenema spp. were highly abundant in the summer months as a result of the slow moving water improving light, temperature and increasing supply of phosphorous and nitrogen.

The grain size of the sand intercalated with peat in this zone is larger than the silty sized grains in zones 1, 4, 5 and 7. Sedimentation from reduced river flow at the upper tidal limit would have improved conditions for eutrophic to mesotrophic species to thrive as they dominate 42% of the assemblage at 2.09m OD. The influence of the tidal range is further evident by the diverse abundance of marine taxa in comparison to the other zones (*Actinoptychus senarius*, *C. dirupta*, *Nitzschia angustata var. Acuta*, *P. stelligera*, *R. amphericos*) fluctuating to almost 10% of the count. Marine taxa are typically found in marine littoral systems and not freshwater environments (Vos and de Wolf 1988). However, *P. sulcata* decreased to below <5% of the percentage count at certain points in this zone. This is possibly indicative of the high nitrogen content of the water body during this period, as *P. sulcata* does not preserve well under these conditions (McQuoid and Nordberg 2003). *P. sulcata* is benthic in temperate coastal environments, yet is abundant almost throughout the assemblage. As a heavily silicified taxa and its ability to survive in a wide range of environmental conditions, it has been known to make paleoenvironmental interpretations difficult (McQuoid and Nordberg 2003). Arguably, the increased strength of the tidal range would have impeded drainage from the river Forth and increased sedimentation in this environment.

In the Forth valley, suspended matter concentrations are higher in the summer months (500mg/l) as a result of seawater penetration resuspending sediment towards the upper reaches of the river, reducing oxygen content to improve eutrophic conditions (Dembowska 2014; Griffiths 1987; Pomfret *et al*. 1991). Furthermore, Maier *et al*. (2012) found increased chlorophyll *a* during decreased river flow which could be another cause for eutrophic to mestrophic conditions. However, it is difficult to consider the seasonality of the diatoms at each zone as it is not the only factor influencing algal blooms in the tidal range of river systems (Rovira *et al*. 2012). Additionally, to be sure of this relationship, a transfer function can quantitatively relate the changes in total phosphorous concentrations - a factor controlling chlorophyll *a* (Schönfelder and Steinberg 2002). Considering Smith *et al*. (2010) suggested sea-level had stabilised by 3000 *cal*. BP, the increase in marine to marine brackish species and increasing eutrophic conditions from sedimentation is indicative of a temporary rise in sea-level increasing the strength of the upper tidal limit in this area. However, it cannot be completely defined as a minor transgressional phase as the diatom assemblage would be expected to reflect an increased brackish influence replacing freshwater species which is not present. Further research of late Holocene sediments downstream from Netherton will be able to confirm whether a brief transgressional period occurred in correlation to zone 3.

6.6. Zone 4

The intercalated sand recorded is fine grained, suggesting an increase in river flow and freshwater inputs or sea-level fall compared to zone 3. This is further evident by the presence of *E. silesiacum*, dominating the count at 2.25m OD (21%), and *Achnanthes linearis* (>5%), signifying a strong freshwater input into the river Forth. These species are indicative of less polluted waters from anthropogenic activities further upstream from Netherton (Bere 2010). However, a sharp spike in marine influence at 2.27m OD to 16.67% of the percentage count, dominated by the abundance of *P. sulcata* (16.3%), is recorded in the diatom assemblage, indicative of a strong tidal influence. The marine-brackish species *P. sulcata* is robust as a result of its highly silicified structure (Barlow *et al*. 2013). As this species originates from coastal environments, its composition improves its chances of preservation in the upper tidal limit of river systems (McQuoid and Nordbeg 2003). *P. sulcata* is able to survive in low salinity environments with low phosphorous concentrations (McQuoid and Nordberg 2003). Although eutrophic to mesotrophic taxa have been the most indicative species of trophic characteristics in the river Forth, diatoms that are able to tolerate a range of conditions dominate the assemblage in this zone (e.g. *A. linearis*, *G. angustum* and *Navicula radiosa*). Therefore, it is difficult to interpret specific changes in the environment.

P. sulcata is the only marine to marine brackish species present at certain points of zone 4 and is abundant at >5% of the percentage count. The presence of marine to marine brackish species is indicative of the tidal influence yet the singular sharp increase in *P. sulcata* does not necessarily suggest a rise in sea-level continuing from zone 3. It could be suggested that these particular peaks are storm surge deposits as their abundance remains inconsistent in this zone. The tychopelagic (benthic until storminess incorporated it into the plankton) *P. sulcata* and *P. stelligera* valves were well preserved and its abundance could have been evident of a post storm event, as they are common in coastal plankton after gales (Smith, Cullingford and Haggart 1985). The temporary sea-level rise as a result of the storm surge, would have allowed the tidal range to transport the species into the riverine system at Netherton. Coastal storm surge events and the increased freshwater input would have established highly variable conditions in the river Forth during this period as indicated by the assemblage, dominated by taxa that are able to tolerate a range of conditions.

6.7. Zone 5

The transition from peat with intercalated sand to fine grained clay and silty sand in zone 5 is indicative of flood deposits as the river has temporarily migrated away from Netherton. Species that are able to tolerate a range of trophic conditions (highly abundant in zone 4) decrease as eutrophic to mestrophic species dominate the count (*C. placentula*, *F. vaucheriae* and *R. sinuata*). Additionally, *T. flocculosa* peaks to its highest at 17.67% followed by an increase in other freshwater species associated with mosses (of >1% including *E. sudetica*, *Eunotia tenella*, *Cymbella cymbriformis*, *Pinnularia imperfecta*, *Pinnularia intermedia*, *Pseudostaurosira brevistriata*, *T. fenestrata*, *Cymbella laevis* and *Fragilariforma constricta*). The increase in freshwater species and decline in marine species (>8%), with the exception of *P. sulcata*, suggests an increased riverine influence, transporting acidiphilous taxa into the environment from the eroded peat mosses upstream, similar to the processes in zone 7. The epiphytic taxa, *Meridion circulare* increases to its highest abundance, at >5%+ of the percentage count, indicating an influx of freshwater from upstream regions (Stancheva and Slavchova 2002). Additionally, the silty sand and clay lithology, supported by the increase in freshwater taxa and tychoplanktonic species (>1% are *Diatoma tenue*, *Cyclotella meneghiniana*, *T. flocculosa* and *Tabellaria fenestrata*) increase in this zone. *C. meneghiniana*, *F. ulna* and *C. placentula* are typical of floodplain assemblages and are the most abundant taxa in this zone (Medioli and Brooks 2003). The presence and dominance of planktonic diatoms in this zone could possibly argue the environment had been turned into a shallow lake from recurring floods until the river returned in zone 2.

P. sulcata is abundant at >5%+, suggesting the tidal range is still present, even though there is evidence of increased riverine flow. However, it is the only abundant marine to marine brackish taxa suggesting the upper tidal range may have migrated further downstream during this increased influx of freshwater. This is further evidence of *P. sulcata*'s strong composition and ability to preserve in a range of conditions as the floodplain sediments are in a predominantly freshwater environment. Although the tidal range is present, the lack of diversity in marine species and low abundance of *P. sulcata* is arguably indicative of sea-level fall. Similarly to zone 7, sea-level would have adjusted as a result of glacio-isostatic adjustment. On the other hand, the diatom assemblage could be indicative of localised changes rather than sea-level as it would be difficult to infer these from floodplain deposits. The presence of the floodplain is indicative of how dynamic the river Forth is as it has migrated away from the site in zone 5 and migrates back in zone 6. The dominance of riverine taxa in the diatom assemblage throughout the sediment core suggests Netherton is always in contact with the river Forth, even if the stratigraphy is not indicative of riverine sediment.

Schönfelder and Steinberg (2002) found riverine taxa in floodplain sediments were difficult to relate to using a transfer function. Therefore, without the use of a transfer function based on benthic diatoms in floodplain sediments by the river Forth at Netherton, the research is able to include tychoplanktonic species (e.g. *T. flocculosa* and *P. sulcata*) to extrapolate changes of the surrounding environment. Additionally, it may be difficult to infer diatom assemblages of floodplain sediments for this zone as they are usually destroyed by agricultural settlements in modern assemblages (Schönfelder and Steinberg 2002).

6.8. Zone 6

Zone 6 comprises of peat and may suggest an increased influence of flooding from zone 5. The increased flooding and influence of the river Forth in this area would have caused continuous waterlogging of the surrounding vegetation, allowing organic matter to accumulate in this area. Although the stratigraphy does not suggest any direct riverine influence, from the absence of silts and sands, the marine to marine brackish influence still prevails throughout this zone. However, marine species, including *P. sulcata*, continue to remain below 5% of the overall count, suggesting the tidal range has remained in its position further downstream as in zone 5. The diatom assemblage of the organic matter is similar to the structure found in zone 1. Unlike zone 1, zone 6 has transitioned into a predominantly freshwater environment with less influence from the tidal range.

T. flocculosa (>5%), *Eunotia* spp. (>1%) and *Pinnularia* spp. (>1%) are present, yet this zone is still dominated by riverine diatom taxa (*C. placentula*, *Fragilaria* spp. and *Navicula* spp. at >5%). Eutrophic to mesotrophic peatlands, for example, fens, are typical of a wet environment that would have inputs from a river system (Gaiser and Rühland 2010). Rich fens have a pH that is typically >5.0 as their water source is from groundwater, therefore, circumneutral and alkali taxa are able to tolerate conditions in these environments (Gaiser and Rühland 2010; Holden 2005). Although peaty environments are typically acidic, the diatom composition is still indicative of an alkaliphilous environment suggesting the peat formation was not the acidic bog type (O'Driscoll *et al*. 2012). Similar to the peat layers in zone 1, the high abundance of alkaliphilous and riverine diatoms indicate the stratigraphy is indicative of fen-peat in this zone. Peat formation was in its early stages but was not able to fully develop as the river continued to migrate back to the study site (zone 7) and therefore, represents a temporary accumulation of organic matter. Additionally, it has been argued that settlements were present along the margin between the river and the peat mosses for as long as the prehistoric period (Harrison 2003). However, owing to the dynamic nature of the river system shown in these results and the high abundance of fluvial diatom taxa, it would be difficult to suggest that these river banks were habitable.

6.9. Zone 7

The river Forth returns to its position at Netherton in zone 7. Although *E. silesiacum* remains abundant throughout the stratigraphy, it decreases to below 10% of the percentage count and is indicative of anthropogenic influences. This is further evident by the increase of the anthropogenic pollutant-tolerant taxa *F. ulna* exceeding approximately 10% of the count (Kavya and Ulavi 2014). Additionally, *A. linearis* increases to above 5% of the count and is also considered to be tolerant of anthropogenic pollution (Bere 2010). Therefore, an increased density of settlements or anthroprogenic activity surrounding the river Forth occurs in zone 7, hence species less tolerant of pollution (e.g. *E. silesiacum*) decrease.

Additionally, acidic taxa (*T. flocculosa, E. sudetica, E. tenella*, *Cymbella heteropleura*, and *Pinnularia* spp.) exceed 20% of the count in this zone. *C. laevis* increases in abundance, fluctuating to approximately 10% of the percentage count. The gradual increase in this taxa is indicative of peat clearance as these species are typically found attached to mosses (Krammer and Lange-Bertalot 1986). As peat mosses were cleared during the 17th century, the drainage of the organic matter would have been transported downstream and therefore, diatom species associated with this environment (e.g. *C. laevis*, *T. flocculosa*, *Eunotia* spp. and *Pinnularia* spp.) would be present downstream. Drainage of peat mosses increases ammonia and therefore, algal blooms to improve conditions for eutrophication (Tada *et al*. 2009; Holden, Chapman and Labadz 2005). Eutrophic diatom flora (*F. ulna, F. pinatta, C. meneghiniana* and *Nitzschia palea*) fluctuate to approximately 20% of the count. This is potentially indicative of increased cultivation activity in relation to the exposure of the carselands, increasing nutrient concentrations in the river Forth. However, in alkaline conditions ammonia forms into ammonium hydroxide which cannot be utilised by diatoms for growth (Patrick 1977). Considering the eutrophic species are dominated by the increase of *F. ulna* and *F. pinatta*, it is possible that the abundance of these species originated from peat mosses upstream and were deposited at Netherton. The assemblage overall is still indicative of an alkaline environment, further evidence of these peat moss clearances occurring upstream.

The tidal range is still influencing the environment with the consistent abundance of marine to marine-brackish species dominated by *P. sulcata*. A spike in *P. sulcata* to 13.67% may indicate a brief period where the tidal range increases its influence at Netherton. However, as the diversity of marine and brackish species remains low, it is not indicative of a rise in sea-level. Additionally, as this sudden spike to above 10% is from one sample and not persistent through consecutive samples in this zone, it is possibly indicative of a single storm surge event. This is further evident by the poor preservation of the *P. sulcata* valves from the diatom count. With the exception of this point, sea-level has remained steady through zones 5, 6 and 7 as the upper tidal limit continues to transport marine to marine-brackish diatoms into the environment in low abundance, suggesting these assemblage changes are indicative of terrestrial activity rather than sea-level change.

Tipping, Smith and Jordan (2013) have assumed that burns connected to the river Forth would have larger volumes during the late Holocene and therefore, more erosive power to remove peaty materials from mosses. Several hundred acres at Polders Moss (east of East Flanders Moss) was cleared during the late 18th century and continued until 1860, depositing peat into the river Forth (Harrison 2003). It has been suggested, from pollen analysis, that agricultural activities are the cause of the deposited inorganic layers in peat sections during the late Holocene (similar to stratigraphic zones 1, 3, 4 and 7) (Edwards, Hirons and Newell 1991). Peat with intercalated sand was found in stratigraphic investigations of Loch Dee in southwest Scotland (Edwards, Hirons and Newell 1991). The layering of peat and silty sand is indicative of some fluvial sorting and an unstable channel course (Edwards, Hirons and Newell 1991). However, Edwards, Hirons and Newell (1991) were unsure of the exact cause of this deposition but were confident about the possibility of anthropogenic involvement. They concluded that land clearances would have exposed mineorgenic materials and this sediment would have been deposited in fluvial systems through overland flow. As the diatom composition suggests evidence of increased anthropogenic activity in zone 1, it is possible that local land clearances exposed the silty sand material when the carselands were exposed. However, without radiocarbon dates in this zone, it is difficult to directly correlate these results with land clearances during the 18th century. The sand in the stratigraphy may correspond to the soil from the floodplains of the Frew area (west of Stirling) which are sandier and were attractive for early settlements in need of fertile farmland (Harrison 2003). As Smith *et al*. (2010) found evidence of agricultural activity potentially before 2200 *cal*. BP, it is possible the stratigraphy in zones 1, 3 and 4 represent this anthropogenic activity too.

6.10. Sea-Level in the Forth Valley during the Late Holocene

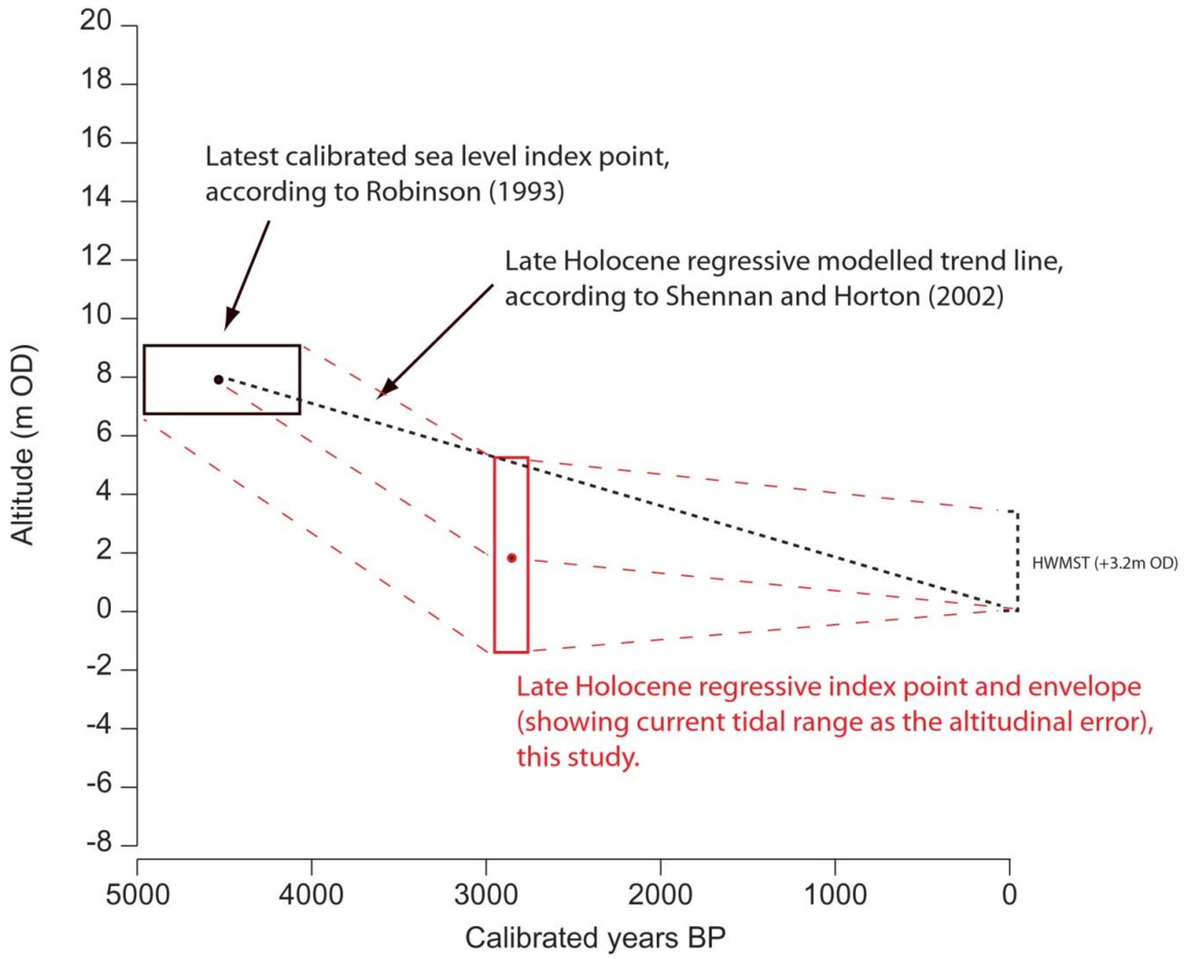

Fig. 6.10.1. A summary diagram of late Holocene sea-level in the Forth valley. The new sea-level index point from this study is highlighted in red.

As a result of this study, a summary diagram of sea-level changes during the late Holocene in the Forth Valley has been presented in Fig 6.10.1. The sea-level index point included from this study is the regressive point dated at the top of Zone 7, with High Water Mark Spring Tides (HWMST) used as an error margin for altitude. The central tendency line indicates how the model could be used to extrapolate information on the age and altitude of late Holocene sea-level changes in the Forth valley. This has been created by linking the latest sea-level index point from Robinson's (1993) study with the data from this study to sea-level at its current position. The Shennan and Horton (2002) modelled trend line (from Fig 2.4.3) has been included, as this was the best estimation for sea-level changes during the late Holocene.

As illustrated, sea-level has fallen from the latest calibrated sea-level index point identified by Robinson (1993) and the sea-level index point from this study. Arguably, the new sea-level index point agrees with Shennan and Horton's (2002) trend line for sea-level fall, included in Fig 6.10.1. However, this would assume their model is at the peak of the tidal range and does not represent mean sea-level, as the trend line overlaps the upper section of the error margin. Therefore, using the link between the tidal range error margins from both Robinson (1993) and this study, it is very likely that sea-level withdrew more rapidly than Shennan and Horton's (2002) projections between approximately 4500 *cal*. BP to 2862±94 *cal*. BP. This is further evident by the high abundance of fresh and fresh to brackish diatom species present throughout Zones 1 to 7. Glacio-isostatic uplift may have occurred more rapidly than previously estimated in the Forth valley during this period. Furthermore, as evident from the increase of marine species in Zone 3, a slight transgressional phase would have occurred between 2862±94 *cal*. BP to the present. However, it is not possible to include this fluctuation in Fig 6.10.1 as a radiocarbon date has not been provided for this section. Shennan and Horton's (2002) modelled trend line does not demonstrate how sea-level would have fluctuated throughout the late Holocene to its current position.

6.11. Summary

The river Forth was a highly dynamic river system during the late Holocene. As the river migrated away (zones 1, 2, 5 and 6), organic matter accumulated where wetlands could have potentially formed until it reinstated its position at Netherton. In terms of sea-level, zone 3 identified a slight transgressional phase but further work needs to be undertaken downstream to support this theory. The consistent presence of acidic taxa (e.g. *T. flocculosa*) supports the theory of peat deposition into the river Forth. Anthropogenic influences and environmental changes have been outlined by stratigraphical changes and diatom composition around 2862±94 *cal*. BP. This study potentially disagrees with Shennan and Horton's (2002) modelled trend line for the late Holocene regression, as sea-level would have withdrawn more rapidly than previously estimated and fluctuated to its current position.

Chapter 7. Conclusion

7.1. Introduction

This chapter concludes the research and assesses to what extent the aim and objectives have been satisfied (Chapter 1). Additionally, recommendations for further work are presented as certain aspects of the discussion needed more evidence to support conclusions.

7.2. Conclusions

Stratigraphical and diatom analysis was undertaken to determine environmental changes in the Forth valley. A radiocarbon date of 2761±45 BP (2862±94 *cal.* BP) was distinguished in the peat layer of zone 1. The river Forth was a highly dynamic river system during the late Holocene as the evidence indicated influences from the tidal range, upstream activity, anthropogenic impacts and localised environmental changes. Zones 1 to 7 demonstrated evidence of erosion or removal of peatlands upstream from the study site. These materials were drained through the river Forth and are intercalated with the riverine sediment in the stratigraphy. This is further evident from the presence of acidic diatom species. However, these species do not dominate the assemblage as the alkaliphilous riverine taxa are highly abundant throughout.

Although the peat and riverine deposits were indicative of a freshwater environment, the diatom composition throughout the core indicated a slight marine influence as the tidal range lay near Netherton. This study found that the late Holocene regression occurred more rapidly than originally estimated between 4500 *cal.* BP - 2862±94 *cal.* BP. The diatom composition and larger sand grains in the sediment of zone 3 is possibly indicative of a temporary rise in sea-level. However, further investigation needs to be incorporated into this research to determine whether the evidence is an implication of sea-level rise. Sea-level remained consistent between zones 5 to 7, with the exception of the possible storm surge recorded in zone 7, as marine to marine-brackish species remained below 10% of the count.

Additionally, the stratigraphy revealed sections of sediment not related to direct riverine deposition. When correlated with diatom analysis, these sections have been defined as floodplain sediments (zone 5) or wetlands (zones 1, 2 and 6). Although the river has migrated temporarily away, the site remains in contact with the river Forth, as indicated by the diatom assemblage. Therefore, the dynamic nature of the river system has been verified in this research from the recorded phases of temporary migration and wetland or floodplain development.

7.3. Further Work

Improvements and further work to improve the robustness of this research:

- To include more radiocarbon dates from conformable contact points, including the sections of peat in zones 1 and 6 to correlate findings with data and archaeological evidence in the Forth valley. Furthermore, a radiocarbon date in zone 3 will improve Fig. 6.10.1 as it is an alleged transgressional phase.
- To include pollen analysis (or use of another proxy) to support the evidence presented in this research. Pollen analysis would be particularly useful to determine the environment of the peat layers in zones 1 and 6.
- More core samples need to be taken in the surrounding area, particularly downstream, with available late Holocene data to distinguish local and overall changes in the Forth valley.

- To create a comparable training set, providing a modern analogue of the environment to distinguish localised environmental changes.

7.4. Summary

This research found evidence of environmental changes during the late Holocene in the Forth valley. A possible temporary rise in sea-level, after 2761±45 BP (2862±94 *cal*. BP), was recorded in zone 3. There is scope for further work to make the findings of this study more robust.

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