The Quaternary Evolution of the Gordano Valley, North Somerset, UK.

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A thesis submitted in partial fulfilment of the

requirements of the University of the West of England, Bristol

for the degree of Doctor of Philosophy.

Faculty of the Built Environment, University of the West of England, Bristol

January 2006

Abstract

The Gordano Valley is a low-lying valley positioned in close proximity to the Severn Estuary, in southwest England. Although its late Quaternary and Holocene sedimentary archive is extensive, the spatial and temporal evolution of the Gordano Valley has received only limited attention from previous researchers.

In this study, stratigraphic analysis of the valley archive, combined with pollen, diatom and particle size analysis are utilised in a detailed reconstruction of the evolution of the Gordano Valley. Two contrasting depositional environments are present, separated by a sedimentary ridge traversing the width of the valley. A tentative mechanism is presented for the development of the ridge in response to periglacial hillslope erosion and deposition during the Devensian glacial period (*c*. 115,000-11,500 Cal. yrs BP). In contrast, the chronology and development of the two depositional environments is clearer. Detailed multiproxy analysis of the two sedimentary archives reveals the development of an enclosed lake basin headward of the ridge during the late glacial period (*c*. 18,000-15,000 Cal. yrs BP). Subsequent climatic amelioration in response to the transition from glacial to interglacial conditions resulted in the terrestrialisation of the lake at the onset of the Bølling/Allerød interstadial, *c*. 15,000 Cal. yrs BP. A complete hydroseral succession sequence is present in the headward region of the valley, where the terrestrialised lake sequence developed into the fen peatland that is present today. Seaward of the ridge, interbedded peat and marine sediments have developed since *c*. 7,200 Cal. yrs BP and reflect the typical deposits that characterise the Severn Estuary lowlands. Whilst an overall tend of sea-level rise occurred during the Holocene, periods of episodic marine inundation occurred in the Gordano Valley in response to variations in

the rate of sea-level rise. This thesis also attempts for the first time in southwest England, to construct and apply a diatom-based sea-level transfer function to an interbedded coastal sequence in order to quantitatively infer changes in sea level since sedimentation began. Although the transfer function proved successful, autocompaction of the sedimentary archive restricted the reconstruction of sea level as age-altitude plots.

The high-resolution lithostratigraphic analysis combined with the multiproxy analysis of the sedimentary archive has enhanced the understanding of the evolution of the Gordano Valley since the late glacial period. The terrestrialised lake sequence may also be the oldest of its kind in southwest England. Although autocompaction restricted a true reconstruction of sea level since sedimentation began, the initial success of the transfer function has indicated its applicability to a macrotidal environment such as the Severn Estuary.

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Acknowledgements

Funding for my research project was provided by the Faculty of the Built Environment within the University of the West of England, Bristol. Radiocarbon dating was also funded through a research grant provided by UWE.

Access to the Gordano Valley was granted primarily through English Nature and the Avon Wildlife Trust. I would like to thank Simon Lee from English Nature and Tim McGrath from the Avon Wildlife Trust for their assistance throughout the three years. Permission from Robert Fowler, Tom Letts, John Redman and Sally Saysell for access to their private land within the valley was also much appreciated.

There is an almost endless list of people I would like to thank from the Faculty of the Built Environment at the University of the West of England, particularly:

My supervisors – Wendy Woodland, Chris Spencer and Sue Marriott. Their combined and individual efforts to assist me throughout the three year period were invaluable and I owe them all a great debt of gratitude. After putting up with me all this time I am sure they can take on any PhD student!

The laboratory staff in the School of Geography and Environmental Management – Atul Vadgama and Andy Geary, for always providing the assistance when needed and never making a day in the labs dull! Very special thanks to fellow PhD student Paul Rae, for helping me in the field when times were hard, and those pep talks when all seemed so dark!

The departmental computing staff, especially Jan Major, who was almost part of the furniture in the research office as my computer never seemed to like me, thanks!

Also, special thanks must go to:

Dr Ben Horton (University of Durham) and Dr Roland Gehrels (University of Plymouth) for their assistance and advice regarding the construction and implementation of the Diatom Transfer Function. Thanks also to Ben and Professor Ian Shennan for allowing me to use their sea-level data set for southwest England.

Dr Andy Plater (University of Liverpool) for his continued encouragement during both undergraduate and postgraduate research.

Hilda Hull and Irene Cooper (University of Liverpool) for their assistance in hydrofluoric acid pollen treatment, and the swift preparation of the samples when needed.

And last, but by no means least, thanks to Mom & Dad, without whom none of this would have ever been possible. I thank you both from the bottom of my heart for your never ending support, advice and love throughout the last 6 years of my degree and Ph.D.

Part I:

Introduction.

Chapter 1: Introduction

Lowland environments proximal to coastal settings often provide a valuable sedimentary archive from which a region's depositional history may be reconstructed. A sound knowledge of palaeoenvironments enables a researcher to understand both short and long term trends in environmental change. It may elucidate the spatial scale of such changes, for example over local (such as a valley system), regional (southwest England) or continental areas (the UK and NW Europe), and enable an understanding of the temporal aspects of those changes to be achieved. A further benefit of palaeoenvironmental research lies in the construction of scenarios of future environmental change. This is based on the initial findings of Lyell (1832) who indicated that an understanding of present environmental and depositional processes is the key to understanding the changes that have occurred in the past (uniformitarianism). Birks and Birks (1980) developed this theory, noting that an understanding of the past provides information on the future response of a depositional system to global climate and environmental change (known as "reverse uniformitarianism").

The research presented in this thesis will concentrate on the Gordano Valley, a low-lying valley with a considerable Quaternary sedimentary archive found in North Somerset, southwest England (see Figures 1.1 and 1.2). Limited palaeoenvironmental work has been undertaken in the past (Jefferies *et al.*, 1968; Mills, 1984; Gilbertson *et al.*, 1990) and this study aims to improve upon this through the development of new and original research within the valley.

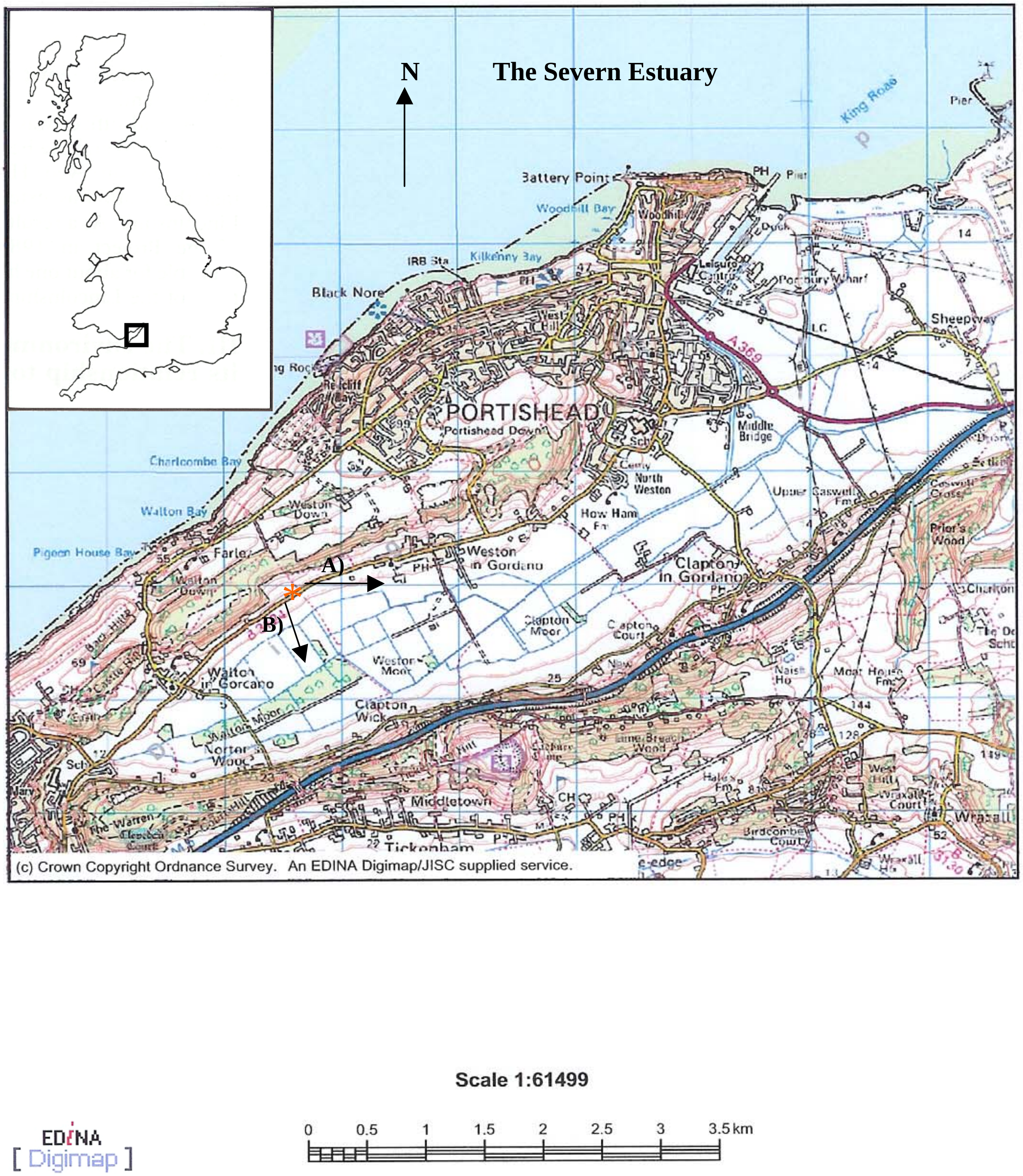

Figure 1.1 Location of the Gordano Valley, trending WSW-ENE. Note the proximity of the valley to the Severn Estuary together with its enclosed and isolated form. * = site location for photographs in Figure 1.2, and the arrows indicate the orientation of the photographs (Digimap, 2004).

A)

B)

Figure 1.2 Photographs of the Gordano Valley, looking A) east towards the Severn Estuary and B) southeast towards the M5. See Figure 1.1 for photograph location.

The Gordano Valley is positioned directly south of Portishead, North Somerset. The valley trends WSW-ENE, parallel to the Severn Estuary which is situated to the north (ST 460 740). The head of the valley originates near Clevedon and it widens towards the Severn Estuary and the River Avon. The valley extends approximately eight kilometres from Clevedon to the coast and is over a kilometre wide along much of its length (Figure 1.1).

The geological history of the valley is explained fully in Chapter 3. The bedrock is characterised by Devonian Old Red Sandstone which forms the northern valley side, and Carboniferous Limestone which lies to the south (British Geological Survey, 1974). Post depositional folding and subsequent erosion during the Palaeozoic era resulted in the formation of the present valley shape. Following this period, the last major contribution to the region's geology occurred during the Triassic period, during which mudstones were deposited unconformably on the Devonian and Carboniferous bedrock, along the valley floor (Green, 1992).

A significant depositional hiatus is present in the valley from the Triassic to the Quaternary periods. Glacial tills, coversands and breccias, combined with interglacial beach deposits, all dating from the Quaternary, have all been discovered within the Gordano Valley (ApSimon & Donovan, 1956; Gilbertson & Hawkins, 1974, 1978a, 1978b; Hunt, 1998), although precise chronologies for each deposit are unknown. However, according to Jefferies *et al.* (1968) the majority of the sedimentary archive preserved within the valley has accumulated over the last *c*. 11,500 yrs of the Quaternary. These sediments represent the Holocene epoch, which is characterised by climatic amelioration after the Devensian glacial episode (Lowe & Walker, 1997). For coastal lowlands, a major consequence of this climatic amelioration was sea-level rise.

Jefferies *et al.* (1968) produced the first sedimentary reconstruction of Quaternary environmental conditions within the Gordano Valley, which revealed a sub-topographical sand bar traversing the valley floor (see Figures 3.4 and 3.5). This sediment ridge is believed to have acted as an environmental barrier that separated two depositional sedimentary systems within the valley. Landward of the ridge (towards the head of the valley), Jefferies *et al.* (1968) suggested that an enclosed basin was formed in which, after a short period of clastic sedimentation during the late glacial period, uninterrupted peat accumulation has continued to the present day. Seaward of the ridge, blue-grey clay bands interbedded with peat were interpreted by Jefferies *et al*. (1968) as evidence of episodic marine inundations within the valley from the Bristol Channel, in response to Holocene sea-level fluctuations. Two typecores were obtained by Jefferies *et al.* (1968) and vegetation changes within the valley were reconstructed via pollen analysis. Both cores were taken landward of the ridge (Figure 3.4), thus little attention was directed towards the interbedded peat and marine clay deposits at the seaward end of the valley.

Whilst Jefferies *et al.* (1968) implemented a relatively coarse coring strategy through the valley, research by Mills (1984) reconstructed the environmental history of the Gordano Valley from only a single core, also using pollen analysis as the primary analytical technique. This was further analysed by Gilbertson *et al.* (1990) through the application of radiocarbon dating. The sample core was located close to one of Jefferies *et al.'s* (1968) cores for comparison of results. As these studies were based on the analysis of a single core from the Gordano Valley, subsequent interpretations were limited in terms of a) palaeoenvironmental information and b) understanding the influence of regional trends in environmental change on the valley's evolution. Since this study, no other research has been undertaken. A full summary of the past research into the Gordano Valley is provided in Chapter 3.

1.1 Justification of study

The previous research that has been undertaken in the Gordano Valley identified the presence of a sedimentary archive that justifies further palaeoenvironmental analysis. The valley's isolation, combined with its low gradient, means that the Quaternary deposits preserved may provide an important source of palaeoenvironmental information. The unique geomorphology of the Gordano Valley and its proximity to the Bristol Channel has produced an archive that reflects the influence of both terrestrial and marine environmental conditions during its evolution. Research at such a site provides the opportunity to analyse and reconstruct the coastal lowland environmental conditions that have prevailed in the past.

Considering the lack of palaeoenvironmental research that has been undertaken within the Gordano Valley, a number of gaps exist in the current understanding of the site's Quaternary evolution. The relatively coarse network of coring in past research leaves much of the valley's sedimentary development open to interpretation. The same is also true for the vegetation history of the valley. The influence of Quaternary sea-level change within the Gordano Valley remains unresolved, because of limited spatial and temporal comparisons between the two separate depositional environments either side of the sub-topographical sediment ridge. Similarly, limited interpretations exist regarding the mode and timing of the ridge formation, although disturbance from a major tipping site and access restrictions means that this feature of the valley cannot be investigated fully during this research.

Late-glacial records for the southwest of England are rare (see section 2.4), although previous research has suggested that the deposits preserved landward of the sand bar in the Gordano Valley extend to the late-glacial period (Jefferies *et al*., 1968: Gilbertson *et al*., 1990). If this is the case, the site may contribute to the current knowledge of the late Quaternary evolution of southwest England during this period. This, in turn, would help to demonstrate how southwest England fits into a larger-context of climate and environmental change (see section 2.2). For example, the timescale involved regarding the evolution of the theorised late-glacial sedimentary archive may correlate with other sites from the southwest (and beyond), thus lending support for major climatic events having influenced lowland evolution. In addition, North Atlantic Ocean circulation is known to have contributed to climate change during the late-glacial. Consequently, evidence relating to the influence of such controls may be present within the stratigraphic archive, placing the Gordano Valley into a wider climatic context.

Much research has been undertaken in the lowlands of the Severn Estuary relating to coastal evolution and sea-level change during the Holocene (section 2.4), but the Gordano Valley has contributed little to this. Hence, it is not clear how this lowland coastal site sits within the typical Severn Estuary stratigraphic archive. Stratigraphic modelling of Holocene coastal sequences (Long *et al*., 2000; Streif, 2004) provides the opportunity to compare the evolution of the Gordano Valley to other proximal coastal sites and place the study into a wider stratigraphic context (see section 2.3.4). By analysing in detail the coastal archive, this study will evaluate the influence of Holocene sea-level change upon the site's evolution. Factors such as glacio-isostasy and autocompaction significantly influence the elevation of lowland stratigraphic archives, but are not normally considered in sea-level reconstructions. Attempts will be made to quantify the influence of these factors and incorporate this knowledge into the subsequent sea-level reconstructions from the Gordano Valley. An understanding of the sea-level history of the Gordano Valley will contribute to the growing sea-level dataset for southwest England.

Quaternary lithological and biological analytical techniques have been refined considerably since the work of Jefferies *et al*., (1968), Mills (1984) and Gilbertson *et al*. (1990), particularly with respect to quantitative reconstructions. The application of quantitative analysis to the understanding of sea-level change will be attempted for the first time at a site in southwest England. Diatom analysis, a palaeoenvironmental technique not previously applied to the Gordano Valley, will be used to quantify changes in the depositional altitude (in relation to sea level) of the fossil assemblages during the development of the sedimentary archive. The application of diatom analysis, combined with a number of other proxy techniques, will yield an environmental reconstruction which will considerably improve on past research in the Gordano Valley. This is due to the existing palaeoenvironmental reconstructions being qualitative in nature, and the quantitative diatom approach will provide the opportunity to investigate a relatively new reconstruction technique. This, in turn, will be compared to other quantitative palaeoenvironmental investigations to assess the validity of such a technique to the Severn Estuary lowlands.

1.2 Research Aims and Objectives

With the research potential in mind, the aim of this thesis is to **reconstruct the Quaternary palaeoenvironmental evolution of the Gordano Valley**. This will be achieved via the reconstruction of depositional environments landward and seaward of the sub-topographic ridge, and an analysis of the influence of sea-level change on the valley's evolution. To address this aim, a number of objectives have been identified to derive a clear understanding of the spatial and temporal evolution of the site:

1. **To log the Quaternary stratigraphy of the Gordano Valley and reconstruct the sedimentary environments.**

A high resolution, gridded network of cores will be located across the Gordano Valley to produce a more detailed representation of spatial and temporal variations in the valley's stratigraphic profile than hitherto achieved. From this, typecores will be selected that contain representative archives of Quaternary environments within the valley. Their analysis will identify key environmental changes that have occurred in the valley during its Quaternary depositional history.

2. **To determine the influence of sea-level change on the Gordano Valley's Quaternary sedimentary sequence.**

Diatom analysis will be applied to the typecore sediments to reconstruct sea-level changes since sediment deposition began. Changes in diatom assemblages can indicate changing environmental conditions at the study site, which in turn may indicate the influence of sea level on lowland evolution. The relationship between sea level and contemporary diatom assemblages will be quantified in order to produce a reconstruction of sea-level change from fossil assemblages.

3. **To determine ecological and vegetation change within the Gordano Valley's Quaternary sedimentary sequence.**

Reconstructed vegetation communities will be compared to previous research through pollen analysis. The appearance of certain indicator species will allow for the relative dating of events during the evolution of the valley (Godwin, 1975; Moore *et al.*, 1991). Vegetation communities will also reveal the presence of marine conditions within the valley thereby indicating the influence of sea level on the evolution of the valley.

4. **To integrate the sea-level, vegetation and sedimentological data to reconstruct the Quaternary environmental history of the Gordano Valley.**

Once the first three research objectives have been satisfied, the results will be combined in a multiproxy reconstruction of the valley's palaeoenvironmental history. This will considerably enhance the current knowledge of the valley's evolution.

5. **To place the Gordano Valley archive and its interpretation within the contexts of established work in the Severn Estuary region and of frameworks for climate change.**

An understanding of the spatial and temporal extent of environmental change in the Gordano Valley will be achieved by comparing the palaeoenvironmental reconstruction of the Gordano Valley to other research that has taken place in the Severn Estuary, southwest England. The study will contribute to the current regional knowledge of the influence of climate and sea-level change on coastal lowland evolution.

This research will introduce a new suite of analytical techniques to the Gordano Valley. These include diatom analysis, palaeoenvironmental transfer functions and certain aspects of particle size analysis (see Chapters 4 and 8). Combined with the traditional approach of pollen analysis, they will allow the research objectives to be examined with rigour, thereby providing a substantial contribution to current knowledge of the Gordano Valley and the surrounding region.

Chapter 2: Previous Research into Quaternary Coastal Lowland Environments

2.1 Introduction

This chapter begins by describing patterns of Quaternary climate change to place the research into a clear climatic context. Studies into sea-level change within the Severn Estuary are then reviewed and the influence of sea level on coastal stratigraphy is assessed. A summary of past research into environmental change in coastal lowlands is also provided within this chapter. Sites proximal to the Gordano Valley are analysed to reveal the geomorphic and sedimentologic response to the palaeoenvironmental change that has occurred in the Severn Estuary region. Such inter-site analyses provide a geographic context into which the study site can be placed.

2.2 Quaternary climate change

The influence of glacial-interglacial cycles on continental (and indeed hemispheric) climate change has long been seen as substantial. Initial research concentrated on glacial deposits scattered throughout northwest Europe to indicate recognised shifts in glacial activity (and thus climate) but, since the 1960s, studies have exploited the palaeoenvironmental archive preserved within the world's contemporary ice sheets (Lowe & Walker, 1997). Ice core records from Greenland and Antarctica have revealed a high degree of temporal resolution, indicated by annual increments of snow which are subsequently compacted to form ice (Johnsen, 2002).

A large amount of palaeoclimatic information is preserved in the annual layers of ice. This includes volcanic and aeolian dust particles, trace gases and pollen grains, which can be used to reconstruct climatic conditions at the time of deposition. One of the most significant records preserved in the ice sheets are stable isotopes of oxygen. The oxygen isotope composition of the ice core is measured in annual intervals and expressed as a deviation from a standard ($\delta^{18}O$). The deviation in ^{18}O is broadly dependent on temperature and is believed to reflect global temperature changes (Johnsen *et al.*, 1992; Dansgaard *et al.*, 1993). Analysis of $\delta^{18}O$ within individual layers of ice from Greenland (GRIP, Greenland Ice-core Project; GISP, Greenland Ice Sheet Project) and Antarctica (Vostok) have confirmed this by revealing strong spatial and temporal correlations between the Earth's major ice sheets. A detailed explanation regarding the process of $\delta^{18}O$ analysis is presented by Johnsen *et al.* (1992).

The reliability of the $\delta^{18}O$ records from the GRIP, GISP and Vostok ice cores as indicators of climate change has been validated via comparisons with other palaeoenvironmental records (Broecker & Denton, 1989; Lowe *et al.*, 2001; Litt *et al.*, 2001; Freidrich *et al.*, 2001; Jones *et al.*, 2002). The evidence inferred from archives from both land (e.g. lake sediments) and sea (e.g. marine sedimentary cores) indicates that the $\delta^{18}O$ record stored in the ice is a strong indicator of past climate change (Johnsen *et al.*, 1992; Hughen *et al.*, 1996). A proxy technique such as $\delta^{18}O$ can thus be used as a reference against which other proxies are compared. This multiproxy palaeoenvironmental reconstruction demonstrates significant shifts in climate, notably recorded in northwest Europe, since the last glacial maximum (LGM; *c.* 22,000 Cal. yrs BP; Lambeck, 1995). Consequently, a comprehensive understanding of the known changes in climate, together with the perceived forcing factors is required if a satisfactory palaeoenvironmental reconstruction of the Gordano Valley is to be achieved.

2.2.1 Evidence from the GRIP, GISP and Vostok ice-cores

The variations in $\delta^{18}O$ profiles recovered from the world's major ice sheets reflect glacial-interglacial shifts that have been experienced throughout Earth's Quaternary history. Although temporal resolution decreases with depth (and thus age) due to compaction, the $\delta^{18}O$ records from ice cores cover the last 250,000 yrs and beyond, and they indicate general instability within the climate during this time (Dansgaard *et al*., 1993). Regular, cyclical fluctuations in the $\delta^{18}O$ content are evident, with periods of higher $\delta^{18}O$ (relative to $\delta^{18}O$ concentrations in mean ocean water) relating to interglacials and lower $\delta^{18}O$ relating to glacial phases (Johnsen *et al*., 1992). When the ice records from Greenland (GRIP and GISP) are compared to those of the Antarctic (from the Vostok core), glacial-interglacial cycles are present in all, although minor short-term fluctuations are more distinct in the Greenland archives. This suggests that global climatic forcing mechanisms are responsible for the glacial-interglacial shifts, whereas more localised (hemispheric) internal forcing mechanisms superimpose climatic instability onto the general trends (Johnsen *et al*., 1972, 1992; Hughen, 1996; Nesje *et al*., 2004).

Figure 2.1 summarises the reconstructed $\delta^{18}O$ record over the last 250,000 yrs, embracing the last major glacial (Devensian) and interglacial (Ipswichian) stages. In contrast to the relative stability of $\delta^{18}O$ levels during the Holocene (last 11,500 yrs, as indicated in Figure 2.1A), the Devensian and Ipswichian are characterised by continuous shifts in $\delta^{18}O$ and thus temperature (Figure 2.1B).

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<u>Figure 2.1</u> The continuous GRIP $\delta^{18}O$ record for the last c. 250,000 yrs. ***A***, from surface to 1,500m (last *c*.10,000 yrs); ***B***, from 1,500 to 3,000m depth (10,000-250,000 yrs BP). 'IS numbers' in **B**, relate to the recognised interstadial periods in the ice core, names relate to northwest European terminology. Source: Dansgaard *et al*., (1993), p. 218.

The transition from the Devensian glacial episode to the present day interglacial typifies the fluctuating climatic conditions of the Quaternary. Environmental records throughout northwest Europe indicate synchronised climatic shifts which can be correlated with the GRIP, GISP and (to a lesser extent) Vostok $\delta^{18}O$ profiles (Nolan *et al*., 1999; Litt *et al*., 2001; Friedrich *et al*., 2001, Jones *et al.*, 2002). Figure 2.2 summarises in detail the $\delta^{18}O$ record from the GRIP ice core (Bjorck *et al.*, 1998), in which the recovery from the Devensian glaciation between *c*. 22,000 and 11,500 Cal. yrs BP is divided into short-term stadial and interstadial periods (cold and warm phases within a glacial cycle respectively).

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Figure 2.2 The $\delta^{18}O$ record from the GRIP ice core between 11,000 and 23,000 GRIP yrs BP. Initial isotope stratigraphy by Johnsen *et al*. (1992), adapted by and taken from Bjork *et al*. (1998).

Precise dating through counting of annual ice layers has produced a more accurate record of the initiation and termination of individual climatic episodes (previously understood through radiocarbon dating; see section 8.5.1). Figure 2.2 divides the transition period into stadials, interstadials, substadials and subinterstadials. Table 2.1 summarises these climatic episodes with precise ages and, to assist comparisons, includes the common terminology related to these periods.

Events	Episodes		Ice-core age (yrs) for the onset
Holocene epoch			11,500
GS-1		Younger Dryas	12,650
	GI-1a		12,900
	GI-1b		13,150
	GI-1c	Allerød	13,900
	GI-1d	Older Dryas	14,050
GI-1	GI-1e	Bølling	14,600
	GS-2a	Oldest Dryas	16,900
	GS-2b	Pleniglacial	19,500
GS-2	GS-2c		21,200
GI-2			21,800

Table 2.1 Ages of the onset of events and episodes in the GRIP ice-core, adapted from Bjork *et al.* (1998).

Figure 2.2 reveals that 22,000-14,700 yrs BP was characterised by a short-lived interstadial (21,800-21,200 yrs BP) and a major stadial (21,200-14,700 yrs BP). Although the $\delta^{18}O$ record fluctuates significantly, the overall trend indicates a gradual amelioration of climate was occurring. This sequence is interrupted by the Oldest Dryas substadial. A distinct increase in $\delta^{18}O$ values to levels similar to those recorded for the early Holocene then follows, which relates to the onset of the Bølling/Allerød interstadial (14,600 yrs BP). This interstadial can be further subdivided into subinterstadials according to short-lived but distinct shifts in climate. These are the Bølling, Older Dryas, Allerød, and the unnamed periods known as GI-1b and GI-1a (Bjork *et al*., 1998). The Bølling and Allerød subinterstadials, for example, relate to warmer climatic periods separated by the cooler interval known as the Older Dryas. The onset of the Holocene epoch is dated to 11,500 yrs BP and is defined by a sudden rise in $\delta^{18}O$ records over a very small time scale. In comparison to the rest of the Quaternary, climatic stability dominates the Holocene (Figure 2.1). A subtle deviation in $\delta^{18}O$ has, however, been recorded in the GRIP ice core which is dated to *c.* 8,200 yrs BP. A decrease in $\delta^{18}O$ of *c.* –2 to –4δ was recorded, out of synchronisation with the common isotope profile for the early Holocene and this is known as the "8,200 BP event" (Figure 2.1).

2.3 The importance of sea-level change on coastal lowlands

Variations in ocean circulation in response to glacial-interglacial cycles have been shown to be an important aspect of late Quaternary climate change (Broeker & Denton, 1989; Clark *et al*., 2002). The coastal lowlands of northwest Europe have preserved palaeoenvironmental evidence for changing climatic conditions during the late Quaternary period. Sea-level change is seen as the most influential factor regarding the response of coastal lowlands to climate change, due to its impact on coastal systems since the transition from the LGM. As marine deposits are known to have accumulated during the evolution of the sedimentary archives preserved in the Severn Estuary lowlands (Allen, 2000a; Bell, 2000), the influence of changes in relative sea level must be considered and understood.

The extensive assessment of sea-level change since the LGM indicates that significant spatial variations have occurred throughout the UK. The impact of changing sea levels on lowland sites proximal to the Severn Estuary has been shown to be considerable (Kidson & Heyworth, 1973; Heyworth & Kidson, 1982; Shennan, 1989; Jennings *et al.*, 1998; Haslett *et al.*, 1998; Bell, 2000). During the Devensian glacial maximum (*c*. 22,000 Cal. yrs BP; Lambeck, 1995), sea level was some 120m lower than present in southwest England (Lambeck, 1991). In response to the initiation of glacial retreat, melt-water from the ice caps began to contribute to a rise in eustatic sea level. However, the response to eustatic sea-level rise was not uniform across the British Isles. For example, during the Late Devensian glacial retreat (*c*. 15-11,000 Cal. yrs BP), rapid melting of the ice mass was occurring, but Scottish records show a lowering of sea level. In contrast, records produced in southwest England showed relatively uninterrupted rising sea levels (Lambeck, 1991). Differences of this scale over such a small geographic area are a result of other 'external' factors that influence changes in sea level. Whilst 'eustatic sea-level changes' refer to absolute changes in the global water supply (i.e. the sea water : global ice ratio), 'relative sea-level change' implies the inclusion of vertical crustal movements that will have considerable influence on the rate of *relative* sea-level rise at a given point on a coastline (in this case, in the Severn Estuary/Bristol Channel region). Such external influences are responsible for the variations in sea level throughout the UK since the end of the glaciation. The main controls on relative sea level are summarised by Morner (1976) and divided into two groups; those that influence the land, and those that influence the sea. Whilst the sea is predominantly influenced by eustasy, crustal movements and sediment compaction can cause considerable effects on land elevation (see section 2.3.2).

The following section will review the techniques used to reconstruct sea level and will also consider a number of factors that need to be accounted for when assessing the sea-level history of a site. Stratigraphic models of coastal evolution will then be summarised because of their relevance to the lowland development of southwest

England, after which a detailed review of the Quaternary history of southwest England is provided.

2.3.1 Techniques of sea-level reconstruction

The analysis of sedimentary archives from a lowland coastal setting can provide valuable palaeoenvironmental information which can be used in the reconstruction of sea level. Interbedded sequences of freshwater peat and marine clays and silts indicate the variation in influence of sea level over time, and are a common feature throughout stratigraphic archives in the Severn Estuary (see section 2.4). A sedimentary sample, such as a peat-clay unit boundary, can be interpreted as being deposited at a specific altitude in relation to a former sea level, creating a sea-level index point (SLIP). This is possible as lithostratigraphic and biostratigraphic data can be used to quantify the water level at which the sample formed in relation to the tidal regime (Shennan *et al*, 2000), from which the position of sea level can be attained. In order for a sample to be classified as a SLIP, five characteristics must be determined: location, age, altitude, indicative meaning and tendency. The age of a sample is most commonly obtained through radiocarbon dating (see section 8.5.1). The tendency of a sample relates to the sea-level movement represented. A positive tendency is an increase in marine influence and a negative tendency is a decrease in marine influence. Indicative meaning of a sample is the relationship of the environment in which it accumulated to a reference tidal level (Shennan, 1986). Stratigraphic analysis of a coastal site can provide a number of SLIPs to indicate the evolution of that locality in response to apparent sea-level change. However, it is possible to combine the results of a number of sites to increase the size of the data set and to discover the underlying regional trend in sea-level change. This was achieved by Shennan & Horton (2002) for southwest England and is summarised in section 2.3.3.

One characteristic of a SLIP, however, must be understood further to ensure an accurate reconstruction of sea level. The indicative meaning of a sample will enable the estimation of the height of sea level in relation to the stratigraphic boundary in question. Shennan (1986) studied the relationship between tidal range and contemporary depositional environments in the Fenland, East Anglia. Each sedimentary environment was related to an altitude at which it would accumulate (relative to the region's tidal frame) to provide an indicative range for this reference water level. If the relationship between depositional environment and relative sea level can be understood, such information can be applied to stratigraphic records to calculate the change in sea level that has occurred during the evolution of a lowland coastal site. Such reconstructions from sedimentary records can present problems, including the influence of post-depositional sedimentary compaction (autocompaction), accurate levelling of index horizons and variations in palaeo tidal levels (a full consideration of such limitations is given by Shennan, 1986). Table 2.2 indicates the relationship between different sedimentary boundaries and the position of the palaeo sea level responsible for their development in the Fenland.

Type of sedimentary boundary	Indicative range	Reference water level
Phragmites or monocotyledous peat:		
- directly above saltmarsh deposit	20 cm	M1-20cm
- directly below saltmarsh deposit	20 cm	MHWST-20cm
- directly above fen wood deposit	20 cm	MHWST-10cm
- directly below fen wood deposit	20 cm	M1-10cm
- middle of layer	70 cm	infer from strat
Fen wood peat:		
- directly above *Phragmites* peat or saltmarsh deposit	20 cm	M1
- directly below *Phragmites* peat or saltmarsh deposit	20 cm	MHWST
Basal peat:	80 cm	MTL to MHWST

Table 2.2 Summary of relationship between sedimentary boundaries and inferred reference water level in the Fenland (adapted from Shennan, 1986 p.157). M1 is calculated (HAT+MHWST)/2.

The indicative meaning of stratigraphic boundaries is site specific, primarily due to the considerable variation in tidal ranges throughout the UK lowlands. The Fenland, for example, has a highest astronomical tide (HAT) of *c*. 5.2m in contrast to *c*. 8.15m for the Severn Estuary. Consequently, applying a reference water table with a single tidal level ± a constant factor (e.g. MHWST – 20cm) to a site with a tidal range that is greater than the site from which it was derived would infer quite different tidal inundation characteristics (Shennan, 1986). Consequently, such an approach to the reconstruction of sea level in the Gordano Valley was not possible, as it required an extensive assessment of the relationship between sedimentary environments and tidal conditions to be undertaken in the Severn Estuary.

In contrast to the use of stratigraphical boundaries for reconstructing sea level, new methods of understanding past sea-level changes have been developed that use biological environmental indicators. It has now been established that the relationship between diatom, foraminifera and testate amoebae species with a reference tidal level is strong (Zong & Horton, 1999; Haslett *et al*, 2001a; Charman, 2001; Gehrels *et al.*, 2001). An understanding of how each individual species relates to tidal settings in a modern environment can be applied to fossil remains in the form of a "transfer function". The transfer function applies the contemporary environmental requirements of the species in question to those discovered in the fossil archive to calculate the environmental conditions that were present at the time of deposition. If the environmental variable in question is altitude (relative to mean sea level), then it would be possible to associate quantitatively a reference altitude to each fossil assemblage preserved in a stratigraphic archive. This can, in turn, be calculated to infer the position of relative sea level at the time of deposition. This quantitative method of sea-level reconstruction is in its relative infancy, but has yielded promising results (Zong & Horton, 1999; Ng & Sin, 2003). The reconstruction of past sea-level changes from microfossil assemblages is utilised in this study in place of the traditional stratigraphic SLIP method. This technique provides a valuable contribution to this thesis and the approach is further analysed in Chapter 4.

2.3.2 Factors influencing sea-level reconstructions from stratigraphic archives

As stated in section 2.3.1, sea-level reconstructions often rely on the analysis and interpretation of sedimentary archives to infer the position of sea level at various times during a site's depositional history. Interbedded sequences of freshwater peat and marine clays and silts are valuable indicators of sea-level change and lowland evolution.

However, a number of factors influence the development of lowland stratigraphic archives and subsequent sea-level reconstructions.

Glacio-isostasy has now been accepted as one of the most important controls on relative sea level. During major glacial episodes, loading of the ice mass on the crust results in crustal depression (Jamieson, 1882). On removal of the mass as the glacier retreats, the land mass attempts to reach equilibrium by migrating to its original position. The migration adjustment of the landmass, known as a forebulge, involves mass redistribution of the highly viscous interior of the Earth. This cannot keep pace with the comparatively rapid glacial retreat and the readjustment continues long after deglaciation is complete. The importance of the Devensian ice mass loading on the British Isles has been reported by Lambeck (1991, 1993, 1995, 1996) and Peltier *et al.*, (2002). As a consequence, glacio-isostasy is able to explain the differing rates of relative sea-level change experienced within Britain. The positioning of the Devensian glacial mass over Scotland and much of northern England, Wales and Ireland caused severe crustal depression which, upon glacial removal, rebounded towards its original position faster than eustatic sea-level rise; this caused a drop in relative sea level. In contrast, reconstructions of sea level in southwest England indicate a uniform rise in sea level along the coastal lowlands, and were initially interpreted as evidence for crustal stability (and hence the dominance of eustatic changes in sea level during the Holocene; Kidson and Heyworth, 1978). This, however, has been shown not to be the case (Shennan & Horton, 2002; Waller & Long, 2003), as isostatic movements in southern England have continued throughout the Holocene. Waller & Long (2003) state that southern England has experienced long-term regional tectonic crustal uplift during the Pleistocene, but interglacial subsidence in response to glacio-isostasy has, to a certain extent, counteracted this movement. In contrast, through the compilation of seventy SLIPs from past research in southwest England and their comparison with glacio-isostatic adjustment (GIA) models, Shennan and Horton (2002) reveal that ever since *c*. 4,000 Cal. yrs BP, the Bristol Channel region has been subsiding at a relative rate of 0.76mm yr^{-1}. A lack of reliable data points prior to 4,000 Cal. yrs BP prevented the analysis of crustal movements during the early-mid Holocene. Therefore, if such relative crustal subsidence has indeed affected southwest England during the Holocene, this must be considered when assessing the record of sea-level change reconstructed from the Gordano Valley sedimentary archive.

Another factor, autocompaction, is accepted as one of the most significant factors that will affect a SLIP, and is defined by Allen (2000b, p239) as "the group of interlinked processes whereby the sediment within a growing stratigraphic column diminishes in volume, on account of burial and self weight …..(and) a loss of mass as a result of biological and chemical decay". The vertical lowering of a stratigraphic boundary due to autocompaction will result in subsequent sea-level reconstructions producing erroneous results. As autocompaction is pertinent to studies of sedimentary archives within the Severn Estuary coastal lowlands, attempts have been made to calculate its impact on Holocene sediments (Haslett *et al*., 1998; Crooks, 1999; Allen, 2000b; Shennan *et al*., 2000) and to highlight the difficulties related to such reconstructions. An understanding of the precise sedimentological and geotechnical properties for all sediments within a depositional profile is needed when assessing post-depositional consolidation. Estimates for the influence of autocompaction on the change in altitude of buried estuarine peat vary from 2.22m (Haslett *et al*., 1998) to 3-4m in experimental and field data analysis (Allen, 2000b). The consolidation potential of estuarine sediments can be significantly affected by subtle changes in geotechnical characteristics (Crooks, 1999). Consequently, if peat positioned on bedrock can be related to a former water level, it is seen as the only reliable source of past sea-level reconstruction because compaction will not affect the basal sedimentary boundary (Allen, 2000b).

Haslett *et al*. (1998) were able to account for autocompaction at Nyland Hill, Somerset, because the main peat unit was positioned in close proximity to bedrock. Figure 2.3 indicates the lithostratigraphy of the site. Samples were taken at the peat-clay boundary from a number of cores along the sedimentary transect and radiocarbon dated. As all the dates were found to be similar (*c*. 3,720-3.640 Cal. yrs BP), the peat surface was considered to have been at a common altitude prior to marine inundation. As the peat unit's upper boundary was positioned directly over bedrock along the sedimentary transect, it was possible to conclude that the altitude of the peat surface at that site was the original surface altitude of the Nyland Hill area before marine transgression occurred. The dated peat-clay boundaries could then be assigned a corrected altitude to provide SLIPs for the site. The application of such a compaction-correction technique in this thesis is strongly dependent on the sedimentary archive of the Gordano Valley.

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Figure 2.3 Lithostratigraphy of the Nyland Hill transect (Haslett & Davies, 2002, p41).

A final autocompaction correction technique is an adaptation of the approach of Haslett *et al*. (1998), and has been employed by Gehrels (1999), Shennan *et al*. (2000) and Shennan & Horton, (2002). It utilises basal peat index points from a regional data set of SLIPs because this is likely to contain a number of stable basal peat index points of various ages which can be compared with compaction susceptible index points from intercalated peat and clay (Shennan & Horton, 2002). Linear regressions can be performed on susceptible index points whose ages are between the mean weighted age of two basal peat index points (Gehrels, 1999). The difference in altitude between the two basal peat index points and the compaction susceptible index point indicates the possible vertical movement of the intercalated peat boundary in response to autocompaction. The difference is added onto the reconstructed mean sea level for the SLIP in question. This process can be applied to each SLIP that is likely to have experienced autocompaction to bring the points in line with the basal peat index points (Gehrels, 1999). As Shennan & Horton (2002) have compiled a regional sea-level data set for the Bristol Channel region that includes both basal peat and intercalated peat index points (section 2.3.3), this could be utilised to account for the influence of autocompaction on the sedimentary deposits present within the Gordano Valley.

A final factor that must also be considered is the influence of a site's tidal range on sea-level reconstructions. When discovering the indicative meaning of a stratigraphic boundary, the contemporary tidal frame is commonly used to position that unit boundary in relation to mean sea level at the time of deposition. For example, if the transition from salt marsh to peat deposition occurs in the modern coastal zone at Mean High Water Spring tide (MHWS), *c*. 7m O.D., then a stratigraphic boundary of peat underlain by clay from a fossil archive at the same site would be inferred as also having developed at 7m O.D. However, if the tidal range had been smaller or larger in the past, then the application of the modern tidal parameters would consequently under- or overestimate respectively the position of sea level at the time of deposition. Research in the Bay of Fundy, Canada, where the tidal range is similar to that of the Severn Estuary, has indicated that only 60% of the contemporary tidal range was present by c. 6.000 Cal. yrs BP (Gehrels *et al*., 1995). Factors such as changes in bottom friction, continental shelf-edge boundary conditions, crustal movements and bathymetry (width and depth of the water body) occur in response to sea-level rise (Austin, 1991) to influence the tidal regime of an estuary setting such as the Severn Estuary. However, Holocene tidal modelling in NW Europe by Austin (1991) suggests that there was a *c*. 50 to 70cm larger tidal range in the Severn Estuary *c*. 7.000-9,000 Cal. yrs BP when compared to the contemporary tidal frame. This contrasts markedly to the results of Gehrels *et al*. (1995). If this is the case, the lower sea level during the early to mid Holocene created a larger tidal range, possibly in response to the change in bathymetry of the Irish Sea. However, the model of Austin (1991) only took into account the continental shelf-edge boundary conditions when calculating the palaeo-tidal variations for the Bristol Channel, and did not include the actual detailed variations in bathymetry that are present within the Bristol Channel region. These would have been strongly influential on subsequent palaeo-tidal predictions (Gehrels *et al*., 1995), and consequently, the palaeo-tidal variations calculated by Austin (1991) are not reliable enough to be applied to any sea-level reconstructions from this study. Further analysis of the Holocene tidal change for the Bristol Channel is required before this factor can be accurately taken into account.

2.3.3 Sea-level reconstructions in southwest England

Cyclical fluctuations in climate have resulted in regular periods of glacial and interglacial activity throughout the Quaternary, which have been associated with low and high sea-level stands respectively. This regular shift in the sea water : global ice ratio would leave its imprint in the coastal lowlands of the Severn Estuary in the form of raised beaches and other sedimentary deposits associated with fluctuating sea levels. Aalbersberg (1999) has summarised some of the key Quaternary landforms and deposits of southwest England and the Bristol Channel area (see Table 2.3).

Chronostratigraphy		Feature	Location	Sea level
Devensian	Glacial Maximum	Low sea level		120m below OD
	Interstadials?	Raised beach gravels	Widespread	42-45m below OD
	Early?	Buried rock channels	All major rivers	Very low
Ipswichian	Late	Burtle Beds	Somerset Levels	MHWST 18-20m above OD, MSL 9-12m OD
	Early & Middle	Raised beaches, Patella beach	English Channel coast, South Wales	6-9.5m above OD
		Llanwern buried beach	Llanwern	4m below OD
		Estuarine?	Kenniper	Unknown
		Trimming of older beaches		
Wolstonian?		Buried rock channels	Major rivers	Very low
		Giant erratics?	Widespread	Higher than today
Early and middle Pleistocene		High level gravels	Around Bristol	Fluctuating, but much higher than today
Earliest Pleistocene		210m shore platform	Widespread	210m above OD
		Giant erratics?	Widespread	Higher than today

Table 2.3 A summary of the key Pleistocene coastal deposits and landforms in southwest England and Bristol Channel area (compiled by and adapted from Aalbersberg, 1999, p.21).

Whilst there is an abundance of coastal deposits that date from earlier stages of the Quaternary (see section 2.4), most of the stratigraphic sequences found in the coastal lowlands of the Severn Estuary have accumulated since the LGM, *c.* 22,000 Cal. yrs BP (Allen, 2000a). Consequently, the majority of sea-level studies concentrate on sea-level change since the Devensian glacial.

Using the known impact of glacio-isostasy on sea-level change (section 2.3.2), computer-based models have been developed that take into account crustal movements. By modelling the isostatic influence at a given point on the coastline in the UK, predictions of past sea level can be produced that can be compared with SLIPs to test their accuracy. Within the Severn Estuary, predictions of sea-level change vary between isostatic models. Lambeck (1991,1993,1995) estimated that glacio-isostasy, combined with eustatic changes in sea level, resulted in rates of sea-level rise of up to 6mm/yr from *c*. 8,500 to 6,000 yrs BP, rising from –27 to –7m O.D. over a 2,500 yr period (as shown in Figure 2.4). From 6,000 yrs BP to present, the negligible freshwater input from melting ice masses in temperate latitudes, combined with relative crustal stability, has maintained the rate of sea-level rise to *c*. 1.2mm/yr.

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Figure 2.4 Model prediction of sea-level change for Bridgwater Bay, Somerset, during the Holocene. The vertical scale for relative sea-level change is in metres (Lambeck, 1995, p.441).

A sea level model constructed by Peltier *et al*. (2002) contrasts markedly with that of Lambeck (1995), primarily through variations in the calculated lithospheric thickness and lower mantle viscosity of the Earth. The sea-level curve spans a much larger timescale, from the LGM to present day, and also implies that the shift in rates of sea-level rise occurred at around 8,000 yrs BP and not 6,000 yrs BP as suggested by Lambeck (1995). Figure 2.5 shows the sea-level curve created by Peltier *et al*. (2002) for the Bristol Channel. Peltier *et al.* (2002) show relatively stable sea level rise between the LGM and *c.* 15,000 yrs BP, and from 8,000 yrs BP to present day (*c*. 1.4mm/yr). In contrast, from *c.* 15,000 to *c.* 8,000 yrs BP an estimated increase of *c*. 70m occurs at an average rate of c. 10mm/yr.

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Figure 2.5 Sea level model for the Bristol Channel since the LGM. Two contrasting sea level curves (solid and dashed lines) are present and were created by variations in the thickness of the ice mass and the lithosphere during the development of the sea level model (Peltier *et al*. 2002, p.461). '+' indicate the position of observed sea-level index points.

Although considerable advances have been made regarding the ability of glacio-isostatic models to explain the spatial and temporal patterns of sea-level changes in the UK, significant disagreements still remain between model predictions and sea-level observations (Shennan & Horton, 2002). The various models provide accurate predictions for the general patterns of relative sea-level change between areas under thickest ice or those beyond the glacial limits, but none of the models give predictions that agree with relative sea-level observations at all sites. Shennan & Horton (2002) compiled all known

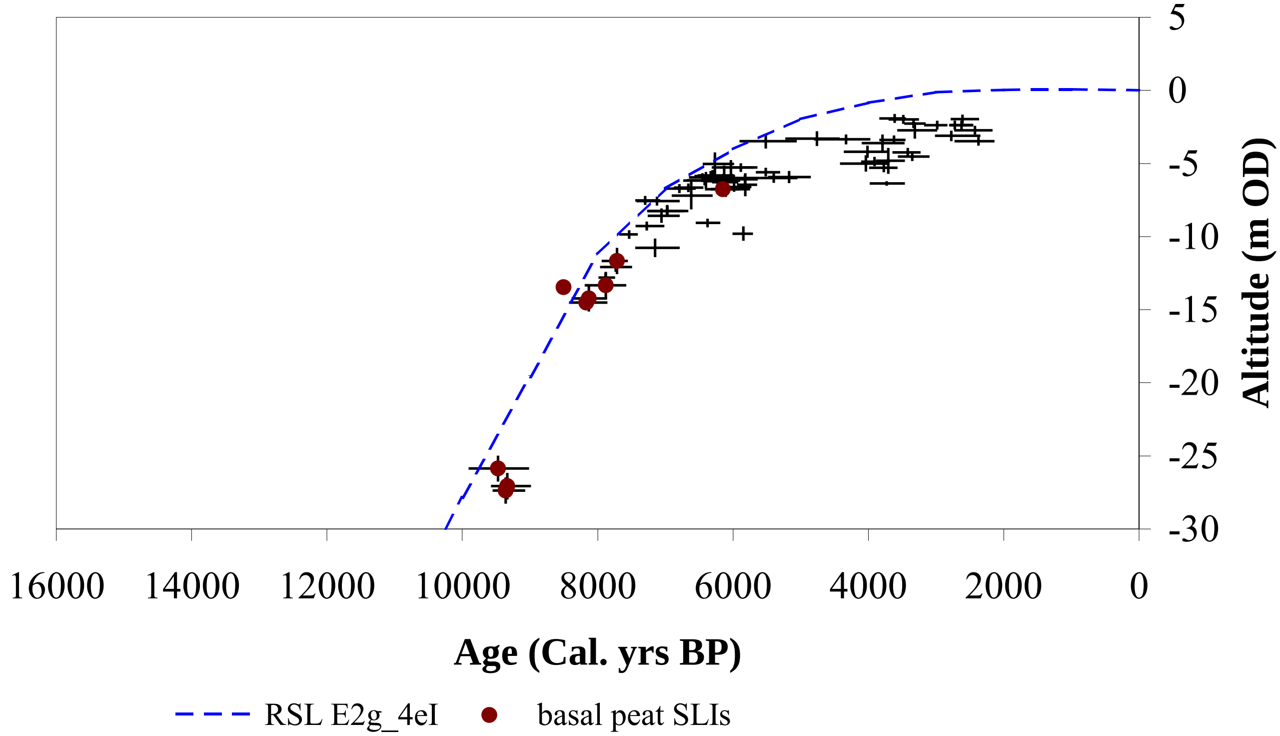

Figure 2.6 Sea-level index points for the Bristol Channel, including data from both basal peat and intercalated peat index points. Geophysical model 'RSL E2g_4eI' is included within the data set. Adapted from Shennan & Horton (2002).

SITE	LABCODE	Age (Cal. yrs BP)	RSL (m OD)	LITREF
Bridgewater, Somerset *	I2690	8168	-14.52	Heyworth & Kidson (1982)
Highbridge, Somerset *	I4403	9337	-27.07	Heyworth & Kidson (1982)
Highbridge, Somerset *	I4402	9474	-25.87	Heyworth & Kidson (1982)
Bridgewater, Somerset *	I3713	8130	-14.22	Heyworth & Kidson (1982)
Bridgewater, Somerset *	I2688	7879	-13.335	Heyworth & Kidson (1982)
Highbridge, Somerset *	IGS53	9359	-27.37	Heyworth & Kidson (1982)
Porlock Forest Bed *	Be81655	8502	-13.47	Jennings & Orford (1998)
Stolford, Somerset *	NPL147	6149	-6.77	Heyworth & Kidson (1982)
Porlock Forest Bed *	Be61544	7712	-11.67	Jennings & Orford (1998)
Elmore	Be81686	2425	-2.73	Hewlett & Birnie (1996)
Nyland Hill 4 Somerset	Be101740	3609	-1.92	Haslett *et al.* (1998)
Nyland Hill 11 Somerset	Be101741	3621	-3.38	Haslett *et al.* (1998)
Nyland Hill 12 Somerset	Be101742	3484	-1.99	Haslett *et al.* (1998)
Slimbridge	Be80696	3330	-2.28	Hewlett & Birnie (1996)
Longney - R Severn	Be80693	2373	-3.48	Hewlett & Birnie (1996)
Godney Island Somerset Levels	Q2459	2608	-1.97	Housley (1988)
Burnham on Sea	WK5300	5518	-5.59	Druce (1998)
Burnham, Somerset	Q134	7152	-10.77	Heyworth & Kidson (1982)
Godney Island Somerset Levels	GU3247	2623	-2.38	Somerset Dist Council Rpt,1992
Godney Island Somerset Levels	GU3246	2724	-2.38	Somerset Dist Council Rpt,1992
Tealham, Somerset	Q126	6420	-6.16	Heyworth & Kidson (1982)
Goldcliff 2	CAR778	6452	-5.96	Smith & Morgan (1989)
Goldcliff 2	CAR776	6270	-5.03	Smith & Morgan (1989)
Goldcliff 1	CAR657	6329	-5.81	Smith & Morgan (1989)
Weston-S-M, Somerset	IGS41	5173	-5.93	Heyworth & Kidson (1982)
Goldcliff 1	CAR656	6132	-6.28	Smith & Morgan (1989)
Goldcliff 1	CAR655	6225	-6.22	Smith & Morgan (1989)
Goldcliff 1	CAR654	5825	-6.08	Smith & Morgan (1989)
Goldcliff 1	CAR645	3704	-4.82	Smith & Morgan (1989)
Goldcliff 1	CAR644	3350	-4.53	Smith & Morgan (1989)
Porlock Forest Bed	Be86775	7886	-12.8	Jennings & Orford (1998)
Goldcliff 1	CAR658	6658	-6.66	Smith & Morgan (1989)
Kenn Moor, Avon	IGS26	6972	-8.24	Gilbertson & Hawkins (1983b)
Avonmouth, Bristol Channel	IGS27	3312	-2.74	Heyworth & Kidson (1982)
Avonmouth, Bristol Channel	IGS28	4330	-3.35	Heyworth & Kidson (1982)
Kingston Seymour	I4846	4036	-5	Heyworth & Kidson (1982)
Porlock Bay, Somerset	SRR440	5849	-9.8	Shennan & Horton (2002)
Kingston Seymour	I4844	6398	-6.15	Heyworth & Kidson (1982)
Portbury, Bristol Channel	I4842	4759	-3.3	Heyworth & Kidson (1982)
Stolford, Bristol Channel	I3397	6107	-6.77	Heyworth & Kidson (1982)
Stolford, Somerset	NPL146	3730	-6.37	Heyworth & Kidson (1982)
Stolford, Bristol Channel	I3395	5514	-3.47	Heyworth & Kidson (1982)
Tealham, Somerset	Q120	6186	-6.16	Heyworth & Kidson (1982)
Bridgewater, Somerset	I2689	7734	-12.09	Heyworth & Kidson (1982)
Clevedon, Somerset	IGS34	6618	-7.2	Heyworth & Kidson (1982)
Clevedon, Somerset	IGS35	6132	-6.07	Heyworth & Kidson (1982)
Kenn Pier, Somerset	IGS36	3790	-3.61	Heyworth & Kidson (1982)
Kenn Pier, Somerset	IGS39	6974	-8.24	Heyworth & Kidson (1982)
Weston-S-M, Somerset	IGS40	4014	-4.2	Heyworth & Kidson (1982)
Bridgewater, Somerset	NPL148	7121	-7.57	Heyworth & Kidson (1982)
Stolford, Bristol Channel	I3396	6031	-5.27	Heyworth & Kidson (1982)
Tarnock, Somerset	Be142352	3418	-4.25	Haslett *et al.* (2001)
Llanwern, Monmouth	Q691	2775	-3.11	Shennan & Horton (2002)
Porlock Forest Bed	Be81654	7057	-8.57	Jennings & Orford (1998)
Goldcliff 1	CAR659	6792	-6.72	Smith & Morgan (1989)
Godney Island Somerset Levels	Q2458	2983	-2.38	Housley (1988)
Caldicot Pill, Oscar	B79887	7298	-7.52	Scaife & Long (1995)
North Yeo Farm, Somerset	Be142351	5398	-6	Haslett *et al* . (2001)
Caldicot Pill, 333	B79886	7535	-9.86	Scaife & Long (1995)
Tarnock, Somerset	Be142353	6145	-6.06	Haslett *et al* . (2001)
Burnham on Sea	WK5297	6378	-9.07	Druce (1998)
Burnham on Sea	WK5298	7275	-9.28	Druce (1998)
Porlock Forest Bed	Be81653	5817	-6.46	Jennings & Orford (1998)
North Yeo Farm, Somerset	Be142350	3908	-4.87	Haslett *et al.* (2001)
Shapwick Heath, Somerset	Q423	6300	-5.87	Heyworth & Kidson (1982)
Porlock Marsh	Be61543	5887	-5.28	Jennigns & Orford (1998)
Porlock Marsh	Be61542	6025	-5.99	Jennings & Orford (1998)
Wick Farm, Somerset	Be142355	5982	-6.61	Haslett *et al.* (2001)
Wick Farm, Somerset	Be142354	3774	-5.29	Haslett *et al.* (2001)
Burnham on Sea	WK5299	6142	-6.01	Druce (1998)

Table 2.4 List of sea-level index points for the Bristol Channel used by Shennan & Horton (2002). An * after a site name identifies basal peat index points.

sea-level index points for the UK, seventy of which were from the Bristol Channel/Severn Estuary region. The SLIPs are derived from a combination of basal peat and intercalated peat units. Figure 2.6 plots the age-altitude relationship between these SLIPs and superimposes the glacio-isostatic sea-level model "RSL E2g_4eI" of Peltier *et al*. (2002). Table 2.4 summarises the references for the sea-level index points used to develop Figure 2.6. A data set such as this provides a comparison for the results obtained from the Gordano Valley. The presence of basal peat index points will enable the influence of autocompaction to be considered. Consequently, analysis of sea-level change within this study will provide valuable information and contribute to the developing picture of late Quaternary sea-level change and coastal evolution for southwest England.

2.3.4 Stratigraphic models of coastal evolution during the Holocene

The stratigraphic response of coastal lowlands to sea-level change has received much attention over the years, but only recently have attempts been made to model such relationships in NW Europe (Long *et al*., 2000). In order to establish a firm conceptual framework regarding sea-level change and coastal evolution, two stratigraphic models will be introduced here. These will assist in the subsequent analysis and interpretation of the stratigraphic archive preserved in the Gordano Valley and elsewhere in the Severn Estuary.

Streif (2004) analysed the sedimentary record of the North Sea coast of Lower Saxony, Germany, in order to understand the dynamics of Holocene sea-level changes and their record in the sedimentary sequences of the coastal zone. Figure 2.7 shows the relationship between stratigraphy and sea-level change. Characteristic of the coastal zone is a “wedge -like” body of sediments consisting of fine-grained sand, silt and clay and intercalated layers of peat. Basal peat, overlying Pleistocene sediments, is commonly found at the start of Holocene sedimentary sequences. This is believed to be the result of rising ground water levels that developed in response to rising sea levels during the early Holocene, which provided saturated depositional conditions suitable for bog formation in the coastal region (Petzelberger, 2000). A rapid, uninterrupted rise in sea level *c.* 7,500 Cal. yrs BP resulted in the formation of a transgressive sedimentary overlap and marine inundation of the coastal lowlands, initially depositing in lagoonal environments, and

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Figure 2.7 Stratigraphic model of coastal lowlands in response to sea-level change (Streif, 2004, p13).

later mainly in tidal flats and salt marshes (Figure 2.7). However, from *c*. 7,300 Cal. yrs BP onwards, a number of regressive stratigraphic overlaps are present, with peat layers interbedded within the clastic tidal flat and salt marsh sediments. Suitable conditions for the formation of widespread peat layers occurred on the German coast between 4,800 and 4,200 Cal. yrs BP and between 3,300 and 3,200 Cal. yrs BP. Streif (2004) states that such regressive overlaps are not explained through a lowering of sea level (and the related groundwater level), but instead suggests that regressive overlaps occur during phases of slowly rising water table when the rate of bog growth exceeds the rise in sea level. The continued rise in sea level (although at a slower rate) is a preferred explanation than a drop in sea level, as a rising water table is required firstly to assist the accumulation of organic matter in a fen and also to prevent the organic material from decomposing. In contrast, transgressive overlaps indicate periods during which the rate of sea-level rise is greater than that of peat growth (Streif, 2004).

A second model was created by Long *et al.* (2000) for southern England, using stratigraphic studies of estuarine deposits from Southampton Water. Initial analysis used the "transgressive" model of estuarine development that had been applied to sites throughout USA, Canada and Australia, but it was apparent that such a model could not be used to provide a full explanation for Holocene lowland coastal evolution in southern England. Long *et al.* (2000) suggest a tripartite model of estuary development (also applicable to the Severn and the Thames Estuaries) characterised by estuarine expansion during the early and late Holocene, and separated by a significant period of estuary contraction during the mid Holocene. Figure 2.8 shows a typical stratigraphic section recorded in southern England.

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Figure 2.8 Generalised stratigraphy of coastal lowlands in southern England (Long *et al.*, 2000 p.275).

Long *et al*. (2000) also believe that the influence of elevated groundwater tables in the early Holocene, driven by rising sea level, resulted in the widespread formation of basal peat. As sea level continued to rise, the coastal lowlands were inundated and temporary fluctuations between freshwater, salt marsh and tidal flat conditions occurred. However, from *c*. 7,800-3,200 Cal. yrs BP a reduction in the extent of intertidal environments occurred, being replaced by freshwater peat deposition (Long *et al*., 2000). From *c*. 3,200 Cal. yrs BP onwards minerogenic sedimentation has occurred, with continued vertical and landward expansion.

The coastal sites used to develop the models of both Streif (2004) and Long *et al*. (2000), although separated geographically by considerable distances, are broadly similar in stratigraphy. Periods of estuarine expansion and reduction correlate well with one another, with initial basal peat development being replaced by estuarine deposition during the early Holocene. A return to peat development (interbedded with some minerogenic deposits) occurs during the mid Holocene, only to once again be replaced by the landward advance of estuarine conditions from *c*. 3,200 Cal. yrs BP onwards. The influence of the rate of sea-level rise and groundwater level are seen as the major controls on coastal evolution in both models. The scale at which similarities can be seen in stratigraphy through NW Europe would suggest that a regional trend in sea-level change is responsible, whilst factors such as sediment supply, sediment compaction and anthropogenic activity cause the localised variation (Long *et al*., 2000; Streif, 2004).

2.4 Quaternary coastal lowlands surrounding the Severn Estuary

Before a detailed analysis of the evolution of the Gordano Valley region is presented, it is important to provide a regional context for environmental change. The development of coastal lowlands surrounding the Severn Estuary (Figure 2.9) will be considered in order to identify regional trends in environmental change and their influence on the sedimentary archives.

The majority of the sedimentary archives preserved in the coastal lowlands of the Severn Estuary were deposited during the Holocene epoch. However, considerable evidence are available relating to depositional environments dating to before 11,500 Cal. yrs BP. One of the main controversies in the Quaternary history of southwest England has been the extent to which the Quaternary ice sheets affected the region. The earliest known glacial deposits are present only 3km south of the Gordano Valley, at Kennpier,

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Figure 2.9 The Bristol Channel and Severn Estuary, showing the main coastal lowlands and the location of the Gordano Valley (Allen, 2002a, p.73).

Yew Tree Farm and Kenn Church (Gilbertson & Hawkins, 1978a; Hunt, 1998) and they are believed to be pre-Cromerian, (*c*. 0.7Ma BP). The glacial deposits, believed to have formed as a result of both pro-glacial and sub-glacial processes (Gilbertson & Hawkins, 1978a), underlie Cromerian fluvial and estuarine sediments, which have been dated to Oxygen Isotope stage 15 (*c*. 0.6Ma BP); thus the underlying glacial deposits predate this stage (Campbell *et al.* 1998). The south-eastern extent of this early glacial phase is believed to be around Bath University (Bathampton Down; Hunt, 1998). Figure 2.10(c) illustrates the theorised glacial limit initially thought to be of Anglian age (*c*. 0.45Ma BP; Gilbertson & Hawkins, 1978a), but which has now been assigned to the pre-Cromerian glacial event (Hunt, 1998). Up to 6m of sands and gravels have been found on Bleadon Hill, Mendip, Somerset; these are also thought to be of glacial origin, but their age is unknown (Findlay *et al*., 1972). The deposits formed through either glacio-fluvial or glacio-lacustrine processes and occur at *c*. 85m O.D (similar in mode of formation and altitude to the glacial sediments present in the Gordano Valley; see section 3.2.2).

Two other periods of glacial activity followed the Cromerian: the Anglian and Saalian stages. Whilst the Anglian period is known to have been a profoundly cold glacial event, evidence suggests a much more complex climatic history relating to the Saalian period. The Saalian has been shown to include more than one climatic cycle and at present the extent of its influence on southwest England is not fully understood.

There is evidence for direct glacial activity in the regions surrounding the Gordano Valley, and although precise ages for these events are unknown at present, they must be taken into account when considering the valley's Quaternary history. Although the impact of each glacial phase on the landscape evolution of southwest England is not fully known, the evidence suggests that the peninsula was not entirely glaciated during this or any other stage of the Pleistocene (Figure 2.10; Campbell *et al.* 1998). The geomorphological position of the glacial deposits in the Bristol district (along with those of West Angle Bay, at the entrance to Milford Haven) shows that the geomorphology of the coastal fringe was similar to that of the present (Campbell & Bowen, 1989).

Marine shelly gravels have been identified along the Severn Estuary coastline and assigned to the interglacial period that followed after the Saalian glacial; the Ipswichian, *c*. 125,000 yrs BP (Allen, 2002b). The Ipswichian sediments that are preserved around

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Figure 2.10 (a) The extent of British ice sheets during the Quaternary glaciations, (b) British glacial sediment systems (Campbell *et al*. 1998, p23), (c) suggested extent of the pre-Cromerian glaciation in the Severn Estuary (form Gilbertson & Hawkins, 1978a).

the Severn Estuary (in the Somerset Levels and Gwent Levels for example; Kidson *et al*., 1978; Allen, 2001, 2002a) consist predominantly of sands and gravels, and have been found both close to the contemporary coastline and also as far as 4km inland (Haslett, 1997). Allen (2002a) also noted the clear differences in sedimentary processes that characterise the Ipswichian when compared to the present depositional system. Such coarse sands and gravels are not found in the present day depositional setting. Instead, a tide-dominated coastal region accumulates mainly silts and clays on tidal flats. It is therefore likely that the depositional regime was significantly different during the Ipswichian. Allen (2002a) suggests that the Bristol Channel/Severn Estuary was wave-dominated, with the higher sea levels resulting in smaller tidal ranges due to greater water depths. Such conditions would have encouraged much coarser clastic deposits to accumulate in contrast to those under the present tidal setting. Haslett (1997) supports this theory through foraminiferal analysis of the Ipswichian sediments in the Gwent Levels. Agglutinating species are common on the extensive saltmarshes bordering the contemporary estuary, but absent from the Ipswichian coarse sands, which is indicative of contrasting depositional processes during the present and last interglacial.

During the subsequent glacial stage, the Devensian ice limit did not reach as far as southwest England (Figure 2.10). Consequently, periglacial processes dominated in southwest England and the Severn Estuary lowlands. Solifluction, head and alluvial fan deposits characterise the Devensian sediments found in the region (Campbell *et al*., 1998) and they are characterised by accumulations of poorly sorted, angular and coarse gravels, with the clasts being grain- or matrix-supported (Leeder, 1999). Macklin & Hunt (1988) described the Upper Axe Valley Mendip floor sedimentation that occurred during the late

Quaternary in response to periglacial freeze-thaw and solifluction processes. Similar late Quaternary head deposits are found at Brean Down, Somerset, which have been compared with the sequence found proximal to the Gordano Valley at Holly Lane, Clevedon (ApSimon & Taylor, 1961). The majority of ancient alluvial fan deposits are located at basin margins adjacent to geologic fault zones (Leeder, 1999) due to the susceptibility of the faulted bedrock to periglacial erosion. Also, the influence of permafrost on the lowlands restricted mass movements to a very localised scale and most deposits are found to be in close proximity to their source (Carson & Kirkby, 1975; Campbell *et al*., 1998). Such deposits typify coastal cliffs and many inland slopes of the coastal lowlands of southwest England.

Detailed records of the transition from the Devensian late glacial period into the Holocene are rare in southwest England, reflecting a lack of suitable depositional basins in the region (Campbell *et al*., 1998, 1999). The most reliable record comes from Hawks Tor on Bodmin Moor, where sediments dating from the Allerød subinterstadial (*c*. 13,000 Cal. yrs BP) are present (Brown, 1980). Pollen, plant macrofossil and lithological evidence show the changing environmental conditions in response to the late glacial transition. The minerogenic sediments found above the granite bedrock at Hawks Tor were overlain by peaty-silts and represent the transition from the Older Dryas stadial to the Allerød subinterstadial (Brown, 1977). However, Campbell *et al*. (1998) stated that, as Hawks Tor was characterised by acidic soils and situated in some of the highest relief of southwest England, the palaeoenvironmental record is not necessarily indicative of typical regional conditions. But Hawks Tor is still of palaeoenvironmental importance because it provides the most complete record in the southwest for the climatic and environmental conditions of this timescale. There is also no evidence in southwest England of deposits dating from the full glacial phase of the Devensian glaciation, and none for the Bølling subinterstadial temperature oscillation (*c.* 15,000 Cal. yrs BP) that is recorded in the Earth's ice sheets and elsewhere in northwest Europe (Campbell *et al.*, 1998). Consequently, the majority of sediments from the coastal lowlands of southwest England date from the Holocene period.

Whilst periglacial activity was responsible for the majority of sedimentary accumulation in southwest England during the glacial and late glacial periods, there are records of wind-blown loess sediments overlying these deposits (Kidson, 1977). These are believed to have derived from glacial outwash from the North Sea basin (Shotton, 1977) and were deposited during the late Devensian period, between 18,000 and 13,000 Cal. yrs BP (Catt, 2001). Well-sorted, fine-grained sediments (45-25µm) are in relative abundance in the southwest, though post-depositional erosion and redeposition limits their abundance to isolated outcrops (Shotton, 1977). The subsequent transition into the Holocene resulted in a rise in eustatic sea level and marine inundation of coastal lowlands throughout the Severn Estuary. Consequently, coastal processes became the most influential environmental control on lowland evolution throughout the Holocene (Allen, 2000c). As explained by Long *et al.* (2000) and Streif (2004) (section 2.3.4), sea level and the associated transgressions and regressions would have significantly influenced the lowland evolution of the Severn Estuary region. A record of these changes is preserved in areas such as south Wales (including the Gwent Levels) and the Somerset Levels (see Figure 2.9), reflecting low-lying topography and thus susceptibility to changing sea levels (Allen, 1995, 2002a; Haslett *et al.*, 1998).

Variations in sea level had considerable influence on the coastal zones proximal to the Severn Estuary/Bristol Channel during the Holocene. Lambeck (1995) estimated that sea level rose by *c*. 20m between 8,000 and 4,000 yrs BP (see Figure 2.4) whilst Peltier *et al.* (2002) estimated a rise of *c.* 5m over the same period (see Figure 2.5). Based on research in the Severn Estuary, Allen (1990) developed a numerical model to show how the rate of sea-level rise controls the growth and elevation of a salt marsh. When sea-level rise is sufficiently fast, the vertical growth of the upper salt marsh is lower than that of the highest astronomical tide (HAT), allowing marine deposits to accumulate. In contrast, slower sea-level rise enables salt-marsh development to maintain growth relative to sea-level rise and even emerge from HAT if organic sediments are in constant supply (thus enabling peat accumulation). The same principles are emphasised in the stratigraphic models of Long *et al*. (2000) and Streif (2004). Such research provides an estimation of the rates of sea-level rise responsible for the development of salt-marsh/peat deposits known to be present within the Gordano Valley (Jefferies *et al.*, 1968). Allen (1995) has also shown through modelling experimental salt marshes that oscillations in Holocene sea-level rise of the scale of decimetres occurred, in which organic-rich and salt-marsh facies are intercalated. Sedimentological, palaeogeomorphological and stratigraphical analyses have enabled Allen (2000a, 2003) to recognise phases of salt-marsh evolution that are applicable to coastal environments throughout northwest Europe. Such information may be relevant to Gordano Valley, as the low gradient of the region would have resulted in any minor sea-level fluctuations having considerable influence on the depositional environments present at the time.

Archaeological evidence within the Severn Estuary region allows an assessment of the anthropogenic impact on coastal lowland development. Much of the present-day coastal lowlands of the Severn Estuary would experience tidal inundation, had it not been for land reclamation during the Late Holocene period. Bell (2000) summarised much of the extensive archaeological evidence that has been discovered within the intercalated peat and marine silts from the Severn Estuary, Bristol Channel and Pembrokeshire regions. The archaeological evidence is concentrated around two phases of coastal sequences; Mesolithic sites underlying the basal peat of the region (initiated *c*. 8-6,000 Cal. yrs BP) relating to coastal exploitation prior to a marine transgression, and human activity during the middle Bronze Age and Iron Age (*c*. 3,400-2,200 Cal. yrs BP). An example of early Holocene human activity is present at Goldcliff East on the Caldicot Levels, south Wales. Excavations have revealed an occupation horizon on an old land surface that contained archaeological finds and evidence of tree burning during the Mesolithic period (Bell *et al*., 2002). However, the subsequent marine transgression and initiation of estuarine sedimentation around Goldcliff East would have resulted in abandonment of the lowland settlement. Evidence of Iron Age activity is present at Hallen on the Avon Levels, where the remains of round houses were discovered (Gardiner *et al*. 2002). These were built on the coastal margin by the local population *c*. 2,250 Cal. yrs BP, for the seasonal exploitation of the lowlands by grazing sheep and cattle.

The most significant episode of human activity to affect the Severn Estuary region, however, occurred in historic times, when the construction of coastal sea walls appears to have artificially halted minerogenic sedimentation at many lowland sites

(Rippon, 1997). The late Holocene period is typically characterised by minerogenic deposition in the coastal lowlands, which is believed to be a result of human activity within the Severn Estuary catchment that enhances terrigenous sediment input from the Bronze Age onwards (Long *et al*., 2000). However, the sea-wall construction and land reclamation during the Romano-British period temporarily restricted the accumulation of the estuarine sediments. Rippon (1997) suggests that throughout the coastal regions of the Severn Estuary, up to 55km of barriers were required to protect open coast and tidal rivers from inundation. Whilst reclamation was believed to have begun during the early Roman period (*c*. 1,900 Cal. yrs BP), precise dates vary between sites (*c*. 1,900-1,700 Cal. yrs BP). In the North Somerset Levels, lowland reclamation has been dated to the 3rd Century and evidence for a predominantly freshwater lowland environment was obtained through pollen, diatom, foraminiferal, beetle and snail analyses (Rippon, 2000). Reclamation enabled the exploitation of the former salt-marsh environments for cattle grazing throughout the year, whilst the lowlands could also be utilised for cereal cultivation shortly after reclamation. The late Roman period is marked by marine flooding and barrier abandonment (*c*. 4th Century), evident within many lowland sites by the presence of a further 0.5m or more of alluvium (Rippon, 1997) and is described by Godwin (1943) as the "late Roman marine transgression". However, Rippon (1997) suggests that this may not be an actual rise in relative sea level, but instead an infilling of the back-barrier reclaimed land that was below the altitude of the seaward salt marsh. Upon removal/abandonment of sea defences, the exposed reclaimed land became susceptible to tidal flooding. Enhanced sedimentary accumulation in the exposed lowlands occurred over a short time period and coastal surfaces at altitudes similar to the proximal salt marshes were eventually attained. It is unclear why the lowlands were abandoned before the end of the Roman period, but it is possible that the demand for the reclaimed land was lower, resulting in poor barrier maintenance and eventual abandonment. Pollen analysis at Banwell Moor indicates an increase in arboreal pollen at the time marine inundation resumed, evidence for woodland regeneration as the North Somerset Levels were being used less intensively (Rippon, 2000). Most areas that were inundated during the post-Roman period are believed to have been protected by reconstructed sea walls by the 12th Century, preventing the continued accumulation of salt-marsh deposits over much of the lowlands (Rippon, 1996). The timescale for the onset of coastal management of the Severn Estuary region is clearly critical when considering the late Holocene evolution of the Gordano Valley.

2.4.1 Quaternary coastal lowlands of the Somerset Levels

The Quaternary evolution of the coastal lowlands of the Somerset Levels (Figure 2.9), southwest of the Gordano Valley, provides additional context for this study. Clear links exist between climate, sea level and lowland evolution.

Kidson (1977) provides a detailed summary of the sedimentary evolution of the Somerset Levels, concentrating on the postglacial period during which sea-level rise dominated lowland development. The transgressing sea submerged previously exposed land surfaces and reworked much of the periglacial material deposited during the Devensian (see section 2.4). Submerged and buried terrestrial deposits cover a vertical range of at least 47m and represent stages in the drowning of the land surface by the transgressing Holocene sea (Kidson, 1977). The rising sea level caused the waterlogging of coastal lowlands which, in turn, caused local ground water tables to rise. As a result, the influence of fluctuating water tables, combined with terrestrial sedimentation, favoured the accumulation of peat deposits that would eventually be submerged by the rising sea level. Consequently, the stratigraphy of the Somerset Levels is characterised by interbedded peat and estuarine sediments.

Sedimentary accumulation since 6,000 Cal. yrs BP in the Glastonbury and Panborough areas of Somerset have been analysed and compared with several climatic proxies from NW Europe (Aalbersberg, 1999). This has allowed the relative dominance of sea level upon environmental change to be identified in coastal lowlands. A salt-marsh environment was present *c*. 6,300 Cal. yrs BP, but from *c*. 6,000 to 5,000 Cal. yrs BP this was slowly replaced by freshwater peat as higher groundwater levels accompanied rising sea levels. Consequently, carr forest and ombrotrophic bog development was initiated and this dominated until *c*. 3,600 Cal. yrs BP. Marine conditions began to return at *c*. 3,600 Cal. yrs BP and wholly dominated the region by 3,100 Cal. yrs BP.

At Nyland Hill, on the Somerset Levels, minerogenic silts and clays of marine origin accumulated in response to rapid sea-level rise between *c*. 10,000-7,000 Cal. yrs BP (Haslett *et al*., 2000). A reduction in the rate of sea-level rise allowed organic sedimentation to outpace sea-level change, resulting in peat deposition between *c*. 6,800-3,700 Cal. yrs BP. Biostratigraphic data suggest that a gradual transition to marine conditions and a return to minerogenic deposition followed. There is also clear evidence of surface reclamation around the time of the Roman occupation (1,776 ± 46 Cal. yrs BP; Haslett *et al*., 1998). This was shown by the increase in lead and zinc in the sedimentary deposits, brought on by the onset of Roman mining in the area (between AD 43-49). The research by Haslett *et al.* (1998) and Allen & Haslett (2002) also emphasised the influence of sediment compaction upon the altitude of transgressive SLIPs where peat underlies clay (even at relatively shallow depths).

Whilst marine incursions are believed to have occurred in the Gordano Valley to the north during the Romano-British period (*c.* 2,000 Cal. yrs BP; Jefferies *et al.*, 1968), the regions of Panborough and Glastonbury did not experience such extensive marine inundation. It is believed that this was the result of salt-marsh reclamation by the Roman population (Rippon, 1997, 2000). Environmental reconstruction from 1,500 Cal. yrs BP to present is relatively difficult due to the influence of anthropogenic activity (including peat-cutting, agriculture and pollution), although wet meadows and the removal of most hillside forests are believed to have occurred during this period (Aalbersberg, 1999).

Bridgwater Bay, Somerset, is a further comparator for events within the Gordano Valley. Freshwater peat and marine silts and clays within the Bay were utilised by Kidson and Heyworth (1973) to construct a relative sea-level curve for the last 9,000 Cal. yrs. Pollen analysis and radiocarbon dating have revealed the influence of Holocene sea-level rise on adjacent coastal lowlands, and highlighted the interaction of terrestrial and marine sedimentation in response to sea-level change during this period (Kidson and Heyworth, 1973). Areas closer to the coastal zone contain much thinner beds of peat due to the considerable influence of the sea, whilst landward sites have experienced organic sedimentation for prolonged periods, thus containing thicker peat sequences. There is no evidence for the Romano-British transgression in this area.

Research at Porlock, Somerset (Jennings *et al.*, 1998) has also provided evidence of environmental change during the Holocene. As for Allen (1990), emphasis is placed on the relationship between sea-level rise and organic development (in this case, in a back-barrier setting). Intercalated organic sediments are also found in the Porlock region, formed between 7,800 Cal. yrs BP and 5,700 Cal. yrs BP, and these have been related to the influence of decelerating sea-level rise (Jennings *et al.*, 1998). The widespread recognition of organic development post-6,000 Cal. yrs BP (Smith & Morgan, 1989; Allen, 1995) is, however, not present here as clastic sedimentation has dominated the region of Porlock due to the interaction of the environment with coastal barrier dynamics. However, such data may still prove relevant to Gordano Valley due to the known influence of barrier systems on catchment development during the Holocene (Spencer, 1996; Plater *et al.,* 1999; Lario *et al.*, 2002) and the presence of the barrier within the Gordano Valley (Jefferies *et al.,* 1968).

The distinct stratigraphy present throughout the lowlands of the Somerset Levels prompted Haslett *et al.* (2001b) to introduce Lower, Middle and Upper lithostratigraphic subdivisions to the sedimentary sequence that had been previously defined by Bowen (1999) as the Somerset Levels Formation. The Lower Somerset Levels Formation consists of 6m or more of minerogenic blue-grey silty clay of marine origin. This is overlain by the Middle Somerset Levels Formation, which is composed of 0.5-2m of organogenic peat facies, either as a single bed or interbedded with estuarine silty clay deposits. The Upper Somerset Levels Formation contains up to 5m of marine minerogenic silty clay. The lithostratigraphic divisions can be applied to most Holocene sedimentary sequences in the Somerset Levels. To comply with the International Code of Stratigraphic Nomenclature, the Lower Middle and Upper subdivisions of the Somerest

Levels Formation were subsequently renamed the North Yeo Member, the Nyland Hill Peat Member and the Nyland Hill Clay Member respectively (Haslett & Davies, 2002).

2.4.2 Quaternary coastal lowlands of south Wales

Regions proximal to the Bristol Channel/Severn Estuary within south Wales are considered viable archives of the regional palaeoenvironmental record. Although the majority of sediments within the coastal lowlands of south Wales were derived during the Holocene period, raised beaches from the Ipswichian period (Oxygen Isotope stage 5e) have also been discovered (Allen, 2000c, 2001, 2002a). A discontinuous development of littoral shelly sands and gravels are present at –3.6 to –4m O.D. along the inner margin of the Gwent Levels at Llanwern, *c*. 4km inland of the present coastline. These beach deposits are overlain by *c*. 8m of Holocene sediments. Temperate-water molluscan and foraminiferal assemblages have been dated to the Ipswichian (Andrews *et al*., 1984). Haslett (1997) compared these deposits to a similar coarse yellow sand unit exposed low within the contemporary intertidal zone (-4 to –6m O.D.) at Goldcliff. It is suggested that a stratigraphic succession is present, with the coarse yellow sand at Goldcliff being a seaward extension of the Ipswichian palaeo-beach. The Goldcliff unit may have been deposited in subtidal conditions, whilst Llanwern, further up the tidal frame, experienced intertidal deposition.

The remnants of the Ipswichian raised beaches are commonly overlain by Holocene sediments that comprise of alternating layers of estuarine silts and peat. Along the coastline of south Wales, Holocene sea-level rise culminated about 5,000 Cal. yrs BP, and is recorded by such interbedded sedimentary sequences in Swansea Bay, Camarthan

Bay and the Gwent Levels. This regional trend is further supported by evidence from sites to the west and northeast including Clarach and Cardigan Bay, and along the coast of Clwyd (Campbell & Bowen, 1989). Palaeoecological investigations of the mid to late Holocene peat beds of the Caldicot Levels (Walker *et al.*, 1998) have suggested that widespread terrestrial organic accumulation began *c.* 7,000-6,400 Cal. yrs BP in the south Wales coastal lowlands. This remained relatively uninterrupted until a transition from ombrogenous mire to tidal mudflats occurred rapidly at *c.* 2,800-2,400 Cal. yrs BP. Similar radiocarbon dates were found at proximal sites to the east at Caldicot Pill (Scaife, 1995). One site provided a date for the initiation of peat accumulation between *c.* 6,800-6,400 Cal. yrs BP, whilst a date of between *c.* 7,670-7,430 Cal. yrs BP was found at a separate site (Scaife, 1995; Scaife & Long, 1995). The general trend of results at Caldicot Pill indicates an initial period of marine conditions, before regression from the Bristol Channel region between *c.* 7,500 and 6,000 Cal. yrs BP, and replacement by reed swamp, localised fen woodland and local freshwater rivers or lagoons. The timing of the final change from organic to minerogenic sedimentation throughout the south Wales coastal lowlands, however, is site-specific and varies considerably between 5,350-2,975 Cal. yrs BP (Bell, 2000). Evidence of land reclamation during the Roman occupation is also present, during which the re-establishment of land use occurred through sea-wall construction and the introduction of drainage ditches (Walker *et al.*, 1998).

The Holocene lithostratigraphy of south Wales generally comprises a tripartite sequence which, on average, is 10-15m thick and similar to that of the Somerset Levels Formation. Allen & Rae (1987) subdivided the sedimentary sequence into the Lower, Middle and Upper Wentlooge Formations. The Lower Wentlooge Formation is composed of fine sands grading into blue-grey clayey silts, originating from early Holocene estuarine conditions. The Middle Wentlooge Formation contains alternating peat beds with estuarine clayey silts, indicative of a regional reduction in the rate of sea-level rise and enhanced peat development. The Upper Wentlooge Formation is composed of grey clayey silts up to 2.5m thick, deposited in response to the return of estuarine conditions in the south Wales lowlands.

2.4.3 Quaternary coastal lowlands of the Avon Levels

A further regional context for events in the Gordano Valley is provided by the Avon Levels (Figure 2.9). A detailed review of the archaeological and stratigraphic studies undertaken in the Avon Levels is provided by Gardiner *et al*. (2002) and a summary of the research is provided here. The similarity between the stratigraphy of the Avon Levels and the Gwent Levels resulted in Gardiner *et al*.'s (2002) reference to the sequence as part of the Wentlooge Formation. Relative sea-level rise during the early and mid Holocene periods was responsible for the deposition of marine silts and sands (Lower Wentlooge Formation) until *c*. 6,400 Cal. yrs BP. A deceleration in relative sea-level rise around this time resulted in coastal emergence and the development of extensive fen carr and peat accumulation, which was maintained until *c*. 4,500 Cal. yrs BP (Middle Wentlooge Formation). During this period, alder carr woodland initially dominated, before localised water table variations (possibly in response to fluctuations in relative sea level) resulted in disturbance of the woodland and establishment of herb fen vegetation. Although archaeological evidence is limited from this period, increases in herb vegetation and sporadic appearances of cereal type pollen are probably the first indication of human disturbance and agriculture on the lowlands. After c. 4,500 Cal. yrs BP, deposition of the Upper Wentlooge Formation began, with mudflat and salt-marsh environments accumulating clayey-silts on top of the peat unit.

2.4.4 Summary of the coastal lowlands proximal to the Gordano valley

Within the regional coastal lowlands of the Severn Estuary, there are clear similarities in previous research objectives and results. Although local factors may explain many inter-site differences, the rate of sea-level change seems to have exerted most influence on lowland sedimentary deposition in the Severn Estuary and Bristol Channel region. The stratigraphic models of Long *et al.* (2000) and Streif (2004) can be applied to the Severn Estuary with considerable accuracy, especially when considering the lithostratigraphic sequences of the Wentlooge and Somerset Levels Formations. Whilst sea-level change dominated coastal evolution during the Holocene, localised factors such as sediment supply and autocompaction are also likely to have contributed to each site to account for local variability. A 'standard' Holocene lithostratigraphic sequence for the Severn Estuary has been suggested by Allen (2000a), consisting of "a) a basal peat resting on pre-Holocene basement, deposited prior to marine inundation, b) silts and sands deposited during the early Holocene phase of rapidly rising sea-level, c) intercalated silts and peat beds spanning c. 6,000-2,500 Cal. yrs BP and reflecting the mid Holocene slowing of the rate of sea-level rise, and d) a late Holocene period of further silt deposition" (Haslett *et al*., 2000).

Table 2.5 summarises the major changes in apparent sea level during the Holocene found from research into the Severn Estuary lowlands. The regional trend in environmental change will provide a critical reference to events in the Gordano Valley.

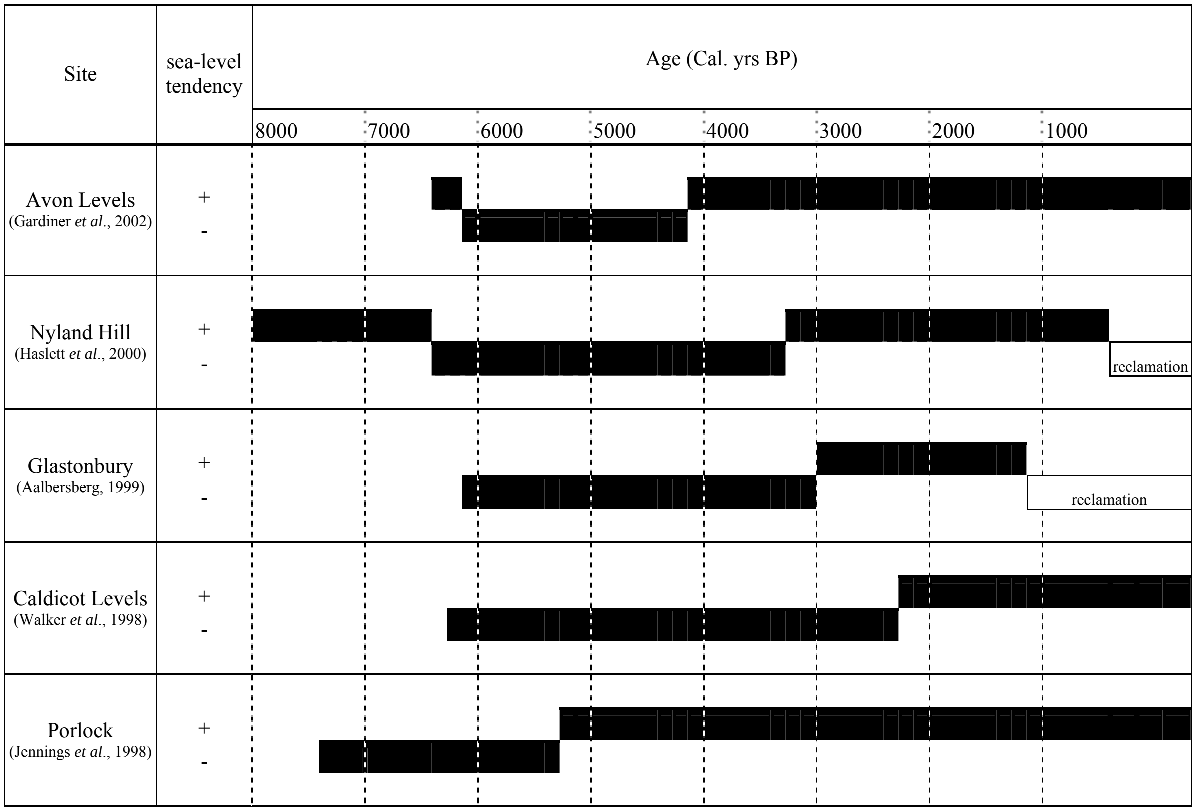

Table 2.5 Summary of changes in apparent sea level preserved in the sedimentary archives of the Severn Estuary lowlands. Radiocarbon dates have been rounded to the nearest 250 Cal. yrs BP for inclusion within the diagram.

Chapter 3: The Study Site - The Gordano Valley

3.1 Introduction

This chapter summarises past research that has been undertaken in the Gordano Valley. After an introduction to the geological setting of the study site, an assessment of previous research relating to the Quaternary evolution of the Gordano Valley will be provided. This will place the valley into a geographic context in relation to the Quaternary evolution of the Severn Estuary beyond that which was provided in Chapter 2.

3.2 Geological setting of the Gordano Valley

3.2.1 The geological foundation to the Gordano Valley

The regional geology of southwest England is described in detail by Green (1992). The geology of the Gordano region is relatively complex due to post-depositional folding and faulting of the surrounding bedrock (Figure 3.1). The area incorporates a mix of bedrock from the Devonian, Carboniferous and Permo-Triassic periods, the consequent age of which varies from *c*. 400 to 200 million years (Ma) BP. These have been subsequently folded, with a possible synclinal axial plane that runs through the Gordano Valley itself (Green, 1992). The extent of the folding is minimal in the younger Permo-Triassic rocks, as major phases of tectonic activity occurred before these geological periods. Consequently, the Devonian and Carboniferous bedrock experienced much more intense folding and subsequent erosion, contributing to the present geomorphological form of the valley (British Geological Survey, 1967, 1974).

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Figure 3.1 Geological map of Gordano Valley region, N. Somerset. The predominant solid geological components are the Carboniferous Limestones, Devonian Old Red Sandstone and the Keuper Marl (British Geological Survey, 1967).

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Figure 3.2 Geological cross-section through the Gordano valley region. See Figure 3.1 for geological key (British Geological Survey, 1967).

The oldest geological component of the region is that of the Devonian Old Red Sandstone found along the coast around Portishead. Both the Lower and Upper Old Red Sandstone (ORS) facies occur in the Clevedon-Portishead ridge (anticlinal axial plane trace), to the north of Gordano Valley. The Lower ORS is red and brown in colour, well sorted, fine to coarse-grained, with several types of cross-bedding, parallel lamination and cross lamination (Green, 1992). The Upper ORS is composed predominantly of interbedded sandstone, conglomerate and mudstone (see Figure 3.1 and 'Portishead beds' unit in Figure. 3.2). The uppermost beds include interdigitations of fossiliferous marine shales and limestones, indicative of the onset of the Carboniferous period (Green, 1992). These interdigitations increase in scale and frequency and grade into the Lower Limestone Shale of the Carboniferous sequence, found in thicknesses of up to 100m in the Portishead region. The deposits are characterised by bioclastic and oolitic limestones at the base, and shales and crinoidal limestones towards the top. During the Upper Carboniferous period, swamp conditions prevailed, within which the Coal Measures of the area developed. Sedimentation and uplift during the latter part of the period caused the region to convert from a shallow marine environment to freshwater swamp conditions (see Figure 3.1 and 3.2 for the blue, grey and green d-units, which correspond to the Carboniferous bedrock). The “Clapton-in-Gordano inlier” was worked for the extraction of coal during the eighteenth and nineteenth centuries (Mills, 1984), although on a very limited scale due to the concealed nature of the inlier (Green, 1992). To the south, Jefferies *et al*. (1968), Mills (1984) and Campbell *et al*. (1998) observed that the geology is almost entirely made up of Carboniferous Limestone within the Clevedon-Bristol ridge.

Throughout the Palaeozoic Era and during the region’s geological development, the Gordano Valley and surrounding areas experienced periods of tectonic movement. An initial phase of folding occurred in the Lower Carboniferous period, during which a major anticline developed which runs broadly parallel with the present day southern Severn Estuary coastline: the Lower Severn Axis (Green, 1992). This phase of folding is regarded as the first pulse of the main Variscan/Hercynian orogenic event, a period during which the ancient continents of Gondwana and Laurassia collided (Doyle *et al*. 1994). The resultant crustal movement is partly responsible for the creation of the Clevedon-Portishead ridge. Stability then returned until the end of the Carboniferous period, after which the main phase of orogenic activity occurred. The Devonian and Carboniferous rocks were folded and thrust-faulted in response to the crustal movements, with axial planes trending roughly east-west throughout the Bristol region. The Lower Severn Axis influenced the subsequent developing folds and faults and was responsible for a WSW-ENE axial trend in the Gordano Valley. The Clevedon-Portishead ridge continued to develop during this tectonic phase, whilst the Clevedon-Bristol ridge experienced uplift and subsequent thrust-faulting of Carboniferous Limestone from the south (see Figure 3.2). The valley floor experienced either the development of a synclinal fold running through its axis (Green, 1992), or a theorised thrust-fault is present (British Geological Survey, 1968). The Intra-Palaeozoic folding and faulting, followed by the subsequent extensive erosion of the exposed Devonian and Carboniferous outcrops, created the valley form present today. A hiatus in sedimentation then occurred, after which the Triassic rocks within the study area were deposited, comprising of mudstones (Keuper Marl, see Figure 3.1). These were unconformably deposited along the valley floor (rock unit f6 in Figure 3.2).

3.2.2 Quaternary development of the Gordano Valley

The most significant contribution to the region's evolution after the Triassic times is believed to have resulted from the influence of the Quaternary glaciations. This respective waxing and waning of ice sheets was in response to climatic conditioning that affected much of Britain, and was believed to be primarily due to its latitude and position relative to the Atlantic Ocean (Campbell & Bowen, 1989).

Section 2.4 introduced the present understanding of Quaternary glacial-interglacial activity in southwest England. Evidence for glacial activity within Gordano Valley can be found at Weston-in-Gordano (ApSimon & Donovan, 1956), Nightingale Valley (Hunt, 1998), the East Clevedon Gap (Hawkins & Kellaway, 1971), Tickenham Hill (Hawkins, 1972) and Court Hill (Gilbertson & Hawkins, 1978b). Site locations are indicated on Figure 3.3. However, it is not known at present whether these sedimentary sequences accumulated during the same glacial event, and their precise ages are also unknown. ApSimon & Donovan (1956) and Hunt (1998) suggest that the sediments at Weston-in-Gordano indicate three marine transgressions which predate the Holocene and are likely to have ages exceeding Oxygen Isotope stage 7 (215 ka BP). These marine transgressions are likely to have occurred during past interglacial periods, at which time the climatic conditions were warmer than today allowing higher sea levels than present to inundate the valley. The altitudes at which the marine deposits are encountered suggest that mean sea level was positioned at 4.5-6m, 8m and 13.6m O.D. for each of the transgressive phases. There is also believed to be a ‘till-like material’ stratified within the interglacial marine bands, a possible indicator of direct glacigenic processes (and is dated as being no younger than 200 ka BP), but its origin is still only theorised and the unit is suggested to be reworked till deposits from a glacial phase prior to the marine transgressions (Hunt, 1998).

To the north of Weston-in-Gordano, glacial sediments are present at Nightingale Valley, on the Clevedon-Portishead ridge. The stratigraphy, erratic content and clast alignment within the deposits imply the advance of an ice sheet from the Bristol Channel, which possibly overtopped the ridge and expanded south into the Gordano Valley. Glacio-fluvial deposits and possible flow tills have been identified within the site stratigraphy (Hunt, 1998). Glacial deposits are also found directly south, at Court Hill on the Clevedon-Bristol ridge (Gilbertson & Hawkins, 1978b). Unstratified tills, ice-contact deposits and glacio-lacustrine sediments are present in a col-gully eroded through the Carboniferous Limestone. The red sandy silts that dominate the sedimentary matrix originate from the Keuper Marl and they confirm that the deposits are glacial till, as the sequence is positioned at an altitude higher than the Triassic outcrops. A decaying ice sheet is believed to have downwasted and been divided into two parts by the emergence of the Clevedon-Bristol Ridge. Glacio-lacustrine sediments accumulated on top of the till due to a small water body developing between the two ice masses. As the bedrock to the north of the gully is predominantly Carboniferous Sandstone (unit d^4 in Figure 3.2), the absence of clasts from this outcrop within the glacial deposits would suggest that the source of the till originated from the south of the Clevedon-Bristol ridge. This is supported by the gully becoming wider and deeper towards the north (Gilbertson & Hawkins, 1978b). At Tickenham Hill, east of Court Hill on the Clevedon-Bristol ridge, glacial till has not been identified, but Hawkins (1972) states that its similarity in form to that of Court Hill would suggest a glacial origin of a similar age.

The glacial deposits at Nightingale Valley and Court Hill Col are both found at *c*. 85m O.D. This similarity in altitude suggests that they may have accumulated during the same period of glacial activity. Alternatively, two separate glacial periods would have been required that created ice sheets of similar thickness to enable pro-glacial sedimentation to occur at the same altitude at both sites. Even if the deposits did indeed form during the same event, the age of the glacial episode is still undecided. They may, however, relate to the pre-Cromerian glacial deposits at Kenn and Yew Tree Farm (see section 2.4). Since then, the majority of Quaternary cold episodes are likely to have been restricted to periglacial conditions throughout much of southwest England.

Because scattered evidence is available for the direct/indirect influence of a number of glacial episodes in southwest England, the influence of the last major glacial phase is most commonly considered. This is predominantly because the most recent glacial episode commonly reworks any deposits from previous phases of glacial activity. The Devensian glacial phase is believed to have continued until *c.* 11,500 Cal. yrs BP (including within it a number of ‘stadials’ and ‘interstadials’; see section 2.2.1), at which point climatic warming initiated the present Holocene interglacial. Although the

Devensian glaciation would have influenced the Gordano Valley through periglacial processes only, the impact on climate, isostasy, sea level, geomorphological processes and sedimentary regimes would have been considerable. These factors would have directly influenced the depositional environments that evolved in the valley once the glacial episode had passed.

Periglacial activity during the Devensian was characterised by frost-assisted processes and by a wide range of frost- and ice-generated landforms and deposits (Campbell *et al.* 1998). Figure 2.10 shows ice limits across the British Isles during the Quaternary. The lack of ice positioned over southwest England after the pre-Cromerian period confirms the likelihood of periglacial rather than glacial conditions. Aeolian coversands underlying Holocene deposits have been identified south of the Gordano Valley at at Kennpier, Yew Tree Farm and Kenn Church (Gilbertson & Hawkins, 1978a; Hunt, 1998) and they date to the Devensian glacial period. Similar sediments have been found at Holly Lane (Gilbertson & Hawkins, 1974) and Court Hill Col (Gilbertson & Hawkins, 1978b) in the Gordano Valley and they have also been associated with aeolian sedimentation during the Devensian. The aeolian deposits at Holly Lane (Figure 3.3) are interbedded with thick breccia horizons and represent one continuous but cold episode during the Devensian. Intense frost-shattering of the surrounding bedrock occurred during cold and wet periods, and loess horizons developed during drier periods (Gilbertson & Hawkins, 1974). Further periglacial evidence such as soliflucted limestone breccias, soliflucted Keuper Marl, ice wedge clasts, involutions and widened rock joints have also been identified on the Clevedon-Bristol ridge of the Gordano Valley by Gilbertson & Hawkins (1983a).

3.3 Previous palaeoenvironmental research in the Gordano valley

Although a date for the initiation of recent sedimentary deposition in the Gordano valley is not known, a late Quaternary timescale is likely. Much of the accumulated sediment within the valley catchment would have derived from local bedrock sources due to the enclosed geological nature of the catchment. The valley's proximity to the Severn Estuary suggests that coastal processes are likely to have contributed to the sedimentary evolution of the site. The valley is also believed to have experienced *in-situ* sedimentation through biogenic sources, resulting in the accumulation of organic sediments at various points throughout its recent history (Jefferies *et al.*, 1968; Mills, 1984; Gilbertson *et al.* 1990). Such deposits are indicative of terrestrial freshwater-dominated sedimentation during periods of low sea level relative to land elevation. In contrast, periods of sea-level high-stands resulted in the inundation of the low-lying valley region with marine waters. This encouraged the deposition of marine-derived clastic sediments, the last of which was believed to have taken place during the Romano-British period (*c.* 2,000 yrs BP; Jefferies *et al.*, 1968). The provenance of such sediments may therefore not be confined to the immediate region, having been transported considerable distances by the sea. Analysis of previous research therefore suggests that the sedimentary evolution of the Gordano Valley derives from a combination of terrestrial clastic and biogenic sediments, with the input of marine deposits during relative sea-level high-stands.

Investigations by Jefferies *et al.*, (1968), Mills (1984) and Gilbertson *et al.*, (1990), although limited, have shown a number of depositional characteristics within the Gordano Valley. Mills (1984) and Gilbertson *et al.* (1990) concentrated on the Walton

Moor region in the western region of Gordano Valley (Figure 3.3), while Jefferies *et al.* (1968) attempted a larger-scale analysis of the sedimentological variations throughout the valley catchment. All studies reconstructed vegetation changes in the valley; in the case of Gilbertson *et al.* (1990), local pollen assemblage zones (LPAZs) were produced to cater for the unique nature of the pollen spectra within the valley. Jefferies *et al*. (1968) attempted to compare the vegetation history of the Gordano Valley with that of other sites within the Severn Estuary region in an attempt to understand the scale of local and regional vegetation changes and, consequently, to identify the cause of such change.

Based on limited particle size analysis, Jefferies *et al.* (1968) believed that basal sands, found at the bedrock-sediment boundary, were deposited during the Ipswichian interglacial (*c*. 125,000yrs BP). Their tentative conclusion was of an aeolian or a shallow marine provenance for the sediments. However, based on the evidence for glacial activity in the valley (see section 3.2.2), Hawkins (1972) suggested that these basal sands were glacial outwash from a previous glacial phase. At Portbury, positioned at the mouth of the Gordano Valley, abundant coarse gravels were discovered resting on bedrock at *c*. –13 to –6m O.D. (Hawkins, 1968) and these are believed to have derived from the Clevedon-Bristol Ridge, lending support to the glacial outwash theory.

One of the main discoveries made by Jefferies *et al.* (1968) was the presence of a sub-topographic sand bar traversing the width of the valley (referred to as a 'ridge' throughout this thesis). It is thought to be up to 90 metres wide and it may be associated with the surrounding Ipswichian basal sediment. The sediment's depositional extent can be seen in Figure 3.4 (which shows the original reconstruction of the influence of the basal sand by Jefferies *et al*., 1968) and Figure 3.5 (a three-dimensional reconstruction of

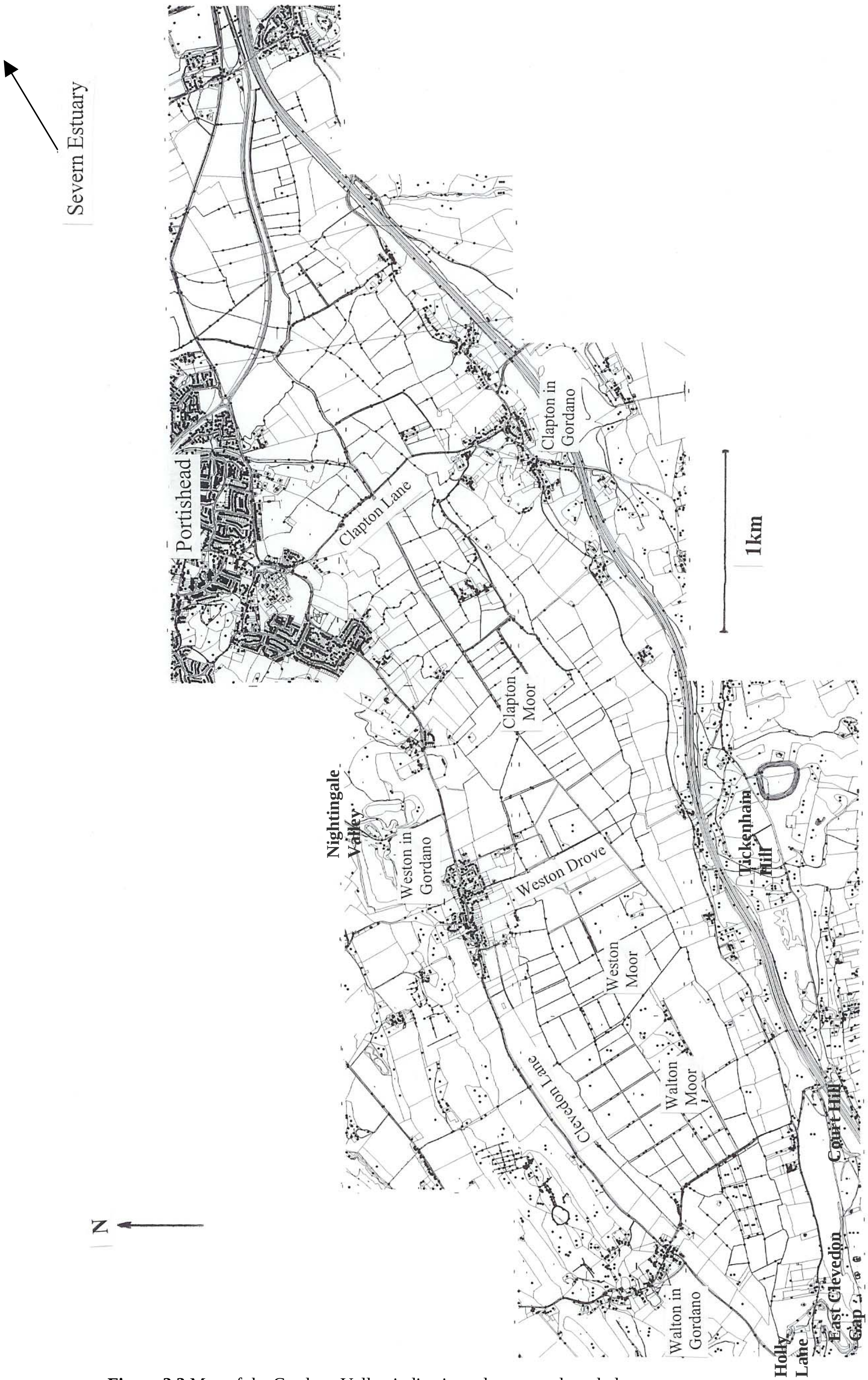

Figure 3.3 Map of the Gordano Valley indicating relevant roads and place names (MapInfo Professional 6.5).

the upper surface of the basal sediment using information from Jefferies *et al*., 1968).

Subsequent analysis of the surrounding sediments indicated that this feature must have acted as a barrier, separating two different depositional environments to the west and east. To the west of the ridge (towards Weston Moor), organic peat dominated during sedimentation; to the east (towards Clapton Moor), peat accumulation was regularly interrupted by the accumulation of blue-grey clays in response to sea-level rise and marine inundation (see Figure 3.3 for reference). The ridge prevented marine transgression further inland, maintaining freshwater peat development to the west. Dating of the sediments found within the Gordano Valley was not undertaken by Jefferies *et al.* (1968), although comparison with work by Godwin (1941) at Shapwick Heath (Somerset) enabled estimated chronologies to be associated with the known changes in stratigraphy.

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Figure 3.4 Contours representing the upper limit of the basal sediment (the 100 and 50ft contours serve only for O.D. reference). The ridge runs parallel to Weston Drove above (see Figure 3.3). The position of the Mills (1984) typecore (*) and the Jefferies *et al*. (1968) typecores (*) are also shown to the west of the valley (Jefferies *et al.*, 1968).

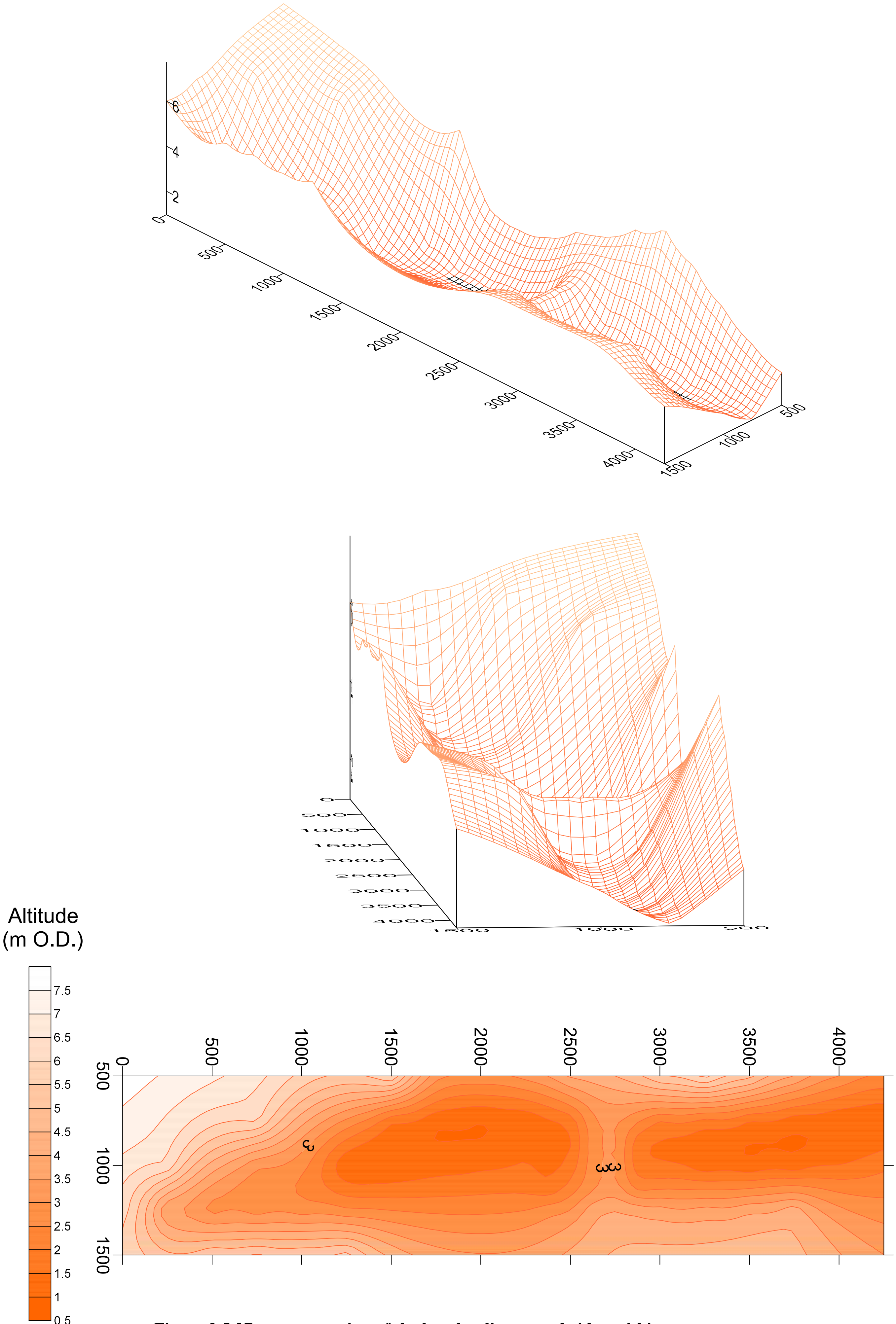

Figure 3.5 3D reconstruction of the basal sediment and ridge within the Gordano Valley (Surfer 7)

Two major phases of relative sea-level rise have been suggested (Jefferies *et al.* 1968) in relation to the sedimentary archive seaward of the ridge. The first marine transgression is believed to have occurred prior to *c.* 5,500 yrs BP, after which a shift to freshwater peat development occurred. This transgression appears to have penetrated inland only as far as Clapton Lane (see Figure 3.3), whilst the interspersion of narrow clay layers within the overlying wood peat is believed to indicate a number of minor incursions by the sea at this time (Jefferies *et al.*, 1968). The formation of peat in the Clapton Moor region of the valley was halted a second time during the Romano-British marine period, *c.* 2,000 Cal. yrs BP. Marine conditions extended as far as Weston Drove, the area within which the ridge is positioned. Except for some limited pollen analysis of the upper interbedded peat and clay boundary, no analysis of the theorised marine and peat beds was conducted. The typecores extracted by Jefferies *et al*. (1968) for palynological analysis were all positioned on the landward side of the ridge. Commercial borehole data from the Severn Estuary lowlands was utilised by Murray & Hawkins (1976) to assess estuarine sediment transport during the Holocene. One borehole was taken from the West Dock region, proximal to the mouth of the Gordano Valley, and was found to contain three interbedded peat units. Radiocarbon dating of these peat units revealed terrestrial sedimentation occurring around the present day coastline at 6,052 ± 70 yrs BP, 5,015 ± 65 yrs BP and 4,485 ± 65 yrs BP. The peat units were much thinner than those encountered by Jefferies *et al*. (1968), being replaced by an increase in the thickness of estuarine deposits. There was therefore an increase in the influence of estuarine sedimentation with distance towards the Severn Estuary. To assist analysis and subsequent interpretations, the sedimentary archive preserved seaward of the ridge will be referred to as the Clapton Moor sequence throughout the thesis.

To the west of the ridge, Jefferies *et al.* (1968) discovered a contrasting depositional environment. Overlying the basal sands that cover the valley floor (Figures 3.4 and 3.5) was a light grey minerogenic horizon, overlain by a “yellow-grey detritus mud”, both averaging 40cm in thickness. This was occasionally replaced by a thin minerogenic horizon (although not present throughout all core profiles) replaced, in turn, by up to 2m of *Phragmites* and sedge peat. Peat development ceased in more recent times due to irrigation and peat cutting (Jefferies *et al.*, 1968, Williams, 1970). Pollen analysis was undertaken by Jefferies *et al.* (1968) on the two typecores extracted from the valley (see Figure 3.4 for position of core sites) to infer palaeo-vegetation changes. Jefferies *et al.* (1968) did not undertake pollen analysis in the lower grey minerogenic deposits, but stated that the pollen counts discovered in the overlying yellow-grey detritus mud infer deposition during the late glacial period. The onset of fen peat development was estimated to *c.* 9-8,000 yrs BP, continuing to the present day (except for those areas affected by irrigation and/or peat cutting). The sedimentary archive preserved to the west of the ridge will be referred to as the Weston Moor sequence throughout the thesis.

Mills (1984) concentrated on a single core profile obtained from the Weston Moor sequence, positioned to the west of the ridge found by Jefferies *et al.* (1968) (refer to Figure 3.4 for core location). The core was located near to one of the sample cores of Jefferies *et al.* (1968), to facilitate the comparison of results. Pollen and limited plant macrofossil analyses were applied to reconstruct the local environmental history of the site. A slow-moving or stagnant water body, such as a stream or lake was identified as the origin of the minerogenic sediment overlying the orange-brown basal sediment. An estimation of late Devensian origin for these sediments was suggested, due to the presence of certain cold-climate indicator species. The same core was subjected to more detailed analysis by Gilbertson *et al*. (1990). The overall results of the two investigations were similar to that of Jefferies *et al.* (1968), with no evidence of marine inundation in the upper catchment of the valley (landward of the ridge). The infill deposits here are suggested to extend from the Allerød interstadial (also known as the Windermere Interstadial, 13,900-13,150 Cal. yrs BP) to the present. Although again the orange-brown basal sediments are of unknown origin (stated as possibly intertidal/sea-bed or aeolian), analysis of the overlying silts and biogenic deposits have been interpreted as evidence for a period of lacustrine conditions. Radiocarbon dating of the core was undertaken by Gilbertson *et al*. (1990; summarised in Table 3.1) and indicated that the theorised lake setting began experiencing terrestrialisation at *c*. 11,020 ±190 yrs BP and fen bog development was established by 7,260 ±160 yrs BP.

Sample Code	Sample depth	Altitude (O.D.)	Sample description	Radiocarbon age
SRR-3199	0.9m	n/a	Black humified peat	3820 ± 100 yrs BP
SRR-3200	1.5m	n/a	Black humified peat	5050 ± 140 yrs BP
SRR-3201	1.8m	n/a	Brownish black well-humified peat	5260 ± 120 yrs BP
SRR-3202	2.2m	n/a	Black hunified peat	7260 ± 160 yrs BP
SRR-3203	3.7m	n/a	Greyish olive silty organic peaty mud	11020 ± 190 yrs BP

Table 3.1 Summary of radiocarbon dates from the research of Gilbertson *et al*. (1990)

The Holocene sequence from the Weston Moor region was reported by Gilbertson *et al.* (1990) to be composed of biologically-rich lacustrine peaty muds interbedded with marshy peat, which were eventually replaced by carr and fen peat (cited as evidence for lacustrine terrestrialisation). Pollen analysis within the Holocene peat also showed two distinct episodes of decline in both *Quercus* and *Ulmus* at the lower and upper limits of LPAZ WM6 (dated at 5,260 ±120 Cal. yrs BP and 5,050 ±140 Cal. yrs BP). It is not known at present whether these events resulted from human influence or from factors such as Dutch Elm Disease (Gilbertson *et al.*, 1990). The altitude of the typecore utilised by Mills (1984) and Gilbertson *et al.* (1990) was not recorded during fieldwork, and this prevents accurate and reliable comparisons from being made with other cores extracted within the region.

One final factor regarding the evolution of the Gordano Valley site relates to late Holocene anthropogenic activity, notably the impact of peat cutting within the valley. Available records, although limited, do make passing references to peat digging at Weston-in-Gordano during the 14th Century (Williams, 1970). However, the dominance of peat-cutting in the proximal Somerset Levels region, and the relative lack of recorded activity in the Gordano Valley would suggest that peat cutting was restricted and of little influence upon the site's evolution.

Section 2.4 highlighted the known impact of reclamation upon coastal evolution during the late prehistoric and early Roman periods. Such activity would have halted sedimentation in lowland regions previously exposed to tidal inundation. Although more restricted during the Iron Age and Bronze Age, archaeological evidence indicates that sea wall construction dates from the Roman period (Rippon, 1997, 2000). Whilst evidence of lowland reclamation is present in many areas surrounding the Gordano Valley, the site itself has very limited records relating to any such activity. There is evidence for a Roman temple on the southern valley side at Cadbury-Tickenham (ST 455 725; Rodwell, 1980) and a hoard of Roman coins were discovered in Clapton-in-Gordano (Symonds, 1928), but both sites were above the influence of tidal flooding during the Roman times and would therefore not be an indicator that reclamation had occurred by this time. No other historical or archaeological records are available for the valley floor itself. Thus, a reliable date for the initial exploitation and reclamation of the tidally-influenced saltmarshes and tidal flats to the seaward end of the valley is difficult to estimate. However, Rippon (pers. comm.) suggests that the character of field boundary patterns within the valley is typical of medieval reclamation, therefore indicating reclamation sometime between the 9th and 13th Centuries. An extensive Saxon estate is suggested by a series of '-ton' place names suffixed by '-in-Gordano': Clapton, Walton, Weston (Rippon, 1997), placing reclamation around the 11th Century. It must be stated however, that a lack of historic/archaeological evidence does not prove that reclamation did not occur before this time.

The soils within the catchment of the Gordano Valley have developed during the Holocene and primarily reflect the underlying geology and drift deposits (Soil Survey, 1983). The Clevedon-Portishead ridge and the southern slope of the Clevedon-Bristol ridge have developed shallow, well-drained loamy soils, typical of soils with Carboniferous Limestone parent material. Overlying the Triassic Keuper Marl bedrock at the valley sides, reddish fine loamy-clayey soils have developed, which are prone to seasonal waterlogging. The abundance of Devensian loess deposits on the northern and southern valley sides (Gilbertson & Hawkins, 1974, 1978b; Hunt, 1998) is likely to have contributed to the nature of the present soils. Deep peat soils with earthy topsoil are described landward of the ridge where the Holocene terrestrialisation sequence is believed to be present. Towards the east, calcareous clayey soils have developed on the estuarine alluvium, which are prone to flooding and managed through drainage ditches.

The published research into the development of the Gordano Valley has been summarised. In order to contribute to the present knowledge of the study site, this project aims to reconstruct the Quaternary palaeoenvironmental evolution of the Gordano Valley. This will be achieved by the application of traditional analytical techniques combined with methods of palaeoenvironmental reconstruction that have not been applied to the Gordano Valley before. Part II of the thesis explains how a diatom-based sea-level transfer function was developed to derive quantitative reconstructions of sea level, whilst Parts III and IV analyse and interpret the sedimentary archive of the Gordano Valley respectively.

Part II:

A Diatom-Based Sea-Level Transfer Function for the Severn Estuary.

Chapter 4: Development of a diatom-based transfer function

Through the development of a diatom-based sea-level transfer function, it would be possible to reconstruct quantitatively changes in sea level responsible for the evolution of the sedimentary archive preserved in the Gordano Valley. Considering the lack of research that has been undertaken in the interbedded marine deposits, the creation and application of such a transfer function to the valley archive provides an opportunity to utilise a relatively new analytical technique in this study. This chapter introduces diatom analysis and explains its application to palaeoenvironmental studies.

4.1 Introduction to diatom analysis

Diatoms are unicellular microscopic algae (Bacillariophyta) which have been widely used to reconstruct depositional environments throughout the Quaternary and Holocene (Vos & de Wolf, 1993; Lowe & Walker, 1997; Zong & Horton, 1999). Diatom analysis facilitates the reconstruction of the water conditions in which the sediment was derived (freshwater, brackish water, marine water or a mix). Such interpretations can be achieved because individual species are sensitive to ecological conditions such as salinity, trophic status and pH and can consequently only survive within certain thresholds of each environmental parameter.

Diatom preservation is good in most sediments due to the siliceous composition of the diatom frustule. They are found in most water-lain deposits, but preserved in abundance in finer sediments such as silts and clays which experience much lower-energy depositional environments (and thus favour frustule accumulation with minimal disarticulation). The significant extent of fine sedimentary deposits found within the Gordano Valley (Jefferies *et al.*, 1968) made this site potentially ideal for the application of such analysis. This factor was thus taken into account when considering the sites for typecore extraction.

4.1.1 The application of diatom analysis in palaeoenvironmental studies

Analysis of present day species provides the means by which environmental characteristics are identified for the fossil diatom frustules within sediments. It is thus assumed that diatoms employ uniformitarian principles; species present in today's subaquatic environments require the same conditions (such as salinity, temperature and nutrient supply) as in the past (Lowe & Walker, 1997). This is in accordance with the analysis of other microfossils, including testate amoebae (Woodland *et al.*, 1998), chironomids (Bedford *et al*., 2004) and foraminiferal analysis (Edwards & Horton, 2000), all of which have used the distribution of contemporary assemblages to infer environmental controls in the past.

Vos & de Wolf (1993) attempted to infer specific depositional environments from diatom assemblages (e.g. saltmarsh environments around/above Mean High Water {MHW}, non-tidal lagoons). This has been continued more recently by Zong & Horton (1999), Campeau *et al.* (2000) and Ng & Sin (2003), who have calculated transfer functions to enable the interpretation of palaeo sea levels from diatom assemblages in the UK, southeastern Beaufort Sea and Hong Kong respectively. Zong & Horton (1999) for example, studied six separate coastal sites around the coast of northeast and northwest England and Scotland. From known palaeo-tidal levels in a known setting (where tidal variations are understood), it should be possible to infer mean sea-level change at that site. However, the work by Zong and Horton (1999), Campeau *et al.* (2000) and Ng & Sin (2003) are site-specific, and each coastal region has an individual tidal regime. Also, the Severn Estuary experiences such a high tidal range that it cannot be matched anywhere else in the British Isles (14.65m O.D.). Consequently, any attempts to reconstruct sea-level changes in the Severn Estuary would require a new transfer function to be developed specifically for this locality.

4.2 The generation of a diatom-based sea-level transfer function

A significant shift in recent years has occurred regarding palaeoecological analysis. Qualitative analysis dominated past research, indicating when relative shifts from one environmental condition to another took place (Waller *et al*., 1994). Whilst such results were once more than adequate, it is now possible to reconstruct quantitatively a range of environmental conditions through numerical modelling. For example, qualitative analysis may identify a shift from freshwater to marine conditions within a sedimentary archive; quantitative analysis will provide a reconstruction of the ground surface relative to the tide level, and the change in depositional setting may be understood more clearly. The known influence of marine conditions on the evolution of the Gordano Valley (Jefferies *et al*., 1968), combined with the abundance of diatoms within the sedimentary archive, provides the opportunity to infer quantitatively the palaeoenvironmental conditions required during the valley's depositional history. Consequently, quantitative analysis forms the basis to sea-level reconstruction within the Gordano Valley.

There are a number of benefits in using diatoms over other biological analytical techniques for quantitative reconstructions of sea level. Diatoms are often well preserved in coastal sedimentary sequences, and their analysis as been widely used to validate SLIPs by considering the changes in composition of diatom groups of different salinity preference (Zong, 1997). The well-established relationship between altitude and the distribution of diatom species on salt marshes and tidal flats indicates that a transfer function can be developed and applied to Holocene diatom assemblages to reconstruct former reference water levels, and hence Holocene sea-level trends (Plater *et al*., 2000). In contrast, the relationship between sea level and proxies such as testate amoebae and foraminifera is not as strong. Testate amoebae for example, do show vertical zonation on contemporary salt marshes, but other environmental variables that are not directly related to sea level can often explain the species distribution as effectively as altitude (Charman *et al*. 2002). The occurrence of fossil testate amoebae in coastal sediments has also seen to often be low (Charman, 2001), suggesting that their application to quantitative sea-level studies could be questioned. Foraminifera have also been used in sea-level studies, and show similar vertical zonation, but they are exclusively marine species and have been found to not commonly occur in the modern Severn Estuary between MHWS and HAT (Haslett *et al*., 1997). As biological assemblages are required from MSL to HAT to ensure a full representation tidal (and hence sea-level) influence (Zong & Horton, 1999), subsequent transfer functions may not be as accurate. In contrast, diatoms are found in abundance throughout the contemporary coastal zone, show strong vertical zonation, and are commonly well preserved in coastal sediments.

Transfer functions can be utilised to reconstruct a region's environmental history. A transfer function is the result of quantitative analysis and it produces a statistical relationship between species abundance and diversity (in this case, diatoms), and influential environmental variables. When assessing the species-environment relationship, the environmental variables and their relationship with species abundance and diversity is explored using gradient analysis (Woodland, 1996). It is assumed that all species have unimodal responses to environmental gradients; that is, a species will attain a maximum abundance at a particular point on the gradient of an environmental variable (the 'optimum'). Although linear relationships between taxa and quantitative environmental variables exist, it is almost general law of nature that the relationships are non-linear and the abundance of taxa is a unimodal function of the environmental variables (Birks, 1995). The abundance of that particular species will decrease with distance away from the environmental optimum until its tolerance is exceeded, beyond which the species cannot survive. Figure 4.1 displays the Gaussian relationship between species and an environmental variable if a unimodal relationship is assumed (Woodland, 1996). Species with a narrow tolerance range, as defined through the application of weighted averaging (see section 7.2), are considered to be robust environmental indicators. They will therefore be given more weight in subsequent weighted averaging regression. In contrast, those species that appear to thrive over a wide environmental range are deemed less sensitive and are given a lower weighting.

In order to create a diatom-based sea-level transfer function that can be applied to the Gordano Valley, it was therefore necessary to understand the relationship between diatom species and the environmental variables that influence their abundance and diversity. Applying uniformitarianism, it was assumed that similar conditions were required in the past as in the present. By analysing the diatom species present on a contemporary coastal transect, the relationship between species and environmental variables could then be applied to the archived diatom assemblages preserved in the valley deposits (Plater *et al*., 2000).

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Figure 4.1 The Gaussian model of species distribution, shown as the response to a single environmental factor (Woodland, 1996 p.208).

4.3 Sea-level reconstruction in the Gordano Valley using diatom analysis

To reconstruct a palaeo sea-level curve for the Gordano Valley via quantitative diatom analysis, a modern ecological transfer function was developed. This required ecological data that described the variation in diatom species abundance and diversity on the contemporary coastline of the Severn Estuary. The modern distribution of diatom assemblages on a coastal transect sampling at different altitudes would be dependent on a number of environmental variables. An understanding of how these variables impact on the distribution of diatoms in the contemporary environment allows their application to fossil assemblages within the valley's sedimentary archive. Consequently, using the environmental information from the relevant modern assemblage, estimates of the tide levels (and thus the palaeo sea level) for the respective fossil sedimentary deposits were attained. An abundance of diatom assemblages within the valley deposits would enable the construction of an accurate sea-level curve for the valley since sedimentation began. This technique could provide a sea-level history for the area which can be compared to the more traditional reconstruction techniques such as SLIPs derived from stratigraphic boundaries (Shennan & Horton, 2002). Chapter 5 describes the field and laboratory methods utilized to create a contemporary coastal diatom data set, whilst Chapters 6 and 7 explain the analysis of the diatom data set and the construction of the diatom-based sea-level transfer function respectively.

Chapter 5: Field and laboratory methods for the development of the diatom-based sea-level transfer function

5.1 Introduction

Analysis of the species-environment interactions in a contemporary diatom data set was required in order to construct a diatom-based sea-level transfer function. This chapter summarises the field and laboratory techniques utilised in order to describe the relationships between diatom species and environmental variables along a coastal transect on the Severn Estuary.

5.2 Site selection for the sea-level diatom data set

A quantitative reconstruction of sea level using diatoms has not previously been applied to the south coast of the Severn Estuary. As this is the case, a new transfer function was required specifically for the Gordano Valley. To create the modern ecological transfer function, sampling of diatom assemblages within contemporary coastal sediments was required. These would be used to produce a reconstruction of the former height of the ground surface relative to sea level, from which sea level can be calculated. Consequently, modern samples were required from altitudinal intervals between Mean Sea Level (MSL) and Highest Astronomical Tide (HAT) on the Severn Estuary (Zong & Horton, 1999; Gehrels *et al.*, 2001) to represent the variation in diatom assemblages in relation to tidal range.

The comparison of the diatom archive from the Gordano Valley with that of a contemporary data set from the Severn Estuary needs to be justified. Considering the isolated nature of the Gordano Valley in contrast to the open estuarine setting present along the contemporary coastal margin, the variation in geomorphology, aspect and groundwater influences must be considered. Whilst the present-day Gordano Valley is relatively enclosed and separated from the coastal zone through artificial defences and reclaimed land, during its accumulation of estuarine sediment in the Clapton Moor region (Jefferies *et al.*, 1968), the valley's lowlands would have been fully exposed to estuarine and tidal influences. In addition, the influence of groundwater on the valley would have been minimal due to its small catchment and the surrounding limestone bedrock acting as an aquifer. Consequently, the environmental conditions in the past would have been similar to those experienced today, thus justifying the creation of such a data set.

A major constraint upon this element of the study relates to the tidal regime of the Severn Estuary. The Severn Estuary has the second largest tidal range in the world (14.65m; Proudman Oceanographic Laboratory, 2004), and the high population density around the coastal zone requires much of the lowlands to be protected by sea defences below HAT. As a consequence, identifying an unmanaged site that contained the entire MSL to HAT gradient proved difficult. Proximity of the sampling site to the Gordano Valley was a priority, in order to attain a close match between modern and fossil depositional environments. Portbury Wharf (ST 485 785) was initially chosen for the modern data set due to its proximity to the valley. The site is positioned where the Gordano Valley's lowlands meet the Severn Estuary, and is therefore an ideal choice for sampling. Figure 5.1 locates the sampling site in relation to the Severn Estuary and Figure 5.2 indicates the position of the sampling transect on Portbury Wharf. However,

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Figure 5.1 Location of the two coastal sampling sites from the Severn Estuary (Adapted from Allen & Haslett, 2002 p304).

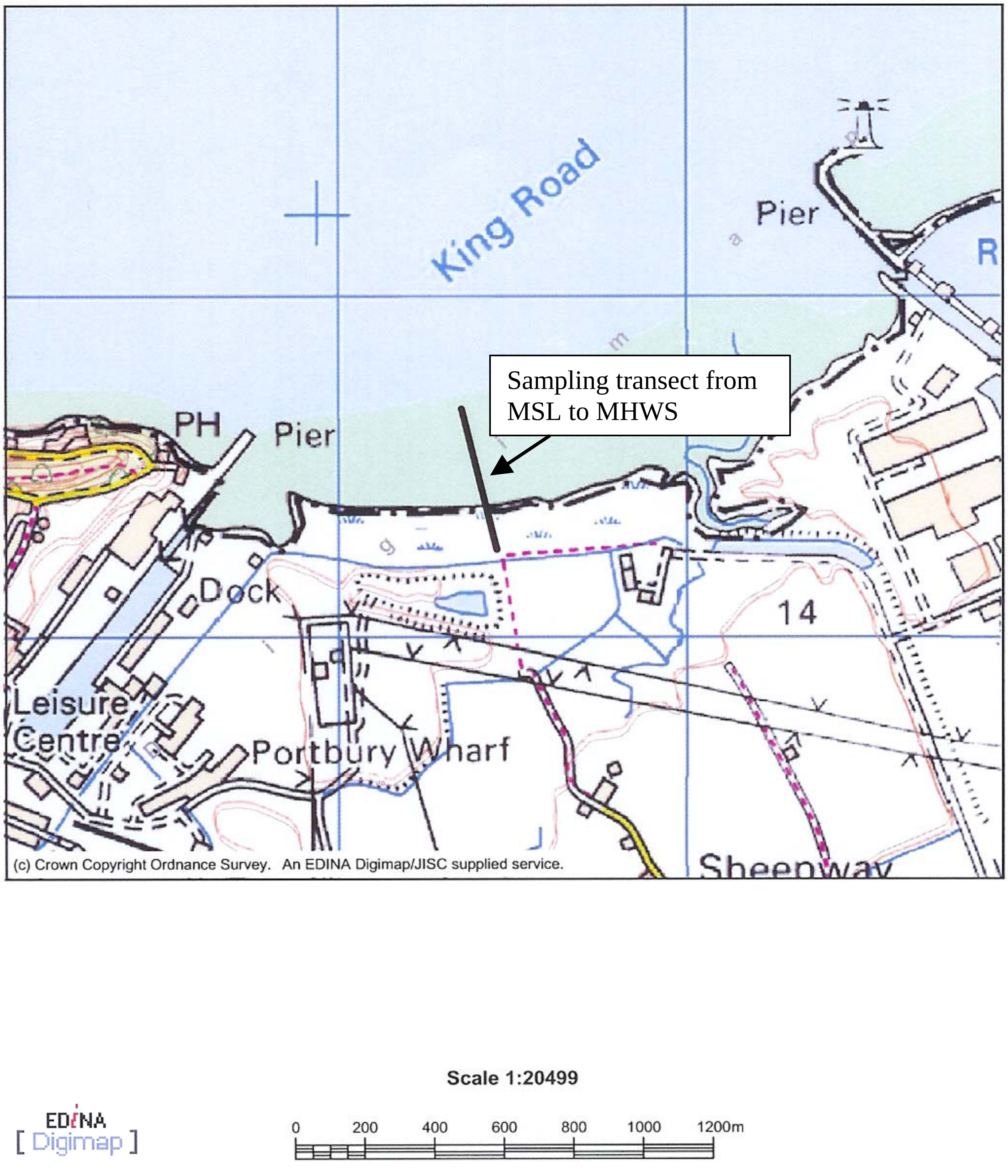


Figure 5.2 Location of the sampling transect from Portbury Wharf along the coast of the Severn Estuary (Digimap, 2004).

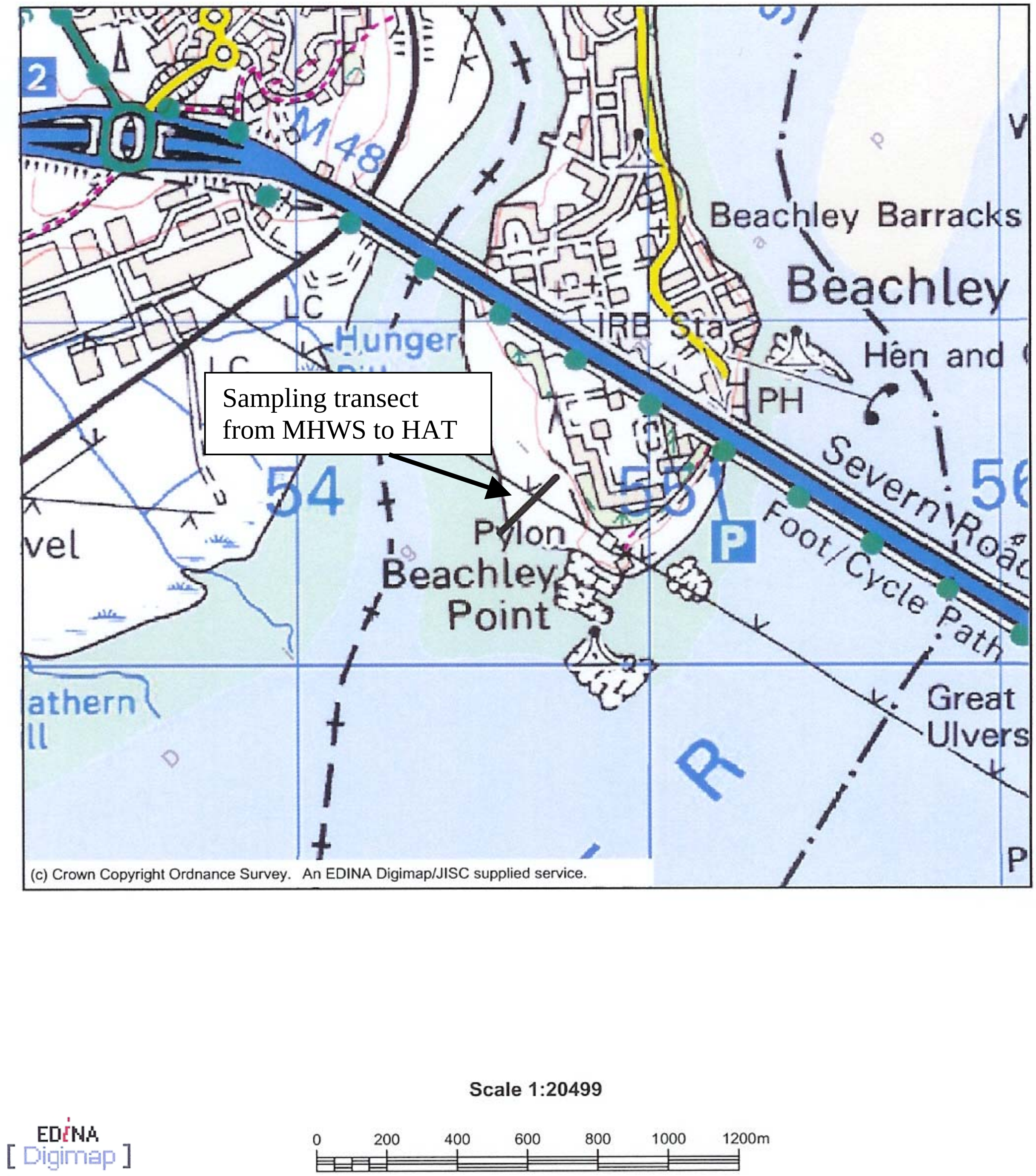


Figure 5.3 Location of the sampling transect from Beachley Point along the coast of the Severn Estuary (Digimap, 2004).

this coastal site, like most in the surrounding area, had an embankment positioned above MHWS (at approx. 6.7m O.D.), preventing a full altitudinal gradient from being sampled. A second site, at Beachley Point (on the Welsh side of the Severn Estuary, northeast of the Gordano Valley; ST 545 905), was found to provide a full altitudinal transect from MSL to HAT but the proximity of the site to the River Wye meant that the enhanced influence of freshwater input, especially at low tide, could potentially produce an unreliable modern analogue for comparison with the diatom archive within the Gordano Valley. As a result, to maintain relative proximity to the research site, and to restrict the potential for erroneous diatom assemblages through freshwater input, transects were sampled for diatoms at both sites, using Portbury Wharf to attain samples
from MSL to MHWS (Figure 5.2), and Beachley Head to attain samples from MHWS to HAT (Figure 5.3). The sampling strategy ensured an altitudinal overlap of the two transects to enable the comparison of the species assemblages at the sites. Figure 5.4 shows the topographic transects of the two sites used for diatom analysis.

5.3 Diatom sampling for the coastal data set

The upper saltmarsh/tidal flat region was sampled every 10cm drop in altitude at Beachley Point (from 8.11m to 6.0m OD) and Portbury Wharf (from 6.52 to 3.4m OD), to ensure that an overlap between the two sites was attained (Figure 5.4). Further down the tidal flat at Portbury Wharf, a very low surface gradient produced a large expanse of mudflat to be covered. Samples were taken every 20cm drop in altitude (from 3.4m to 0.4m OD). A 5cm^3 sample of sediment was taken at each site, to a depth of 1cm to account for seasonal changes in diatom assemblages (Zong & Horton, 1999). The samples were returned to the laboratory for diatom analysis.

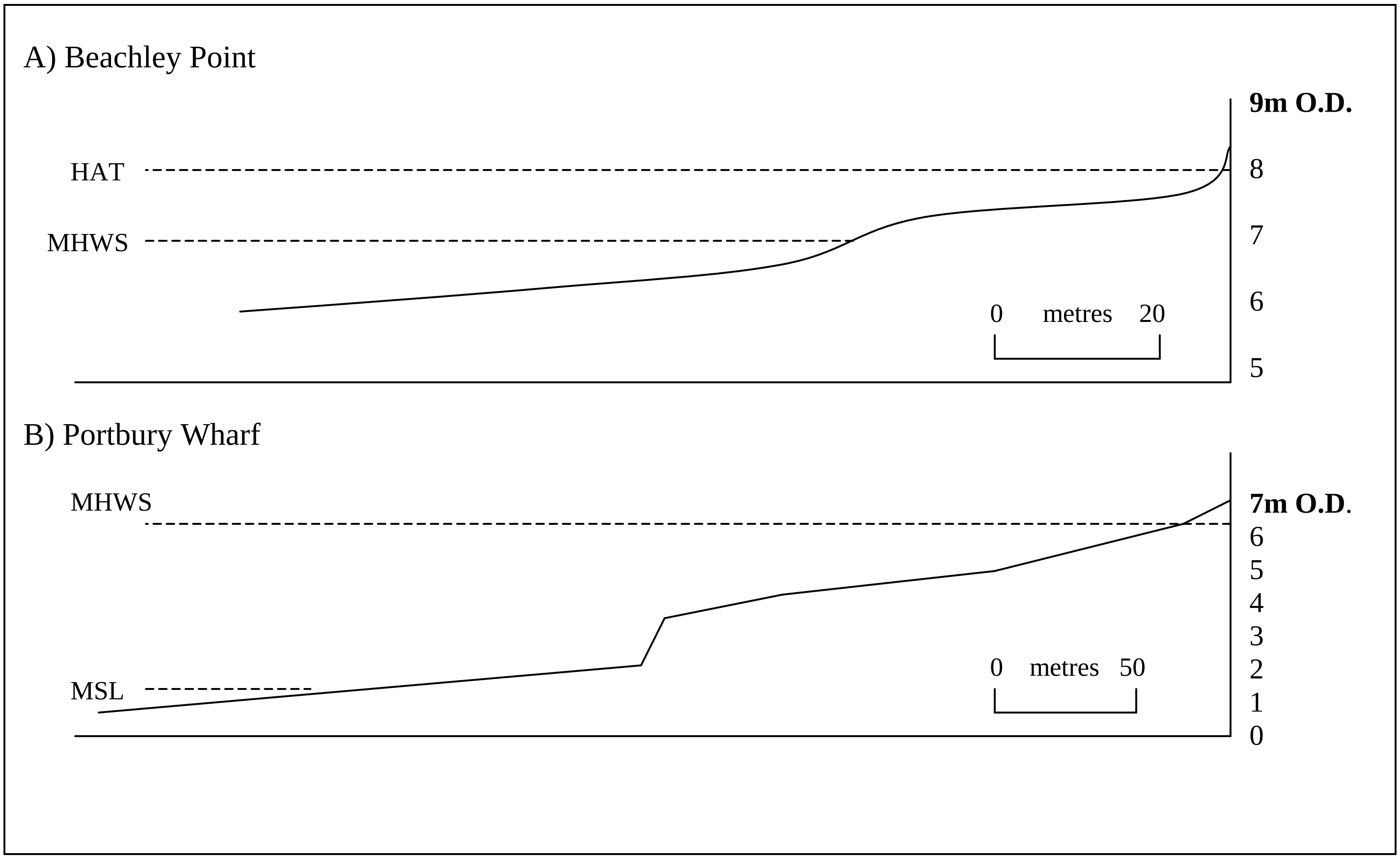


Figure 5.4 Topographic transects of the contemporary diatom data sets from Beachley Point and Portbury Wharf. The vertical and horizontal scales vary between transects.

5.4 Laboratory preparation and analysis of the diatom assemblages

Each sediment sample selected for diatom analysis comprised 0.5cm^3 of sediment. Each sample was digested via heating in a 20% solution of 100 volume hydrogen peroxide (H_2O_2) to remove organic matter. Once the majority of the hydrogen peroxide had been removed (maintaining the sample's volume with distilled water), a small amount of the solution was evaporated on a cover slip (25x50mm) by heating on a hot plate. This was then mounted onto a slide using Naphrax and left to cool in preparation for diatom counting. A Carl Zeiss Standard 25 microscope with the magnifications of x600 and x1000 was used for microscopic analysis. Diatom species were identified with reference to van der Werff and Huls (1958-74), Hendy (1964) and Krammer & Lange-Bertalot (1986-1991).

A minimum of 200 diatom valves were counted in each sample. Where one species dominated the diatom count (>50%), at least 200 other valves were counted to limit bias and achieve statistically viable counts. An attempt was also made to identify at least 20 species in each sample. During the sample counts, a record of cumulative species diversity was made (Woodland, 1996). This approach established that a nominal count of 200 diatoms provided a reliable representation of the potential diatom community within a sample. Figure 5.5 shows graphs indicating the number of diatom species discovered during sample analysis against the cumulative count. Commonly, once a count of around 200 diatom frustules had been achieved, a plateau effect occurred after which few new species were found. Those species present beyond *c*. 200 valves would also not be significant in subsequent qualitative/quantitative environmental reconstructions due to their low abundance.

5.5 Environmental controls on diatom distribution from the contemporary coastal transect

Past research has identified tidal flooding and altitude as the most significant environmental controls on diatom assemblages on saltmarshes (Zong & Horton, 1999; Gehrels *et al*., 2001). Other variables believed to have a secondary influence are grain

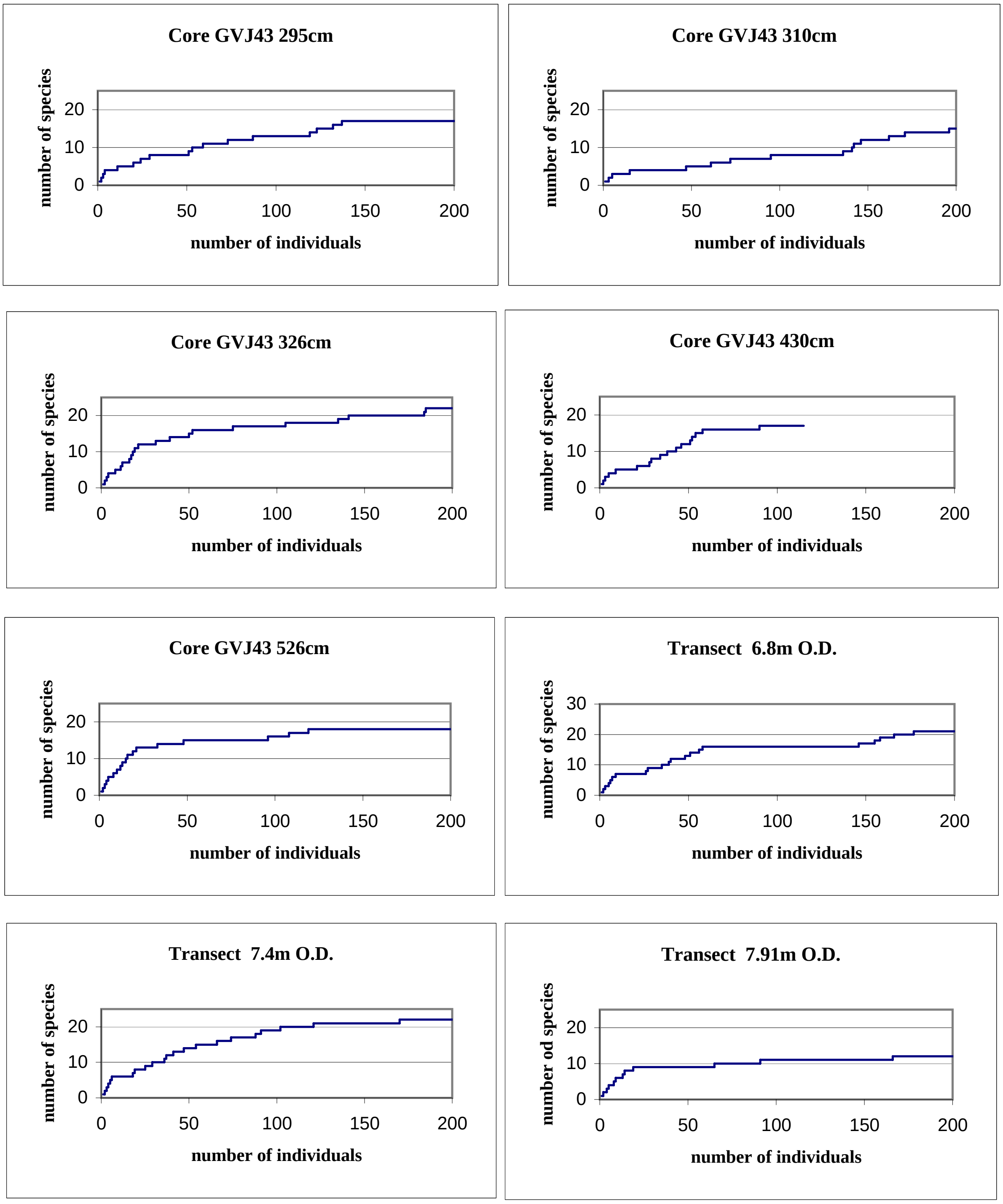


Figure 5.5 Number of individual diatom frustules plotted against the number of species from selected typecore samples

size and organic content of the substrate. Alternative variables such as salinity, pH and % total carbon have been applied to quantitative palaeoenvironmental reconstructions in the past (Charman *et al.*, 2002) and could have been utilised in this study. However, due to the infancy of this technique in relation to diatoms and sea-level studies, the environmental variables investigated by Zong & Horton (1999) were incorporated into this study to support the technique's development and enable inter-site comparisons to be made. Therefore, the same environmental variables were assessed during this study (tidal flooding, altitude, grain size, organic content). The altitude of each sampling site along the two coastal transects was recorded during coastal sampling. This was achieved through the levelling of each sample site into a benchmark of known altitude.

5.5.1 Calculation of duration of flooding

The influence of tidal flooding on the coastal setting was quantified using the 2002 tidal statistics for Avonmouth (Admiralty Tide Tables, 2001). The overall duration of flooding at each sampling site was calculated as a percentage in relation to the whole year's tidal variations. Gehrels *et al.* (2001) computed the duration of tidal flooding in the Taf estuary (southwest Wales) with considerable success. Consequently, the same equation was used to assess the duration of tidal submergence (T) of a given height on a marsh surface (h):

$$T = \frac{(t_2 - t_1)\left\{\frac{1}{2}\pi - \arcsin\left[2\left(\frac{h - L_1}{H - L_1}\right) - 1\right]\right\} + (t_3 - t_2)\left\{\arccos\left[2\left(\frac{h - L_2}{H - L_2}\right) - 1\right]\right\}}{\pi}$$

where L_1 is the height of low tide at time t_1, H is the height of high tide at time t_2, and L_2 is the height of low-tide at time t_3. Heights were initially expressed relative to Chart Datum (C.D.) during calculations, and then converted to Ordnance Datum (O.D.) (Gehrels *et al*., 2001). The total time period for which each sample altitude was submerged was expressed as a percentage of total time (from a one year data set). This was incorporated as the second environmental variable (in addition to altitude) into the modern ecological transfer function.

5.5.2 Grain size methodology

$1cm^3$ of sediment was taken from each coastal sample and placed into a 250ml beaker, to which *c*. 150ml of distilled water was added. Samples were then gently heated on a hot plate to assist disaggregation. Whilst the majority of the minerogenic sediments contained very low amounts of organic matter, some organic material was present (especially within samples close to HAT), which may potentially affect the results of particle size analysis and produce erroneous results. Whilst extraneous organic matter (indigenous plant litter and post-depositional roots) can be removed from samples by physical means, hydrogen peroxide (H_2O_2) is used to remove all plant material regardless of type (as used in diatom analysis, see section 5.4). Allen & Thornley (2004) however, state that, by applying hydrogen peroxide treatment to the sedimentary sample, all organic matter, including detritus that was a co-deposited part of the sediment, is removed. The research, applied to Severn Estuary sediments, concluded that the mean particle size was “drastically reduced” by the treatment (Allen & Thornley, 2004, p.290), when compared to the samples analysed without digestion. Consequently, hydrogen peroxide was not applied to the Severn Estuary samples.

To provide the particle size data for the transfer function, an AccuSizer 780 Optical Particle Sizer was used. The AccuSizer is able to measure the size of mineral grains from 0.5-500 μm, or 11-1 Phi (ϕ), and plots the grain size distribution of each sample, as well as recording measurements such as the sediment's mean grain size, mode, standard deviation, median, kurtosis and skewness. Due to the fine-grained substrate present, all samples from the coastal transect could be analysed with the use of the AccuSizer 780.

Each sample was placed on a magnetic plate and magnetic stirrers were used to ensure all particles were entrained in suspension. A pipette was then used to sub-sample the sediment solution whilst being stirred, and the sample was added into the AccuSizer Dilution Chamber. The procedure of particle size analysis is explained in AccuSizer (2001). The AccuSizer provided the cumulative grain size distribution of each coastal substrate sample, from which calculations were made regarding the contribution of clay (<4µm), silt (4-64µm) and sand (>64µm) to each sample expressed as a percentage. Each sample was analysed three times to ensure accuracy and from which averages of each grain size component could be calculated.

The AccuSizer 780 program was set up to provide the particle size results in terms of the "volume weighted differential distribution" of each sample. The computer program applies a volume weighted function to each sample's data set, where volume (V) is given by $V = 4/3 \pi (d/2)^3$. This statistical approach ensures that the particle size distribution of the sample produced is consistent with all other methods of particle size analysis to enable comparisons. The AccuSizer also assumes a constant density of all particles analysed. This is unlikely to be the case due to variations in grain mineralogy (and thus density), but research has shown (Isphording, 2002) that even when densities have varied from 2.0 to over 3.2, no statistical differences were recognised (when calculating mean, median, skewness, standard deviation etc) when compared to the generally assumed density value of 2.65.

5.5.3 Organic content

The organic content of each coastal sample was calculated via loss on ignition (LOI) using the methodology proposed by Ball (1964). A visual examination of each sample was first conducted to ensure that no shells or shell fragments were present that could influence the LOI results. A *c.* 10g sample of the substrate was placed into a porcelain crucible and dried (overnight at 105ºC) to remove all water. The samples were reweighed and placed in a furnace at 550ºC for two hours to remove the organic content within the substrate. Each sample was finally reweighed in order to calculate the amount of organic matter originally present.

Chapter 6: Analysis of the contemporary diatom data set

6.1 Introduction

Chapter 6 describes the analytical techniques that were applied to the contemporary data set to understand the environmental relationships of the contemporary diatom assemblages in the Severn Estuary. The results of the diatom analysis and the analysis of the environmental variables allows an assessment of the validity of the contemporary coastal transect as a data set from which a diatom-based sea-level transfer function could be developed.

6.2 Ecological classification of the contemporary diatom data set

6.2.1 Classification scheme of Vos & deWolf (1993)

The diatom ecological classification scheme of Vos and deWolf (1993) was developed to assist in the reconstruction of past environmental conditions from archived diatom assemblages. The scheme classifies diatom assemblages into ecological groups and consequently into specific sedimentary environments. Although it is common practice to apply this scheme to palaeoenvironmental reconstructions of UK coastal deposits, this method was based on diatom assemblages found in archived coastal deposits from the Netherlands. To ensure that this interpretative technique was applicable to archived diatom assemblages from the UK, the methodology was applied to the contemporary Severn Estuary diatom assemblages. The degree of similarity between the environmental reconstructions produced by the classification of Vos and deWolf (1993) and the known depositional setting of each diatom assemblage on the contemporary transect, should determine the validity of this methodology within the Gordano Valley and the Severn Estuary as a whole.

Ecological groups	**Macro- and mesotidal environments (%TDV)**						
	Subtidal area		Intertidal area		Supratidal area		
	open marine tidal channels	estuarine tidal conditions	sand-flats	mud-flats	salt-marshes, around MHW	salt-marshes, above MHW	pools in the salt-marshes
Marine plankton	10-80	10-60	1-25	10-70	10-70	10-70	10-50
Marine tychoplankton	20-90	15-60	1-25	10-70	10-70	10-70	10-50
Brackish plankton	1-10	20-70	1-10	1-30	1-30	1-30	1-15
Marine/brackish epipsammon	1-40	1-45	50-95	1-45	0-15	0-15	0-15
Marine/brackish epipelon	0-5	0-5	1-30	15-50	1-40	0-5	5-30
Marine/brackish aerophilous	0-1	0-1	0-1	0-1	10-40	15-95	10-40
Brackish/freshwater aerophilous	0-1	0-1	0-1	0-1	10-40	15-95	10-40
Marine/brackish epiphytes	0-1	0-1	0-5	0-5	0-5	0-5	10-60
Brackish/freshwater plankton	0-1	0-25	0-1	0-1	0-1	0-1	0-1
Brackish/freshwater tychoplankton	0-1	0-1	0-5	0-5	0-5	0-5	5-50
Brackish/freshwater epiphytes	0-1	0-1	0-5	0-5	0-5	0-5	1-50
Freshwater epiphytes	0-1	0-1	0-1	0-1	0-5	0-5	0-10
Freshwater epipelon	0-1	0-1	0-1	0-1	0-1	0-1	0-10
Freshwater plankton	0-1	0-1	0-1	0-1	0-1	0-1	0-5

Table 6.1 Relationship between the relative abundance (% total diatom valves; TDV) of the ecological groups and the sedimentary environments, modified from Vos & de Wolf (1993).

Each species found in the coastal samples was allocated an ecological group based on salinity and lifeform (Vos and deWolf, 1993). Such ecological classifications were achieved with the use of Vos and deWolf, (1988, 1993), Van Dam *et al*., (1994) and Denys, (1991-92, 1994). Table 6.1 summarises the relationship between ecological abundance and diversity and sedimentary environments (adapted from Vos and deWolf, 1993). Planktonic and tychoplanktonic species live predominantly in the water column. They are consequently easily transported into a depositional setting and thus restrict interpretation of sea level. Other life forms however are more useful for sea-level studies. Epipelic and epipsammic species attach to muddy and sandy substrates respectively, whilst epiphytic species attach to plants. Finally, aerophilous species require periods of tidal emergence and submergence and are commonly found in abundance towards high tide.

6.2.2 Autochthonous *vs*. allochthonous classification of diatom species

Whilst the ecological classification scheme of Vos and deWolf (1993) provided an indication of the sedimentary environment present along the coastal transect, a further key factor to be taken into consideration was the ratio of autochthonous to allochthonous diatoms. This was highlighted by Vos and de Wolf (1993), Beyens & Denys (1982) and Spencer (1996). In tidally influenced environments such as the Severn Estuary, the proportion of autochthonous diatoms (species that lived in their place of deposition) to allochthonous diatoms (species that have been transported and deposited away from their original habitat) can be a considerable problem. The movement of diatoms from other environmental settings by the tide contaminates the life assemblages found at all altitudes along the saltmarsh and tidal flat. Therefore when attempting to classify diatom assemblages into their relevant sedimentary environments, only autochthonous species will provide an accurate picture. When Vos and deWolf (1993) created their ecological classification scheme and related the diatom assemblages to specific depositional environments, both allochthonous and autochthonous diatoms were included within the analysis. Table 6.1 shows the different depositional environments and the associated ecological diatom groups. The largest ranges in the relative abundance of the ecological groups are found in the planktonic and tychoplanktonic species. Due to the variation in abundance, large margins of error are present (e.g. marine planktonic species may contribute between 10% and 80% of the total diatom valves (TDV) of a tidal channel's diatom assemblage). The diatom species that live attached to or in the substrate have much lower abundance ranges in relation to TDV. When applying the ecological classification scheme of Vos and deWolf (1993) to the modern and archived diatom assemblages however, the allochthonous component of the assemblages were included due to their incorporation in environmental interpretation.

When analysing the sediments from the contemporary coastal transect, the abundance of allochthonous and autochthonous diatoms was taken into account. Section 8.3.4 provides an explanation of how the ratio of autochthonous-allochthonous species is determined. This approach was undertaken on the contemporary diatom assemblages primarily due to its application to the diatom assemblages preserved within the Gordano Valley sediments. The diatoms present on the contemporary coastal transect however, were only subdivided into allochthonous or autochthonous ecological groups during analysis. The autochthonous and allochthonous components of the fossil diatom assemblages from the Gordano Valley were analysed further to assist palaeoenvironmental interpretations. The approach enabled the autochthonous component of the contemporary diatom assemblages to be identified which, by definition of their lifeform, would indicate the dominant salinity conditions. In the instances where allochthonous and autochthonous diatoms need to be distinguished, the model of Beyens and Denys (1982) provided the foundation for the analysis, which was further improved by Spencer (1996). The amount of epiphytic/benthic (species that live attached to or within the substrate, respectively) and planktonic diatoms were calculated (in relation to TDV). The variation in influence of allocthonous and autochthonous species with height along the coastal transect could then be assessed (section 8.3.4).

6.2.3 Analysis of contemporary diatom assemblages in preparation for the transfer function

Only diatom species with a count of >5% TDV within a sample were utilised in the contemporary data set. This was due to species with frequencies of <5% TDV being regarded as statistically insignificant when attempting quantitative environmental interpretations (Zong, 1997).

Both autochthonous and allochthonous species were assessed for their influence on the coastal transect because, although the allochthonous diatom content may be seen to hinder environmental reconstruction, the study assumes that such a mixture of allochthonous and autochthonous diatom valves would occur in sediments at present and in the past (Zong & Horton, 1999).

6.2.4 Graphical representation of diatom results

The TILIA computer package (Grimm, 1991) was used to plot the diatom abundances from the Portbury Wharf and Beachley Point coastal transects as a percentage of TDV. Separate TILIA graphs were produced for the diatom classifications based on Vos and deWolf (1993) and the analysis of the allocthonous and autochthonous species contributions. Diatom zonation within the modern transect was applied with the use of stratigraphically constrained cluster analysis (CONISS) in the TILIA program (Grimm, 1991).

6.3 Diatom results from the contemporary diatom data set

Coastal samples from MSL to HAT were analysed for diatoms from the two coastal sites of Portbury Wharf and Beachley Point. An overlap of 4 samples (covering 30cm altitude) was achieved for diatom abundance and diversity between the two transect sites. This was undertaken to assess the variation in diatom assemblages between the two sites in order to discover if such an inter-site collaboration was viable. Table 6.2 summarises the diatom species that were found in both transects within the altitudinal overlap. Of the 54 diatom species encountered between the two sites, only 24 were present at both Portbury Wharf and Beachley Point. However, the majority of the species encountered at both sites were not deemed statistically significant due to their low abundances. As mentioned in section 6.2.3, only species with an abundance of >5%TDV would be used for quantitative analysis, as they are believed to provide statistically robust environmental information for the diatom transfer function (Zong, 1997). Among those diatom species with an abundance of >5% TDV, eight of the twelve species (in bold on

		Portbury Wharf Transect - % TDV				Beachley Head Transect - % TDV			
	Altitude (m O.D.)	6.52	6.42	6.31	6.21	6.50	6.40	6.30	6.20
Marine species	**Actinoptychus senarius**	**0.00**	**2.02**	**3.02**	**5.08**	**6.05**	**3.98**	**7.14**	**0.74**
	Biddulphia rostrata	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00
	Gyrosigma litorale	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00
	Paralia sulcata	**1.63**	**11.11**	**23.93**	**18.37**	**24.56**	**22.94**	**15.71**	**17.34**
	Pseudopodosira westii	0.54	1.01	1.01	0.00	1.42	0.31	1.07	0.00
	Navicula palpebralis	0.00	0.00	0.00	0.82	0.00	0.00	0.00	0.00
	Nitzschia socialis	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00
	Nitzschia ponduriformis	0.00	0.00	0.00	1.22	0.00	0.00	1.07	1.48
	Nitzschia spathulata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74
	Pleurosigma affini	0.54	0.00	0.00	0.00	0.36	0.00	0.00	0.00
	Podosira stelliger	0.00	0.00	0.00	0.00	1.42	0.92	4.29	0.00
	Triceratum alterans	0.00	1.01	0.00	0.00	0.00	1.53	0.36	0.37
Marine-Brackish species	**Thallasiosira excentricus**	**2.17**	**11.11**	**13.35**	**22.04**	**18.86**	**19.27**	**26.43**	**7.75**
	Diploneis didyma	0.00	0.00	0.00	0.00	1.07	0.00	0.00	0.00
	Navicula humerosa	0.00	0.00	0.00	0.00	0.00	0.31	0.36	0.00
	Rhaphoneis amphiceros	0.00	0.00	2.52	2.45	1.42	1.22	1.43	1.11
	Delphineis surirella	**4.35**	**0.00**	**8.82**	**6.12**	**6.76**	**12.84**	**9.64**	**1.85**
Brackish-Marine species	Achnanthes brevipes Spp.	0.00	5.05	0.00	0.00	0.00	0.00	0.00	0.00
	Diploneis aesturii	0.54	0.00	0.50	0.41	0.00	0.00	0.00	0.74
	Nitzschia linkei	1.63	0.00	0.00	0.00	0.00	0.31	0.00	0.00
	Nitzschia punctata	0.00	1.01	0.00	0.00	0.00	0.00	0.00	0.00
	Pleurosigma aesturii	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00
Brackish species	Achnahthes brevipes Spp.	0.00	0.00	0.00	2.04	0.00	0.00	0.00	0.00
	Caloneis formosa	1.63	0.00	0.00	0.00	0.00	0.00	0.36	0.00
	Gyrosigma distortum	0.54	0.00	1.26	0.00	0.00	0.00	2.50	0.00
	Gyrosigma spencerii	**11.41**	**15.15**	**0.00**	**0.00**	**6.76**	**8.87**	**16.43**	**12.18**
	Gyrosigma wansbecki	**4.89**	**12.12**	**31.99**	**7.35**	0.00	1.22	0.00	2.21
	Navicula digitoradiata	**27.72**	**7.07**	**0.50**	**13.88**	0.00	0.00	0.00	0.00
	Navicula avenacea	3.26	0.00	0.00	0.82	0.00	0.00	0.00	0.00
	Navicula elegans	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00
	Navicula gracilis	0.00	0.00	0.00	0.00	0.00	0.00	1.07	2.21
	Navicula peregrina	0.00	0.00	1.01	0.00	0.00	0.00	0.00	0.00
	Nitzschia bilobata	0.00	0.00	0.00	1.63	1.07	0.00	0.00	0.00
	Nitzschia fasciculata	**2.17**	**2.02**	**0.00**	**6.94**	**5.34**	**0.61**	**0.00**	**0.74**
	Nitzschia filiformis	0.00	0.00	0.00	1.22	0.00	0.00	0.00	0.00
	Nitzschia lanceolata	0.00	2.02	1.26	0.00	0.00	0.00	0.00	0.00
	Nitzschia navicularis	0.00	0.00	0.76	0.00	**6.76**	**3.98**	**0.36**	**0.00**
	Nitzschia vitrea	0.00	0.00	0.00	0.00	2.14	1.22	0.00	0.74
	Synedra tabulata	0.00	2.02	0.00	0.00	0.00	0.00	0.00	0.00
Brackish-Fresh species	**Gyrosigma peisonis**	**9.78**	**19.19**	**0.00**	**1.63**	**11.39**	**7.03**	**4.29**	**5.17**
	Gyrosigma scalproides	0.00	3.03	0.00	0.82	3.56	10.40	2.14	23.25
	Diploneis ovalis	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00
	Navicula clementis	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00
	Navicula peregrina	**13.04**	**0.00**	**0.00**	**0.00**	0.00	0.00	0.00	0.00
	Nitzschia sigma	0.00	0.00	2.02	2.86	0.00	0.00	2.14	0.37
Fresh-Brackish species	Achnanthes hungarica	1.09	0.00	0.00	0.00	0.71	0.00	0.00	0.00
	Epithemia frickei	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00
	Gomphonema ovilaceum	0.00	0.00	0.00	0.00	0.00	1.83	0.00	0.00
	Navicula cincta	**5.43**	**3.03**	**0.00**	**0.82**	**0.00**	**0.92**	**2.14**	**32.10**
	Navicula pelliculosa	1.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Navicula viridula	0.00	1.01	0.00	1.63	0.00	0.00	0.00	0.00
	Nitzschia palea	0.00	0.00	1.76	0.00	0.00	0.31	0.00	0.00
	Pinnularia borealis	3.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fresh Species	Cymbella ehrenbergi	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00
	Navicula hungarica	2.17	0.00	0.00	2.86	0.00	0.00	0.00	0.00

Table 6.2 Summary of diatom species discovered on the data set overlap between Portbury Wharf and Beachley Point. Species in **bold** relate to those that are statistically significant (5%TDV)

Table 6.2) were found in both sampling sites. This suggests a much higher correlation between the species abundance and diversity between the two sites if quantitative analysis was to be applied. This is further supported by the application of CONISS to the full diatom transect when analysed in TILIA (Figures 6.1 and 6.2). Whilst CONISS assisted in the identification of four local diatom assemblage zones (LDAZs) along the transect, a significant zonal boundary was not identified at the cross-over from the Portbury Wharf transect and the Beachley Point transect (*c.* 6.52m O.D.). This suggests that the similarities between the two sites are statistically strong enough to enable the combination of both data sets to form a single transect.

A total of 61 samples were analysed from the coastal transect. Four LDAZs were described by CONISS in Tilia*Graph (Grimm, 1991). These zones have been named ‘lower mudflat’, ‘upper mudflat’, ‘lower marsh’ and ‘upper marsh’, in relation to altitudinal position. The diatom assemblages were analysed following two separate classification schemes to infer the depositional environment (Vos and deWolf, 1993) and the influence of allochthonous and autochthonous species (Spencer, 1996).

6.3.1 Ecological classification of contemporary data set following Vos & deWolf (1993)

The ecological classification scheme of Vos and deWolf (1993) was applied in order to assess whether such a classification scheme, created in the Netherlands, is viable for deposits in southwest England. Figures 6.1a) and b) present the diatom assemblages from the contemporary coastal transect classified according to Vos and deWolf

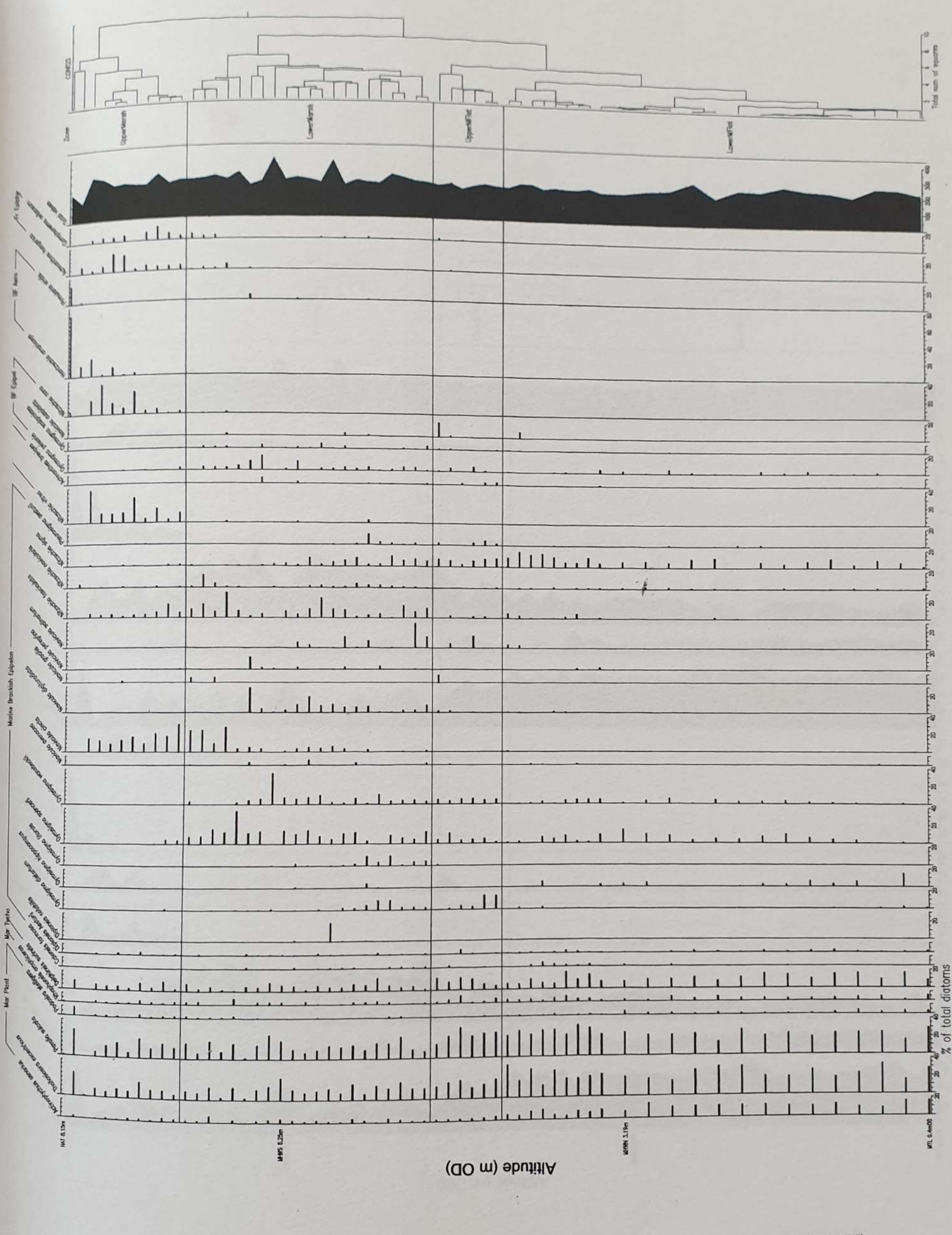


Figure 6.1a) Contemporary diatom data set – Individual species abundance (>5%TDV) according to Vos & deWolf (1993).

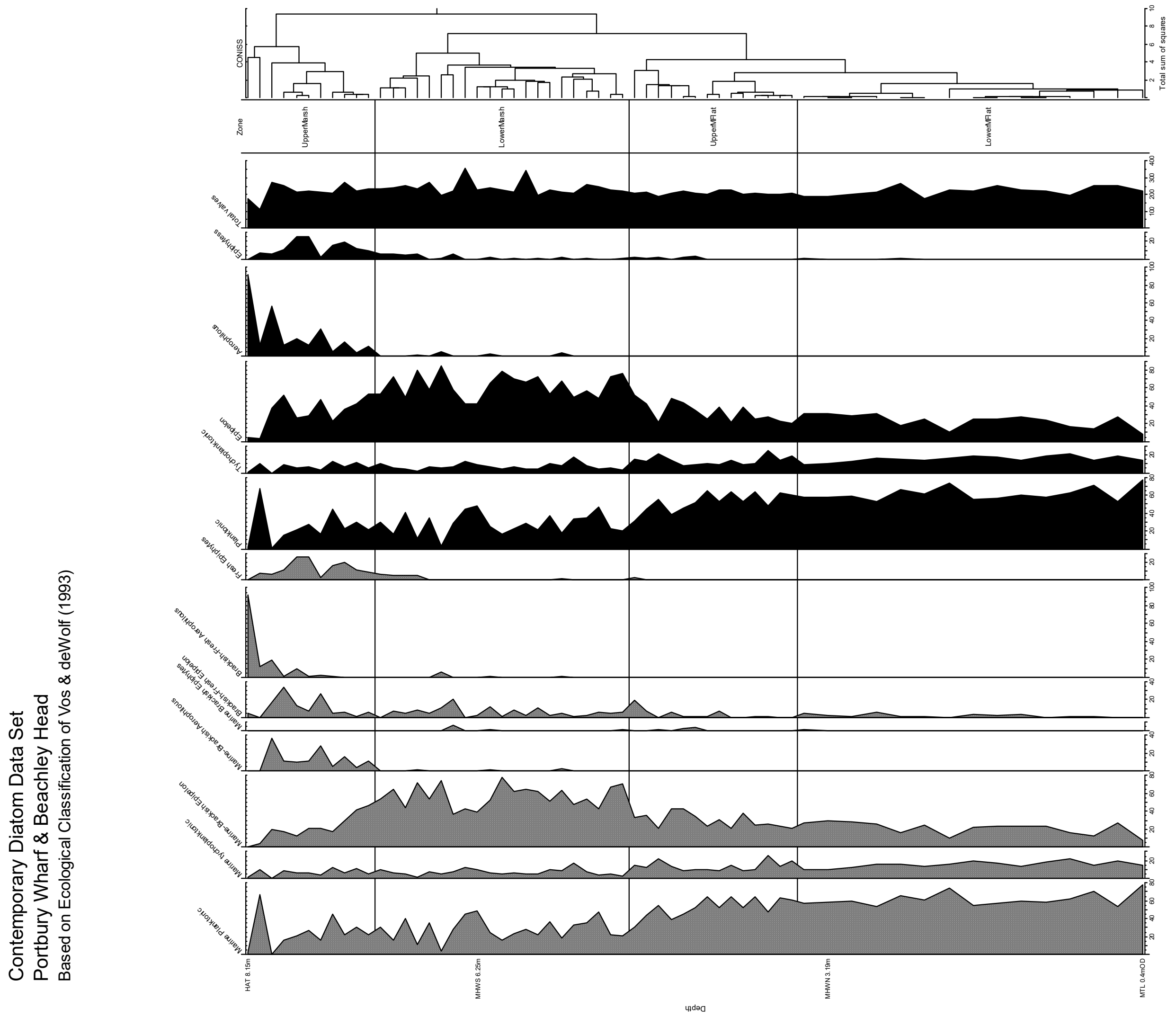


Fig 6.1b contemporary diatom data set – ecological group according to lifeform (%TDV) Vos and deWold (1993)

Altitude (m O.D.)	Mar Plank	Mar Tych	MB Epip	MB Aero	MB Epiphyt	BF Epipel	BF Aero	Fr Epiphyt	Depositional Environment
8.11	2.3	1.2	0	0	0	4.6	91.9	0	SM above MHW
8.02	67	9.8	3.6	0	0	0	12.5	7.1	Pools in SM
7.91	0.7	0	20.4	36.7	0	16.7	19.6	5.9	SM above MHW
7.79	15.4	8.7	17.7	11	0	34.3	1.6	11.4	SM around MHW
7.7	21.4	6	13	10.2	0	13.5	9.8	26	Pools in SM
7.6	27.4	6.3	21.1	11.2	0	7.6	0.9	25.6	Pools in SM
7.5	15.8	3.3	21.4	28.8	0	26	2.3	2.3	SM around MHW
7.4	44.5	12.3	17.5	4.7	0	4.7	0.5	15.6	Pools in SM
7.3	22.5	6.2	29.7	16.3	0	5.8	0	19.6	Pools in SM
7.2	30.5	11.5	41.3	3.7	0	1.4	0	11.9	SM around MHW
7.1	21.5	5.2	46.4	11.2	0	6.4	0	9.4	SM around MHW
7	29.9	10.3	53.4	0	0	0	0	6.4	SM around MHW
6.9	16.2	5.8	65.1	0	0	7.1	0	5.8	Mud-flats
6.8	40.8	4.7	44.3	0	0	5.1	0	5.1	SM around MHW
6.71	11.3	1.3	71.9	1.7	0	8.2	0	5.6	Mud-flats
6.6	34.9	7	53.3	0	0	4.8	0	0	Mud-flats
6.52	3.6	5.1	74.4	0	0	10.3	5.6	1	Mud-flats
6.42	28.4	6.9	37.2	0.5	6.4	20.6	0	0	SM around MHW
6.31	44.8	12.6	42.6	0	0	0	0	0	SM around MHW
6.21	48.4	9.3	39.6	0	0	2.7	0	0	SM around MHW
6.12	24.5	6.2	52.7	1.7	2.1	12	0	0	Mud-flats
6.02	16.3	4.8	78	0	0	0.9	0	0	Mud-flats
5.93	22.6	6.1	62.3	0	0	8	0	0.9	Mud-flats
5.82	28.4	4.7	64.2	0	0	2.6	0	0	Mud-flats
5.72	21.4	4.6	62.8	0	0	10.2	0	1	Mud-flats
5.62	36.7	9.7	51.3	0	0	2.2	0	0	Mud-flats
5.53	18.1	8.4	63.3	3.3	0.5	4.7	0.5	1.4	Mud-flats
5.4	33.5	17.2	47.8	0	0.5	1	0	0	Mud-flats
5.34	35	8	54	0	0.4	2.3	0	0.4	Mud-flats
5.24	47.4	4	42.9	0	0	5.7	0	0	Mud-flats
5.13	22.6	5.3	67.3	0	0	4.9	0	0	Mud-flats
5.03	20.5	2.7	70.3	0	0.9	5.5	0	0	Mud-flats
4.91	30.6	15	33	0	0	18.9	0	2.4	Mud-flats
4.8	43.8	12.9	35.5	0	0	6.9	0	0.9	Mud-flats
4.68	54.8	21.5	21.5	0	2.7	0	0	0.5	Mud-flats
4.58	38.5	13.5	42.3	0	3.3	5.8	0	0	Mud-flats
4.48	45.2	8.1	42.5	0	0.5	1.4	0	0	Mud-flats
4.34	52.2	9.6	34.4	0	0	0.5	0	0	Mud-flats
4.23	65	9.9	23.2	0	0	1.5	0	0	Mud-flats
4.13	52.4	8.8	31.3	0	0	7.5	0	0	Mud-flats
4.02	64.2	14.4	21.4	0	0	0	0	0	Mud-flats
3.92	52.8	9	38.2	0	0	0	0	0	Mud-flats
3.82	64.3	10.1	25.1	0	0	0.5	0	0	Mud-flats
3.71	47.8	25.1	25.6	0	0	1.5	0	0	Mud-flats
3.6	63.1	13.8	23.2	0	0	0	0	0	Mud-flats
3.52	60.5	19	20.5	0	0	0	0	0	Mud-flats
3.4	57.8	9.6	27.3	0	1.1	4.3	0	0	Mud-flats
3.2	58.2	10.1	29.1	0	0	2.6	0	0	Mud-flats
3	59.3	12.3	27.9	0	0	0.5	0	0	Mud-flats
2.8	53	15.8	25.6	0	0	5.6	0	0	Mud-flats
2.6	65.7	15.5	16.6	0	0.8	1.5	0	0	Mud-flats
2.4	61.1	13.7	24.6	0	0	0.6	0	0	Mud-flats
2.2	73.9	15.9	10.2	0	0	0	0	0	Open Mar Channels
2	55.3	19.2	22.4	0	0	3.2	0	0	Mud-flats
1.8	56.7	17.7	23.6	0	0	2	0	0	Mud-flats
1.6	59.6	13.5	23.5	0	0	3.5	0	0	Mud-flats
1.2	58.3	18.4	22.9	0	0	0.4	0	0	Mud-flats
1	62.2	21.4	15.8	0	0	0.5	0	0	Mud-flats
0.8	70.6	14.5	12.9	0	0.4	1.6	0	0	Open Mar Channels
0.6	53	19.1	27.5	0	0.4	0	0	0	Mud-flats
0.4	77.4	14.5	7.7	0	0	0.5	0	0	Open Mar Channels

Table 6.3 Analysis of the contemporary diatom data set (% TDV) according to the ecological classification scheme of Vos & deWolf (1993)

Ecological Groups

Mar Plank = Marine plankton
Mar Tych = Marine tychoplankton
MB Epip = Marine/brackish epipelon
MB Aero = Marine/brackish aerophilous
MB Epiphyt = Marine/brackish epiphytes
BF Epipel = Brakish/fresh epipelon
BF Aero = Brackish/fresh aerophilous
FR Epiphyt = Fresh epiphytes

Depositional Environment

Pools in SM = Pools in the saltmarsh
SM abobe MHW = Saltmarsh above Mean High Waters
SM around MHW = Saltmarsh around Mean High Waters
Mud-flats = Intertidal mud-flat deposition

(1993). Figure 6.1a) summarises abundance of the individual species across the transect, whilst Figure 6.1b) groups the species into ecological groups according to their lifeform. Table 6.3 provides a breakdown of the dominant ecological groups (% TDV) and the inferred depositional setting where such assemblages would be found in Dutch sedimentary environments (Vos & deWolf, 1993).

Lower Mudflat: 0.4 to 4.3m O.D.

Marine planktonic (e.g. *Paralia sulcata*) and tychoplanktonic (e.g. *Delphineis surirella*) species dominate the assemblages of the lower zone, contributing *c*. 60% and 15% TDV respectively. Marine-brackish epipelon species are also a significant component, increasing in frequency from *c*. 20-30% TDV with altitude. Low counts (<5% TDV) of brackish-fresh epipelon species are recorded.

Planktonic species dominate, maintaining abundances of >60% TDV throughout the zone. Epipelon and to a lesser extent, tychoplanktonic species also influence the overall ecological assemblage.

Upper Mudflat: 4.3 to 5.03m O.D.

A decline in marine planktonic species occurs through the zone, from *c*. 60% to 25% TDV, characterised by declining frequencies of *Paralia sulcata* and *Thallasiosira excentricus*. Tychoplanktonic species increase to c. 20% TDV within the zone. Marine-brackish epipelon species, whilst fluctuating, rise to c. 40% TDV towards the upper mudflat zonal boundary (e.g. *Gyrosigma spencerii, Nitzschia sigma*). Subtle increases in brackish-fresh epipelon species are also indicated through *Nitzschia nana* and *Gyrosigma peisonis*.

Planktonic diatom species continue to dominate, although their overall influence decreases with height up the zone, to be replaced by epipelon species. Tychoplanktonic species experience a subtle yet clear increase in abundance within the zone.

Lower Marsh: 5.03 to 7.1m O.D.

A significant shift towards marine-brackish epipelon species occurs within the lower marsh zone. Frequencies fluctuate between *c.* 40% and 80% TDV, with dominant species including *Gyrosigma var. spencerii* and *var. wansbeckii, Navicula cincta* and *Nitzschia fasciculata*. There are respective declines in the abundance of marine planktonic and tychoplanktonic species. Brackish-fresh epipelon species increase to *c.* 10% TDV. Epiphytic and aerophilous species begin to appear with height through the zone, although in low abundances (<5% TDV). Marine-brackish epiphytic and aerophilous species are encountered first, whilst fresh epiphytic and brackish-fresh aerophilous species appear with increased altitude.

Epipelon species dominate, contributing up to 90% TDV within the zone. Increases in planktonic assemblages mirror changes in the abundance of the epipelon species. Tychoplanktonic species maintain low (*c.* 10% TDV) frequencies through the zone, whilst aerophilous and epiphytic (<5% TDV) begin to increase in abundance with height.

Upper Marsh: 7.1 to 8.11m O.D.

The zone is characterised by a distinct decline in the influence of marine-brackish epipelon species together with an increase in brackish-fresh aerophilous species towards the upper zone boundary (HAT). The majority of the marine brackish aerophilous and fresh epiphytic species found along the transect are also found in this zone. Brackish fresh epipelon species continue to fluctuate and increase in abundance with height. Marine planktonic and tychoplanktonic species maintain similar frequencies as the lower marsh zone.

Whilst epipelon species dominate at the onset of the zone, the gradual reduction in their frequencies is mirrored by an increase in epiphytic and aerophilous species with height.

The diatom assemblages from the coastal transect are summarised in Figure 6.1b) and Table 6.3. The results indicate the validity of the classification scheme of Vos and deWolf (1993) in a coastal setting such as the Severn Estuary. Although the classification scheme was created for the reconstruction of palaeoenvironmental conditions in the Netherlands, the distinct vertical zonation of the contemporary diatom assemblages, combined with the accurate interpretation of depositional environments provided through Vos and deWolf (1993), suggests its application to palaeoenvironmental studies in the UK is possible.

Upon analysis of the diatom assemblages discovered at each altitudinal interval along the contemporary coastal transect, the inferred sedimentary environments correlated well with the observed environment of deposition at each sampling site. The sedimentary environments interpreted through Vos and deWolf (1993) compared well to the LDAZs created through Tilia*Graph (Grimm, 1991). For example, the upper marsh LDAZ was characterised by diatom assemblages that typify either pools in saltmarshes, or saltmarshes around/above MHW. Also, the samples analysed towards HAT were interpreted as being deposited in saltmarshes *above* MHW, whilst further down towards the lower boundary of the upper marsh zone, the diatom assemblages indicated deposition *around* MHW (primarily as a result of variations in aerophilous and epipelon percentages). The lower marsh LDAZ was characterised initially by assemblages indicating deposition in saltmarshes around MHW and as altitude dropped further, mud-flat assemblages typified the deposits. The upper mud-flat is wholly dominated by mud-flat diatom assemblages and is characterised by decreasing marine-brackish epipelon abundances and increasing marine planktonic abundances. Finally, the lower mud-flat zone contains predominantly mud-flat depositional assemblages, but open marine channels are indicated when assemblages are strongly influenced by marine planktonic species (>70% TDV). Such depositional assemblages would only be found towards and below MSL and are only present towards the base of the lower zone within the contemporary transect.

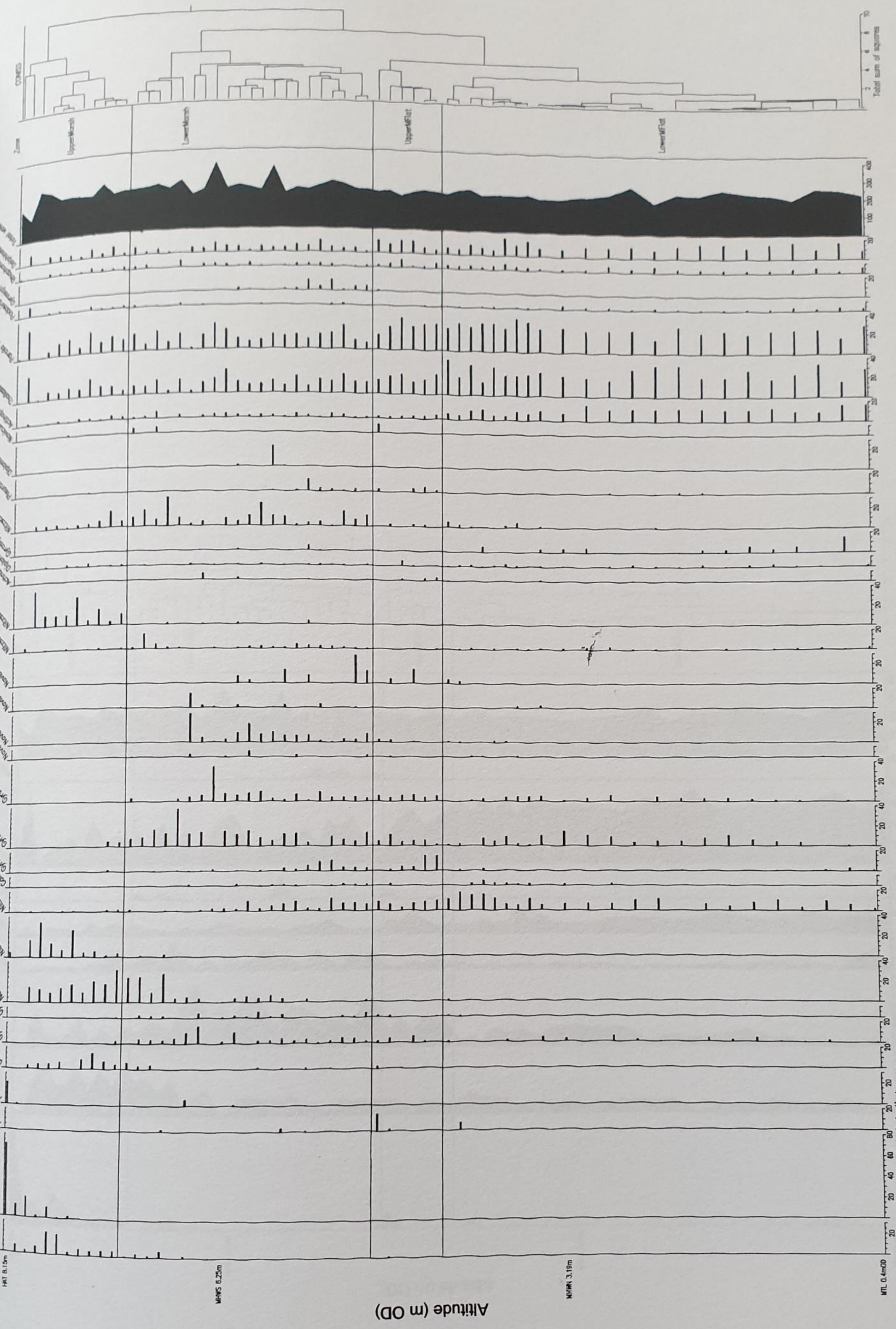
The strong correlation between actual and inferred depositional environments therefore indicates the reliability of the classification scheme towards archived deposits within the Gordano Valley. Its application to the Gordano Valley diatom archive should therefore provide valuable environmental information regarding the change in sedimentary environments over time. It should also provide a qualitative interpretation of variations in land elevation relative to sea level, which can in turn be related sea-level change during the site's depositional history. This can then be compared with changes in sea level inferred through the SLIPs from the stratigraphic boundaries and the reconstruction of land elevation (and hence sea level) achieved through the application of the diatom transfer function.

6.3.2 Allochthonous *vs*. autochthonous species of contemporary data set

The contemporary diatom data set has also been classified according to species lifeform (epiphytic/benthic or planktonic; Spencer, 1996) to assess the influence of allochthonous and autochthonous species through the tidal regime. A graphical representation of the diatom assemblages produced by TILIA is provided in Figure 6.2. Figure 6.2a) summarises the individual species abundances present on the transect, whilst Figure 6.2b) groups the species into their relevant lifeform groups (epiphytic/benthic or planktonic).

Lower Mudflat: 0.4 to 4.3m O.D.

Marine and marine-brackish planktonic species almost wholly dominate the zone, averaging *c.* 60% and 15% TDV respectively throughout. Marine planktonic species such as *Actinoptychus senarius*, *Paralia sulcata* and *Thallasiosira excentricus* are the main contributors to the assemblages, whilst *Rhaphoneis amphiceros* and *Delphineis surirella* contribute the marine-brackish diatoms. Low counts (<10%TDV) of brackish-marine and brackish-fresh epiphytic/benthic species are present through the zone, characterised by the presence of *Diploneis aesturii* and *Nitzschia sigma* respectively. Brackish epiphytic/benthic species gradually increase from *c*. 5% to 20% TDV with height through



<u>Figure 6.2a)</u> Contemporary diatom data set – Individual species abundance (>5%TDV) of epiphytic/benthic vs planktonic species.

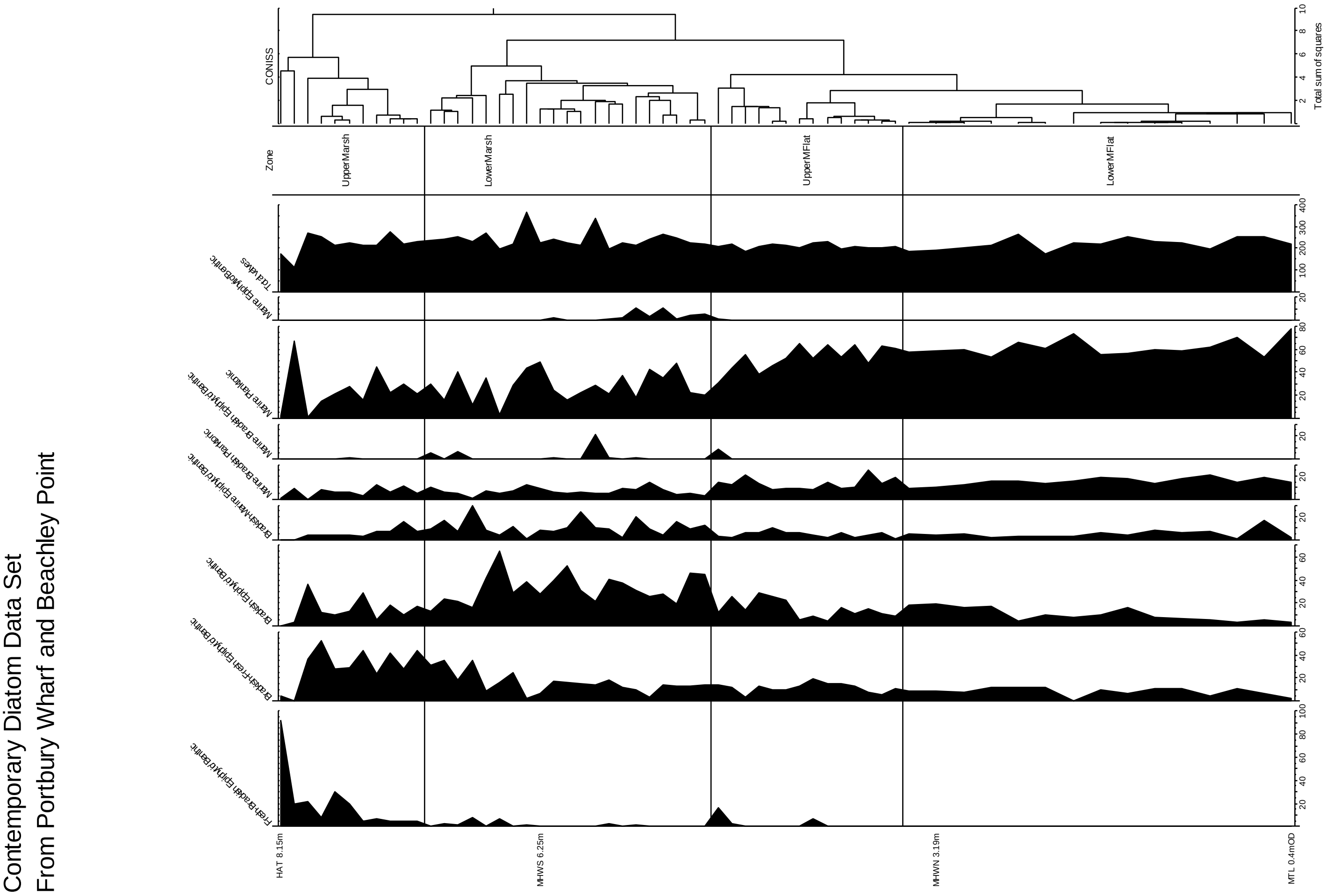


Figure 6.2b Contemporary diatom data set – ecological group according to lifeform (%TDV) of epiphytic/benthic vs planktonic species

the zone, primarily due to the increasing abundances of *Gyrosigma var. spencerii* and *var. wansbeckii*.

Upper Mudflat: 4.3 – 5.03m O.D.

Whilst marine and marine-brackish planktonic species continue to dominate, there is a clear gradational drop in the influence of marine planktonic species in the zone, from *c*. 60% to 25% TDV with height. This trend is characterised by declining frequencies of *Actinoptychus senarius* and *Paralia sulcata*. In contrast, there are distinct peaks in the abundance of marine-brackish planktonic species towards the upper and lower zonal boundaries. Brackish-marine and brackish-fresh epiphytic/benthic species remain in low relative abundances throughout (<5% and <15% TDV respectively), whilst brackish epiphytic/benthic species fluctuate in abundance, gradually rising in frequency through the zone. Fresh-brackish epiphytic/benthic species are introduced with height through *Navicula cuspidata*.

Lower Marsh: 5.03 – 7.1m O.D.

The lower zonal boundary is characterised by a sustained (though fluctuating) decrease in marine planktonic frequencies and a similar fall in marine-brackish planktonic species (to *c.* <10% TDV). Brackish epiphytic/benthic species dominate the zone, with abundances fluctuating throughout (ranging from 20% to 60% TDV), characterised by *Gyrosigma var. spencerii, var. wansbeckii* and *Nitzschia digitoradiata.* The only occurrence of marine epiphytic/benthic species occurs within the lower zone, through the presence of *Gyrosigma litorale* (<10% TDV). Low abundances of marine-brackish epiphytic/benthic species are also confined predominantly to this zone. Fresh-brackish epiphytic/benthic species maintain low abundances (<5%TDV), but begin to appear more often through the zone. Brackish-fresh epiphytic/benthic species initially maintain stable frequencies (*c*. 15% TDV), but increase in abundance with height, via species such as *Gyrosigma peisonis* and *Navicula cincta*.

Upper Marsh: 7.1 – 8.11m O.D.

The upper marsh zone is characterised by the dominance of brackish-fresh epiphytic/benthic species at lower altitudes, and the increasing influence of fresh-brackish epiphytic/benthic species with height. Marine planktonic species remain influential, but fluctuate throughout the zone, primarily due to the presence of *Thallasiosira excentricus* and *Paralia sulcata*. Marine-brackish planktonic species maintain low (<10% TDV) abundances. Marine-brackish epiphytic/benthic species are not present within the upper marsh, whilst a gradual decrease in brackish-marine epiphytic/benthic species is visible with altitude. Brackish epiphytic/benthic species fluctuate but decrease overall towards the upper boundary. Brackish-fresh epiphytic/benthic species dominate the lower zone, contributing *c*. 40% TDV. A sudden drop in abundance occurs towards the upper zone boundary, where fresh-brackish epiphytic/benthic species become dominant and almost wholly dominate towards HAT.

The allochthonous and autochthonous components of the contemporary diatom data set show clear zonal variation with height through the coastal transect (Figure 6.2). The dominance of planktonic (allochthonous) species in the lower zones of the coastal assemblages is expected due to the increased influence of tidal conditions with decreasing altitude. As tidal influence decreases with height, the ability for the transportation of planktonic species into the coastal environments also decreases. The dominance of planktonic species through the lower and upper mud-flat zones is replaced by increasing contributions from the epiphytic/benthic (autochthonous) diatom species that live in or attached to the substrate or vegetation. As these species provide the most reliable indicator of environmental conditions (due to their sessile lifeform), a transition in salinity conditions is indicated through the variation in abundance and diversity of autochthonous species. For example, whilst the lower and upper saltmarsh zones are dominated by the epiphytic/benthic species, the zones can be further subdivided according to the salinity requirements of these species. Fresh-brackish epiphytic/benthic species typify the coastal transect towards HAT (upper marsh zone), only to be replaced by brackish-fresh species with decreasing altitude. These in turn are replaced by brackish, brackish-marine and marine-brackish epiphytic benthic species in the lower marsh zone. There is therefore a distinct increase in saline tolerant species with distance down the coastal transect in response to a) the decreasing influence of freshwater depositional environments and b) the increasing influence of tidal (and thus marine) conditions.

6.4 Analysis of the environmental variables from the coastal transect

The four environmental variables to be included within the diatom-based sea-level transfer function were altitude, duration of flooding, grain size and organic content (LOI). See section 5.5 for the justification of the choice of environmental variables. Figure 6.3 and Table 6.4 summarises the ranges of each environmental variable. As indicated in

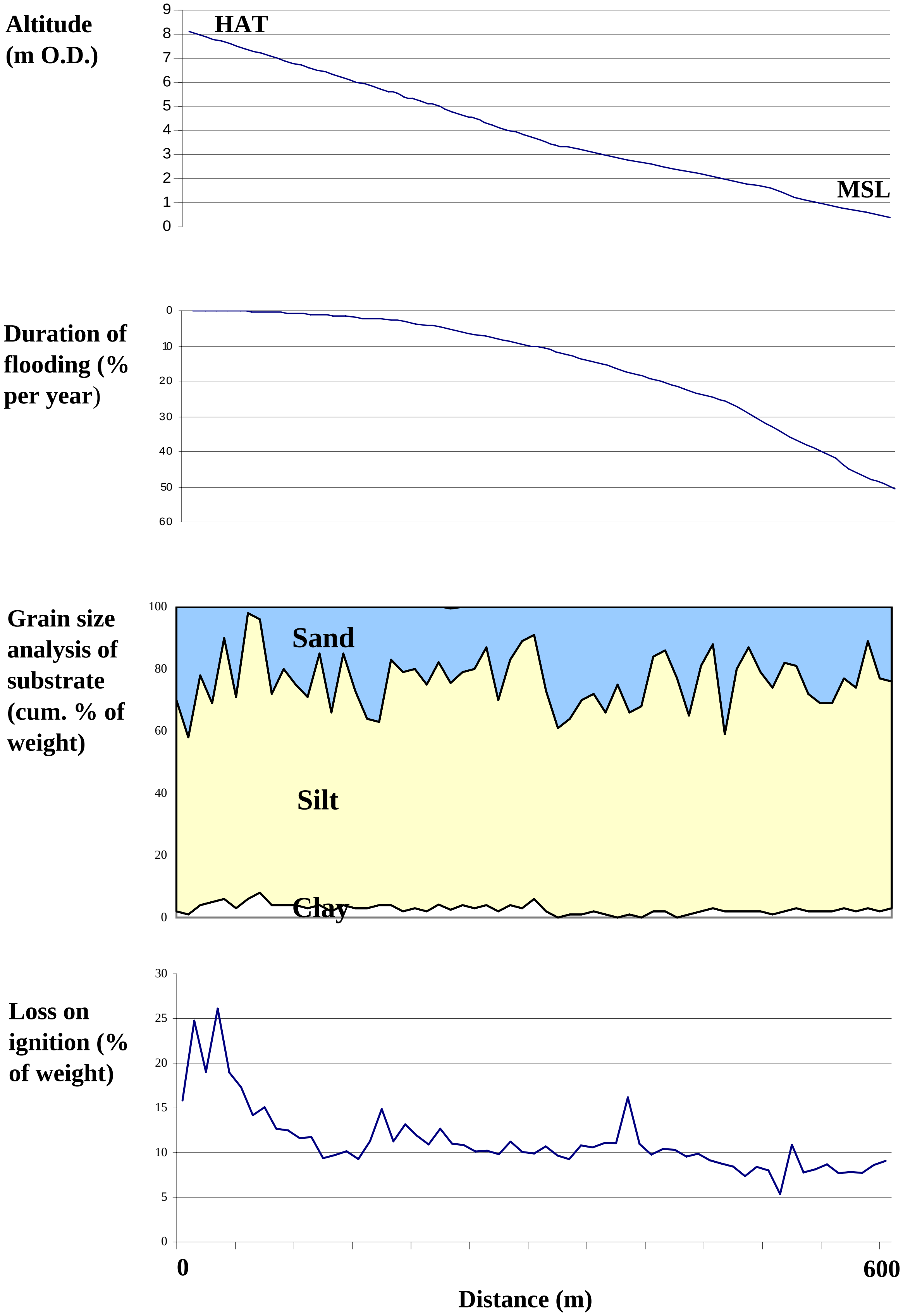


Figure 6.3 Summary of the environmental variables from the contemporary coastal transect.

Sample	Altitude (m O.D.)	Duration of flooding (% per year)	Clay (%)	Silt (%)	Sand (%)	LOI (%)
1	8.11	0	2	68	30	15.84
2	8.02	0	1	57	42	24.76
3	7.91	0.01	4	74	22	19.02
4	7.79	0.12	5	64	31	26.10
5	7.7	0.18	6	84	10	18.95
6	7.6	0.3	3	68	29	17.30
7	7.5	0.41	6	92	2	14.19
8	7.4	0.52	8	88	4	15.06
9	7.3	0.67	4	68	28	12.67
10	7.2	0.85	4	76	20	12.48
11	7.1	1.01	4	71	25	11.61
12	7	1.19	3	68	29	11.72
13	6.9	1.44	4	81	15	9.37
14	6.8	1.67	2	64	34	9.72
15	6.71	1.87	4	81	15	10.15
16	6.6	2.15	3	70	27	9.27
17	6.52	2.41	3	61	36	11.26
18	6.42	2.71	4	59	37	14.87
19	6.31	3.12	4	79	17	11.25
20	6.21	3.62	2	77	21	13.16
21	6.12	4.09	3	77	20	11.89
22	6.02	4.68	2	73	25	10.91
23	5.93	5.21	4	78	18	12.67
24	5.82	5.93	3	73	24	10.99
25	5.72	6.63	4	75	21	10.84
26	5.62	7.29	3	77	20	10.12
27	5.53	7.94	4	83	13	10.21
28	5.4	8.85	2	68	30	9.82
29	5.34	9.31	4	79	17	11.22
30	5.24	10.04	3	86	11	10.06
31	5.13	10.71	6	85	9	9.90
32	5.03	11.65	2	71	27	10.69
33	4.91	12.56	0	61	38	9.66
34	4.8	13.46	1	63	36	9.26
35	4.68	14.45	1	69	30	10.81
36	4.58	15.27	2	70	28	10.58
37	4.48	16.08	1	65	34	11.07
38	4.34	17.25	0	75	24	11.05
39	4.23	18.24	1	65	34	16.17
40	4.13	19.16	0	68	31	10.97
41	4.02	20.16	2	82	16	9.78
42	3.92	21.16	2	84	14	10.40
43	3.82	22.15	2	77	21	10.31
44	3.71	23.21	1	64	35	9.55
45	3.6	24.29	2	79	19	9.87
46	3.52	25.15	3	85	12	9.13
47	3.4	26.3	2	57	41	8.76
48	3.2	28.29	2	78	20	8.42
49	3	30.29	2	85	13	7.36
50	2.8	32.14	2	77	21	8.40
51	2.6	33.98	1	73	26	8.00
52	2.4	35.73	2	80	18	5.36
53	2.2	37.39	3	78	19	10.88
54	2	38.97	2	70	28	7.78
55	1.8	40.5	2	67	31	8.13
56	1.6	42.01	2	67	31	8.68
57	1.2	44.94	3	74	23	7.68
58	1	46.38	2	72	26	7.84
59	0.8	47.81	3	86	11	7.72
60	0.6	49.23	2	75	23	8.61
61	0.4	50.65	3	73	24	9.07

Table 6.4 Summary of the analysis of the environmental variables monitored for the diatom-based sea-level transfer function

Figure 6.3, altitude and duration of flooding show a linear relationship to each other; as altitude decreases with distance along the coastal transect, duration of flooding increases. Sample sites at lower altitudes along the coastal transect were more susceptible to tidal flooding than those positioned towards HAT, due to the increased exposure to tidal waters over a period of a year. As samples were required to be taken from HAT to MSL to create a robust diatom-based transfer function (Zong & Horton, 1999; Gehrels *et al*., 2001), samples were taken from 8.15m O.D. to 0.4m O.D. Consequently, upon calculation of the duration of flooding, the sample sites were submerged by tidal waters from 0% per year (above HAT) to *c*. 50% per year (at MSL).

Analysis of grain size distributions within the samples from the coastal transect yielded relatively consistent results. There is no distinct variation on the grain size of the samples along the coastal transect. The substrate was dominated by silts (between 4-64μm), contributing between 60-80% of the total sediment content. Sands (>64μm) contributed between 20-30% of the substrate and the clay component (<4μm) did not exceed 10%. There is a subtle decline in the clay content with decreasing altitude and increasing tidal flooding. This is likely to be due to the higher energy conditions present within the lower tidal frame, preventing the finest sediments from being deposited. Towards HAT, lower energy depositional conditions would have enabled these finer sediments to accumulate through suspension deposition. Whilst the relatively high sand content may be a true reflection of the substrate's sedimentary composition, it is also possible that organic matter that could not be removed through physical means may have biased the coarse component during grain size analysis. Although the sand content varies through the coastal transect, a subtle increase with height could indicate the influence of organic matter on the grain size results. An overall decline in grain size would be expected with height due to the lower depositional energy conditions in tidal waters towards HAT (Sly, 1994).

There is a clear increase with altitude in the amount of organics present within the coastal samples. The organic content is shown to be below 10% at around MSL, increasing to *c*. 25% towards HAT. The increase in vegetation cover on coastal margins with altitude explains the LOI results. Due to the submergence of the mud-flats and lower saltmarsh regions for much of the year through tidal movements, the majority of the vegetation is found towards HAT where infrequent tidal flooding enables the colonisation and expansion of vegetation. Consequently, organic matter accumulates at greater rates with increased altitude and decreased tidal flooding as shown in Figure 6.3.

Chapter 7: The construction of the diatom-based sea-level transfer function

7.1 Introduction

Field and laboratory analyses of the contemporary coastal lowlands of the Severn Estuary have established that the incorporation of two separate transects has created a reliable diatom data set. The diatom assemblages and environmental variables present on the coastal transect have been quantified. The numerical analysis of the data set to create a statistically robust transfer function is explained within this chapter.

7.2 Ordination analysis

Gradient analysis, as previously mentioned in Chapter 4, enables an assessment of environmental controls on species abundance and diversity through various analytical techniques. One such technique is weighted averaging. Weighted averaging regression has a number of advantages over other regression models that rendered this technique suitable for this study. One such advantage is that weighted averaging works best with a) species rich data, and b) where species may be absent in many of the samples (ter Braak & Juggins, 1993). This technique has also been successfully applied to diatom-based sea-level reconstructions elsewhere (Zong & Horton, 1999; Ng & Sin, 2003).

Ordination is a type of weighted averaging that is widely used for palaeoecological analysis due to its ability to explain community variability. The statistical computer package CANOCO (ter Braak, 1990) provides the ability to apply ordination to a data set. The standard techniques are able to order graphically species and samples into two or three axes of variation, in an attempt to identify similarities and differences between samples within a data set. Such methods are termed “indirect” or “unconstrained” ordination and include techniques such as Correspondence Analysis (CA) and Detrended Correspondence Analysis (DCA) (Woodland, 1996). More complex techniques however, identify the strength of environmental variables upon species distribution. Such methods, termed “direct” or “constrained” ordination, include Canonical Correspondence Analysis (CCA), and this ordination technique statistically relates species, samples and environmental variables together.

In order to select the appropriate correspondence analysis, it was necessary to establish whether a linear or unimodal relationship existed between species and environmental variables within the contemporary data set. The contemporary diatom assemblages were therefore subjected to Detrended Canonical Correspondence Analysis (DCCA) in the CANOCO program in order to understand the statistical relationship present between the species and environmental variables (ter Braak, 1990). In DCCA, the environmental variable with the greatest gradient length has the strongest control on species abundance and diversity. If the gradient lengths are <2 standard deviation (S.D.) units, then the species are considered to show a linear relationship with environmental variable. If the gradients are longer than 2 S.D. units, a unimodal response prevails, as several taxa have their optima located within the gradients (Birks, 1995). Table 7.1 summarises the DCCA results for each environmental variable.

Axis	1	2	3	4	Total Inertia
Length of gradient					
Altitude	2.741	7.884	3.033	2.204	5.899
Flooding	2.442	6.757	4.705	3.219	
LOI	2.471	4.985	6.204	2.891	
Grain size	2.513	1.268	0.978	7.378	

Table 7.1 Summary of DCCA results indicating the gradient lengths for each environmental variable (S.D. units).

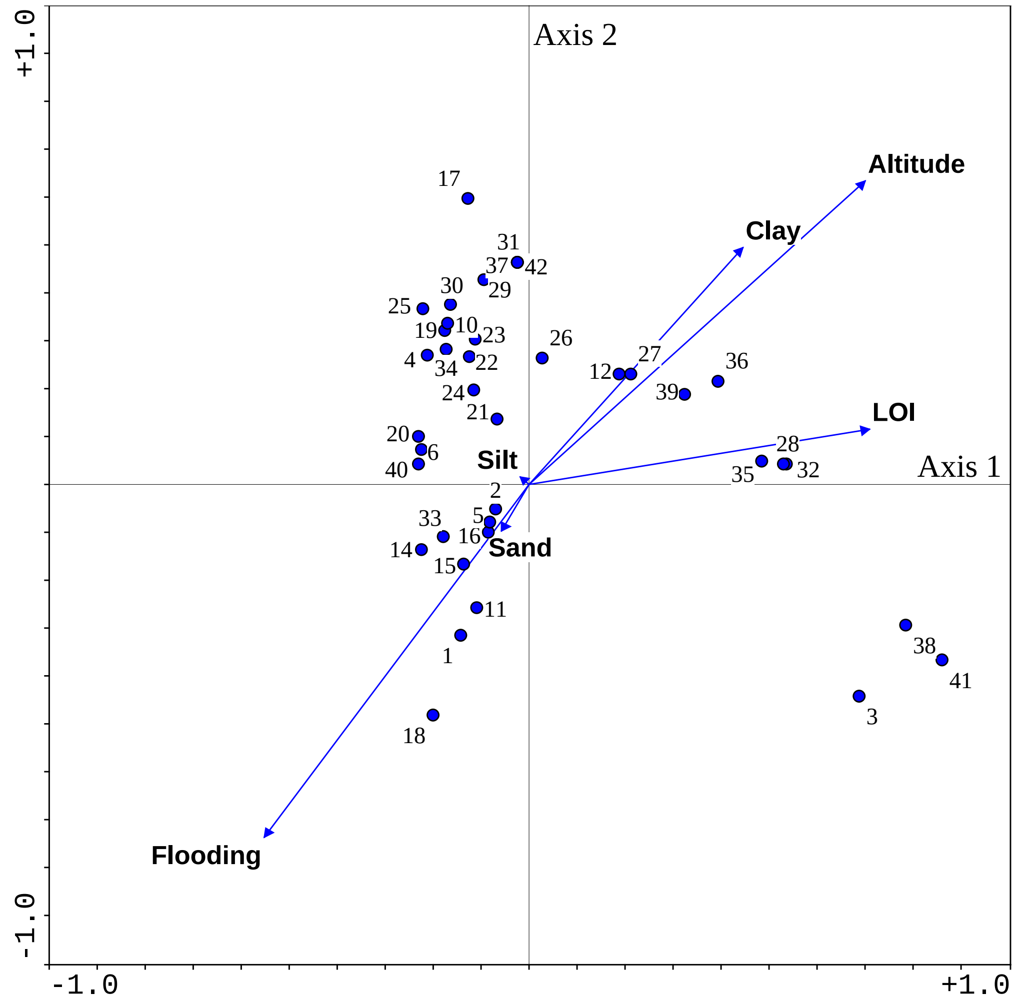
The longest gradient along axis 1 was produced for altitude (2.741). There is a progressive decrease in the gradient length for the other environmental variables of grain size, LOI and duration of flooding respectively. Axis 1 is used as it provides an estimation of the relationship between gradient length and the environmental variable in question (Birks, 1995). DCCA of the data set also indicated that all environmental variables follow a unimodal relationship with the diatom abundance data, as all gradient lengths along axis 1 are above 2 S.D. units. Thus unimodal-based methods of regression and calibration were used in the subsequent analysis and transfer function development. Canonical Correspondence Analysis (CCA), a direct method of ordination, was applied to assess the relationship between species and environmental variables. A summary of the CCA results created from the data set is given in Table 7.2.

Axis	1	2	3	4	Total Inertia
Eigenvalues	0.615	0.351	0.182	0.121	5.899
Species-environment correlations	0.921	0.849	0.678	0.712	
Cumulative percentage variance:					
of species data	10.4	16.4	19.5	21.5	
of species-environment relationship	43.7	68.6	81.5	90.2	
Sum of all unconstrained eigenvalues					5.899
Sum of all canonical eigenvalues					1.408

Table 7.2 Summary of CCA results from the diatom assemblages of the contemporary data set

CCA also indicates the percentage of the species-environment relationships that are explained through the environmental variables, known as the explained variance. Table 7.2 indicates that the CCA axes 1 and 2 explain 16.4% of the total variance in the diatom data. These two axes also represent 68.6% of the species-environment relationship (Table 7.2). These results compare favourably with the results attained through CCA by Zong & Horton (1999), in which 12.9% of the total variance in diatom data was explained by axes one and two, together with 59.7% of the total species-environment relationship. Similarly, Ng & Sin (2003) indicated that, through the application of CCA, 30.5% of the total diatom data was explained by the first two axes, and also explained 50.3% of the species-environment relationship.

The computer package CanoDraw (Smilauer, 1992) was used to assist environmental interpretation through plotting ordination results on a two-dimensional graph. Figure 7.1 displays the CCA species-environment biplot produced through CanoDraw.



<u>Diatom Species Key</u>

1 *Actinoptychus senarius*
2 *Paralia sulcata*
3 *Podosira stelligera*
4 *Striatella unipunctata*
5 *Thallasiosira excentricus*
6 *Gyrosigma litorale*
7 *Dimerogramma spp.*
8 *Diploneis bombus*
9 *Diploneis litoralis*
10 *Diploneis notabilis*
11 *Navicula flanatica*
12 *Navicula gracilis*
13 *Navicula humerosa*
14 *Nitzschia accuminata*
15 *Rhaphoneis amphiceros*
16 *Delphineis surirella*
17 *Achnanthes brevipes spp.*
18 *Gyrosigma hippocampus*
19 *Pleurosigma aesturii*
20 *Gyrosigma distortum*
21 *Gyrosigma spencerii*
22 *Gyrosigma wansbecki*
23 *Navicula digitoradiata*
24 *Navicula avenacea*
25 *Navicula salinarium*
26 *Nitzschia fasciculata*
27 *Nitzschia navicularis*
28 *Nitzschia vitrea*
29 *Gyrosigma peisonis*
30 *Gyrosigma scalproides*
31 *Navicula peregrina spp.*
32 *Nitzschia nana*
33 *Nitzschia sigma*
34 *Nitzschia sigmoida*
35 *Achnanthes hungarica*
36 *Gomphonema ovilaceum*
37 *Gyrosigma attenuatum*
38 *Hantzschia amphioxys*
39 *Navicula cincta*
40 *Navicula cuspidata spp.*
41 *Pinnularia viridis*
42 *Rhoicosphenia curvata*

<u>Figure 7.1</u> CCA biplot of diatom species and environmental variables from the Portbury Wharf/Beachley Point contemporary transect.

The environmental variables are represented in the CCA biplot by arrows (Figure 7.1), with the longest arrows indicating the variables which are the most important in influencing diatom community variation. Each species is presented on the plot as a point. The position of the species point relative to the arrow is an important indicator of the influence of that variable upon the species in question; the closer that species is to the tip of the arrow, the more influenced it is by that environmental variable. Also, the position of the arrow relative to the axis is also important as it indicates how clearly that axis is influenced by that environmental factor.

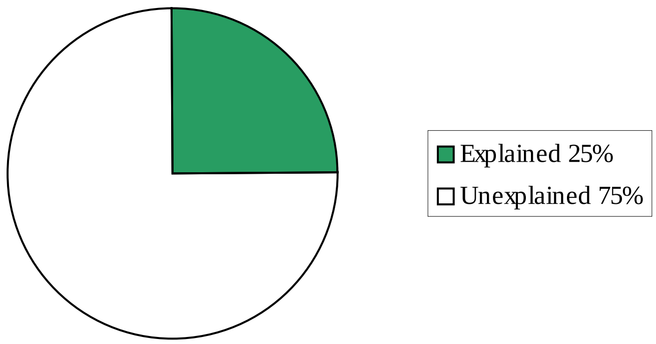
The variables of altitude and flooding duration have the longest environmental arrows, suggesting these variables are the most important when explaining the variance in the diatom data. The loss on ignition (LOI) and clay variable arrows are shorter but of similar length to one another, whilst those of silt and sand have the shortest. The organic content, along with the amount of clay present in the substrate are therefore more influential on diatom abundance than the amount of silt and sand present. LOI is positioned closer to axis one, reflecting a major gradient from high marsh (on the right of the biplot) to tidal flats (on the left of the biplot) as organic content decreases from HAT to MSL. In contrast, the distribution of the grain size arrows suggest a transition from coarser sediments (sand) from the bottom of the biplot, through silts in the central region, to the finest sediments (clay) at the top of the biplot. The gradient arrows of altitude and tidal flooding are positioned at almost 45 degrees to axes one and two. Considering the relative strength of these gradients (indicated by their arrow length and DCCA), the variables do not seem to be correlated with either ordination axes. A possible explanation for this could be that although a unimodal relationship exists between altitude, tidal flooding and the diatom assemblages, the actual data sets obtained for the variables are themselves linear. For example, with distance from MSL to HAT, altitude increased by incremental 10-20cm intervals throughout, whilst flooding duration decreased in a similar fashion with distance onshore. In contrast, values for the other environmental variables were non-linear. This explanation is further supported by the two environmental arrows of altitude and duration of flooding that point in opposite directions. This could be explained by the inverse relationship of the two environmental variables; that is, as altitude at each sample site gradually decreases with distance seaward, duration of flooding increases. Therefore, the relationship shown between altitude and duration of flooding with the other variables is a product of the sampling methodology. The regular sampling points along the contemporary transect caused incremental changes in the altitude and duration of flooding data to be achieved, whilst the results of LOI and grain size did not follow the same trend.

When considering the distribution of diatom species on the CCA biplot, over half the species show strong associations with the environmental variables considered. However, a number of species are positioned in the upper left quadrant of the diagram and seem not to correlate with the variables. If these species were planktonic in lifeform, then their poor correlation could be explained through their mobile nature and therefore would not be constrained by altitude or tidal flooding for example. However, these species live either attached to or within the substrate and thus a stronger association with the environmental variables would be expected. As this is the case, analysis of the diatom ecology may explain the distribution on the CCA biplot. The majority of the species live in brackish environments and thus are unsurprisingly abundant on the coastal zone of the

Severn Estuary. These species may therefore have a broader tolerance to the environmental variables in question and consequently would not show particular correlations with individual variables. Alternatively, considering that all the environmental variables are included within this analysis, if a species distribution was primarily controlled by both altitude and tidal flooding, the strength of both these variables in determining diatom distribution would make it difficult for a species to be plotted accurately on the CCA biplot. Consequently, the biplot would not be able to position a species in close proximity to either environmental arrow without biasing interpretation towards that variable. This could explain the subsequent position of the species in question; towards the centre of the plot, but not associated clearly with either altitude or tidal flooding.

The overall variation in species distribution in the data set is shown by CCA as being 5.899 (Table 7.2). The environmental variables account for 25% of this variation in diatom data (calculated by dividing the sum of all canonical eigenvalues by the sum of all unconstrained eigenvalues, x 100). In a similar study of diatoms and saltmarshes in the UK, Zong and Horton (1999) were able to explain 21.6% of community variability within the diatom data through sampled environmental variables. To understand how each of the variables contributed to the 25% explained variance, partial Canonical Correspondence Analysis (pCCA) was then applied to the environmental variables. This clarified the independence and relative strength of the major gradients, their relationship with the other gradients (termed “covariables”) as well as revealing inter-correlation between variables. Figure 7.2a indicates the total variation of the diatom data set expressed as a percentage of explained and unexplained variation, whilst Figure 7.2b shows the influence of each variable on that explained variance.

a)



b)

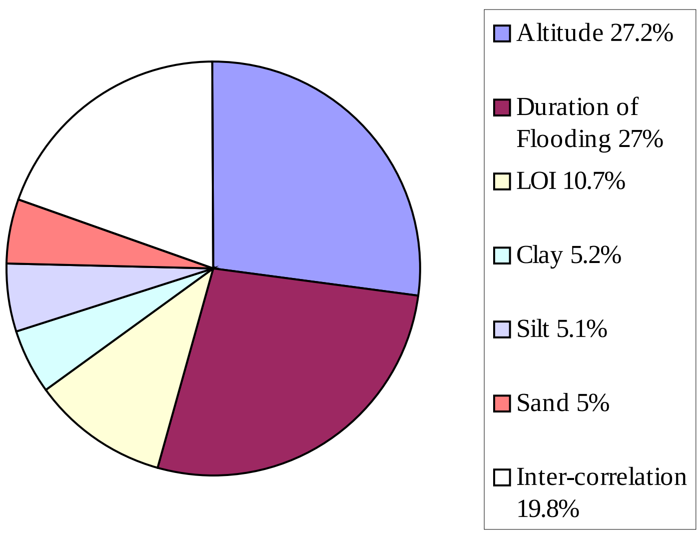


Figure 7.2 Pie charts of a) the explained and unexplained portions of the diatom data set and b) the contribution of each environmental variable to the explained variance.

Of the 25% explained variation within diatom data that is accounted for by the environmental variables measured, pCCAs show that the total explained variance is composed of 27.2% (altitude), 27% (duration of flooding), 10.7& (LOI), 5.2% (clay fraction), 5.1% (silt fraction) and 5% (sand fraction). The remaining 19.8% of the total explained variance is contributed to the data set through inter-correlation between environmental variables.

A considerable amount of the variation within the diatom data set, however, could not be explained through the environmental variables (75%; Figure 7.2a). One possible explanation could be that not all environmental variables that influence the diatom abundance and diversity were analysed and accounted for during the development of the contemporary diatom data set. Charman *et al*. (2002) incorporated eight environmental variables into their data set when assessing the zonation of testate amoebae on contemporary coastal transects, including those variables utilised in this study and salinity, pH and % total carbon. As a result, the relationship between environmental variables and testate amoebae assemblages achieved between *c*. 41% and 69% explained variance when analysed through CCA. When investigating sea-level change in Hong Kong through quantitative diatom analysis, Ng and Sin (2003) included 12 environmental variables to explain 60.5% of the diatom variance. Environmental variables such as water depth, wind fetch, coastal gradient, salt content and water content were also assessed during the development of the transfer function. The results of the contemporary diatom data set for this study, however, explain more of the total variance within the data set (25%), than that of Zong and Horton (1999), who could only account for 21.6% of the variation. The authors have stated that such results could still be used to develop a statistically significant transfer function. This is also the case for the diatom data set compiled for this study.

7.3 Regression analysis

The identification of altitude as the principal environmental control on diatom variability in the Severn Estuary allowed the derivation of a transfer function to reconstruct the former height of depositional surfaces relative to the tide level. This could be used to calculate changes in sea level within the Gordano Valley. It was then possible to express the value of a particular environmental variable as a function of a diatom assemblage; this is known as a transfer function (ter Braak, 1987) and was achieved using regression analysis (Juggins, 2003). Using the contemporary diatom species data set and altitude as the environmental variable, the data were subjected to regression analysis using the C2 program.

As a first step, the response of modern taxa to the contemporary environment was modelled. This was achieved by utilising the modern data set of species assemblages from the Portbury Wharf/Beachley Point coastal transect, together with their associated environmental variables (altitude, duration of flooding, particle size and LOI). This technique is termed “regression analysis”, within which a number of statistical models were applied to the data set in order to identify the methods that would provide the most robust understanding of the modern day species-environment relationship. Weighted averaging-based regression methods were chosen due to their ability to work best with species rich data (ter Braak & Juggins, 1993) and the success achieved with the application of such techniques in similar research (Zong & Horton, 1999). The methods utilised were weighted averaging (WA), tolerance downweighted weighted averaging (WA-Tol) and weighted averaging partial least squares regression (WA-PLS). Each model performance was evaluated by comparing model-predicted values for environmental variables (inferred from diatoms) against the observed values recorded in the modern data set. The model that produced the lowest prediction errors was used to construct the transfer function. Each of the models have been successfully applied to previous quantitative palaeoecological reconstructions (Woodland, 1996; Zong & Horton, 1999; Gehrels *et al.*, 2001; Ng & Sin, 2003).

WA assumes that, given a range of species with optima distributed along an environmental gradient, a particular site along that gradient will be dominated by certain species whose ecological optima are positioned in close proximity to that site (Juggins, 1992). Thus WA describes the optimum environmental conditions required for each diatom species. The WA-Tol model is a modified form of WA and gives species with narrower environmental tolerances greater weight than taxa with wide tolerances (Ng & Sin, 2003). WA-PLS regression is a technique that combines a linear and unimodal model together in an attempt to maximise the predictive power of the transfer function, especially through the improvement of the accuracy achieved in predicted species' optima (Woodland, 1996). WA-PLS uses the residual correlation structure in the data to improve the fit between the diatom data and the environmental variable in the modern data set (Birks, 1995).

During statistical analysis of a modern data set with WA and WA-Tol, it is common for "shrinkage" of the inferred environmental tolerances to occur. This is because the results are averaged twice; once during the initial regression analysis of the modern data set, and again when the calculated tolerances are applied to the archived sediments (Birks, 1995). As a result, two different approaches that limit “deshrinking” are available within the WA and WA-Tol models. These are known as classical regression and inverse regression. Ter Braak (1995) suggests that the inverse approach is a more suitable technique if the subsequent fossil assemblages are from the central part of the distribution of the modern data set, whilst the classic approach may perform better at the extremes of the data set. Both approaches were included within the regression analyses to assess their contribution to a statistically robust transfer function.

Two cross-validation techniques are also available within C2 to assess the performance of modern data sets. The first is known as jack-knifing (or “leave-one-out”) and has been applied to previous quantitative palaeoecological reconstructions (Woodland *et al.*, 1998; Zong & Horton, 1999; Ng & Sin, 2003). The technique evaluates the performance of the regression techniques by applying the model to the data from which it was derived (by leaving one sample out of the data set and using the model to predict its value). Jack-knifing measures the overall predictive abilities of the regression technique in question and produces a standardised margin of error for the whole data set. The second technique is bootstrapping (x 1,000 cycles), which assumes that the influence of a variable (from one sample to another) will differ depending on the composition of the species assemblage and thus estimates the sample-specific errors that occur within a data set (Birks, 1995). Both cross-validation techniques calculate the root mean square error of prediction (RMSEP), which can be used to assess the performance of the transfer function and evaluate how well the model can be expected to function as a predictive tool (Birks, 1995). The coefficient of determination (r^2) was also calculated to measure the strength of the correlation between observed and inferred values for the environmental variable in question (Ng & Sin, 2003).

Using the contemporary diatom species data set and altitude as the environmental variable, the data were subject to regression analysis using the C2 program (Juggins, 2003). The regression analyses WA, WA-Tol and WA-PLS were all used in order to assess their performance in the model. Table 7.3 summarises the statistical information derived from the application of each of the analytical techniques to the data set. Table 7.3a) contains the RMSE and r^2 results obtained from each technique prior to cross-validation, whilst Table 7.3b) summarises the RMSE and r^2 results after cross-validation had been applied in order to evaluate the performance of each regression technique.

The RMSE and r^2 results, which were calculated prior to cross-validation (Table 7.3a), indicate that WA-PLS regression produces a strong correlation between the observed and inferred altitude data ($r^2 = 0.936$) and also produces the lowest apparent error (RMSE = 0.532). However, these results are seen as unreliable as the correlation and error estimates were calculated by applying the regression cycles to the same data set that was used to develop the transfer function (Woodland, 1996, Zong & Horton, 1999). The application of cross-validation to the regression analyses provides a more robust indicator of the performance of each model by removing sections of the data set and then running the developed model against these to assess its prediction performance.

a)

Method	Deshrinking	RMSE	r^2
WA	inverse	1.03469	0.758224
	classic	1.18825	0.758224
WA-Tol	inverse	0.680388	0.895453
	classic	0.719011	0.895453
WA-PLS	n/a	0.531717	0.936275

b)

Method	Deshrinking	$RMSEP_{jack}$	r^2_{jack}	$RMSEP_{boot}$	r^2_{boot}
WA	inverse	1.13522	0.709523	1.17803	0.704026
	classic	1.28744	0.713505	1.33063	0.707601
WA-Tol	inverse	0.824739	0.847057	0.910305	0.855105
	classic	0.876972	0.846632	0.964706	0.854303
WA-PLS	n/a	1.14581	0.752111	1.27009	0.792909

Table 7.3 Performance of the regression models with altitude as the environmental variable for the diatom data set a) prior to cross-validation and b) after jack-knifing and bootstrapping had been applied to each regression model.

Bootstrapping (x 1,000 cycles) and jack-knifing cross-validation techniques were applied to the data set. The advantage of bootstrapping over jack-knifing cross-validation is that, in the final reconstruction, the bootstrapping method takes into account the variation in diatom assemblages present within each sample. As a result, margins of error for each sample can be created to indicate the possible altitudinal variation inferred from each site. In contrast, jack-knifing only provides a standard error that would apply to all samples from the training set.

Analysis of the cross-validated results revealed that inverse and classical deshrinking WA-Tol analyses performed the best, producing the lowest margins of error (RMSEP) and the highest correlations between inferred and observed altitude (r^2) (Table 7.3b). A comparison of the inverse and classical deshrinking results shows that inverse deshrinking performed slightly better. Whilst classic deshrinking provides a prediction error of 0.876m, inverse deshrinking creates a lower error of 0.824m for the data set. The correlation between observed and inferred altitude for both deshrinking methods are almost identical (*c.* $r^2 = 0.846$). The lower prediction error would suggest that inverse deshrinking is the most suitable approach to limiting shrinkage of the inferred environmental tolerances. However, the difference in prediction error is only *c.* 0.05metres, and ter Braak (1995) suggests that the inverse approach is a more suitable technique only if the subsequent fossil assemblages are from the central part of the distribution of the modern data set, whilst the classic approach may perform better at the extremes of the data set. As the sedimentary archive of the Gordano Valley contains interbedded peat and silt units, the majority of the fossil assemblages to be analysed would be in close proximity to the extremes of the palaeo tidal frame, and thus classical deshrinking would perform best during subsequent analysis. Therefore, classical deshrinking was chosen for the calibration analysis. Similar results were attained through both bootstrapping and jack-knifing cross-validation, with WA-Tol classic deshrinking producing low $RMSEP_{jack}$ (0.876) and $RMSEP_{boot}$ (0.964), and high r^2_{jack} (0.846) and r^2_{boot}(0.854). WA-Tol classic jack-knifing, however, performs better in comparison to WA-Tol classic bootstrapping, as it provides a lower apparent prediction error.

Although bootstrapping produces individual margins of error for each fossil sample, jack-knifing performed better when applied to the data set and was therefore applied to the fossil data set. This highlights the importance of using cross-validation to estimate the likely error when a transfer function is to be applied to unknown fossil samples (Zong & Horton, 1999). Figure 7.3 plots the observed altitudinal variations recorded from the saltmarsh, against the inferred altitudinal values predicted through jack-knifed classic WA-Tol analysis of the diatom assemblages.

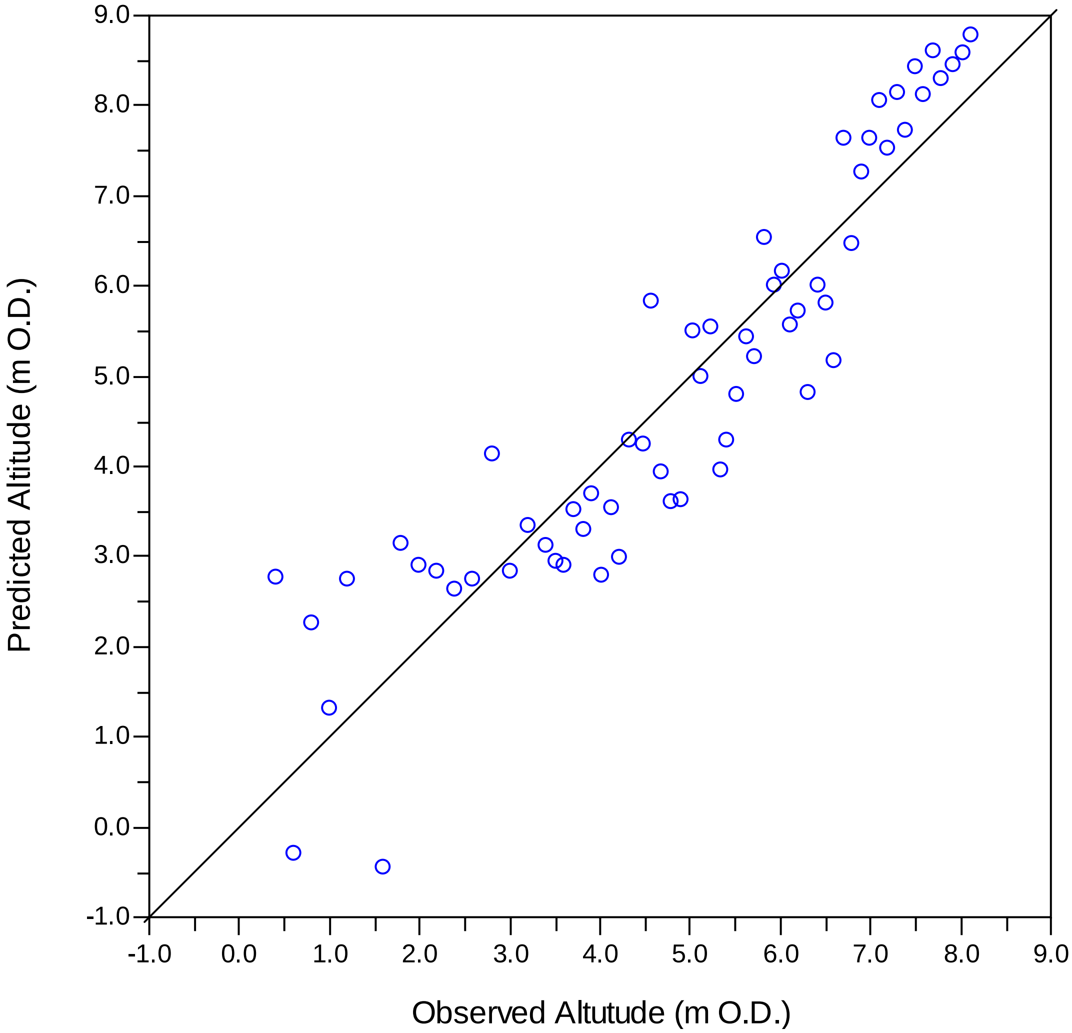


Figure 7.3 Observed versus inferred altitude values created through the application of jack-knifed classic deshrinking WA-Tol (r^2 = 0.846).

With a RMSEP of 0.876, WA-Tol with jack-knifed cross-validation and classic deshrinking is indicated as the most valid statistical model for this study. Comparisons cannot be made between the RMSEP results of this study and that of Zong & Horton (1999) as, whilst the RMSEP results here are in metres (relative to O.D.), Zong & Horton (1999) were analysing a number of coastal sites with contrasting tidal ranges, and consequently a standardised water-level index (SWLI) was created to enable comparisons. Although RMSEP is the parameter of interest when considering the suitability of statistical models, r^2 is a measure of the strength between observed and inferred values and thus should also be considered (Zong & Horton, 1999). The r^2_{jack} value (0.846) further confirms the reliability of altitude as an environmental variable which can be applied to archive diatom assemblages. This compares favourably with Zong & Horton (1999) whose results, also using WA-Tol_{jack}, produced a less accurate relationship between inferred and observed altitude (r^2=0.72). Gehrels *et al*. (2001) achieved similar results (r^2=0.73) when assessing the influence of altitude on diatom assemblages from three UK saltmarsh transects. The strength of the relationship between inferred and observed altitudes for the Severn Estuary coastal transect, therefore, performs better than other studies into contemporary coastal diatom data sets.

As palaeoenvironmental reconstructions are derived from understanding the optima and tolerances of modern diatom species, WA-Tol regression also calculates the environmental optima and tolerances for each diatom species over 5% TDV in the contemporary coastal transect. The individual species' optima and tolerances are presented in Figure 7.4. Table 7.4 provides a summary of the statistical data obtained during regression analysis and used to create Figure 7.4. A number of species occur only once within the contemporary data set (Table 7.4), but due to their abundance being greater than 5% TDV, they are deemed statistically significant and therefore are utilised within the study. There is a clear spatial variation in the tolerance range of each diatom species depending on their altitudinal optimum. For example, *Hantzschia amphioxys* has an altitudinal optima of 8.027m O.D., with a tolerance of 0.17m. In contrast, *Rhaphoneis amphiceros* has an optimum lower down the coastal transect at 3.27m O.D. and has a

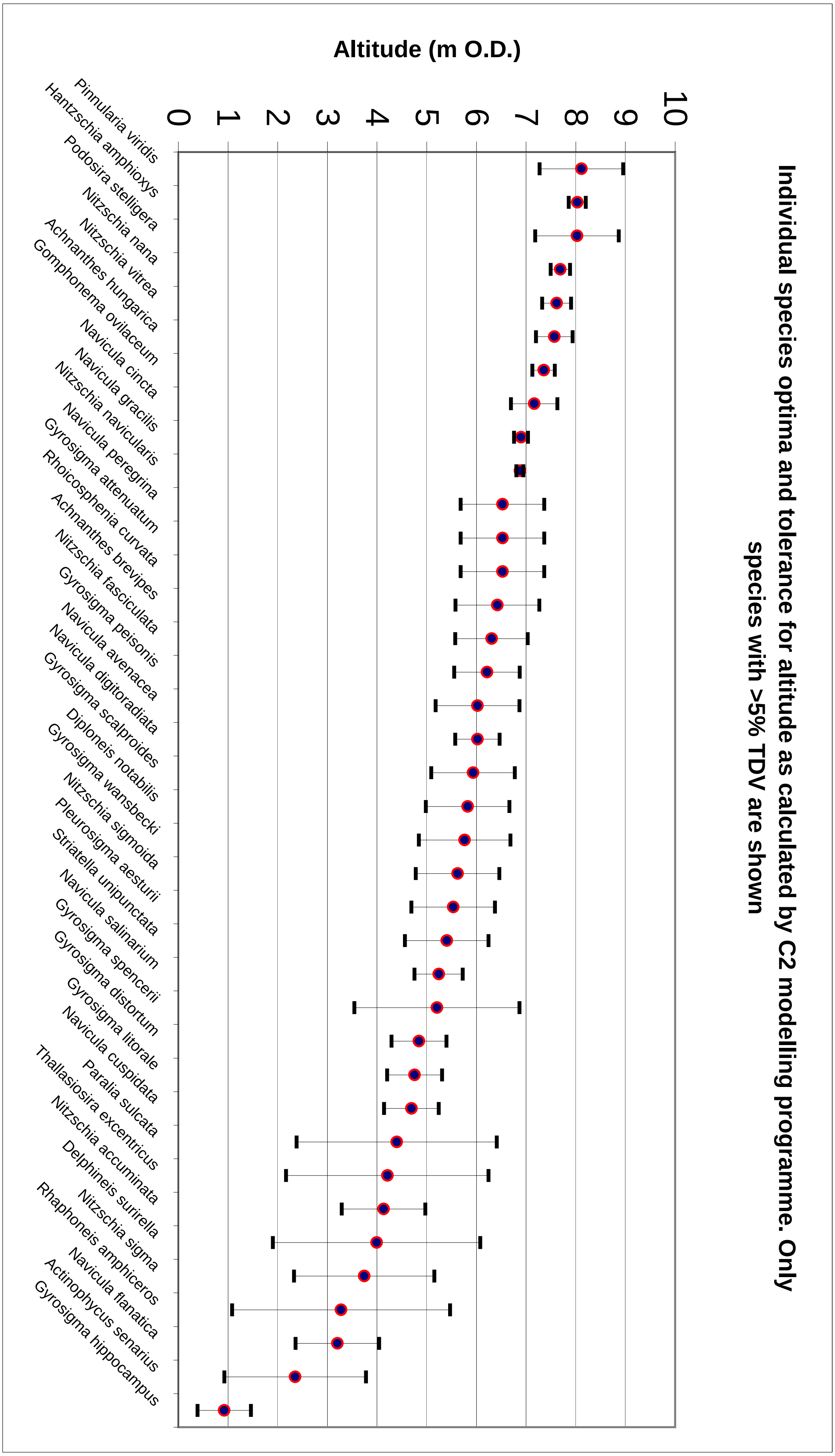


Figure 7.4 Individual species optima and tolerance values in relation to altitude

Name	Count	N2	Max	Lower Tolerance	Optimum Tolerance	Upper Tolerance	Tolerance
Pinnularia viridis	1	1.0	19	7.27	8.11	8.95	0.84
Hantzschia amphioxys	4	2.3	66	7.86	8.03	8.20	0.17
Podosira stelliger	1	1.0	10	7.18	8.02	8.86	0.84
Nitzschia nana	6	4.5	33.1	7.49	7.69	7.88	0.20
Nitzschia vitrea	7	5.4	36.5	7.32	7.61	7.90	0.29
Achnanthes hungarica	7	5.1	19.7	7.19	7.56	7.93	0.37
Gomphonema ovilaceum	6	5.1	14.9	7.12	7.35	7.57	0.23
Navicula cincta	15	12.3	30	6.69	7.16	7.63	0.47
Navicula gracilis	2	2.0	5.6	6.73	6.90	7.06	0.17
Nitzschia navicularis	2	1.6	13.7	6.78	6.87	6.97	0.10
Navicula peregrina	1	1.0	13	5.68	6.52	7.36	0.84
Gyrosigma attenuatum	1	1.0	5	5.68	6.52	7.36	0.84
Rhoicosphenia curvata	1	1.0	5	5.68	6.52	7.36	0.84
Achnanthes brevipes	1	1.0	6	5.58	6.42	7.26	0.84
Nitzschia fasciculata	16	12.3	28.4	5.57	6.30	7.03	0.73
Gyrosigma peisonis	5	3.9	19.1	5.55	6.21	6.87	0.66
Navicula avenacea	1	1.0	5	5.18	6.02	6.86	0.84
Navicula digitoradiata	10	7.4	27.7	5.57	6.02	6.46	0.44
Gyrosigma scalproides	1	1.0	5	5.09	5.93	6.77	0.84
Diploneis notabilis	1	1.0	20.2	4.98	5.82	6.66	0.84
Gyrosigma wansbecki	11	6.6	32	4.84	5.76	6.68	0.92
Nitzschia sigmoida	1	1.0	9	4.78	5.62	6.46	0.84
Pleurosigma aesturii	1	1.0	11	4.69	5.53	6.37	0.84
Striatella unipunctata	1	1.0	18.3	4.56	5.40	6.24	0.84
Navicula salinarium	6	4.6	27.1	4.75	5.24	5.72	0.49
Gyrosigma spencerii	24	18.4	35.8	3.54	5.20	6.86	1.66
Gyrosigma distortum	4	3.9	12.6	4.29	4.84	5.39	0.55
Gyrosigma litorale	7	6.4	16	4.20	4.75	5.30	0.55
Navicula cuspidata	2	1.7	15	4.12	4.68	5.24	0.56
Paralia sulcata	55	48.0	32.1	2.38	4.39	6.41	2.01
Thallasiosira excentricus	53	44.7	32.1	2.16	4.20	6.24	2.04
Nitzschia accuminata	1	1.0	6	3.29	4.13	4.97	0.84
Delphineis surirella	41	36.4	16	1.90	3.99	6.07	2.09
Nitzschia sigma	29	25.2	20	2.33	3.74	5.15	1.41
Rhaphoneis amphiceros	7	6.9	7	1.08	3.27	5.46	2.19
Navicula flanatica	1	1.0	7	2.36	3.20	4.04	0.84
Actinophycus senarius	21	19.6	15.4	0.93	2.35	3.77	1.42
Gyrosigma hippocampus	3	2.4	14	0.39	0.92	1.46	0.53

Count	= Number of occurrences
N2	= Effective number of occurrences
Max	= Maximum abundance
Lower Tolerance	= Lowest altitudinal tolerance for species
Optimal Tolerance	= Optimal altitude for diatom species
Upper Tolerance	= Upper altitudinal tolerance for species
Tolerance	= Species tolerance range either side of optimal tolerance

Table 7.4 Summary of statistical results from WA-Tol regression of the contemporary diatom assemblages, using altitude as the environmental variable.

tolerance of 2.19m. In general, planktonic species (e.g. *Paralia sulcata*, *Thallasiosira excentricus*, *Rhaphoneis spp*.) have a much higher tolerance than species that live attached to or within the substrate. This would be expected as, by definition, planktonic species live in the water column and can be transported considerable distances and (and thus different altitudes) by the tide. As a consequence, in comparison to epiphytic/benthic species with low tolerances in relation to changing altitude (e.g. *Hantzschia amphioxys*, *Nitzschia navicularis*), planktonic species are likely to be less influential when attempting to reconstruct altitudinal variations in the Gordano Valley sedimentary archive. Such species would be given lower weighting through weighted averaging than species considered to be more robust environmental indicators (see section 4.2). However, as planktonic species have been incorporated into the development of transfer functions during past research (Ng and Sin, 2003), all species were included in the transfer function for this study.

Part III:

The Palaeoenvironmental Archive of the Gordano Valley, North Somerset.

Chapter 8: Methodology

8.1 Introduction

This chapter will outline the field, laboratory and interpretative methods utilised in this study to understand the palaeoenvironmental evolution of the Gordano Valley. The theoretical background to each method is reviewed in order to justify its applicability to the research site.

The potential for a multi-proxy approach was investigated at the onset of this project. All previous research into environmental change in the Gordano Valley has relied upon palynology as a single proxy, with limited sediment particle size analysis. Other proxies have been developed and refined since the work of Jefferies *et al.* (1968) that may increase the amount of environmental information available from a sedimentary archive. When combined in multi-proxy analyses, they may be mutually beneficial, producing much more informative, reliable and accurate evidence (Lowe & Walker, 1997).

Given the research objectives of this project, a number of proxy techniques were potentially suitable. An initial reconnaissance in the Gordano Valley was undertaken to assess the presence of biological proxies within the sedimentary archive. Diatoms were abundant in the sediments seaward of the ridge, but were wholly absent landward of the ridge. Diatom analysis could therefore be applied only to the interbedded peats and silts in the valley. Pollen was abundant in sedimentary deposits throughout the valley. Therefore pollen analysis was a suitable technique to reconstruct vegetation change and provide chronostratigraphic markers. The use of testate amoebae analysis to assess the palaeohydrology of the valley was excluded early on in the study due to poor preservation of the testates throughout the sedimentary archive.

Following the initial reconnaissance of the Gordano Valley, the following analytical techniques were selected for use:

- **Lithostratigraphy**: to reconstruct the sedimentary history of the Gordano Valley.
- **Particle size analysis**: to elucidate the depositional environments of the sedimentary archive preserved within the valley.
- **Diatom analysis**: to assess the influence of relative sea level on lowland evolution, and to reconstruct quantitatively palaeo-surface altitudes relative to the tidal frame in order to understand sea-level changes in the valley. Numerical analysis of the diatom frustules aimed to produce quantitative palaeoenvironmental reconstructions of sea level.
- **Pollen analysis**: to reconstruct vegetation changes within the valley.
- **Radiocarbon dating**: to provide a chronological framework for key environmental changes within the valley.

To provide a full rationale for their inclusion in the research, the relevance of each proxy to the individual research objectives is explained in the following section.

8.2 To log the Quaternary stratigraphy of the Gordano Valley and reconstruct the sedimentary environments.

8.2.1 Lithostratigraphy

An understanding of the sedimentological characteristics within a depositional setting is vital for the interpretation of environmental change within a site such as the Gordano Valley. This is because lithostratigraphic investigations enable significant depositional events to be identified and placed in a chronological order. In this study, the physical characteristics of the sediments, both in the field and in the laboratory, were recorded using the Troels-Smith (1955) classification scheme. This scheme breaks down a sediment sample into four main components, and allows the inclusion of extra components that are also present, but that are not dominant. Key physical properties of the sediment layers are also identified according to darkness (Da), stratification (St), elasticity (El), dryness of the sediment (Dr), and the sharpness of the upper sediment boundary (UB). A summary of the sedimentary and physical properties classified by Troels-Smith (1955) and the nomenclature used is provided in Table 8.1. An example of this widely utilised classification technique is shown below:

Depth 53-73cm

Da	St	El	Dr	UB
3	0	0+	2+	0

Sh2, Ag2, Th++, As+, Ga+, Dh+

**Dark Brown Organic Rich Silt Horizon*

Degree of Darkness	
nig.4	black
nig.3	
nig.2	
nig.1	
nig.0	white

Degree of Stratification	
strf.4	well stratified
strf.3	
strf.2	
strf.1	
strf.0	no stratification

Degree of Elasticity	
elas.4	very elastic
elas.3	
elas.2	
elas.1	
elas.0	no elasticity

Degree of Dryness	
sicc.4	very dry
sicc.3	
sicc.2	
sicc.1	
sicc.0	water

	Sharpness of Upper Boundary
lim.4	< 0.5mm
lim.3	< 1.0 & > 0.5mm
lim.2	< 2.0 & > 1.0mm
lim.1	< 10.0 & > 2.0mm
lim.0	> 10.0mm

	Sh	*Substantia humosa*	Humous substance, homogeneous microscopic structure
I Turfa	*Tb*	*T. bryophytica*	Mosses +/- humous substance
	Tl	*T. lignosa*	Stumps, roots, intertwined rootlets, of ligneous plants
	Th	*T. herbacea*	Roots, intertwined rootlets, rhizomes of herbaceous plants
II Detritus	*Dl*	*D. lignosus*	Fragments of ligneous plants >2mm
	Dh	*D. herbosus*	Fragments of herbaceous plants >2mm
	Dg	*D. granosus*	Fragments of ligneous and herbaceous plants <2mm >0.1mm
III Limus	*Lf*	*L. ferrugineus*	Rust, non-hardened. Particles <0.1mm
IV Argilla	*As*	*A.steatodes*	Particles of clay
	Ag	*A. granosa*	Particles of silt
V Grana	*Ga*	*G. arenosa*	Mineral particles 0.6 to 0.2mm
	Gs	*G. saburralia*	Mineral particles 2.0 to 0.6mm
	Gg(min)	*G. glareosa minora*	Mineral particles 6.0 to 2.0mm
	Gg(maj)	*G. glareosa majora*	Mineral particles 20.0 to 6.0mm
	Ptm	*Particulae testae molloscorum*	Fragments of calcareous shells

Table 8.1 Physical and sedimentary properties of deposits according to Troels-Smith (1955)

In this classification, '0' describes a total absence of the physical characteristic in question, whilst '4' is the maximum possible value. For example, a darkness (Da) value of 3 has been given to the sample due to the dark brown coloration of the sediment. A value of 4 would have been given if the sediment was black, whilst a value of 0 would have been given if the sample was white.

The clastic/organic content of the sample is divided into four parts, each of which consists of 25% of the content. Within this example, the main components are *Substantia humosa* (Sh2, i.e. 50%), which is a humic substance (very well decomposed remains with no organic structure present), and particles of silt 0.2 to 0.002mm in size (Ag2). There are also traces of (less than 25%) *Turfa herbacea* (Th++), which consisted of roots and rootlets of herbaceous plants, clay particles <0.002mm in size (As+), sandy mineral particles 0.6 to 2mm in size (Ga+) and *Detritus herbosus* (Dh+; fragments of herbaceous plants >2mm in size).

The Troels-Smith scheme is objective and is applied widely in the study of lowland depositional environments (Aaby & Berglund, 1986; Spencer, 1996); this assures consistency in the recording of sedimentary characteristics and it also allows inter-site comparisons.

8.2.2 Field stratigraphy

The spatial extent of the study area within Gordano Valley (averaging 4km by 1km, with a total area of *c.* 6km^2) required the use of a sampling grid to optimise field descriptions. The coring grid allowed variations in the valley stratigraphy to be interpreted on both a spatial and temporal scale. Such a stratigraphic reconnaissance allows the identification of significant sedimentological and thus environmental shifts, which can then be investigated further through continued coring and typecore analysis. Figure 8.1 provides place names for all the key roads and areas within the Gordano Valley for reference, whilst Figure 8.2 shows the sampling grid and the position of each core taken from the research area. The positioning and orientation of the grid was controlled by the trend of the valley (WSW-ENE) and access permission. Consequently, the grid enabled cores to be sunk at 125m intervals. The position of the ridge feature discovered by Jefferies *et al.* (1968) is also superimposed onto Figure 8.2. Once the coring strategy was completed, higher resolution coring occurred within regions where typecores would be extracted (c. 62m intervals), access permitting. This approach to stratigraphical analysis, when compared to the scattered distribution of core sites in previous work (Jefferies *et al.*, 1968), provides an increased resolution with which to assess the valley's sedimentary archive.

A 3cm-diameter manual gouge corer was used to extract core samples for stratigraphic analysis. All cores were levelled into local altitudinal bench marks to establish the surface altitude of each core and to enable cross-core correlations. The majority of the cores were extracted from the Walton Moor and Weston Moor locales (Figure 8.1). This is primarily due to the access provided by English Nature and Avon Wildlife Trust. However, beyond Weston Drove, in the centre of the valley, access proved more difficult. The majority of the land from Weston Drove towards the Severn Estuary is private land. Whilst all relevant owners were contacted, not all were willing to permit access. Consequently, the sampling grid and subsequent core sites had to accommodate such access restrictions. Another problem was the presence of a tipping

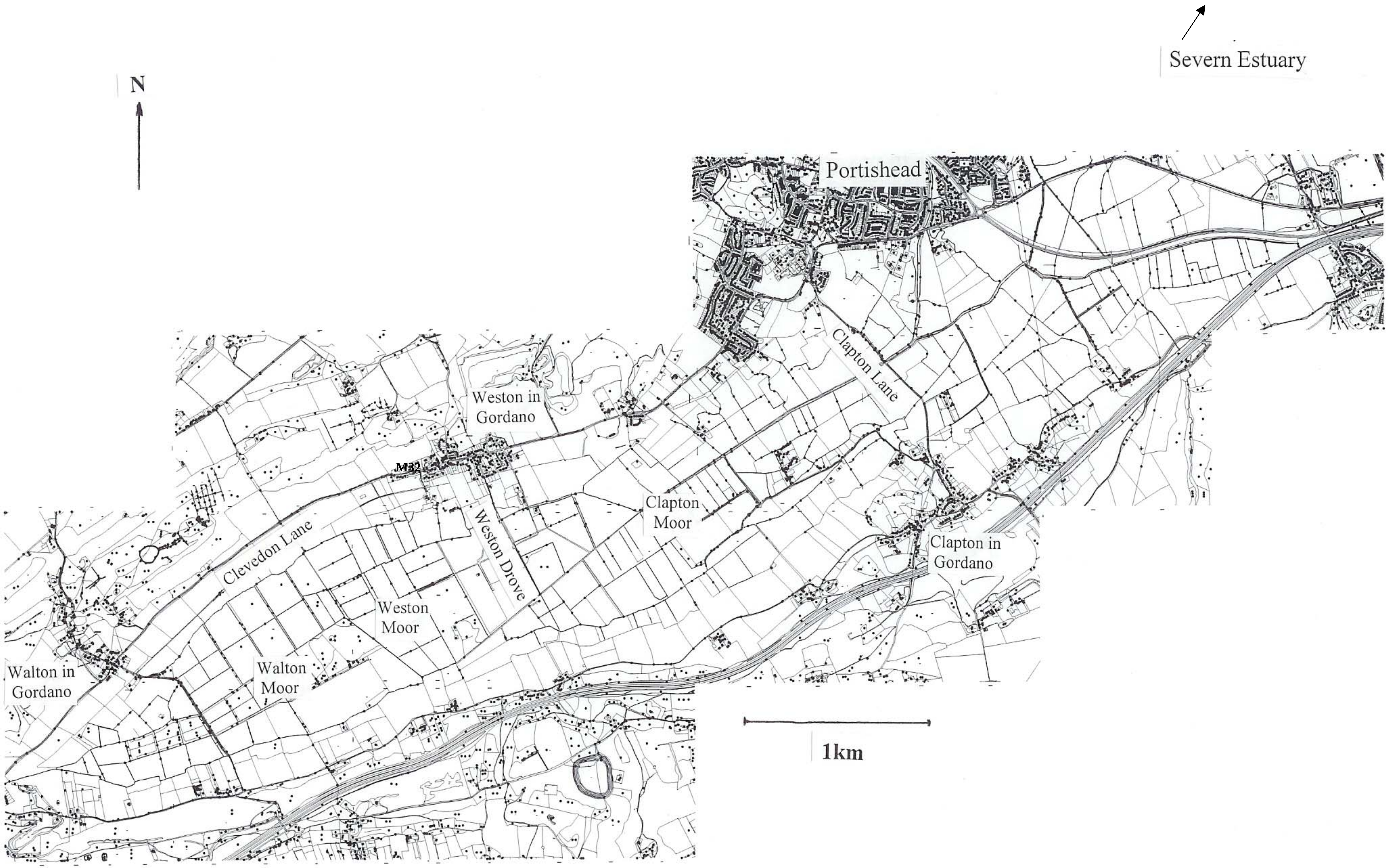
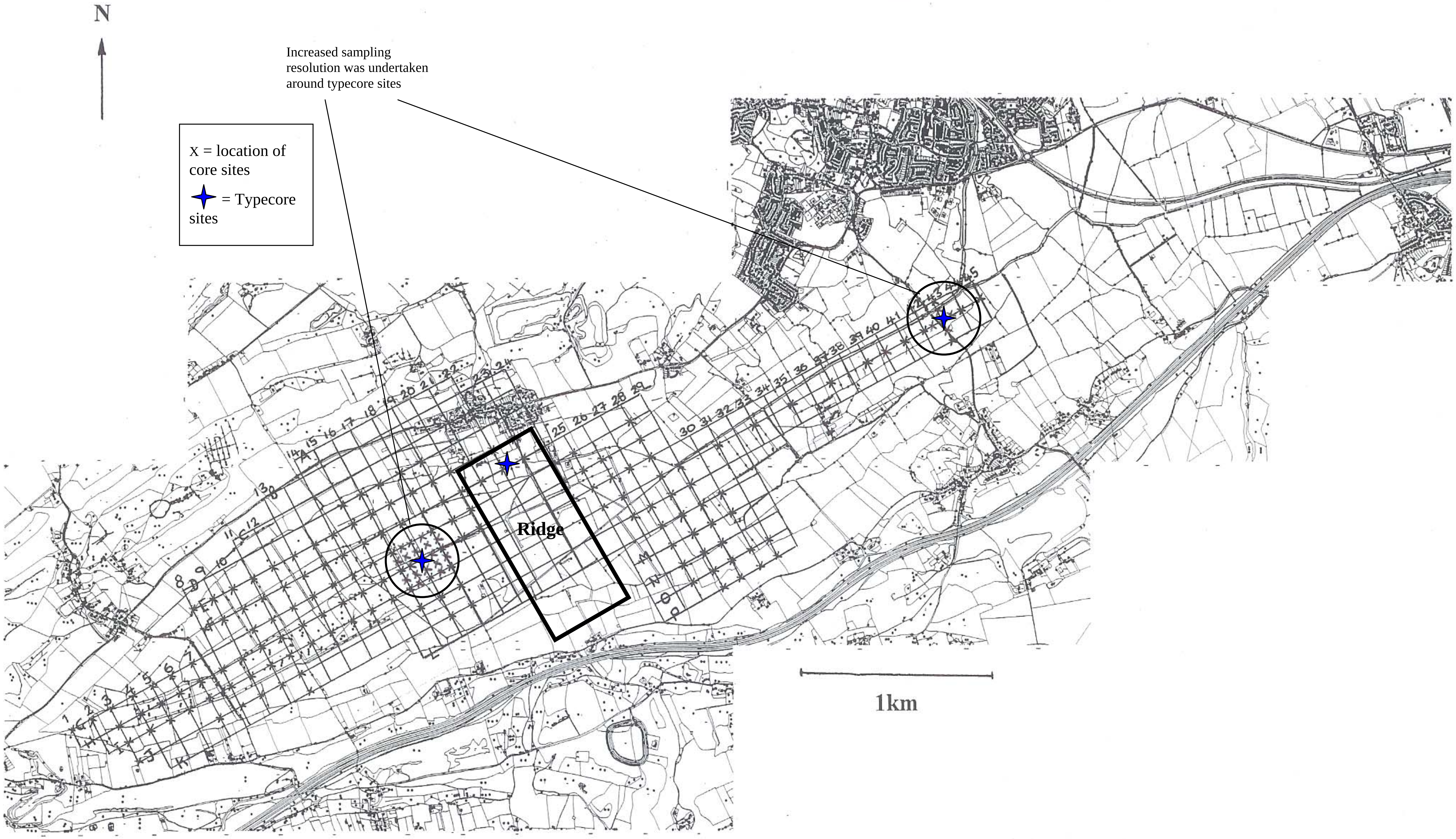


Figure 8.1 Map of the Gordano Valley indicating relevant roads and place names (MapInfo Professional 6.5).



<u>Figure 8.2</u> Map of the Gordano Valley (MapInfo Professional 6.5) showing the sampling grid applied during fieldwork, the position of typecore sites and the location of the ridge discovered by Jefferies *et al.* (1968).

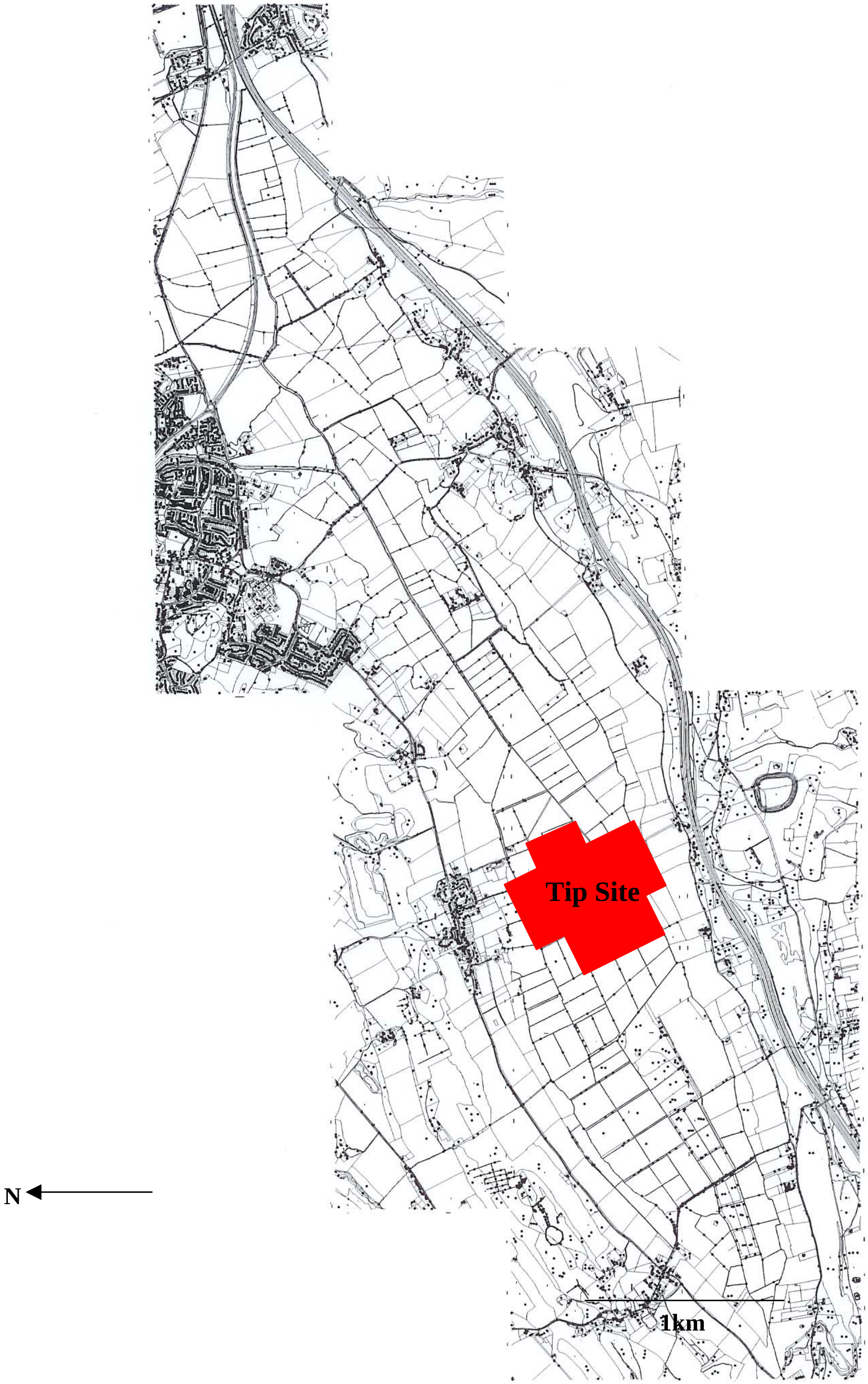


Figure 8.3 Map of the Gordano Valley indicating the position of the tip site which traverses the valley (MapInfo Professional 6.5).

site parallel to Weston Drove, traversing the majority of the valley's width (see Figure 8.3). The tip was positioned directly over the ridge discovered by Jefferies *et al.* (1968), consequently, very little physical evidence of the ridge could be found. To investigate the stratigraphic character of the valley towards the Severn Estuary whilst accommodating access limitations, a single core transect was positioned to follow the axial trend of the valley through Clapton Moor to Clapton Lane (see Figure 8.2).

Once the initial stratigraphical fieldwork was completed, higher resolution coring was conducted in locations identified for potential typecore sites. These locations were chosen due to the presence of the greatest stratigraphic variation within the sediments combined with a valley-wide representativeness of the stratigraphy (Figure 8.2). The typecores, to be extracted and used for laboratory-based investigations, were sampled using a "percussion corer" producing cores with a diameter of 5cm. The percussion corer penetrates the surface of the sampling site with the use of a pneumatic motor, and sediment is extracted in 1m sections. Plastic tubing is inserted into the corer, into which the sediment is stored during extraction to prevent contamination.

8.2.3 Diagrammatic presentation of lithostratigraphy

The computer package TSPPlus (see Waller *et al.*, 1995) was used to show graphically the sedimentological variation along perpendicular and longitudinal transects in relation to the main axial trend of the valley. Individual depositional horizons within each core were recorded using Troels-Smith (1955), which is the same classification scheme utilised by the TSPPlus package. Consequently, any significant changes in the region's depositional environment can be seen clearly, and such changes can be tracked through different cores on a stratigraphic transect.

8.2.4 Three-dimensional representations of the lithostratigraphy

The TSPPlus package provides only two-dimensional images of stratigraphic changes. However, with the use of the computer package Surfer 7 (Golden Software 1999), three-dimensional figures can be produced to represent changes in the depositional environment. The altitudes of the upper boundary of significant individual horizons were plotted into Surfer 7 to show the changes in the trend of their surfaces both across and down the valley. Where such surfaces were not recorded or access to a site was denied, the computer program predicted the trend of the surface between core sites where the stratigraphical unit was present. This extrapolation technique can provide misleading results if the program predicts the position of a sediment boundary when it is in fact not present. However, those sedimentary surfaces included within the Surfer 7 analysis were chosen because they were present throughout the cores. A more detailed understanding of the valley's surface topography was also attained through the use of this package. Variations in a horizon's thickness through the valley could also be depicted with the use of Surfer 7.

Once a sound understanding of valley stratigraphy had been achieved, the typecore locations were chosen which were representative of the valley's sedimentary archive. The typecore sites were determined by the presence of the major sedimentary units discovered during initial coring fieldwork. As such, the typecores provide a strong representation of the typical sediments found in the valley archive, and thus could be used to infer palaeoenvironmental conditions that were present within the valley during its evolution.

8.2.5 Particle size analysis

Jefferies *et al.* (1968), Mills (1984) and Gilbertson *et al.* (1990) reported a mixture of biogenic and minerogenic sediments present within the Gordano Valley. To achieve a full and accurate understanding of the late Quaternary depositional environments, particle size analysis of the minerogenic sediments is required. Particle size parameters can indicate the type of sedimentary environment in question, its energy levels and how the depositional system has changed over time. Particle size analysis was carried out on the typecores extracted from the Gordano Valley. Samples within each core were taken at regular intervals (dependent on the thickness of the minerogenic unit in question), increasing in resolution towards stratigraphic boundaries.

8.2.5.1 AccuSizer 780 particle size analysis

To provide the particle size analytical data required, an AccuSizer 780 Optical Particle Sizer was used (see section 5.5.2 for methodology). The majority of sediment samples contained mineral grains between 0.5-500μm in size and could be analysed with the use of the AccuSizer 780. However, some sediments were too coarse to ensure reliable analysis with this equiptment. For these samples, the sieving method of Folk (1974) was used.

The results of each sample analysis were converted from microns to phi (∅) using the equation:

$$\phi = - (\log d/\log^2)$$

where *d* is the grain size diameter in millimetres. In order to apply statistical analysis to the particle size results of each sample, cumulative percentiles were calculated. Readings of percentiles were made at ϕ_5, ϕ_{16}, ϕ_{25}, ϕ_{50}, ϕ_{75}, ϕ_{84} and ϕ_{95}. The results were then applied to the equations for the calculation of mean (*M*), median (*Md*), standard deviation (σ), skewness (α) and kurtosis (K_G). Each statistical method can indicate sedimentary characteristics of the sample in question and, when combined, palaeoenvironmental conditions can be interpreted (Friedman, 1961; Spencer, 1996; Tanner, 1997; Lario *et al.*, 2002):

Mean (*M*) – This is the best measure of average grain size, and is calculated using percentile values from across the sample data set. It is calculated using the equation:

$$M = 1/3\ (\phi 16 + \phi 50 + \phi 84)$$

(Folk, 1974)

Median (*Md*) – This is the particle size diameter corresponding to the 50% mark on the cumulative frequency curve of particle size distribution. Half of the grains are coarser and half are finer than the median diameter. This is calculated with the equation:

$$Md = \phi 50$$

(Folk, 1974)

Standard Deviation (σ) – This provides the best indication of the "sorting" of a sediment sample. It is calculated using the equation:

$$\sigma = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

(McManus, 1995)

The highest degree of sorting attained by natural sediments is about 0.2-0.25ϕ, with Texas dune sands attaining 0.25-0.35ϕ (Folk, 1974). The most poorly sorted sediments include tills and mudflows (4ϕ+).

Skewness (α) – In a "normal" distribution of grain sizes within a sample, both mean and median would be the same. In most sediment samples, however, this symmetrical distribution is rarely the case. Skewness measures the asymmetry of a sample curve and is calculated using:

$$\alpha = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

(McManus, 1995)

Symmetrical curves would have a skewness of 0.00, whilst those with an excess of fine material (a tail to the right) have a positive skewness and those with an excess of coarse material (tail to the left) have negative skewness.

Kurtosis (K_G) – Kurtosis represents statistically the dispersion and normality of the grain size distribution. If the central portion of the distribution is better sorted than the tails, the curve is said to be excessively peaked, or leptokurtic. In contrast, if the tails are better sorted than the central portion (or a bimodal grain size distribution is present), then the curve is flat-peaked or platykurtic. The kurtosis of a sample is calculated using:

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

(Folk, 1974)

8.2.5.2 Sieve particle size analysis

For sediments with grain sizes coarser than 500μm (1ϕ), sieving was applied. Sieves of varying mesh sizes were used, increasing in ½ ϕ sizes from 63μm (4ϕ) to 100μm (0ϕ). The coarsest sieve was placed on the top, with sieve size reducing downwards. A base pan was used to collect any sediment of <63μm in size. Each sediment sample was placed in the uppermost sieve, enclosed with a lid and placed on a mechanical shaker for 15mins. A full explanation of the methodology is provided by Folk (1974) and McManus (1995). After sieving, the sediment trapped on each sieve was weighed and a cumulative frequency distribution curve was compiled from the data. The relevant cumulative percentile readings required for particle size analysis were taken from the distribution curves to calculate mean, mode, standard deviation, kurtosis and skewness of the samples. If >5% of the sediment sample reached the base pan (and was thus below 63μm in size), a full understanding of the particle size variation within the sediment could not be attained due to the inability to record the ϕ_{95}. Therefore, the sediment in the base pan was weighed and analysed using the AccuSizer (see section 5.5.2; AccuSizer, 2001). The results were then calculated as a percentage of the whole sample and statistical analysis of the sediment's grain size distribution was completed.

Attempts have been made to describe relationships between certain particle size parameters and depositional environments. Friedman (1961) for example, distinguished between dune, beach and river sands according to their textural characteristics (e.g. mean grain size *vs*. skewness; skewness vs. sorting). The comparison of a sample's mean grain size against its standard deviation was also shown to differentiate possible depositional settings from one another (Tanner, 1997; Lario *et al.*, 2002). In order to isolate the environmental conditions responsible for the development of key minerogenic sediments preserved within the valley, where relevant, the relationship between such statistical parameters was investigated.

8.3 To determine the influence of sea-level change on the Gordano Valley's Quaternary sedimentary sequence

8.3.1 Diatom Analysis

Diatom analysis of the Gordano Valley archive was undertaken to reconstruct palaeoenvironmental change during the site's evolution. Chapter 4 provides an introduction to diatom analysis and its application to palaeoenvironmental studies. Whilst the laboratory method for diatom preparation of the core samples is the same as applied to the contemporary coastal diatom assemblages (see section 5.4), the level of analysis and interpretation of the fossil diatom assemblages is different, and is explained here.

8.3.2 Selection of diatom samples from Gordano Valley archive

Diatom analysis was carried out on typecores from the Gordano Valley. Within each core, samples were taken at *c.* 5cm intervals throughout the sedimentary profile. Where significant changes in stratigraphy occurred, the sampling resolution was increased to 2cm intervals to enhance environmental interpretations. Such stratigraphic transitions include changes from minerogenic to organic strata, and are indicators of significant changes in the depositional and thus environmental setting.

8.3.3 Graphical representation of diatom results

The TILIA computer package (Grimm, 1991) was used to plot the diatom assemblage abundances at each altitude in the core samples. Species were expressed as a percentage of total diatom valves (TDV). Diatom zonation within typecores and the modern transect were applied with the use of stratigraphically constrained cluster analysis (CONISS) in the TILIA program (Grimm, 1991).

8.3.4 Interpretation of diatom assemblages

Section 6.3.1 demonstrated that the sedimentary environments inferred from the ecological classification scheme of Vos and deWolf (1993) were an accurate reflection of contemporary depositional conditions in the Severn Estuary. Therefore, the same classification scheme could be applied to the archived diatom assemblages preserved in the Gordano Valley deposits to reconstruct the environmental changes since sedimentation began. As a result, each diatom assemblage from the typecore profile was allocated an inferred sedimentary environment based on Vos and deWolf (1993) (see section 6.2.1 for methodology).

The influence of allochthonous and autochthonous diatoms in the fossil archive was also assessed. Section 6.2.2 highlights the benefits of this approach to diatom analysis. The amount of epiphytic/benthic and planktonic diatoms present in each typecore diatom sample was calculated (in relation to TDV). Once calculated, the diatom species encountered were allocated to a relevant salinity group; the diatom salinity group with the most epiphytic and benthic diatoms is known as the "optimal diatom group". The two neighbouring salinity groups are also included within the optimal diatom group. For example, if the optimal diatom group was brackish-fresh, then the group's percentage (of TDV) would also include the fresh-brackish and brackish water groups. The percentages of epiphytic/benthic diatoms to the freshwater 'side' of the optimal diatom group were added together and divided by the optimal diatom group to produce a ratio; the fresh autochthonous ratio. The same approach with the epiphytic/benthic diatoms to the marine 'side' of the optimal diatom group produced the marine autochthonous ratio (Spencer, 1996).

For example:

Optimal diatom group = Brackish	61.6%
Neighbouring groups:	
Brackish-fresh	+ 3.2%
Brackish-marine	+ 2.7%
Autochthonous component	**= 67.5%**

Fresh autochthonous groups

Fresh-brackish		+ 1.4%
Fresh		+ 0%
Fresh autochthonous ratio	**1.4 / 67.5**	**= 0.021**

Marine autochthonous groups

Marine-brackish		+ 6.8%
Marine		+ 0.5%
Marine autochthonous ratio	**7.3 / 67.5**	**= 0.108**

This analytical approach was applied to the typecore diatom assemblages because it quantifies the variation in the influence of different salinity groups throughout the sedimentary profile, and thus indicates shifts in environmental conditions. Due to the sessile nature of epiphytic/benthic diatom species and the removal of planktonic species from the analysis, the optimal diatom group is not affected by the influence of allochthonous species. There is consequently a decreased 'margin of error' in environmental interpretation than experienced with the classification scheme of Vos and deWolf (1993).

After counting, those species with an abundance of >5% TDV were recorded and incorporated into the sea-level transfer function. Species found to be present in both the contemporary diatom data set and the archived valley data set were then analysed by the computer package C2 (Juggins, 2003). The computer program statistically reconstructed palaeo surface heights for each fossil diatom assemblage, which could then be interpreted to indicate the position of relative sea level at the time of deposition. This is explained further in section 12.5.

8.4 To determine ecological and vegetation change in the Gordano Valley's Quaternary sedimentary sequence

8.4.1 Pollen analysis

Palynology is the study of pollen grains and spores and is considered to be the single most important branch of palaeoecology for the late Pleistocene and Holocene (Roberts, 2000). Pollen grains and spores are of similar size (often around 20-40 μm; Moore *et al.*, 1991) and both are surrounded by tough, resistant walls which are frequently distinct in form. The strength of this rigid outer coat (exine) derived from sporopollenin enables pollen grains and spores to preserve longer than many other biological materials (Lowe & Walker, 1997). Pollen and spore identification relies on the morphological and structural features found on the exine, which distinguish individual genera and species from one another.

Pollen is best preserved under anaerobic, commonly acidic conditions, such as are encountered in peat deposits (Roberts, 2000). The known presence of organic deposits in Gordano Valley resulted in palynological work by previous researchers (Jefferies *et al.*, 1968; Mills, 1984; Gilbertson *et al.*, 1990) and the proxy has great potential for environmental interpretation. Pollen analysis as a proxy for vegetation reconstruction has been widely applied throughout Britain (Moore *et al.*, 1991; Walker *et al.*, 1998; Haslett *et al.*, 1998; Aalbersberg, 1999; Chiverell, 2001), especially during the Holocene. Pollen analysis can also be used as a relative dating technique due to prominent changes in pollen abundance and diversity throughout the late Quaternary and Holocene. In Britain, the establishment, reintroduction or disappearance of individual species since the end of the last glacial period has been identified through the reconstruction of pollen diagrams, and the timing of their arrival in the pollen record has been attained by radiocarbon methods (Birks, 1989; Moore *et al.*, 1991). Palynology would therefore allow correlative dates (to be confirmed by radiocarbon dating) to be applied the Gordano Valley archive.

The record of vegetation change at a site may reflect environmental controls. For example, during a period of climatic stability, vegetation may become established and subsequent expansion and diversification of species is likely (Godwin, 1975). In contrast, climatic deterioration may force species to migrate from the site in response to the inhospitable conditions. Past vegetation communities will therefore provide some indication of palaeoenvironmental conditions since organic accumulation began. Pollen analysis in coastal regions can also elucidate the history of sea-level change, as marine transgressions and regressions will be reflected in local pollen records by changes between salt-marsh and terrestrial or freshwater plant communities (Lowe & Walker, 1997).

8.4.1.1 Limitations of pollen analysis

A number of limitations are recognised in pollen analysis. One of the main issues concerns the relative production of pollen grains and spores. The resistance of pollen grains and spores also varies between species. These two factors alone may result in unrepresentative pollen counts (Lowe & Walker, 1997). It is possible to take into account such factors to produce a realistic representation of vegetation communities.

Human influence is also likely to have affected vegetation patterns in the Gordano Valley since the Mid- to Late Holocene (e.g. the Romano-British occupation, Jefferies *et al.*, 1968). Activities such as deforestation, cultivation and the introduction of exotic species are all likely to influence the pollen assemblage diagrams produced. There is also the difference between regional and local pollen input, which may bias pollen counts. The supply of pollen grains and spores will not be from the Gordano Valley alone (*in-situ*); input of pollen from the region is anticipated due to wind patterns and animal/insect activity from surrounding areas (*ex-situ*). In addition, vegetation communities within the valley itself may vary, with certain species thriving on the valley sides and others in abundance on the valley floor. The effect of such vegetation distribution must also be taken into account when analysing pollen assemblages. Finally, a time lag is likely to have occurred between climate/environmental change and the response by vegetation. The slow migration of vegetation in response to fluctuations in a region’s climate, often calls the accuracy of subsequent dating into question (Lowe and Walker, 1997). All these limitations to palynology must therefore be considered to achieve realistic interpretations of pollen data. However, it must be stressed that the application of pollen analysis in this study is primarily as a qualitative means of palaeoenvironmental reconstruction based on species' response to changing environments. Also, the palynological research applied to the Gordano Valley during this project provides a means of correlation with past research, as well as indicating changes in vegetation during the site's depositional history.

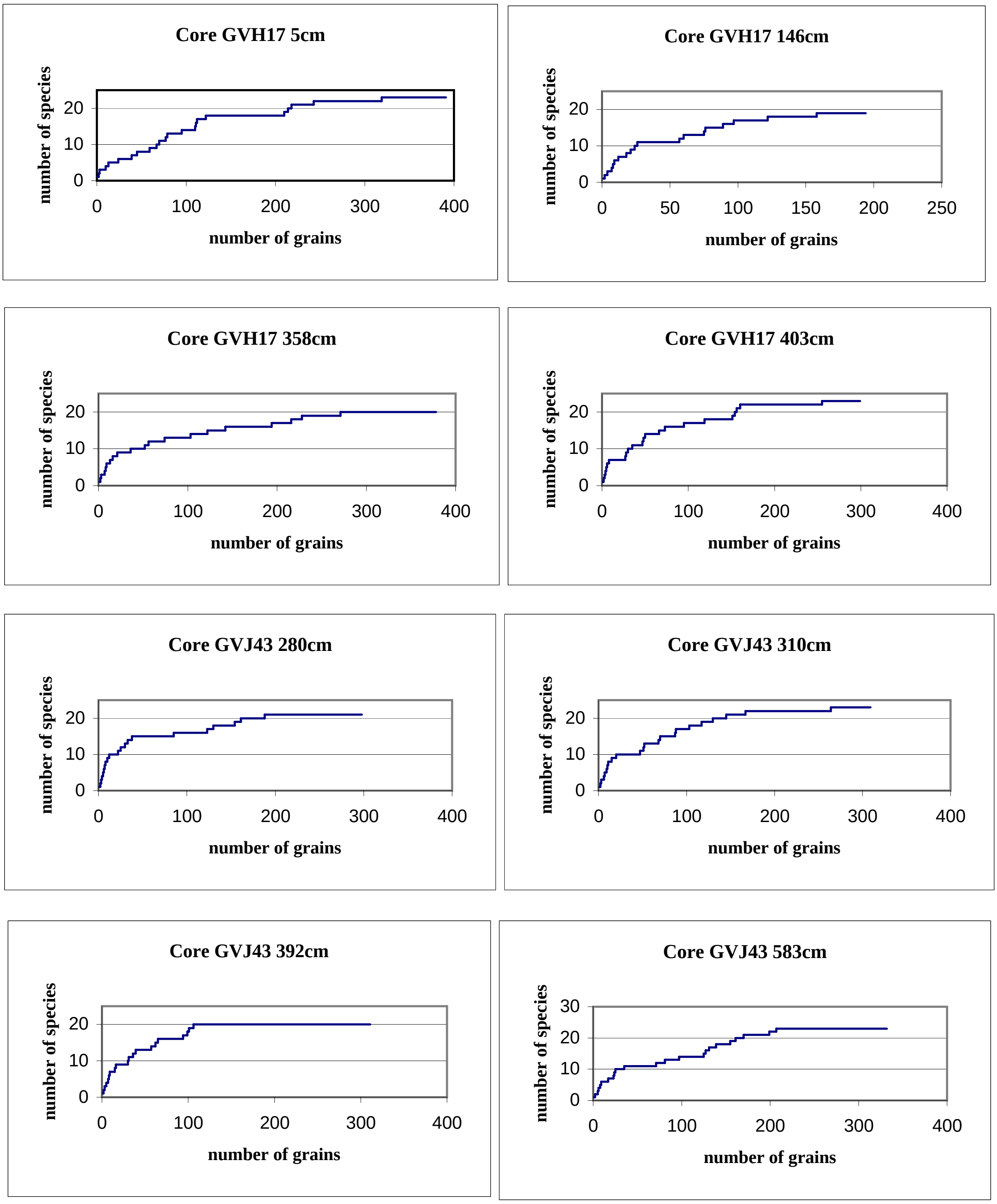
8.4.2 Pollen sample selection

Pollen analysis was undertaken on typecores extracted from the Gordano Valley. At each depositional boundary, where a change in environmental conditions was clear, a sample was taken immediately above and below the boundary. Samples were also taken at 10cm intervals throughout each sedimentary horizon, increasing in resolution towards sedimentary boundaries.

8.4.3 Laboratory preparation and analysis of pollen assemblages

Laboratory preparation for pollen analysis followed the procedure described by Moore *et al.* (1991). A $1cm^3$ sample was required for pollen preparation. Both organic-rich and minerogenic- (especially silica and carbonate) rich sediments were prepared for analysis. Prepared samples were stained with safranin to enhance identification and stored in glycerol to prevent desiccation. Samples were mounted on slides and a cover slip (25x50mm) was sealed in place using clear varnish. Pollen grains were observed under a microscope at 400x and 600x magnification; identification follows Moore *et al.* (1991).

A separate count sheet was also used to record the appearance of new species during the cumulative count. This was to establish the optimum counts for representative species diversity in each sample. Figure 8.4 shows that, when preservation was good,



<u>**Fig 8.4**</u> Number of individual pollen grains plotted against the number of species from selected typecore samples

species numbers reached a plateau after *c*. 300 grains were counted. This suggests that a count of 300 pollen grains provided a robust and reliable representation of the species present and that new species found beyond this point would not be significant in subsequent reconstructions due to their low abundance. Consequently, minimum of 300 pollen grains were counted per sample. Where pollen abundance was low, at least three slides were traversed to achieve a viable count.

8.4.4 Graphical representation of pollen results

The TILIA computer package (Grimm, 1991) was used to plot pollen assemblage abundance at each depth in the core. Species were grouped into 'trees', 'herbs', 'spores' and 'aquatics' to further assist environmental interpretation. Species were expressed as a percentage of total land pollen (TLP). The TILIA statistical program CONISS (Grimm, 1991) was used to subdivide the pollen assemblages into local pollen assemblage zones (LPAZs) to assist palaeoecological interpretation.

8.4.5 Interpretation of pollen results

The LPAZs provide an indication of the stages in the vegetational evolution of the typecore sites. Analysis of the ratio of arboreal and non-arboreal pollen was an indicator of significant vegetational shifts through the site's depositional history. Where clear variations within the typecore stratigraphy occurred, analysis of the pollen assemblages provided an insight into the environmental conditions present at the time of change (for example, shifts from clastic-dominated to biogenic-dominated deposits and *vice versa*). The presence of stenoptic pollen species (species with narrow environmental tolerance parameters) provided information regarding the climatic and environmental conditions present at that time. All these factors were compiled in order to reconstruct the palaeoenvironmental conditions present throughout the depositional evolution of the typecore site, which could then be used to assist the valley-wide reconstruction.

8.5 To integrate the sea-level, vegetation and sedimentological data to reconstruct the Quaternary environmental history of the Gordano Valley

Once all of the above objectives had been achieved, the sedimentary evolution of each typecore site was reconstructed. The results were further analysed to reconstruct a valley-wide model of evolution. Sea-level and vegetation change was assessed through diatom and pollen analysis respectively, whilst particle size analysis indicated the type of depositional systems responsible for these shifts in environmental conditions. Radiocarbon dating of selected horizons was conducted to produce a chronology for these changes. Radiocarbon dating enables the investigation of rates of environmental change at a site and direct comparisons to be made with other sites, providing a local, regional and even hemispheric context to the results found within the Gordano Valley.

8.5.1 Radiocarbon dating

Radiocarbon dating is widely applied to date late Quaternary and Holocene sediments. It is based on the principle that the carbon isotope ^{14}C can be analysed within an organic sediment, from which its decay rate can be applied and an age estimate can be calculated (Roberts, 2000). The constant rate at which the radioactive nuclides decay in an organic sediment limits the application of radiocarbon dating to sediments less than *c*. 50,000 yrs old. Given the ages from previous research (Gilbertson *et al.*, 1990), this range is more than adequate for the organic sediments present within the Gordano Valley. Dates for the Gordano Valley were derived from accelerator mass spectrometry (AMS) analysis, conducted at Beta Analytic, Florida, USA.

Radiocarbon dating was applied to organic horizons within the Gordano Valley typecores that indicated significant environmental shifts, such as the onset or the ending of phases of organic deposition.

8.6 To place the Gordano Valley archive and its interpretation within the contexts of established work in the Severn Estuary region and of frameworks for climate change

The palaeoenvironmental history of the Gordano Valley has been reconstructed through the combination of fieldwork, laboratory studies and analysis of subsequent results. Whilst achieving knowledge of the valley itself, comparison of this project's results with those of other researchers in the southwest (see section 2.4) would show whether the evolution of the Gordano Valley followed a trend shown throughout southwest England, or whether localised controls were responsible for its development (or a combination of the two). There may also be the potential to relate the results of the palaeoenvironmental reconstructions to those changes that are believed to have occurred in northwest Europe since the end of the last glaciation (see section 2.2). A clear understanding will thus be achieved regarding the spatial and temporal scale at which environmental change has affected the Gordano Valley.

Chapter 9: Reconstruction of the Quaternary stratigraphic archive of the Gordano Valley

9.1 Lithostratigraphy of the valley sediments

The stratigraphic data from the Gordano Valley showed the existence of two distinct sedimentary successions within the valley's archive. One sedimentary sequence was located to the west of Weston Drove (Weston Moor sequence), whilst a second sequence was found to the east (Clapton Moor sequence; see Figure 8.1 for reference). Consequently, a summary of the two 'typical' sedimentary successions found in the valley are presented, describing each of the sedimentary units found utilising the Troels-Smith (1955) classification scheme (described in section 8.2.1). The altitudes provided for each depositional horizon are averages estimated from the stratigraphic archive. Variations in sediment thickness and core depth were present throughout the valley.

9.1.1 Weston Moor sequence

Topsoil (5.20-5.0.5m O.D)	3, 0,2, 2, - Dg2, Th1, Dh1, Sh+, Dark brown highly decomposed organic topsoil, commonly with an abundance of fine herbaceous rootlets.
Peat (5.05-2.3m O.D)	3, 1, 2, 2, 0 to 4, 2, 2, 2, 1 Dg2, Dh1, Th1 to Dg2, Sh2 Dl+, Tl+, Th^2+ Reddish-brown to dark brown/black humified to well humified peat, predominantly consisting of *Detritus granosus*, *Substantia humosa* and *Detritus herbosus*. Red-brown peat horizons within unit more common towards base. Averaging *c*.3m in thickness
Sandy-clayey-silt (2.3-2.26m O.D.)	1+, 0, 0, 2, 3 Ag2, As1, Ga1, Th+ Light grey fine clastic unit, no greater than 20cm in thickness. Sharp upper and lower boundaries. More common in cores extracted from the central valley region.
Clastic-rich Peat (2.26-1.60m O.D.)	2, 2, 2+, 2, 1 to 2+, 3, 2, 2, 2 Dh2, Th1, Ag1, As+, Dg+, Sh+, Ptm+, Ga+ Light brown to yellow-brown unit, dominated by *Detritus herbosus*, *Turfa herbacea* and silt. Unit commonly well stratified as a result of layers of leaf litter. Thin silt drapes (<3mm thick) throughout horizon. Some isolated cores contain remains of calcareous shells. Rootlets grow through the layers.
Clayey-silt (1.60-1.10m O.D.)	2, 0, 0, 2, 0 Ag3, As1 to Ag2, As2 Th+, Sh+, Ga+, Dg+ Light grey to grey brown clayey silt. Transitional upper boundary, with organic content decreasing with depth (esp. *Turfa herbacea*). Locally, some laminations are present. Fining of grain size with depth.
Basal Sediment (1.10m O.D.+)	2+, 0, 0, 2, 2+ Ga2, Ag1, Gg(min)1 to Ga1, Ag1, Gg(min)1, Gg(maj)1Gs+, As+ Strong orange-brown to reddish-brown clastic horizon. Organics wholly absent. Commonly dominated by pebbles with sandy matrix. Pebbles sub-angular to sub-rounded. Not always observed due to difficulty in recovery of sediment.

Table 9.1 Summary of the Weston Moor sedimentary succession sequence

9.1.2 Clapton Moor sequence

Topsoil (6.00-5.75m O.D.)	2+, 0, 0+, 3, - Ag2, Dg1, Th1, As+, Sh+, Lf+ Light grey brown topsoil, dominated by silt, but with organic remains and some oxidation mottling.
Clayey-silts (5.75-3.50m O.D.)*	2, 0, 0, 2, 0 Ag2, As2 to As3, Ag1 Ga+, Sh+, Lf+, Th+ Grey to blue-grey clayey silts. Oxidation mottling most abundant towards top of unit. Organics sparse, with some *Substantia humosa* mottles and *Turfa herbacea*.
Upper Peat (3.50-2.80m O.D.)*	3, 0, 2+, 2, 1 Sh2, Dg2 to Dg2, Dh1,Sh1 Dg+, Dh+, Th+, Dl+ Brown to very dark brown horizon. Ranging from humified peat dominated by *Substantia humosa* and *Detritus granosus*, to organic remains richer in herbaceous remains. No minerogenic sediments present. ** Sometimes contains a thin blue-grey clayey silt unit within peat horizon which increases in thickness towards the northeast in the sedimentary archive.*
Clayey-silts (2.80-2.00m O.D.)*	2, 0, 0, 2, 1 Ag 2, As1, Ga1, to Ga2, Ag2 (Dl+, Dh+, Th+, Ptm+ Similar to upper clayey silt, with minimal organic content and only present at upper and lower sedimentary boundaries. Grey to blue-grey in colour, no oxidation mottling present. Visible increases in grain size common both with depth and distance down-valley.
Lower Peat (2.00-1.50m O.D.)*	3, 1, 2+, 2, 2 Dl2, Dh1, Dg1 to Dg2, Dh1, Sh1 Th+, Tl+ Dark red-brown to brown peat. Dominated by *Detritus lignosus*, *granosus* and *herbosus*, with *Substantia humosa*. Woody horizons common within profile
Basal Sediment (1.50m O.D.+)*	2+, 0, 0, 2, 1+ Ga2, Ag1, Gg(min)1 to Ga1, Ag1, Gg(min)1, Gg(maj)1 Gs+, As+ Similar to basal sand in previous succession sequence (9.1.1). Commonly orange/red brown, dominated by small and large pebbles. Sampling was not always successful due to unconsolidated nature of sediment.

Table 9.2 Summary of the Clapton Moor sedimentary succession sequence

* Altitude measurements are only estimates as there is considerable variation in the stratigraphy throughout the valley. Refer to core transects for further stratigraphical information.

9.1.3 Core transects

The computer package TSPPlus (Waller *et al.*, 1995) was used to produce a total of 24 two-dimensional cross-sections of sediments (both cross-valley and down-valley profiles) within the Gordano Valley. All core transects are provided for reference on the CD accompanying this thesis. Numerical transects (e.g. transect 10, 11, 12) traverse the valley (north to south), while alphabetical transects (e.g. transect E, F, G) run down the valley, approximating the valley's axial trend. Due to the number of cores extracted along transects I and J, TSPPlus could not incorporate all cores into single transects. Consequently, two TSPPlus transects were created; one displaying those cores extracted from the Weston Moor sequence (transects I and J), and one from the Clapton Moor sequence (transects I-2 and J-2). Although the grid network provides stratigraphical data representative of the Gordano Valley, the transects produced by TSPPlus provide only a two-dimensional view of the valley's sedimentary archive. Consequently, a broader impression of the valley stratigraphy is presented in Section 9.1.4 as three-dimensional diagrams of the major sedimentary horizons found in the valley.

Whilst there were a number of core transects produced for this project, the key sedimentary profiles (i.e. the Weston and Clapton Moor sequences), as summarised in sections 9.1.1 and 9.1.2, represent the general sedimentary archive within the valley. As a result, key transects are included within the thesis and will be explained here in detail. These can be applied to a valley-wide understanding of the sedimentary evolution of the Gordano Valley. Four transects, transects H, 17, J-2 and 28 will be stratigraphically assessed to summarise the valley's sedimentary archive (Figures 9.2, 9.3, 9.8 and 9.9 respectively). Figure 9.1 indicates the position of each core transect within the Gordano Valley.

The contrasting stratigraphy of the Weston and Clapton Moor sequences (as indicated by the sedimentary profiles in sections 9.1.1 and 9.1.2) is represented by "transect H" and "transect J-2" respectively. These transects follow the axial trend of the valley running roughly ENE-WSW in alignment with the coring strategy (Figure 9.1). Both contain cores extracted from the central region of the valley and include some of the deepest cores recorded in each region. Transects 17 and 28 intersect transects H and J-2 respectively, to enable comparisons between cross-valley and down-valley stratigraphy.

9.1.3.1 Weston Moor Stratigraphy

A total of 122 cores were extracted within the Weston Moor sequence, in the Walton and Weston Moor regions of the Gordano Valley (see Figure 8.1). Transect H (Figure 9.2) comprises of 18 cores, running from near the head of the valley (core H6) to the valley mouth (core H26). The tip site that runs parallel to Weston Drove creates a gap within the transect between core H20 and H24. Transect 17 (Figure 9.3) comprises 8 cores, traversing the width of the valley in Weston Moor from north (core D17) to south (core K17). The depth of the cores increased with distance from the head of the valley and also with distance away from the valley sides. The depth of the cores was dictated by bedrock or the basal sands (known to be the last sedimentary horizon above the bedrock-sediment interface; Jefferies *et al.*, 1968). An attempt was always made to reach the bedrock boundary in every core, but this was often prevented by either obstacles within the basal sand or very poorly-consolidated sediment.

Transects H and 17 provide a good depiction of the sediments preserved within the Weston Moor sedimentary sequence of the valley. Although the sedimentary content is summarised in section 9.1.1, further details are included here. The bedrock-sediment boundary was an orange-brown basal sediment (Unit 1), as described by

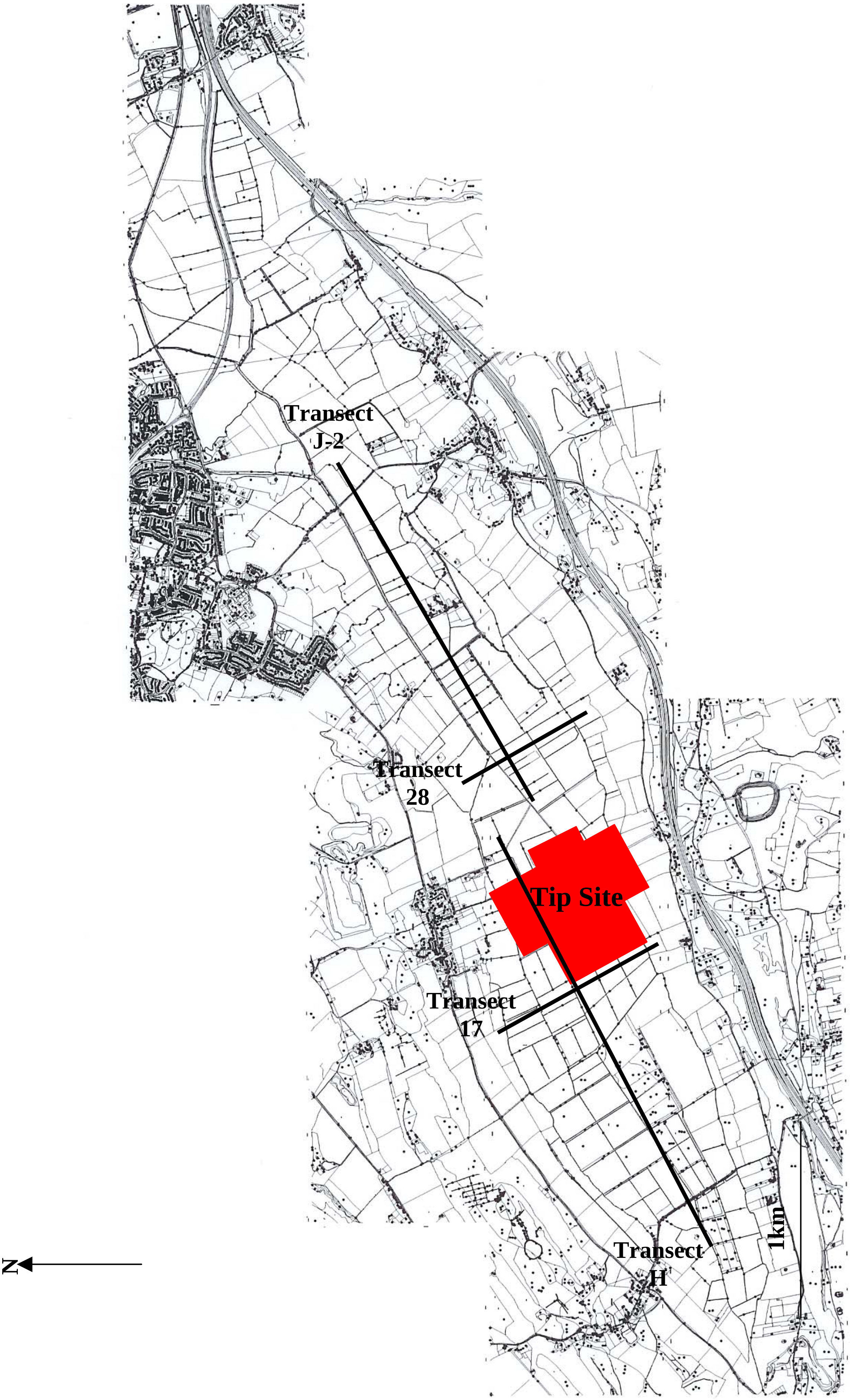


Figure 9.1 Map of the Gordano Valley indicating the position of the four main core transects; transects H, J-2, 17 and 28.

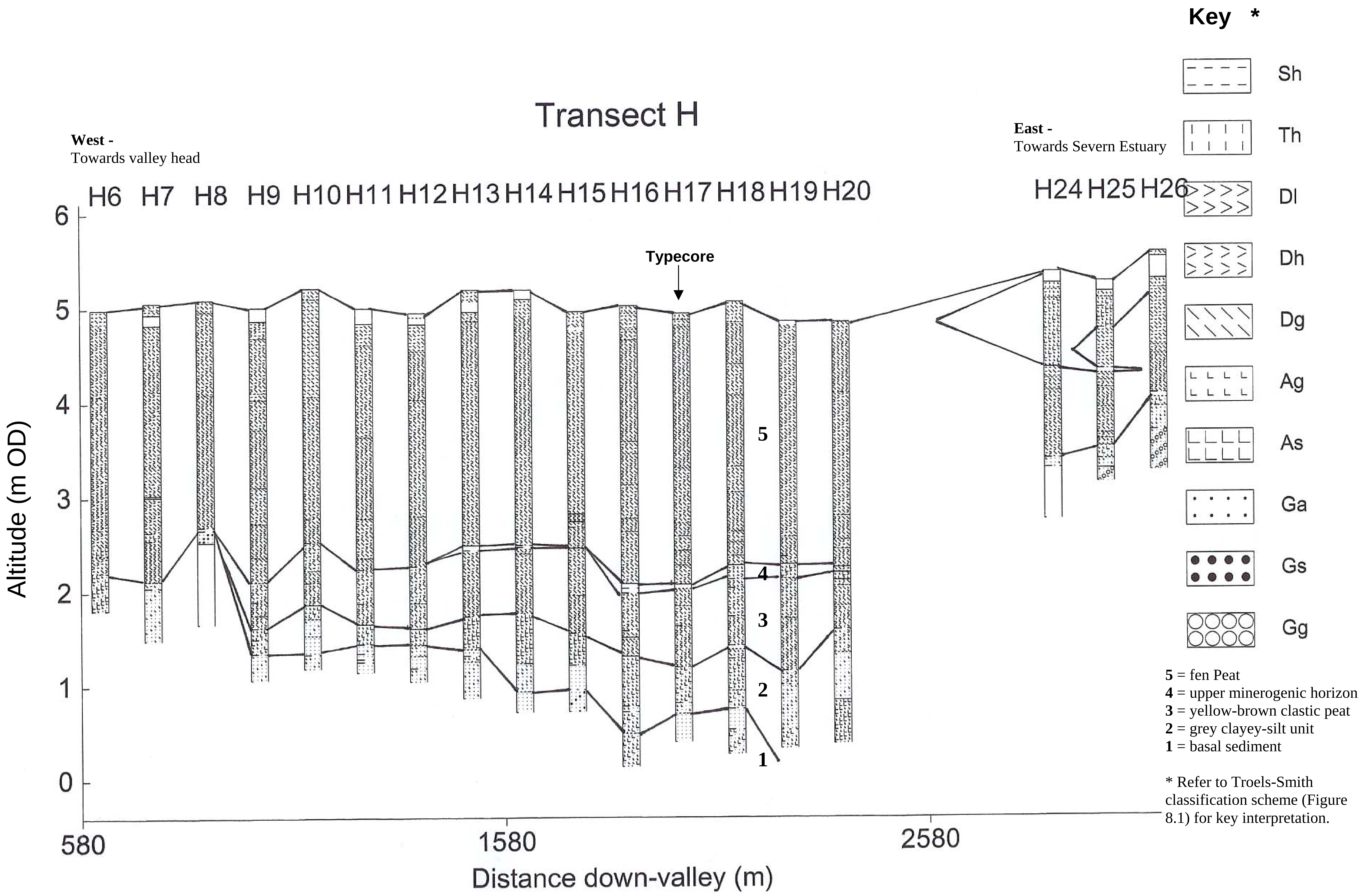
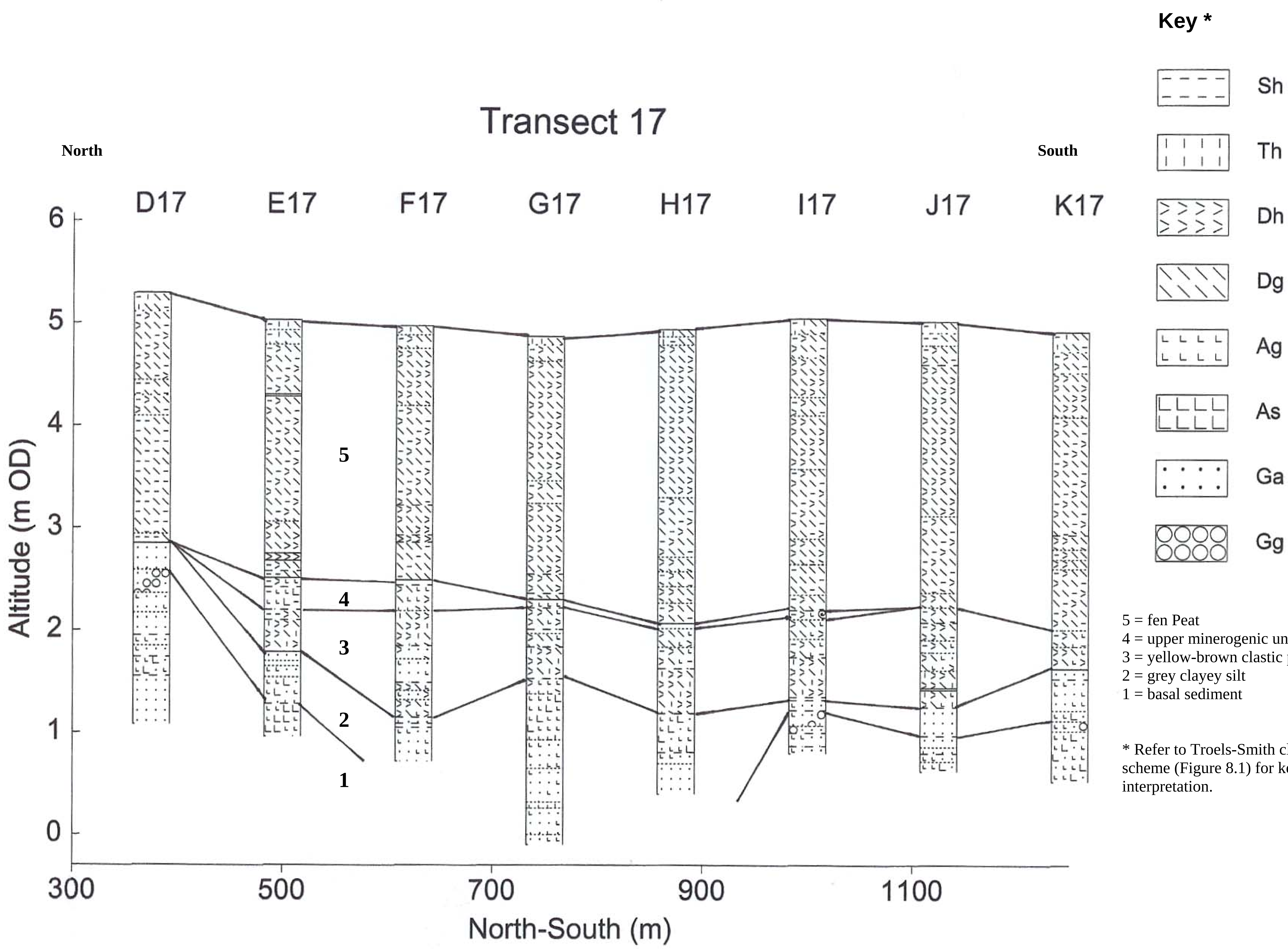


Figure 9.2 Core Transect GVH



5 = fen Peat
4 = upper minerogenic unit
3 = yellow-brown clastic peat
2 = grey clayey silt
1 = basal sediment

* Refer to Troels-Smith classification scheme (Figure 8.1) for key interpretation.

Figure 9.3 Core Transect GV17

Jefferies *et al.*, (1968), Mills, (1984) and Gilbertson *et al.*, (1990). A mix of sands and pebbles dominated the content, and no organic sediments were present. Some cores extracted up to 50cm of the basal unit before encountering either bedrock or an obstacle too large to be sampled by the gouge corer. Generally, the thickness of the extracted basal unit increased with distance from the head of the valley and thinned towards the valley sides. The depth at which Unit 1 was encountered also increased towards the centre of the valley (See Transect H, cores 6-20; Figure 9.2).

Fine grey to grey-brown clayey silts (Unit 2) were present above the basal sediment. The clayey silts varied in thickness from up to 1 metre towards the centre of the valley, to only *c.*10cm towards the valley sides. An average of 40cm thickness was common during the coring. The thickness of this horizon, like Unit 1, increased away from the head of the valley and towards the valley centre. Organic mottles were present within the unit in most of the cores sampled. Towards the upper surface of Unit 2, an increase in the abundance of fine fibrous rootlets was common.

The grey-brown clayey silts were replaced with light yellow-brown clastic rooty peat further up the core profiles (Unit 3). The transition from the underlying clastic-dominated sediment to the organic-dominated sediment is relatively gradual; the transition from grey-brown clayey-silts into yellow-brown clastic rooty peats was usually completed within *c.* 5cm. A mix of fine, fibrous roots with leaf litter frequently dominated Unit 3. The leaf litter was commonly horizontally layered, very compact and, although dominated by organics, a number of cores showed regular thin layers of clayey-silts and fine sands (rarely thicker than a few millimetres). The fibrous rootlets penetrated the horizontally-bedded leaf litter. The organic laminations were more common towards the lower boundary of the unit, whilst the number of clastic laminations decreased with height up-core. The computer package Surfer 7 (Golden software, 1999) was used to plot the overall form of the clastic-rich peat and is shown in Figure 9.4. The plot summarises the variations in thickness of the unit, along with the altitudes of the upper and lower boundaries. The data are from cores extracted from the central region of the Gordano Valley where the unit was most common (Figure 9.5). The diagrams demonstrate the thickening of the clastic peat unit from the valley sides towards the centre of the valley (Figure. 9.4A). The altitudes of the lower peat boundary indicate that the thicker sequences developed in basins that were present in the central valley region (Figure. 9.4C). The underlying grey-brown clayey-silts (Unit 2) are responsible for this lower level of surface elevation. The altitudinal contours representing the upper boundary (Figure 9.4B) indicate a reduction in the gradient of the surface when compared to the basal horizon boundary. The upper peat boundary indicates that, as a result of clastic-peat development, a much less undulating depositional surface had developed at the end of the peat formation.

Although not encountered in all the cores extracted from the Weston Moor sedimentary sequence, a common presence within the central cores extracted down the valley was a light grey sandy-clayey-silt horizon with a thickness averaging between 8-12cm (Unit 4). This was positioned directly above the clastic-rich organics, with a relatively sharp boundary. Figure 9.6 summarises unit thickness (A) and the upper (B) and lower (C) altitudinal levels of this thin minerogenic horizon (the position of the data points in relation to the valley are also shown in Figure 9.7). The unit is thickest towards the northwest of the valley and within the central region (Figure 9.6A). Although the distribution of the horizon is relatively uneven, once again there is an overall trend for thicker sequences to accumulate in areas within the valley that were relatively low-lying at the time of deposition.

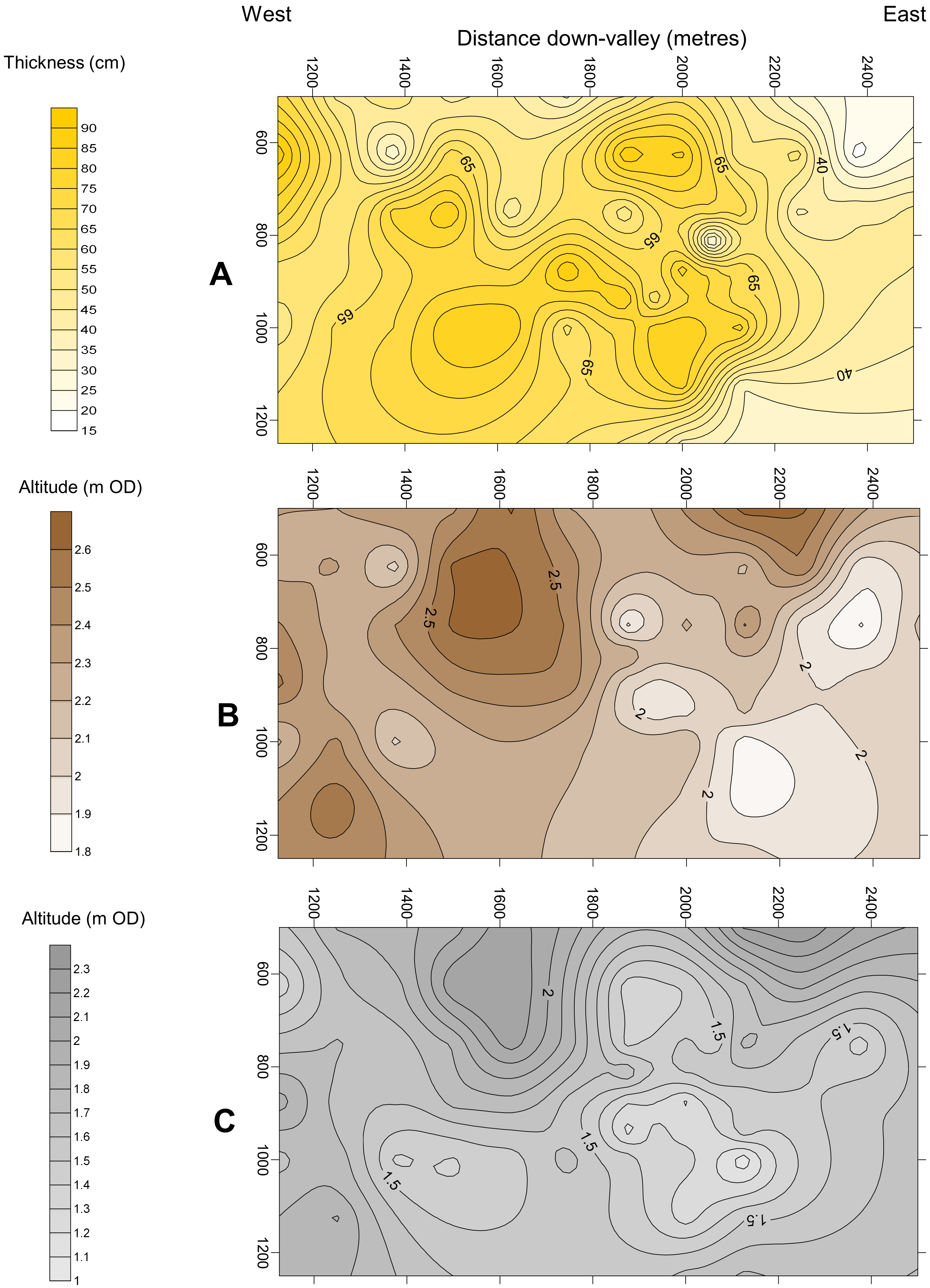


Figure 9.4 Surfer plots summarising the form of the light yellow-brown clastic rich peat horizon (Unit 3). A - Thickness of the horizon, B - Upper altitudinal boundary of the horizon, underlying the upper minerogenic horizon, C - Lower altitudinal boundary of the horizon, overlying the light brown minerogenic sediments.

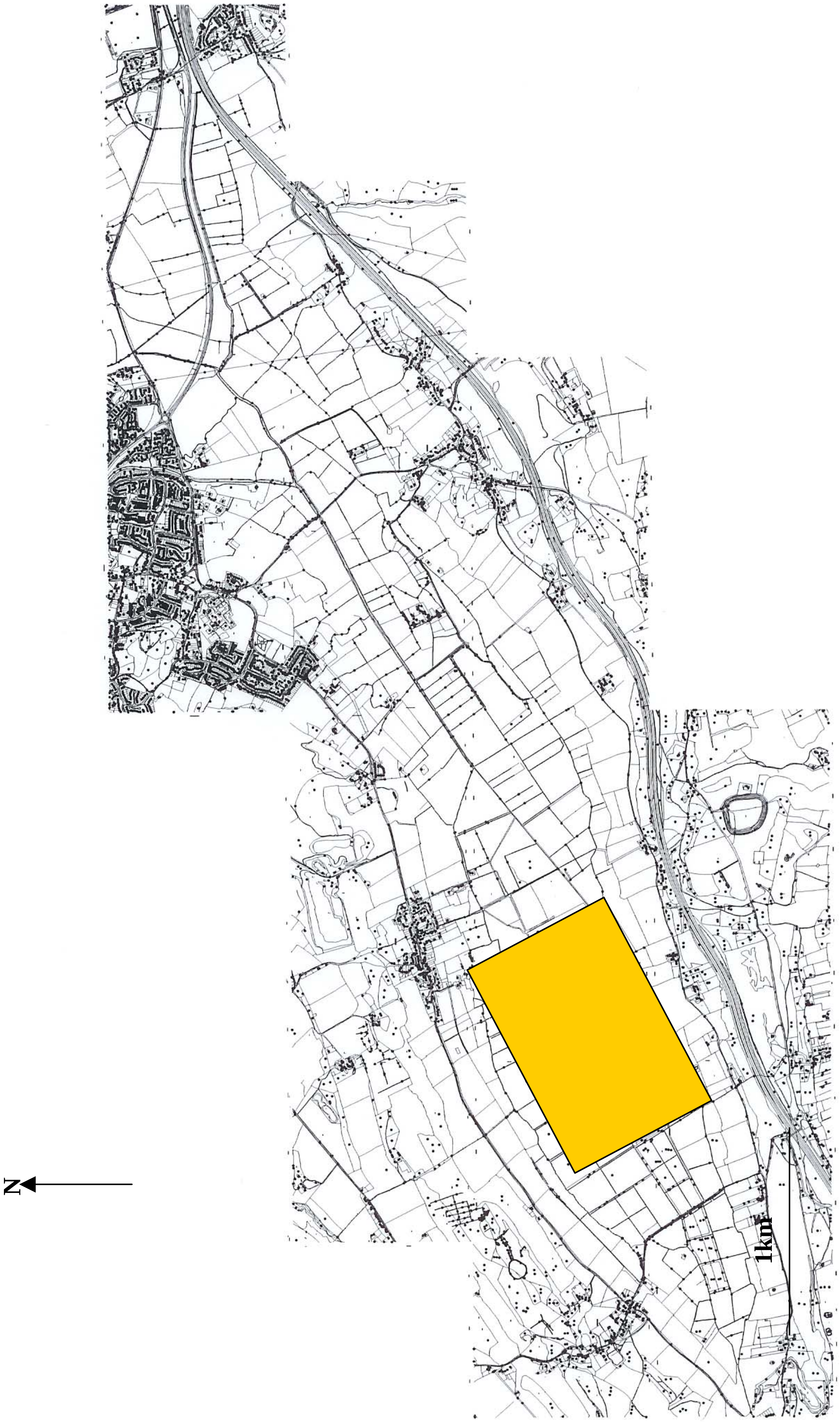


Figure 9.5 Position of data set relating to the Surfer peat horizon reconstruction within the Walton and Weston Moor regions of the Gordano Valley (MapInfo Professional 6.5).

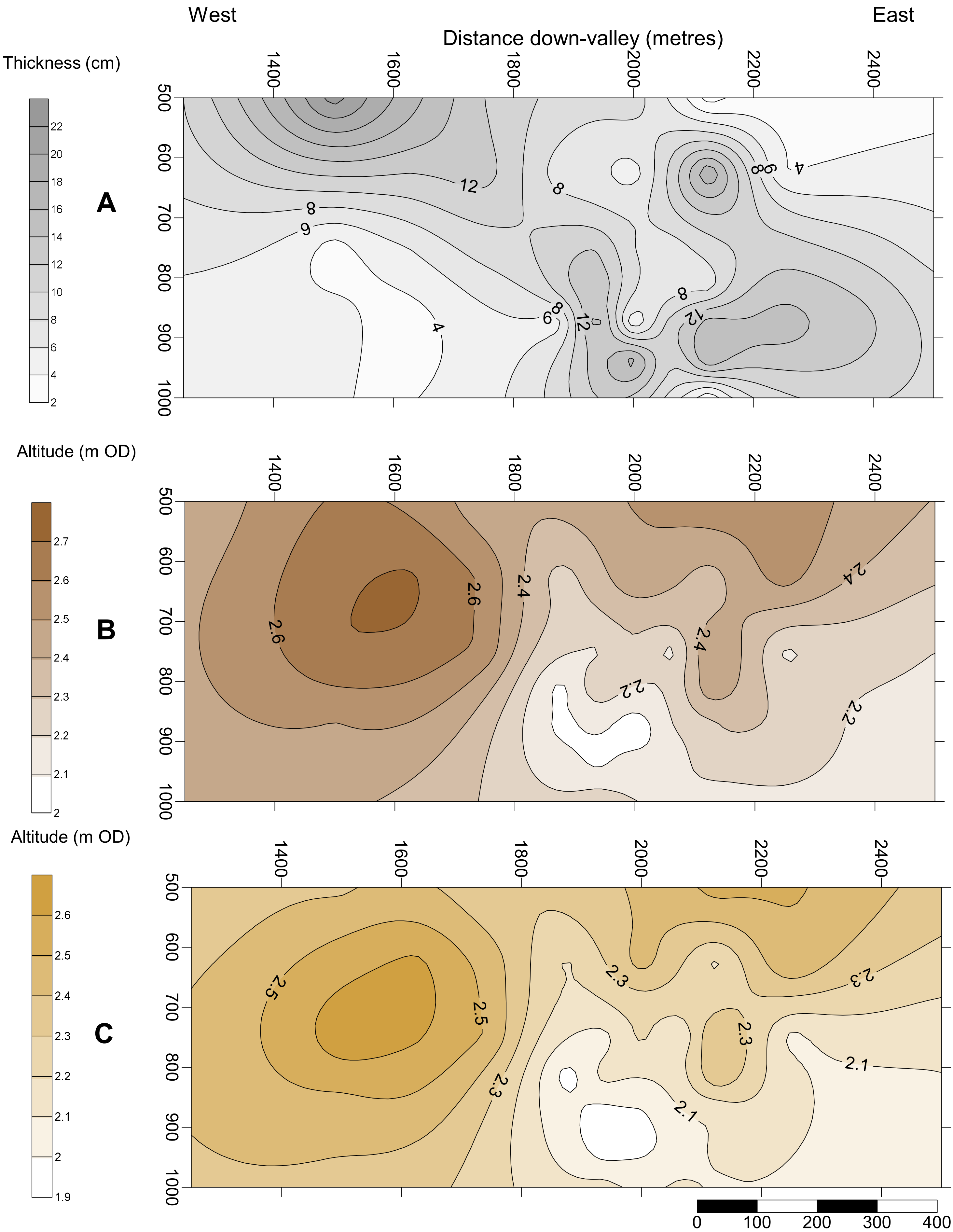


Figure 9.6 Surfer plots summarising the form of the upper minerogenic horizon (Unit 4).
A - Thickness of the horizon, B - Upper altitudinal boundary of horozon, underlying dark brown Fen peat,
C - Lower altitudinal boundary of the horizon, overlying the clastic rich yellow-brown herbaceous peat.

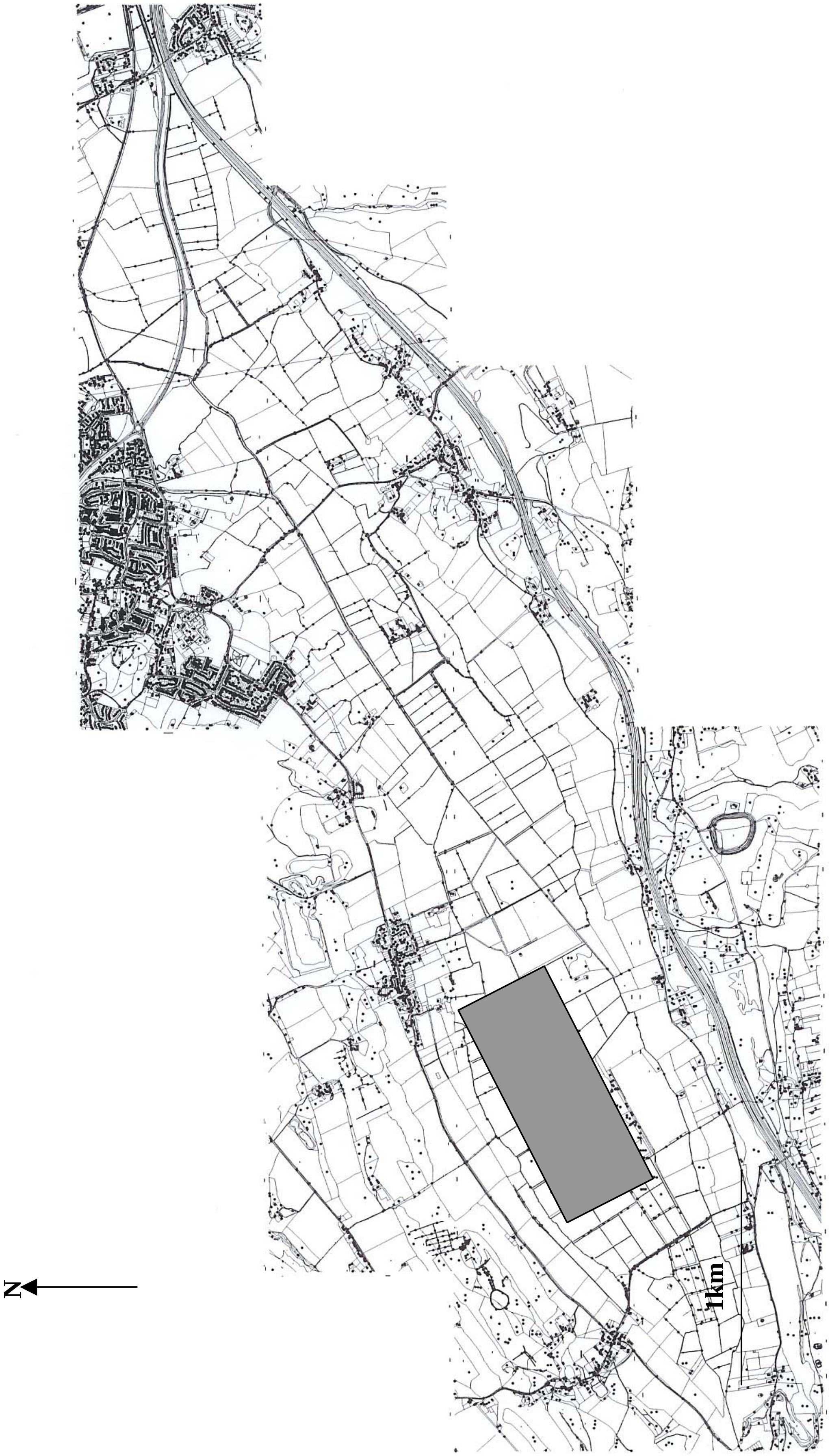


Figure 9.7 Position of data set relating to the Surfer minerogenic horizon reconstruction within the Weston and Walton Moor regions of the Gordano Valley (MapInfo Professional 6.5).

From the underlying sandy-silty-clay or clastic rich organic sediments to the valley surface (depending on the extent of the overlying minerogenic horizon), the remaining 2-3 metres of the valley core contents were found to be dark brown well-humified fen peats (Unit 5). The overall thickness of the fen peat was more consistent than the underlying sedimentary horizons, irrespective of position within the valley. Although the content of the peat varied throughout the valley, the majority of the cores contained an abundance of decomposed detrital material, with organic structure visible but not identifiable. The remaining peat content consisted of a mixture of humic remains, herbaceous leaf litter and isolated woody horizons towards the surface (commonly *Alnus*). Variations in peat colour were also present, although not consistent throughout the sedimentary profiles. A common feature was a much darker, almost black, very well decomposed, thin horizon at the interface with the underlying minerogenic/clastic-peat horizon. The peat was also commonly found to be reddish-brown in colour with increasing depth and was associated with less decomposed organic horizons.

Transect H (Figure. 9.2), also includes 3 cores extracted from the Clapton Moor sequence, beyond the tip site (cores 24-26). A distinct contrast in sedimentary deposition is clear, with the cores averaging no more than 2.5m in depth (compared to the average depth of 4m in the Weston Moor sequence). The sedimentary content of these cores is also different to those on the other side (westward) of the tip site. Orange-brown pebbly sands are encountered at the core bases, which are found at the same altitude as the fen peats (Unit 5) to the west. Bedrock was never reached in these cores, as the pebbly nature of the sands meant obstacles (pebbles greater than 3cm in diameter) were commonly encountered. Above these pebbly sands, the cores are once again dominated by decomposed fen peat with similar organic content to those cores extracted to the west.

However, blue-grey clayey silts are also encountered close to the surface, indicating a significant shift in environmental conditions. The lack of access within the tip site region and the immediate surrounding areas limits further investigation into the cause of this change.

9.1.3.2 Clapton Moor Stratigraphy

The Clapton Moor sequence (to the east of Weston Drove) differs significantly from the Weston Moor sequence. Transects J-2 and 28 summarise the key sedimentological characteristics of this seaward region of the valley (Figures 9.8 and 9.9 respectively).

Section 9.1.2 summarises the sedimentary sequence found to the east of the ridge, but more detail is provided here. The majority of the land in and around Clapton Moor was privately owned, restricting fieldwork to around the Clapton Moor Nature Reserve, just east of Weston Drove. Consequently only 51 cores were extracted east of the ridge. A single longitudinal core transect however was sampled, and transect J-2 (Figure 9.8) shows a line of cores extracted running down the centre of the valley between Weston Drove and Clapton Lane (see Figure 9.1 for position of transect). Like the upper valley transect (Figure 9.2), the depth of individual cores increased with distance towards the valley mouth. This confirms that the surface of the bedrock (Permo-Triassic Marl; see section 3.2.1) is dipping towards the coast. An overall increase was observed in the altitude of the extracted cores towards the coast.

The sediments found cannot be summarised into regular units as easily as those in the Weston Moor sequence; this is due mainly to the considerable spatial variation in stratigraphy. The basal unit is the orange-brown basal sediment found in abundance towards the head of the valley (Unit 1). This pebbly unit was commonly encountered

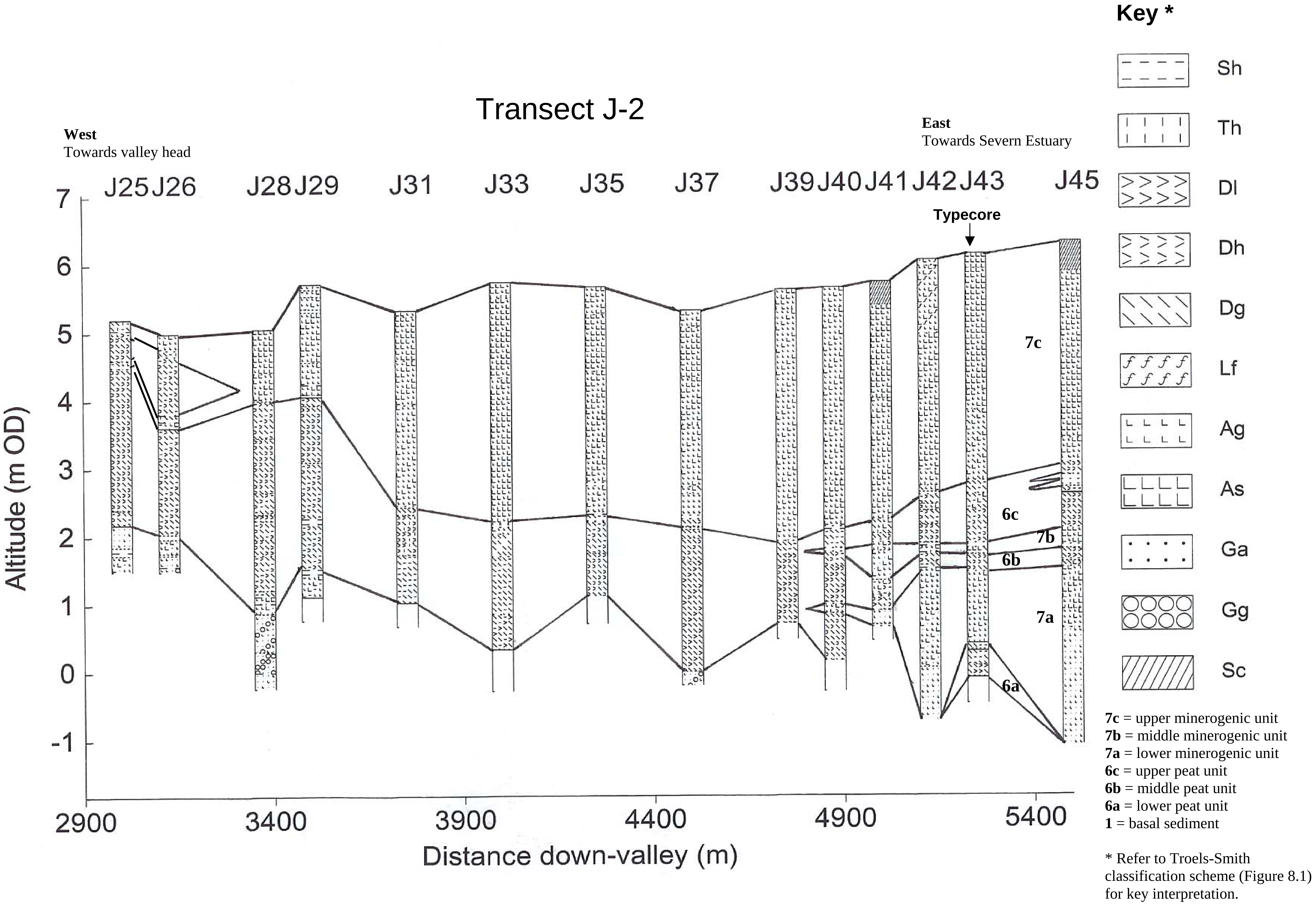
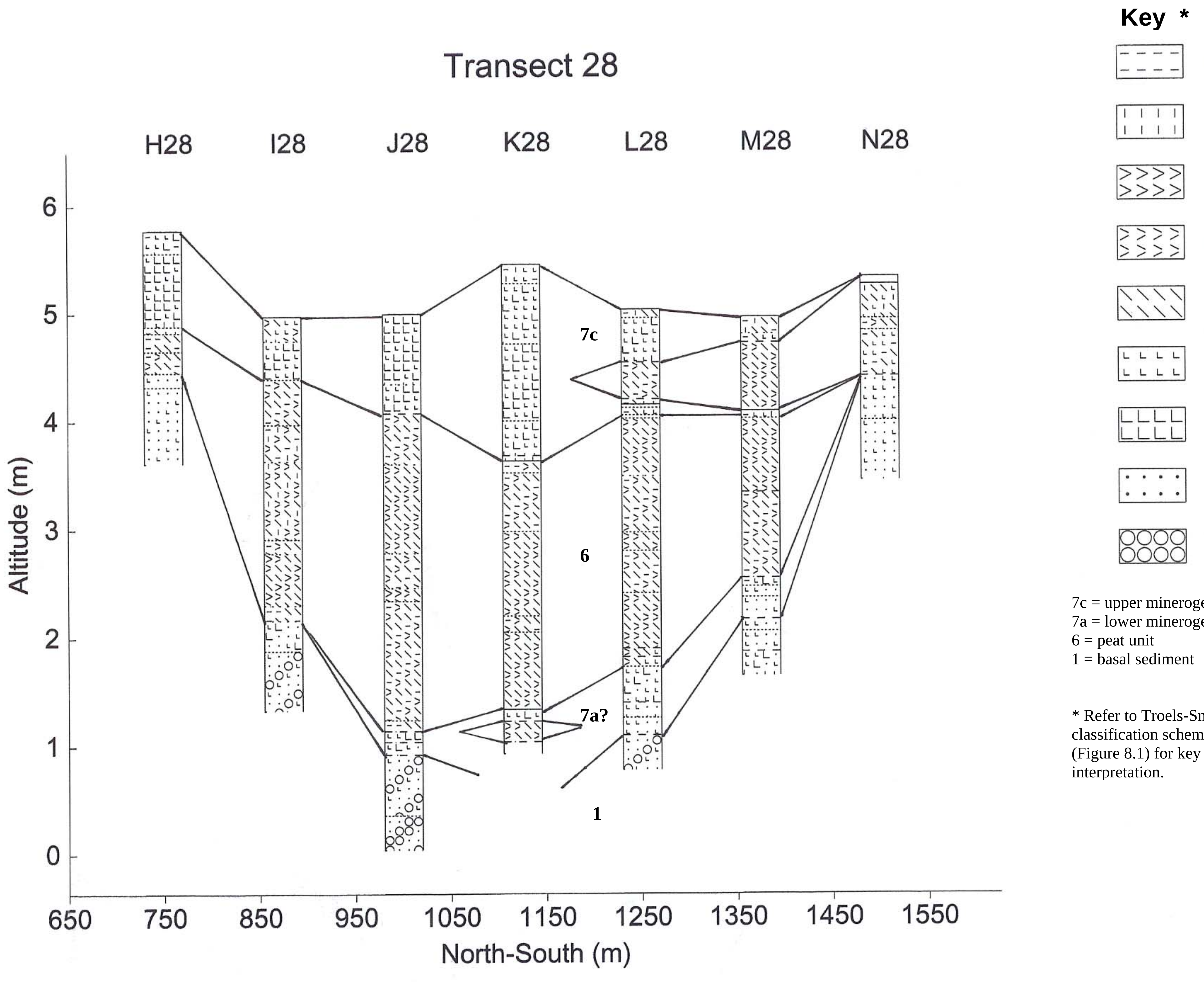


Figure 9.8 Core Transect GVJ-2



7c = upper minerogenic unit
7a = lower minerogenic unit
6 = peat unit
1 = basal sediment

* Refer to Troels-Smith classification scheme (Figure 8.1) for key interpretation.

<u>Figure 9.9</u> Core Transect GV28 during fieldwork in the Clapton Moor region, but it was not always extracted due to its unconsolidated nature. When examined in the field, its upper boundary was relatively sharp.

The majority of the sedimentary archive is made up of varying ratios of dark brown peats (Units 6a-c) and grey-clayey silts (Units 7a-c). The general trend shown in transect J-2 is a decrease in the thickness and abundance of the dark brown peat with distance down-valley, to be replaced by increasing quantities of grey clayey-silts. To the west of transect J-2, in core J25, roughly 3m of peat are present in a *c.* 4m core. The overlying clayey-silts are only *c.* 30cm thick. In contrast, the *c.* 7m core extracted close to Clapton Lane (core J45) contains *c.* 1m of peat distributed between a number of thin peat horizons. The remaining core content consists of thick clayey-silt sequences, up to 3m of which overlies the upper peat layer. As well as thinning with distance towards the sea, transect J-2 also shows the peat unit being split into smaller peat horizons, interbedded with the grey clayey-silts. This implies a number of shifts in the depositional conditions towards Clapton Lane. In contrast, further up the valley, peat accumulation was uninterrupted, which resulted in the formation of one single peat unit.

Transect 28 (Figure 9.9) indicates the spatial variation in stratigraphy in a north-south traverse of the valley profile. The depth at which the basal sediments (Unit 1) are encountered varies considerably when compared to transect 17 (to the west of the ridge; Figure 9.3). At the valley sides the basal sediments are found at *c*. 1m depth (*c*. 4.5m O.D.); towards the valley centre, over 4m of sediment overlies the same deposits (at *c*. –1m O.D.) indicating the general drop in the altitude of the unit surface. The close proximity of the transect to the ridge under Weston Drove is also likely to have influenced the variation in altitude of the basal sediment. The majority of the accumulated sediment consists of dark brown herbaceous, well-humified peats, overlain by (bluey-) grey clayey-silts. Both peat and clayey-silt beds increase in thickness towards the centre of the valley. To the centre of the transect, a bed of peat is present within the clayey-silt sediments, increasing in thickness towards the southern side of the valley, until it replaces the minerogenic sediments (Transect 28, cores L28-N28). Towards the base of the valley-centre cores (K28-M28), grey clayey-silts were present, either directly overlying the basal sands or present within the main peat sequence.

The peat unit consists mainly of well-decomposed organic remains (*Detritus herbosus*, *Detritus granosus* and *Substantia humosa*). There are regular woody horizons present within the unit throughout the valley (commonly *Alnus* remains), especially in cores which contain a basal peat (e.g. cores J41, 43, 45). The colour varies from very dark brown to dark reddish-brown, with the latter commonly being less decomposed than the former. The upper and lower boundaries with the grey clayey-silts are commonly relatively sharp.

The clayey-silts are mainly grey in colour, with some cores containing blue-grey units. Organic remains (esp. *Turfa herbacea,*) and organic mottling (*Substantia humosa*) were occasionally found, especially towards the overlying/underlying peat boundaries. The majority of the sedimentary content is balanced between silts and clays. Grain size variation was much more distinct in the deeper cores extracted towards the seaward end of the valley. These cores commonly contained a thick (up to 3m) upper layer of grey clayey-silts overlying a peat horizon. The upper minerogenic sediments were a mix of silts and clays. However, the minerogenic sediments underlying the peat unit(s) were generally slightly coarser. Cores J42 and J45 for example, contain higher levels of sand within the lower sediment unit. Iron oxidation mottling is common within the upper few metres of the cores, believed to be a result of post-depositional fluctuations in the regions water table (Mayer *et al.*, 1991).

9.1.4 Three Dimensional Views of the Stratigraphy of the Gordano Valley

On completion of fieldwork, stratigraphical data was entered into the computer package Surfer 7 (Golden Software, 1999). Incorporating the altitude of sedimentary boundaries from each core into Surfer 7 enables the three-dimensional visualisation of variations in each key surface. In comparison to the two-dimensional transects produced by TSPPlus (Figures 9.2, 9.3, 9.8 and 9.9), the problems with access further down the valley towards Clapton Lane resulted in the stratigraphic data from the Clapton Moor sequence not being included in Surfer 7. This was because the extraction of only one complete core transect did not provide enough stratigraphical data to attempt 3D reconstructions. However, the sedimentary archive recorded from the Weston Moor sequence could be mapped in Surfer 7.

Figure 9.10 summarises the key sedimentary horizons plotted by Surfer 7. The upper boundary of each horizon was recorded and entered into Surfer 7, providing a three-dimensional view of the sedimentary surfaces. Analysis of the cores extracted to the landward side of the ridge revealed four main sedimentary horizons within the valley stratigraphy; four diagrams have been produced to present the spatial and temporal variation between these horizons. The sedimentary horizons relate to Units 1 to 4 and are named the “basal sediment layer”, the “grey-brown clayey-silt layer”, the “light brown clastic-rich peat layer” and the “upper minerogenic layer”, respectively. A fifth diagram is included to show the present valley surface. All diagrams have been produced to the same scale to show the variations in gradient and form of individual surfaces. Whilst the present valley surface is relatively flat (increasing with altitude to the sides and top of the valley), in marked contrast the surface of the orange-brown basal sediment is more undulating. From the basal sediment (Unit 1) upwards, the gradients of stratigraphical

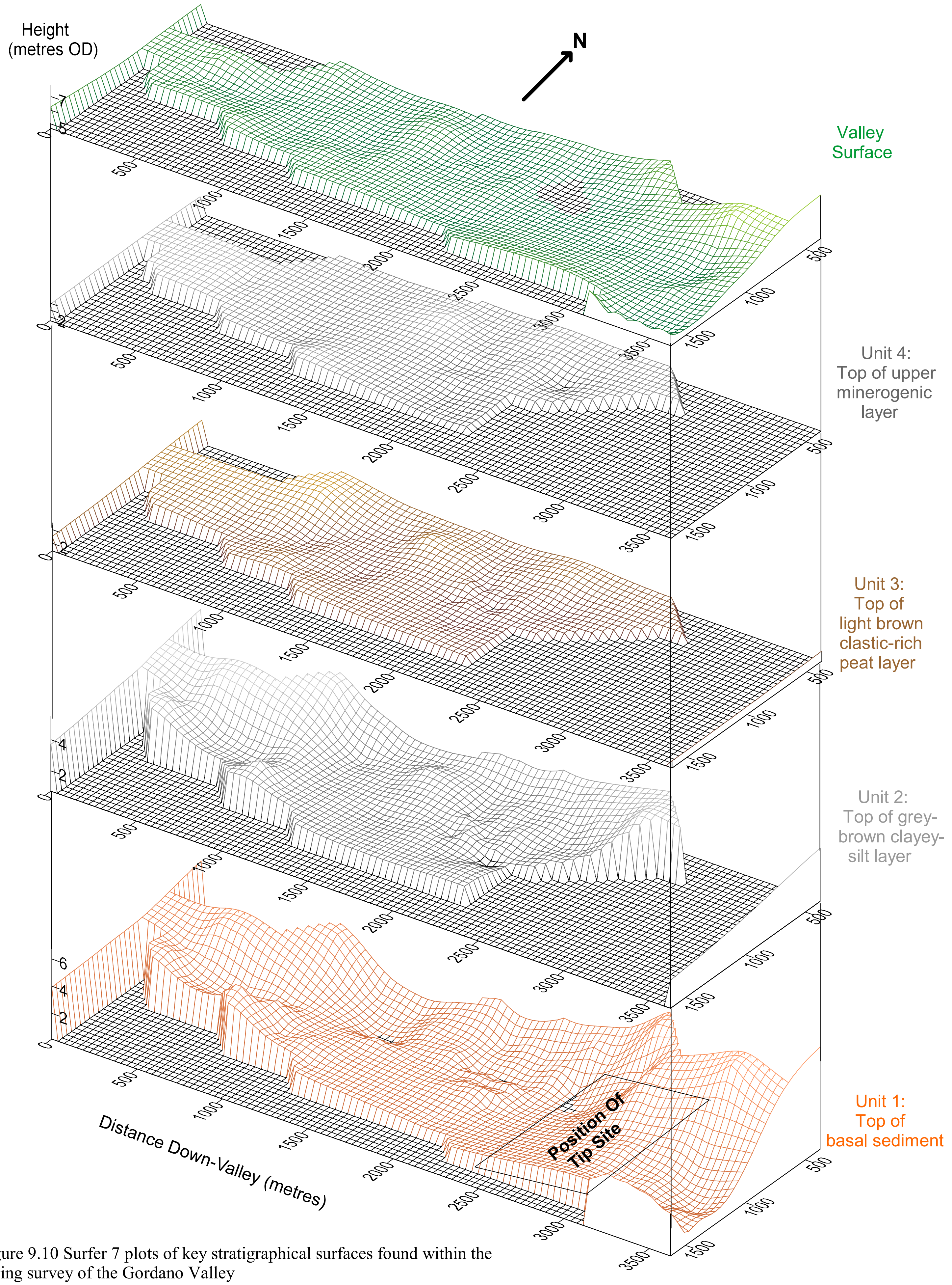


Figure 9.10 Surfer 7 plots of key stratigraphical surfaces found within the coring survey of the Gordano Valley

surfaces become shallower with height (Figure 9.10). The diagrams representing the varying altitudes of the valley surface and the basal sediment provide a complete survey of the valley, as these features were present throughout the coring results. However, the data from the grey clayey-silt (Unit 4), light brown clastic rich peat (Unit 3) and the upper minerogenic horizon (Unit 2) diagrams do not span the whole valley profile, because the ridge restricted their development further down-valley.

The upper valley region is characterised by the basal orange-brown sediment which dips towards the valley centre from the valley head and sides. Further down-valley, towards and just beyond the tip site (as marked on Figure 9.10, Unit 1), the surface of the basal unit rises, after which there is another marked decrease in the unit’s altitude. Either side of the tip-site, the stratigraphic record suggests a rise in the surface altitude of the basal sediment towards the tip-site, and fall in its altitude on the seaward side. The lack of access and hence stratigraphic data from beneath the tip-site prevents a complete representation of the basal unit. The ridge discovered by Jefferies *et al.* (1968) is believed to be positioned directly under the site. Surfer 7, however, attempted to predict the nature of the ridge surface by assessing the surrounding stratigraphy and extrapolating the position of the basal sediment surface from the surrounding data. The access limitations that resulted from the tip-site resulted in the production of a diagram not wholly dissimilar to that produced by Jefferies *et al.* (1968) (see Figures 3.4 and 3.5).

The sedimentary units that overlie Unit 1 reveal a considerable reduction in the gradient of the depositional surfaces with altitude. The grey clayey-silt layer above the basal unit (Figure 9.10, Unit 2) appears to retain a similar surface form (although with a shallower gradient) as the underlying sediments. The light brown clastic-rich peat layer, however, appears as a more uniform and flat depositional surface (Figure 9.10, Unit 3). The greater thickness of the clastic peat horizon towards the centre of the sedimentary sequence is responsible, further supporting the evidence of infilling presented by Figure 9.4. The upper minerogenic layer (Figure 9.10, Unit 4), found throughout most of the central valley region (Figure 9.6) overlies the clastic peat layer and attains a similar surface form. The upper minerogenic surface also represents the base of the onset of fen peat development within the valley.

Chapter 10: Palaeoenvironmental analysis of the Quaternary stratigraphic archive of the Gordano Valley

10.1 Introduction

Once the full stratigraphic survey of the valley had been completed, three sites within the valley were chosen for typecore extraction. To address the aims and objectives of the research, one core was extracted from within the Walton Moor sedimentary sequence (to the west of the ridge) and another core was extracted to the east of the ridge, in the Clapton Moor sedimentary sequence. Both sites were considered to contain an archive representative of the areas landward and seaward of the ridge. The palaeoenvironmental information preserved within the two typecore sites would elucidate a) the influence of sea level on valley evolution, b) the development of the isolated depositional basin towards the head of the valley, and c) the influence of the ridge on the evolution of these two separate depositional settings. The two sites chosen for further palaeoenvironmental analysis were **GVH17** and **GVJ43**. The typecores were extracted using a percussion corer. Sediments were logged using the Troels-Smith classification scheme (1955; see section 8.2.1 for details) and sub-sampled in preparation for multiproxy analysis. Figure 10.1 indicates the location of each of the typecores within the Gordano Valley.

The difficulty experienced when extracting sediments from the ridge, combined with access limitations around the site, required the collection of a third typecore using the percussion corer to confirm the ridge's presence. As the origin and formation of the ridge was not incorporated in the objectives of this project, laboratory analyses were not

Figure 10.1 Position of typecore sites within the Gordano Valley (MapInfo Professional 6.5).

undertaken on typecore **GVF23**. A brief description of the core stratigraphy is, however, included within this chapter (section 10.4) and the position of typecore GVF23 is shown on Figure 10.1.

10.2 Typecore GVH17

Typecore GVH17 contained the sedimentary deposits typical of the Weston Moor sequence (described in section 9.1.3.1). The typecore was levelled into a local benchmark, providing an altitude of 5.16m OD for the ground surface of the typecore site. Figure 10.2 is a profile of the sedimentary content of the core, based on the Troels-Smith (1955) classification scheme and using TSPPlus (Waller *et al.*, 1995).

A summary of the sedimentary sequence preserved in the typecore is provided to assist interpretation of Figure 10.2. A brief description of each sedimentary horizon is included, along with the sedimentary content following the Troels-Smith classification scheme (1955).

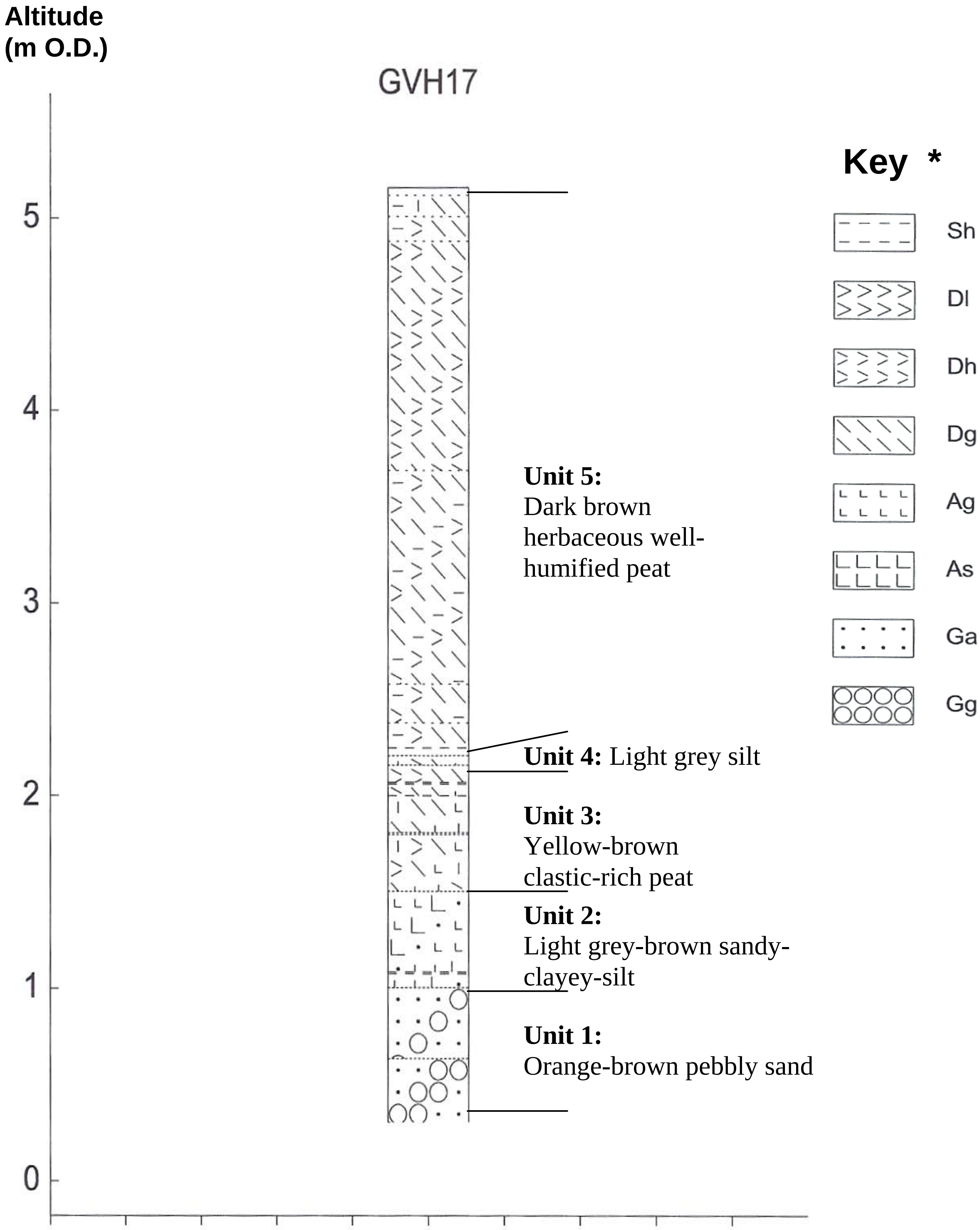


Figure 10.2 Stratigraphic profile of typecore GVH17.
* Refer to Troels-Smith classification scheme (Table 8.1) for key interpretation.

Altitude	Stratigraphy	
5.16-5.12m O.D.	Dg2, Th2, Dh+, Sh+ Dark red-brown rooty humified peat	UNIT 5
5.12-4.88m O.D.	Dg2, Th1, Sh1, Dh+ Dark brown/red-brown well-humified peat	
4.88-3.69m O.D.	Dg2, Dh2, Th+, Sh+ Dark brown/red-brown herbaceous humified peat	
3.69-2.38m O.D.	Dg2, Dh1, Sh1, Th+ Dark brown herbaceous well-humified peat	
2.38-2.25m O.D.	Dg2, Dh1, Sh1, Th+ Very dark brown/black herbaceous well-humified peat	
2.25-2.21m O.D.	Ag2, Dh1, Dg1, As++, Sh+ Light grey organic silt	UNIT 4
2.21-2.07m O.D.	Dg1, Dh1, Th1, Ag1, As+, Sh+ to Dg2, Dh2, Th++, Ag+, As+ Medium/Light brown rooty clastic peat	UNIT 3
2.07-2.06m O.D.	Ag3, Dg1, As+, Dh+ Light grey organic silt	
2.06-1.81m O.D.	Dg2, Dh1, Ag1, Th+, Sh+, As+ to Dg2, Ag1, Th1, Dh++, As+ Medium brown/yellow-brown clastic rooty humified peat	
1.81-1.79m O.D.	Ag2, Dg1, Dh1, As+, Th+ Light grey-brown organic silt	
1.79-1.50m O.D.	Ag1, Dg1, Dh1, Th1, As++, Sh+ Light yellow-brown clastic rooty herbaceous humified peat	
1.50-1.00m O.D.	Ag2, As1, Ga1, Sh+, Dh+, Th+ Light grey-brown sandy-clayey-silt	UNIT 2
1.00-0.88m O.D.	Ga4, Ag+, Ggmin+ Orange-brown pebbly sand	UNIT 1
0.88-0.31m O.D.	Ga2, Ag2, Ggmaj+, Ggmin+, As+ to Ga2, Ggmaj2, Ggmin+ Orange-brown pebbly sand	
0.31m O.D.	Bedrock	

Table 10.1 Summary of typecore GVH17 stratigraphy

Once the key sedimentary units had been identified, samples were prepared for diatom, pollen and particle size analyses (see Chapter 8 for methodology). For all proxies except particle size analysis, samples were taken throughout the core profile at 5-10cm intervals (depending on the proxy in question), with an increase in sampling intensity around sedimentary boundaries. Sampling for particle size analysis was reserved for the clastic sediments towards the base of the core. Subsequent analysis showed that the presence of certain proxy indicators was very low. An absence of diatoms throughout both the biogenic and minerogenic sediments was discovered. Further analysis in the surrounding upper catchment of the Gordano Valley produced similar results, with little or no diatom frustules being present. It is likely that either a) diatoms thrived in the upper valley catchment but were destroyed through post-depositional silica dissolution or, b) diatoms could not survive in the environmental conditions present in the Gordano Valley during deposition. The fact that modern diatoms are found in abundance at Portbury Wharf (*c.* 4km ENE), would suggest that the former explanation is more likely. This is further supported by research (Johnson, 1983) that reports the enhancement of silica dissolution when the surrounding bedrock is carbonate rich. The southern side of the Gordano Valley is almost entirely composed of Carboniferous Limestone (see section 3.2.1) and may have encouraged the post-depositional dissolution of the biogenic silica. The valley’s limestone bedrock could have elevated the pH of runoff and studies have shown that increased pH levels within solutions have a direct relationship with the rate of silica dissolution. Silica dissolution is controlled by the combined properties of the solution in which the diatoms are immersed, the sedimentary matrix and the nature of the silica particles (in this case the diatom frustules; Barker *et al.*, 1994). If the pH of the solution is above 9.0, the dissolution rate increases exponentially due to the dissociation of silicic acid (Barker *et al*., 1994; Ryves *et al*., 2001). Therefore, when taking into consideration that these experiments were undertaken over very short timescales (1 to 92 days), even slightly alkaline waters are likely to influence the potential for diatom preservation when Holocene timescales are applied.

Although diatom analysis was no longer relevant to typecore GVH17, proxy analysis concentrated on particle size and pollen analysis because it was critical to continue with an environmental reconstruction. Radiocarbon dating was applied to key organic horizons in order to produce a chronological understanding to the valley's evolution.

10.2.1 Particle size analysis

A total of twenty two samples from the typecore were collected for particle size analysis. Two samples were analysed from the 5cm-thick upper minerogenic horizon (Unit 4; 2.25-2.21m O.D.) at the boundary between light yellow-brown clastic rooty peats (Unit 3) and very dark brown fen peat deposits (Unit 5). Seventeen samples were extracted at 3cm intervals from the light grey sandy-clayey silt found towards the base of typecore GVH17 (Unit 2; 1.49-1.00m O.D.). These samples were all analysed using the AccuSizer 780. Finally, three samples were taken from the orange-brown basal sediment at the bottom of the typecore (Unit 1; 1.00-0.90m O.D.). Sieving was used to determine sample particle size characteristics for these coarser sediments. Figure 10.3 summarises

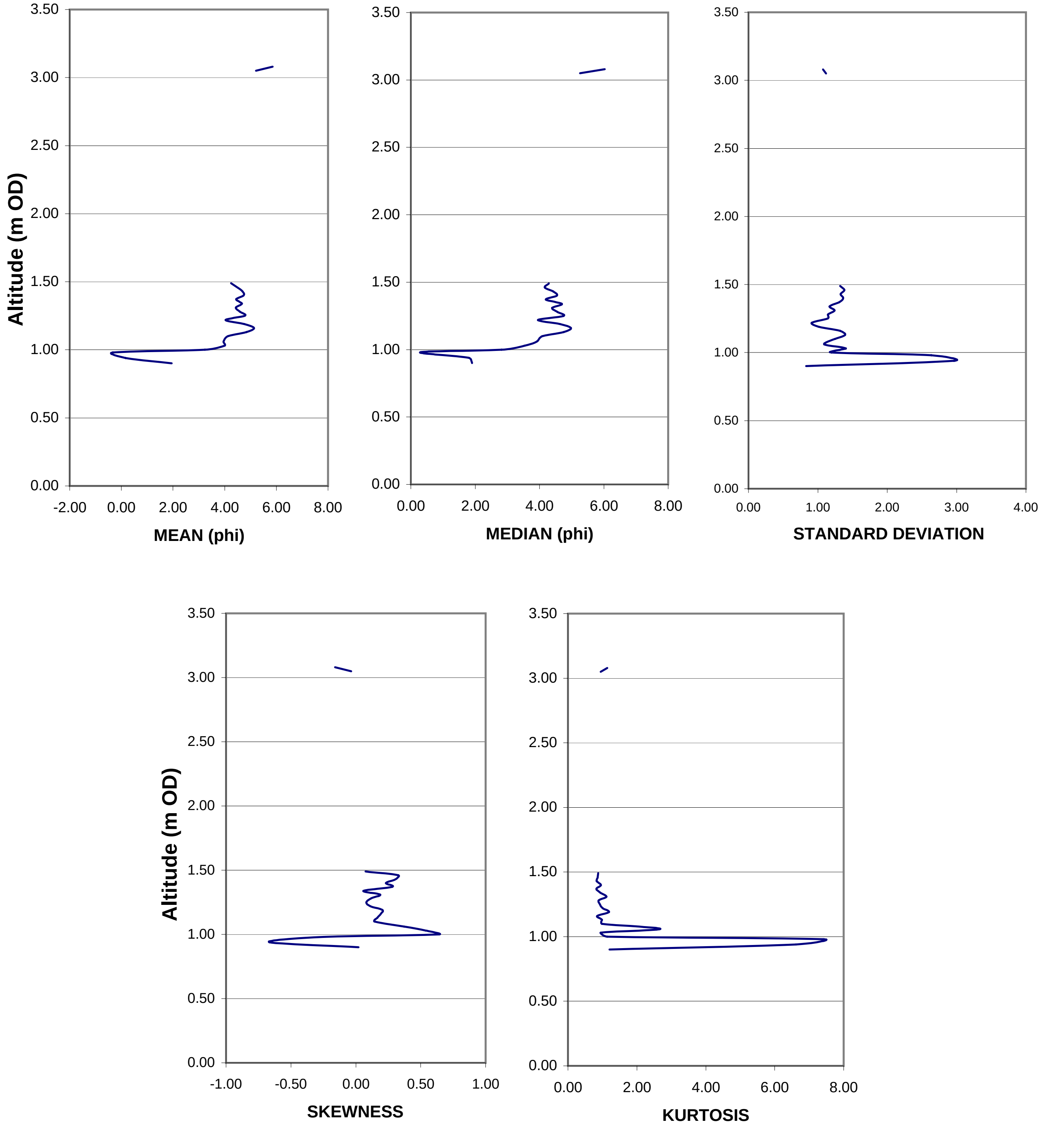


Figure 10.3 Core GVH17 particle size analysis

the grain size parameters that were calculated from analysis of the sediment samples. The gaps present indicate the position of organic deposits within the typecore profile.

The overall trend in the core profile indicates a decrease in the mean grain size of the minerogenic deposits from *c*. 0ϕ to 5.5ϕ with height. The samples extracted from the basal sediment show the most variation in mean grain size, fluctuating from 0ϕ to 3ϕ (coarse to fine sands). A gradual decrease in mean grain size is evident in Unit 2 from 1.00-1.21m O.D., where the grain size changes from 3ϕ to 5ϕ. From 1.22- 1.5m O.D., the mean grain size remains relatively constant at *c*. 4.6ϕ. There follows a break in clastic-dominated deposition, during which light yellow-brown clastic peats develop. The upper minerogenic horizon contained the finest sediments preserved in the core profile, with mean grain size values of *c*. 5.5ϕ. The median grain size parameters mirror the mean grain size results throughout the profile.

The standard deviation of 1-2ϕ S.D. of the minerogenic sediments indicates that the majority of the samples were poorly sorted. Only the basal sediment breaks from this trend, indicating that very poorly sorted sediments are present towards the base of the core (2-4ϕ S.D.). Above the basal unit, the sorting of the sediments fluctuate to around 1.22m O.D., at which point a moderately sorted sample is present (0.7-1). A gradual decrease in sorting occurs with height towards the overlying clastic peat. The standard deviation of the upper minerogenic horizon also indicates a poorly sorted deposit.

Except for the upper minerogenic horizon, all samples above the basal unit were positively skewed, indicating the predominance of fine sediments within the tail of the grain size distributions. The basal unit samples fluctuated significantly in their grain size distribution, shifting from very negatively- to very positively-skewed sediments. The overlying samples contained much higher amounts of finer material, with a decrease in skewness with height through the main minerogenic unit. The remaining samples maintain a positively-skewed nature throughout the sedimentary profile, with values of α = 0.1-0.3. The skewness of some samples within Unit 2, however, indicate an almost symmetrical distribution of grains (α = 0.1). The trend of decreasing skewness with height is continued into the upper minerogenic horizon, where negative skewness readings are present. Therefore, a shift from deposits with an abundance of fines, to those with an abundance of coarse sediments in the grain size distribution has occurred with height.

The basal sediment deposits have kurtosis values that vary considerably. Extremely leptokurtic (K_G=7.5) and leptokurtic (K_G=1.2) readings are attained in close proximity to one another, suggesting an overall dominance of a narrow range of grain size distributions. Apart from a relatively large peak in kurtosis towards the basal unit (1.06m O.D.; K_G = 2.6), the kurtosis of the overlying light-grey minerogenic unit are relatively consistent. Measurements vary from 1.1 to 0.8, with a subtle overall decrease in kurtosis with height through the main minerogenic unit. This classifies the sediments as predominantly mesokurtic.

10.2.2 Pollen analysis

A total of 52 samples were processed for pollen analysis from core GVH17. Samples were extracted and prepared from the core surface (5.16m OD) to a depth of 4.16m (1m OD).

Figure 10.4 is a pollen diagram produced from the computer package TILIA (Grimm, 1991). The stratigraphy of GVH17 is included within the diagram to enable comparisons of changing pollen assemblages with changing sedimentary horizons.

Pollen grains were relatively low in abundance towards the surface of the core. From *c.* 0.50m to *c*. 2.50m depth (4.67-2.67m OD), less than 200 grains were commonly encountered, where a count of 300 was seen to be representative of a sample's vegetation assemblage. Low counts may be due to the same factors that were responsible for the absence of diatom frustules, or because pollen production was very low. Samples with low counts were still included, however, in order to achieve a more complete understanding of temporal variation in vegetation species over time in the Gordano valley.

Constrained cluster analysis (CONISS) in Tilia*Graph (Grimm, 1991) identified seven Local Pollen Assemblage Zones (LPAZs) in GVH17.

LPAZ 1: 1.07 to 1.49m OD

Dominant species : *Pinus, Artemisia, Cyperaceae, Poaceae*

Artemisia and *Poaceae* dominate the pollen assemblages within the zone, contributing up to 35% and 30% total land pollen (TLP) respectively. *Artemisia* shows a subtle decline in abundance upwards through the pollen profile, whilst *Poaceae* fluctuates slightly. *Pinus* remains stable, contributing up to 15% TLP. Similar counts and zonal stability are shown by *Cyperaceae*. Species such as *Betula, Ranunculus* and *Thalictrum* show a clear increase in percentage abundance toward the upper zone boundary. *Trollius* and *unknown spp*. are found only within this zone.

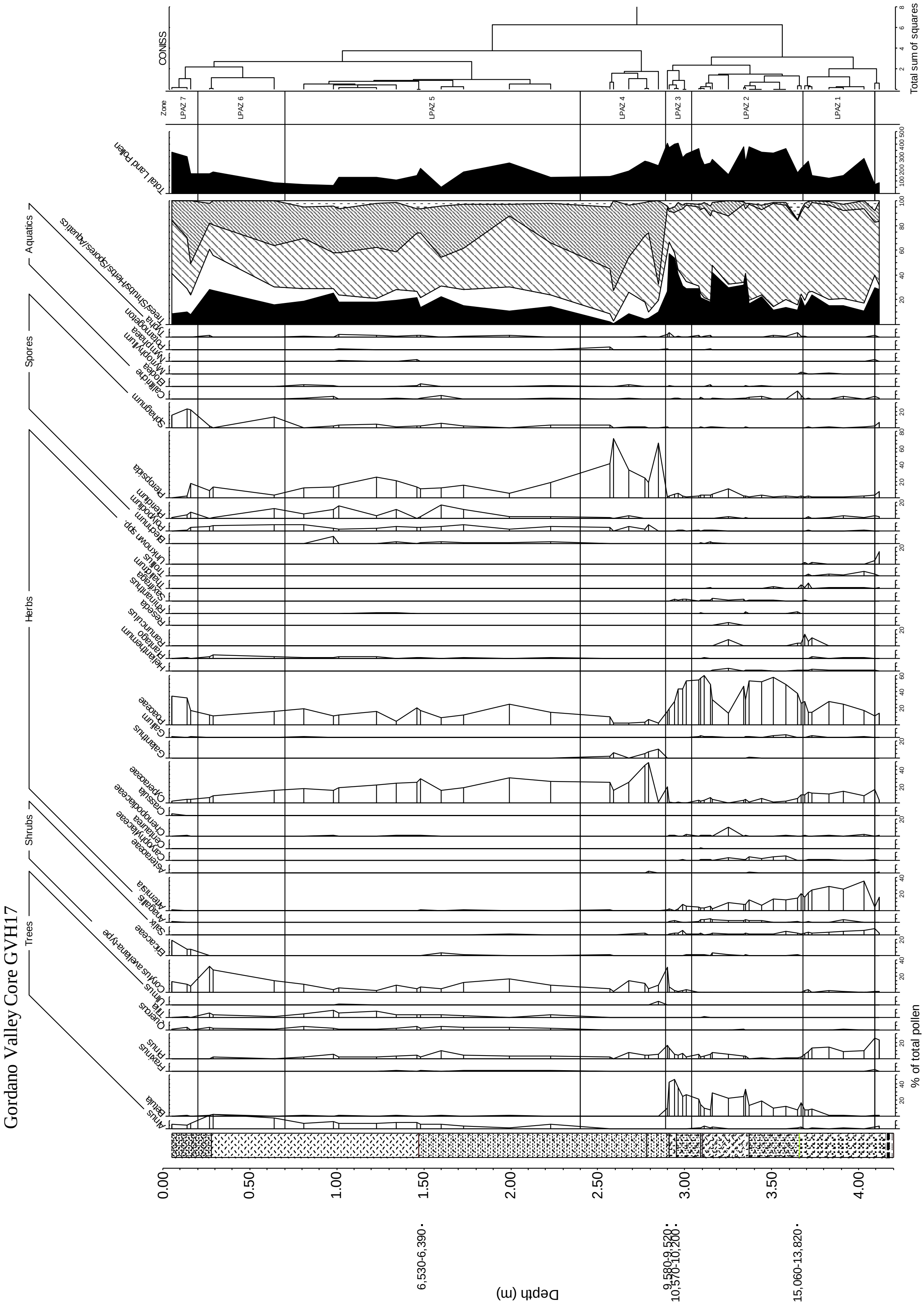


Figure 10.4 Pollen species present in Typecore GVH17

LPAZ 2: 1.49 to 2.12m OD

Dominant species: *Betula, Artemisia, Poaceae*

Poaceae dominates the zone, contributing up to 55% TLP at its peak abundance. *Poaceae* does show a decline in abundance with height, dropping to *c*. 15% TLP, only to recover towards the upper zone boundary. *Artemisia* continues its trend from LPAZ 1, dropping from 20%-5% TLP upwards through the zone. *Cyperaceae* and *Pinus* experience a considerable decline when compared to their relative dominance in the previous zone. In contrast, *Betula* counts, having increased in content at the end of LPAZ 1, continue to increase in frequency, reaching c. 25% TLP towards the centre of the zone. Although herb species dominate LPAZs 1 and 2 (contributing 60-80% TLP), distinct peaks in aquatic species can be seen, especially towards the base of LPAZ 2, represented by species such as *Callitriche* and *Typha*.

LPAZ 3: 2.12 to 2.27m OD

Dominant species: *Betula, Poaceae*

Whilst *Betula* and *Poaceae* remain the dominant species in this zone, LPAZ 3 is characterised by significant changes in the abundance of each. The onset of LPAZ 3 shows *Betula* counts recovering from a significant decline experienced at the end of LPAZ 2, increasing in frequency from 15%-40% with height. *Poaceae,* in contrast, declines gradually from 50% to 10% TLP. The zone is also important as a number of herbs do not appear again in the pollen profile (or are present, but in much lower concentrations) above LPAZ 3. Such species include *Artemisia, Helianthemum, Myriophyllum, Ranunculus, Reseda* and *Saxifraga*.

LPAZ 4: 2.27 to 2.76m OD

Dominant species: *Corylus, Cyperaceae, Filicales*

A distinct shift in pollen types and frequencies occurs into LPAZ 4. *Betula* and *Poaceae* are no longer dominant and reach only *c*. 5% TLP. The zone is typified by the fluctuating high abundances of *Filicales* (up to 70% TLP), *Cyperaceae* (up to 45% TLP) and *Corylus* (up to 20% TLP). *Pinus* maintains low (c.10% TLP) concentrations throughout, whilst other tree species including *Tilia* and *Quercus* appear towards the upper zone boundary. *Polypodium* is found in higher frequencies throughout the zone in comparison to previous zones. Whilst herbaceous species had dominated the lower LPAZs, spore species become dominant during the transition to LPAZ 4.

LPAZ 5: 2.76 to 4.46m OD

Dominant species: *Corylus, Cyperaceae, Poaceae, Filicales, Pteridium*

Corylus (c. 10% TLP) and *Cyperaceae* (20% TLP) maintain relative stability through the zone, although an overall decline in abundance with height is evident. *Poaceae* abundance increases at the onset of LPAZ 5 (25% TLP) and is associated with a fall in *Filicales* (to 5% TP). Towards the top of LPAZ 5, increasing *Poaceae* frequencies are associated with falling *Pteridium* frequencies and *vice versa* throughout the zone. The increasing abundance of *Alnus, Quercus* and *Tilia* raise the contribution of tree pollen from <5% to 20% TLP. Aquatic species (*Callitriche, Potamogeton*, *Typha*) are present, but in small amounts. Spore and herb species show a subtle decline in abundance with height, which are replaced primarily by the expansion of tree species.

LPAZ 6: 4.46 to 4.96m OD

Dominant species: *Alnus, Corylus, Cyperaceae, Poaceae*

LPAZ 6 shows increasing counts of *Alnus* and *Corylus* towards the top of the zone, whilst *Cyperaceae* and *Poaceae* decline. Spore producers fluctuate throughout the zone, but whilst *Filicales* gradually increases in abundance towards the upper boundary, *Polypodium, Pteridium* and *Sphagnum* show overall declines. The overall vegetation trend is one of increases in tree and shrub pollen and a decrease in herb pollen.

LPAZ 7: 4.96 to 5.16m OD

Dominant species: *Ericaceae, Poaceae, Sphagnum*

Herb and shrub abundances increase in abundance to dominate the upper part of LPAZ 9 (40% and 30% respectively). A drop in tree species is caused by a decline in *Alnus* and *Tilia* (30% to <10% TLP). *Poaceae* recovers to contribute ~35% TLP at the top of the zone. Similarly, *Ericaceae* and *Pteridium* increase in abundance. *Corylus* decreases through the zone, whilst *Cyperaceae* continues to decline. The few aquatic species encountered at the onset of LPAZ 9 are not present towards the upper boundary.

10.2.3 Radiocarbon dating

Taking into consideration the variation in stratigraphy and thus depositional environment, three samples were taken from typecore GVH17 for radiocarbon analysis. Two of these samples were located at key stratigraphic boundaries to understand the timing of changes in sedimentation recorded in the valley's depositional archive (1.51m O.D. and 2.26m O.D.). The third sample was taken from the centre of the fen peat (Unit 5 at 3.69m O.D.) to assess the timescale involved during the development of this unit. The depth, sedimentary description, and estimated radiocarbon date of each sample is shown in table 10.2 below, and Figure 10.5 indicates the position of the radiocarbon dates in relation to the sedimentary stratigraphy.

Sample Code	Sample depth	Altitude (O.D.)	Sample description	Conventional radiocarbon age	Radiocarbon date (1 sigma AMS - 68% confidence)	Radiocarbon date (2 sigma AMS - 95% confidence)
Beta-189678	1.47m	3.69m	Dark red-brown herbaceous humified peat	5670 +/- 40yrs BP	6480-6410 Cal. yrs BP	6530-6390 Cal. yrs BP
Beta-189679	2.9m	2.26m	Dark brown herbaceous well humified peat	8600 +/- 40yrs BP	9560-9530 Cal. yrs BP	9580-9520 Cal. yrs BP
Beta-189680	3.65m	1.51m	Light yellow-brown clastic herbaceous peat	12000 +/- 40 yrs BP	14110-13830 Cal. yrs BP	15060-14840 14260-14220, and 14130-13820 Cal. yrs BP

Table 10.2 Summary of radiocarbon results for typecore GVH17

The carbon plateau effect present within the atmosphere during the transition from the last glacial period may affect the accuracy of radiocarbon dates. Due to a reduction in levels of atmospheric ^{14}C concentrations around this time, radiocarbon dating can sometimes underestimate the true age of a sample (Lowe & Walker, 1997). As a result, the estimated radiocarbon date for the basal sample (1.51m O.D.) could only attain a 2 sigma calibrated result (producing a 95% probability of accuracy) by providing three dates. These dates position the initiation of biogenic sedimentation within the upper valley to a time during the Oldest Dryas stadial, *c*. 18,000-15,000 Cal. yrs BP or the Bølling-Allerød interstadial, *c*. 15,000-13,000 Cal. yrs BP. The initiation of dark brown fen peat development (overlying the upper minerogenic horizon, 1.26m O.D.) produced a date of 9,580-9,520 Cal. yrs BP (Early Holocene). The final sample chosen for analysis was towards the centre of the fen peat unit (2.69m O.D.) and was dated to 6,530-6,390 Cal. yrs BP (Figure 10.5).

Assuming a constant rate of sediment deposition in the Gordano Valley (and assuming no unconformable surfaces have been produced by erosional activity), an estimate of rates of deposition can be made. Accumulation rates of *c*. 1.4-1.7cm/100yrs occurred during the initial deposition of light yellow-brown clastic-rich peat (Unit 3), prior to fen peat development (Unit 5). Peat accumulation during the Early-Mid Holocene occurred at a rate of *c*. 4.6cm/100yrs. Mid-Late Holocene peat accumulation is estimated to have occurred at a rate of c. 2.3cm/100yrs, but this does not take into account the possible anthropogenic impact of peat-cutting on the Gordano Valley.

A summary of the multiproxy analysis of typecore GVH17 is provided in Table 10.3. The radiocarbon dates from the typecore are also included to indicate the timescale involved in the sedimentary evolution of the site.

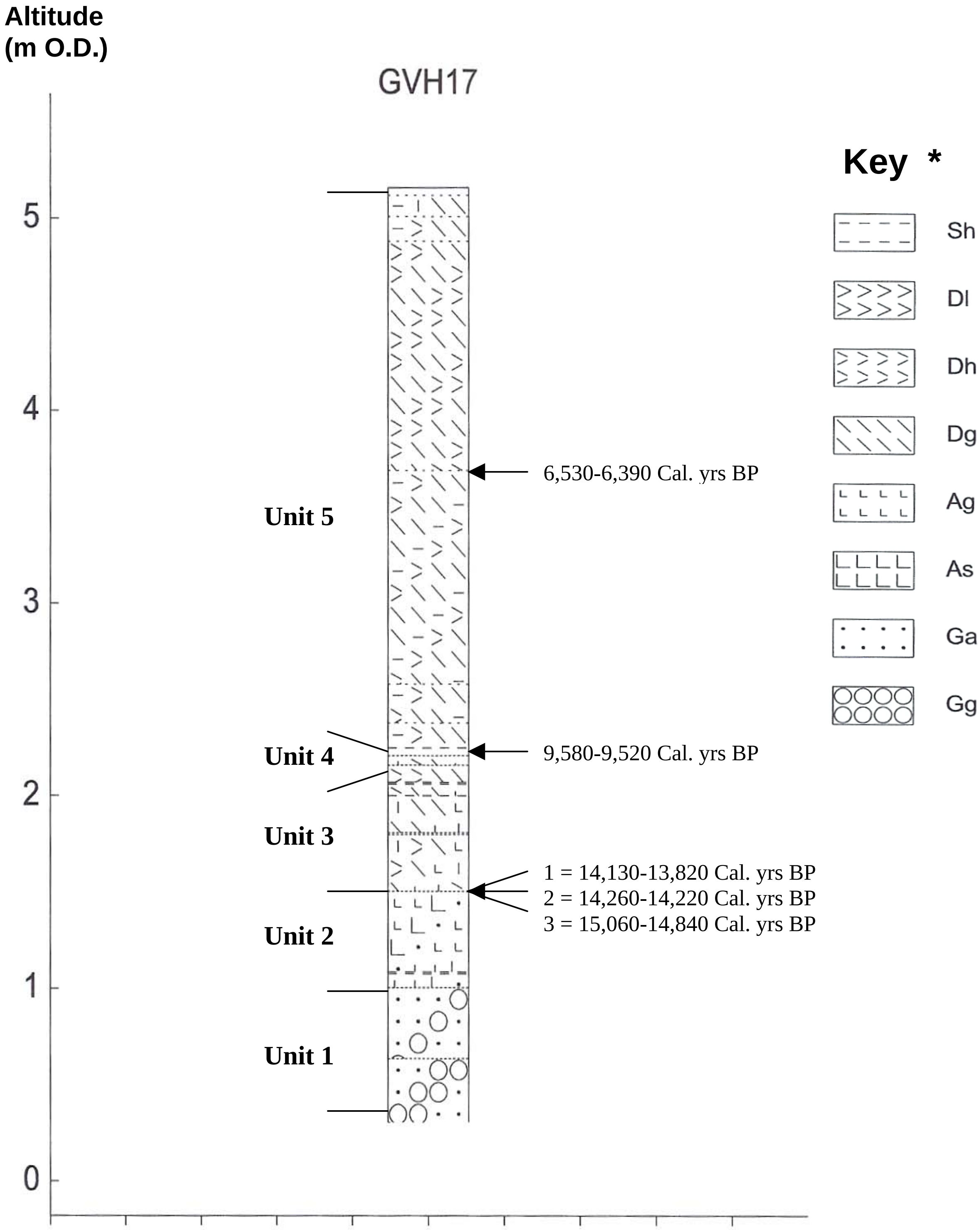


Figure 10.5 Stratigraphical profile of typecore GVH17 indicating the position of AMS radiocarbon dates.
* Refer to Troels-Smith classification scheme (Table 8.1) for key interpretation.

Altitude (m O.D.)	Sediment Type	Particle Size Analysis	Predominant Pollen	^{14}C Age (Cal. yrs BP, 2 sigma)
5.16-2.26m	Unit 5: Dark brown herbaceous well-humified peat	N/S	*Alnus, Corylus, Poaceae, Cyperaceae* and *Filicales.* Increasing levels of *Alnus* and *Corylus* with heigh through unit, whilst *Cyperaceae* and *Filicales* decrease.	3.69m (O.D.) 6,530-6,390 2.26m (O.D.) 9,580-9,520
2.26-2.22m	Unit 4: Light grey organic silt.	Mean grain size 5.5Ø, poorly sorted, negatively skewed, mesokurtic.	*Betula, Pinus, Corylus* and *Poaceae.* Highest tree pollen frequencies in whole archive within unit, primarily due to *Betula* and (to a lesser extent) *Pinus.* Introduction of *Corylus* and decreasing levels of *Poaceae* with height.	N/S
2.22-1.51m	Unit 3: Yellow-brown clastic rich herbaceous peat.	N/S	*Betula, Artemisia* and *Poaceae.* Continues decline in *Artemisia* with height, compensated by increasing *Betula. Poaceae* fluctuates through unit.	1.51 m (O.D.) 13,820-14,840 14,260-14,220 15,060-14,840
1.51-1.00m	Unit 2: Light grey-brown sandy-clayey silt.	Mean grain size 4.6Ø, moderately sorted, positively skewed, mesokurtic.	*Pinus, Artemisia, Poaceae* and *Cyperaceae.* Overall decreases of *Artemisia* and *Pinus* with height, whilst *Poaceae* and *Cyperaceae* remain constant. Introduction of *Betula* and *Ranunculus* towards upper boundary.	N/S
1.00-0.31m	Unit 1: Orange-brown pebbly sand.	Mean grain size 0-3Ø, very poorly sorted, varying skewness, extremily leptokurtic.	N/S	N/S

Table 10.3 Summary of proxy results for typecore GVH17

10.3 Typecore GVJ43

Figure 10.6 provides a sedimentary profile of the second typecore, GVJ43, using TSPPlus (Waller *et al.*, 1995). The typecore was levelled into a local benchmark, providing an altitude of 5.99m O.D. for the ground surface of the typecore site. The typecore site was chosen because it was representative of the typical deposits found seaward of the ridge. The typecore, however, differs from the sedimentary sequence described in 9.1.3.2., due to the presence of three, not two, peat units interbedded within (bluey) grey clayey-silts. This feature however was present in a number of the cores extracted from the Clapton Moor Sequence (as indicated in Figure 9.8). This site allowed an assessment of the influence of late Quaternary sea-level change on the valley to a greater extent than a site further inland (towards the ridge) where only one or two peat units were present within the clayey-silt deposits. Only the orange-brown basal sediment was present on both sides of the ridge, and this is referred to as Unit 1. However, as the sedimentary archive is different to that preserved landward of the ridge, Units 2-5 are absent. Consequently, Unit 6 (a-c) relates to the peat horizons present in the typecore and Unit 7 (a-c) relates to the minerogenic sediments. Due to agricultural activity, the upper 50cm was too disturbed to be sampled reliably during typecore extraction. As a result, sampling began at 0.5m depth (5.49m O.D.)

A summary of the sedimentary sequence preserved in the typecore is provided in Table 10.4 to assist the interpretation of Figure 10.6. A brief description of each sedimentary horizon is included, along with the sedimentary content following the Troels-Smith classification scheme (1955).

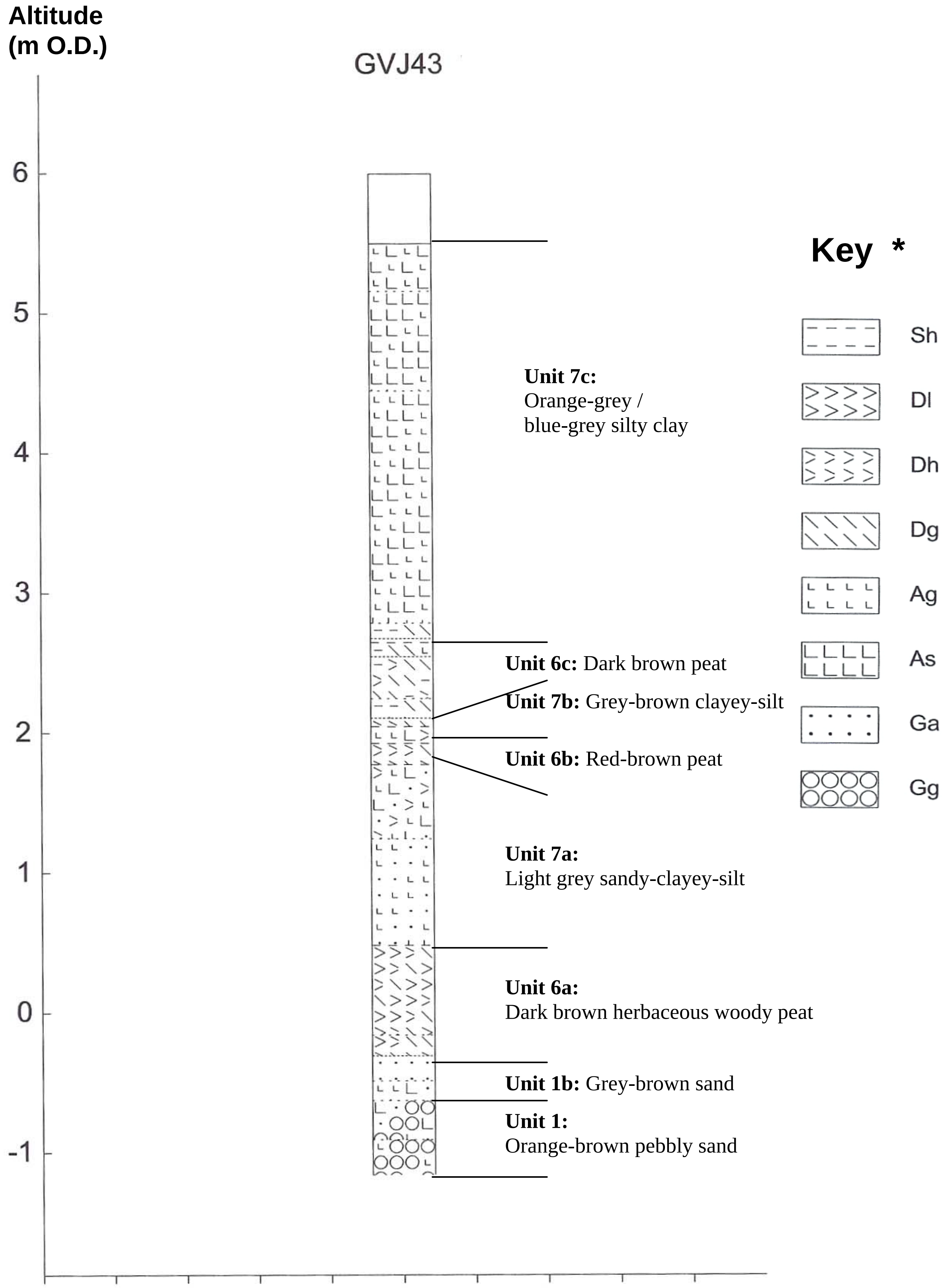


Figure 10.6 Stratigraphic profile of typecore GVJ43.
* Refer to Troels-Smith classification scheme (Table 8.1) for key interpretation.

Altitude	Stratigraphy	
5.99-5.49m O.D.	Unsampled	Unit 7c
5.49-5.19m O.D.	Ag2, As2, Lf++, Sh+ Mottled orange-grey silty clay	
5.19-4.44m O.D.	As3, Ag1, Lf+, Sh+ Mottled orange-grey silty clay	
4.44-2.78m O.D.	Ag2, As2, Sh+, *Lf+, Dh+** Orange-grey/bluey-grey silty clay **Iron mottling decreases with depth, whilst organic mottling increases*	
2.78-2.64m O.D.	Dg2, Dh1, Sh1, Th+ Dark brown herbaceous well-humified peat	Unit 6c
2.64-2.54m O.D.	Dg2, Ag1, Sh1, As+, Dh+, Th+ Light grey-brown silty well-humified peat	
2.54-2.04m O.D.	Dg2, Dh2, Sh+, Dl+ Very dark brown herbaceous well-humified peat	
2.04-1.92m O.D.	Ag2, As1, Dh1, Th+, Sh+, Dg+ Light grey-brown organic clayey silt	**Unit 7b**
1.92-1.77m O.D.	Dh3, Dg1, Dl+, Th+, Sh+ Medium red-brown herbaceous peat	**Unit 6b**
1.77-1.46m O.D.	Ag2, As1, Ga1, Dh+, Th+. Sh+ Medium grey organic sandy clayey silt	Unit 7a
1.46-1.24m O.D.	Ga2, Ag1, As1, Dh+, Th+ Light grey clayey silty sand	
1.24-0.48m O.D.	Ga2, Ag2, As+, *Dh+, Th+, Sh+** Medium grey organic silty sand **organic content increases with depth*	
0.48 to –0.31m O.D.	Dl2, Dh1. Dg1, Sh+ Dark brown herbaceous humified woody peat	**Unit 6a**
-0.31 to –0.49m O.D.	Ga4, Ag+, Gg(maj)+, Gg(min)+, Dh+ Grey-brown sand	**Unit 1b**
-0.49 to –1.16m O.D.	Ag2, As1, Ga1, Gg(min)+, Gg(maj)+ to Gg(maj)2, Gg(min)1, Ag1, Ga+, As+ Orange-brown pebbly sand	**Unit 1**
-1.16m O.D.	Bedrock	

Table 10.4 Summary of typecore GVJ43 stratigraphy

Samples were taken throughout the core profile for pollen and diatom analysis, but only the minerogenic units were sampled for particle size analysis. Diatoms and pollen were present in relative abundance throughout the sedimentary profile. The preservation of diatoms within GVJ43 may further support the theory that post-depositional silica dissolution was responsible for the removal of diatom frustules in typecore GVH17 and the rest of the upper valley sedimentary profile. The presence of the ridge would have produced an enclosed depositional basin within the upper valley region. Carbonate-rich runoff from the surrounding valley sides may have accumulated within this basin throughout, enhancing the dissolution of diatom frustules over time, and this may also explain the relatively low pollen counts experienced (Johnson, 1983; Barker *et al.*, 1994). Meanwhile, the open coastal conditions seaward of the ridge would have prevented the carbonate-rich runoff from having the same impact on the accumulating sediments.

10.3.1 Particle size analysis

A total of 41 samples were taken from the minerogenic sediments preserved in typecore GVJ43. Four main minerogenic sequences were present within the sedimentary profile; the basal sediment (Unit 1) and the overlying grey-brown sand (Unit 1b), from -0.31 to –1.16m O.D; the lower unit (Unit 7a), from 0.48 to 1.77m O.D; the middle unit (Unit 7b), 1.92 to 2.04m O.D; and the upper unit (unit 7c), from 2.78 to 5.49m O.D. Samples were taken at 20cm intervals within the *c*. 3m thick upper unit, and 10cm intervals through each of the remaining horizons, increasing in resolution towards sedimentary boundaries. Overlying and underlying the middle and lower units were organic deposits. All samples from the first three units were analysed using the AccuSizer 780. Six remaining samples from the grey-brown sands (Unit 1b) and orange-brown basal sediments (Unit 1) were too coarse for analysis with the AccuSizer, and thus their grain size characteristics were determined using the sieving method of Folk (1974). Figure 10.7 summarises the grain size parameters that were calculated from analysis of the sediment samples. Gaps within the graphs of the grain size characteristics relate to the position of the organic horizons within the core profile.

An overall decrease in grain size with height is evident through the sedimentary profile. Unit 1 and Unit 1b contained mean grain sizes that decrease from 1-2.5ϕ between –0.31 and –0.5m O.D.; medium sands thus typify these deposits. A peat unit separates the basal sediments from the lower minerogenic unit (Unit 7a). The lower unit (0.48 to 1.77m O.D.) shows a continued decrease in mean and median grain size with height through the profile. The average grain sizes in the middle unit (Unit 7b; 2.04-1.92m O.D.) fluctuate, but show an overall decrease in mean grain size with height from *c.* 5ϕ to 6ϕ, a trend that is again supported by the median grain size data. The average grain size also decreases from *c*. 5ϕ to 6ϕ with height through the upper unit (Unit 7c; 2.78-5.49m O.D.) and is a trend that is reflected in both mean and median grain size results.

The level of sediment sorting is relatively consistent throughout the sedimentary profile, with standard deviation results maintaining levels around 1.5ϕ between 0.5-5.49m O.D. This indicates that these sediments were all poorly sorted (1-2ϕ range). Only

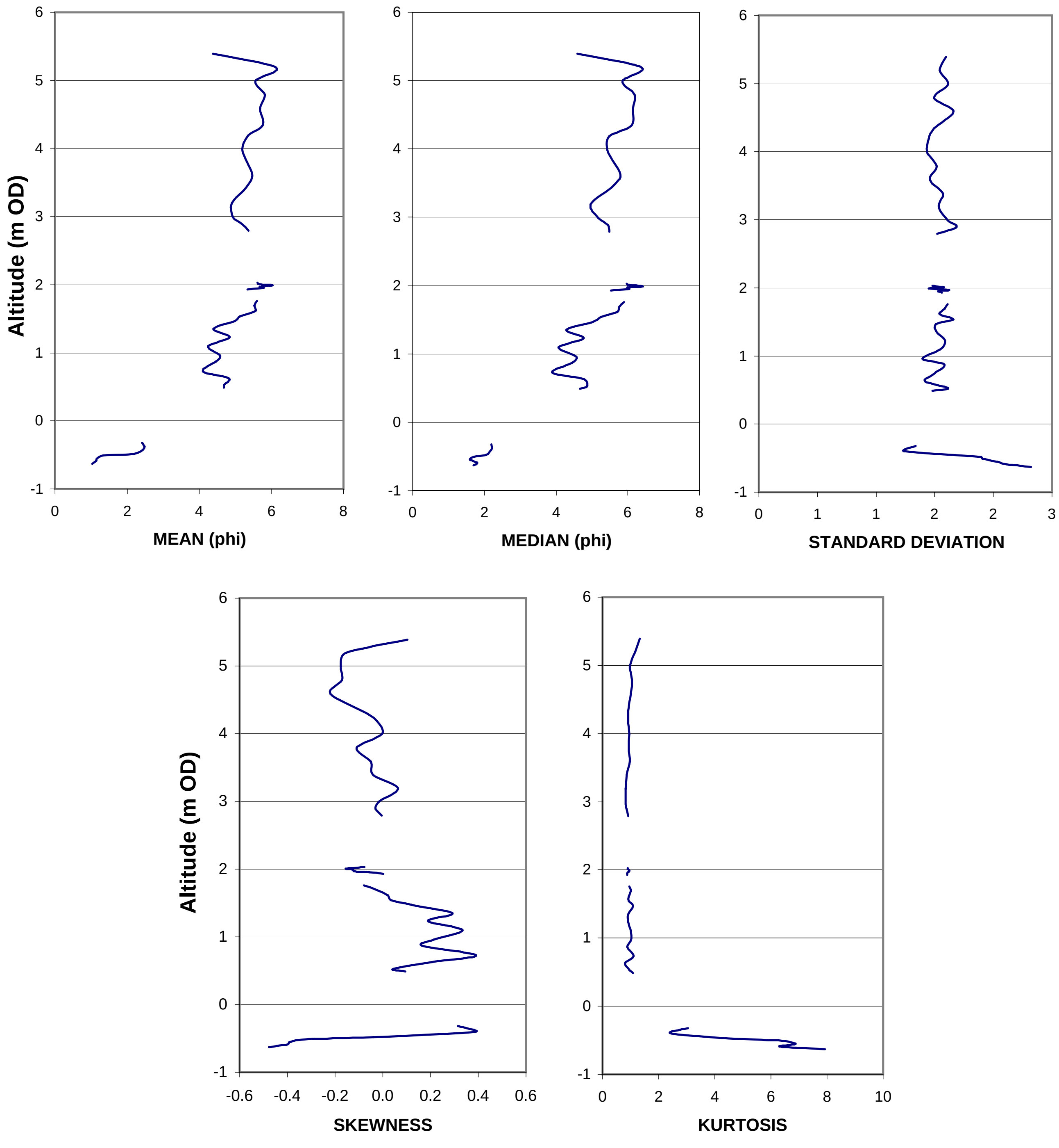


Figure 10.7 Particle size analysis of typecore GVJ43

Unit 1 differs from this trend, with the level of sorting decreasing with depth into a very poorly sorted sediment in the basal sample.

The levels of skewness within the minerogenic sediments show considerable variation through the core profile. Units 1 and 1b show a shift from negatively to positively skewed sediment distribution with height. The lower unit (7a) is positively skewed due to the abundance of fine grain sizes within the tail of its grain size distribution. The unit becomes less positively skewed with height. The middle (7b) and upper (7c) units are dominated by negatively skewed and symmetrical grain size variations, indicating an overall predominance of coarse sediments within the tail of the grain size distributions. Except for Unit 1, each unit shows a trend of becoming more negatively skewed with height.

The kurtosis of the minerogenic sediments indicates predominantly platykurtic and mesokurtic grain size distributions are present throughout the core profile. As kurtosis is a ratio of spreads of the tails and centre of the sediment distribution, the overall stability of the kurtosis results can be associated with the overall level of sorting, which was also found to be consistent. Once again, results from the basal unit differ considerably from the three overlying minerogenic units. These basal sediments are dominantly very leptokurtic in nature. Above Unit 1, as mesokurtic grain size distributions dominate (K_G = 0.9-1.11), there is an overall evenness (normality) in the dispersion of grain sizes through the sediments distribution. Platykurtic sediment distributions (K_G = 0.67-0.9) are present at the bases of the upper and lower units and are indicative of strongly peaked distribution curves.

10.3.2 Pollen analysis

A total of 54 samples were analysed for pollen within the typecore profile. The pollen sampling strategy concentrated on the peat units and the overlying and underlying minerogenic sediments. Samples were taken at regular 10cm intervals from 3.19m O.D. to -0.48m O.D., with increased sampling resolution towards sedimentary boundaries. Minerogenic sediments commonly contained lower pollen abundances than the peat horizons.

Figure 10.8 is a pollen diagram produced using the computer package TILIA (Grimm, 1991). The stratigraphy of GVJ43 is included within the diagram to enable comparisons of changing pollen assemblages with changing sedimentary horizons.

Nine local pollen assemblage zones (LPAZs) were identified by analysing the pollen assemblages within GVJ43 and using the statistical package CONISS in Tilia*Graph (Grimm, 1991).

LPAZ 1: -0.5 to -0.27m OD

Dominant species: *Corylus, Bryophytes, Pteridium*

Corylus abundance increases throughout the zone from 20% TLP to 30% TLP at the top. *Bryophytes* spores are only evident within this zone of the core, contributing 40% TLP at the base, falling to <5% at the upper zone boundary. *Pteridium* remains at around 20% TLP throughout the zone. *Tilia* and *Filicales* show subtle increases in frequency with height, reaching c. 10% and c. 7% TLP respectively. Spores and herbs contribute the majority of the pollen within LPAZ 1, with a gradual increase in tree species upwards.

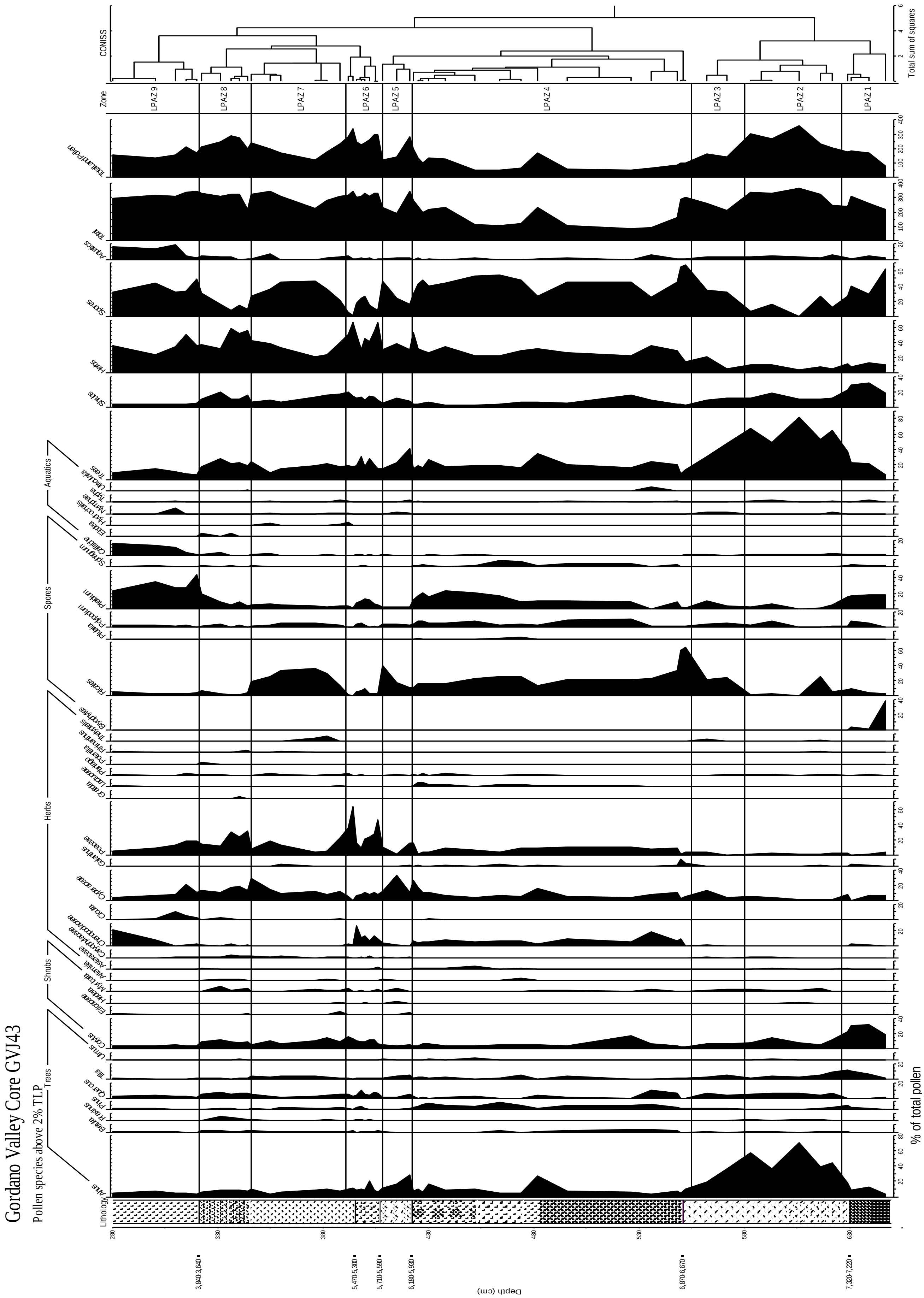


Figure 10.8 Pollen species present in Typecore GVJ43

LPAZ 2: -0.31 to 0.19m OD

Dominant species: *Alnus, Corylus, Quercus, Filicales*

Alnus dominates the zone, rising from 15% TLP to 60% TLP before a fall to *c*. 45% TLP towards the upper zone boundary. Other species such as *Corylus*, *Pteridium* and *Tilia* show simultaneous decreases in frequency with height through LPAZ 2. *Filicales* peaks at 20% TLP at the base of the zone, before decreasing to <5% TLP at the upper zone boundary. The presence of *Quercus, Tilia* and *Pinus* ensure that tree pollen dominates, contributing up to 80% TLP towards the centre of the zone and then decreasing with height to *c*. 60% TLP.

LPAZ 3: 0.19 to 0.44m OD

Dominant species: *Alnus, Cyperaceae, Filicales*

A significant drop in *Alnus* abundance occurs within the zone, falling from 45% to 10% TLP. In contrast, there is an increase in *Filicales* spores from 5% to 50% TLP. *Cyperaceae* rises from 5% to 10% TLP within the zone, but returns to 5% TLP at the upper boundary. *Corylus* shows a gradual decline from 10% to 5% TLP towards the top of the zone, a trend repeated by *Quercus, Tilia* and *Myricaria*. The shift in dominance from *Alnus* to *Filicales* is reflected in the drop in tree pollen frequencies from 60% to 15% TLP and a rise in spore species from 15% to 60% TLP. Herb species rise from 10% to 20% TLP towards the top of the zone.

LPAZ 4: 0.44 to 1.77m OD

Dominant species: *Corylus, Chenopodiaceae, Poaceae, Filicales, Pteridium*

The majority of the species within LPAZ 4 do not experience significant frequency fluctuations. *Corylus, Chenopodiaceae, Cyperaceae, Poaceae* and *Polypodium* all maintain frequencies of around 5% to 10% TLP. *Chenopodiaceae*, *Cyperaceae* and *Poaceae* all peak just above and below the upper and lower boundary. After its initial peak at the onset of LPAZ 4, *Filicales* maintains counts of between 15% and 25% through the zone. *Pteridium* shows a gradual increase in frequencies through the zone, from 5% to 20% TLP towards the upper boundary.

LPAZ 5: 1.77 to 1.91m OD

Dominant species: *Alnus, Cyperaceae, Poaceae, Filicales*

Alnus contributes 30% TLP at the onset of the zone, dropping to 10% TLP at the top of the zone. In contrast, *Filicales* increases in frequency from 15% to 40% TLP up-zone. *Cyperaceae* frequencies peak in the centre of the zone at 30% TLP, decreasing in abundance towards the upper and lower boundaries (to *c*. 10% TLP). *Poaceae* shows an opposing trend to *Cyperaceae*, attaining higher frequencies at the zone margins (10-15% TLP) and lower frequencies in the centre of the zone (<5% TLP). Tree species fall from 40% to 15% TLP, whilst spore frequencies increase from 15% to 45% with height up the zone.

LPAZ 6: 1.91 to 2.08m OD

Dominant species: *Corylus, Chenopodiaceae, Cyperaceae, Poaceae, Pteridium*

Distinct peaks in *Poaceae* and *Chenopodiaceae* at the upper and lower boundaries of the zone characterise LPAZ 7. *Poaceae* reaches 40% TLP at the lower boundary, drops to 15% TLP in the centre of the zone, rising to 60% TLP at the top of the zone. *Chenopodiaceae* frequencies increase from 15% to 25% TLP towards the upper zonal boundary. *Corylus* frequencies show a gradual rise with height through the zone, from 10% to 15 % TLP. *Pteridium* peaks in frequency in the centre of the zone, at *c*. 15% TLP. Herbaceous species dominate the upper and lower boundaries of the zone, being replaced by spore and tree species in the centre.

LPAZ 7: 2.08 to 2.53m OD

Dominant species: *Corylus, Cyperaceae, Poaceae, Filicales*

Filicales dominates the zone, increasing to 35% TLP towards its centre. *Cyperaceae* increases from <5% to 30% TLP through the zone, whilst *Corylus* shows the opposite trend, falling from 15% to 10% TLP with height. *Poaceae* frequencies fluctuate considerably, peaking at 35% TLP at the lower zone boundary, dropping to 5% TLP further up the zone, and returning to frequencies of c. 15% towards the upper boundary. *Alnus, Quercus, Polypodium* and *Pteridium* frequencies, although low (<10% TLP), remain stable throughout the zone. Spores dominate the zone (*c*. 45% TLP), and shrubs show a gradual decline in abundance with height from 20% to 10% TLP.

LPAZ 8: 2.53 to 2.78m OD

Dominant species: *Cyperaceae, Poaceae, Pteridium*

Cyperaceae frequencies drop from 20% to 10% TLP with height through the zone. A similar trend is shown by *Poaceae* which peaks at 30% TLP at the lower zone boundary, before it drops to 15% TLP towards the upper boundary. In contrast, *Pteridium* frequencies rise to c. 45% TLP with height, from 5% TLP at the base of the zone. *Alnus, Quercus* and *Corylus* frequencies all remain stable at c. 10% TLP throughout LPAZ 8. A decline in the contribution of herb pollen from 50% to 35% TLP occurs up the zone, whilst spore frequencies increase from 10% to 45% TLP.

LPAZ 9: 2.78 to 3.19m OD

Dominant species: *Chenopodiaceae, Cyperaceae, Poaceae, Pteridium, Callitriche*.

Pteridium dominates LPAZ 9, contributing 40% TLP at the lower boundary, gradually dropping to 25% TLP with height. *Cyperaceae* and *Poaceae* show a similar trend of declining frequencies with height, dropping from 15% to *c*. 5% TLP. *Chenopodiaceae* and *Callitriche* frequencies increase from <5% to 15% and 20% TLP respectively up the zone. Species such as *Alnus, Quercus, Corylus, Filicales* and *Polypodium* all show distinct drops in frequency at the lower zone boundary, but maintain low but stable frequencies (c. 5% TLP) thereafter. Aquatic species increase in frequency with height up the profile from <5% to 15% TLP. Herb and spore species dominate the zone, varying in frequency through the zone from 25% to 50% TLP, with no distinct trends apparent.

10.3.3 Diatom Analysis

Diatom analysis was conducted on all but the upper *c*. 3m of GVJ43, in which diatoms were absent. Within this section of the core, grey clayey-silts overlie the interbedded peat sequence. These upper minerogenic sediments were characterised by high levels of iron mottling. It is likely that fluctuating water tables in this 3m sequence have caused variations in redox conditions, thereby enhancing frustule dissolution through the precipitation of iron oxides (Mayer *et al.*, 1991). Water table fluctuations are likely to result from artificial drainage in the Gordano Valley, evidenced by a network of drainage ditches (see Figure 1.1). Long periods of low water table would enhance the precipitation of iron oxides within silts and enable the subsequent dissolution of biogenic silica.

Ten local diatom assemblage zones (LDAZs) were identified using constrained cluster analysis (CONISS) in Tilia*Graph (Grimm, 1991). Of these, three zones (LDAZ 1, 6 and 8) are defined by the absence of diatom preservation within peat horizons. Diatom species and salinity groups are expressed as a percentage of total diatom valves (TDV).

To achieve a sound palaeoenvironmental context, the first section of each LDAZ summary describes the diatom assemblages according to the lifeform and salinity classifications of Denys (1991-92). This enables an assessment of the influence of planktonic and epiphytic/benthic species input within the diatom assemblages, via which the influence of allochthonous and autochthonous species can be assessed. This enables an accurate interpretation of palaeodepositional conditions to be achieved through the analysis of the autochthonous (*in-situ*) diatom assemblages. Each LDAZ is then described according to the ecological classification of Vos & deWolf (1993) to allow further refinement of the summary by describing the environmental conditions for different diatom groups (epipelic, epiphytic, aerophilous, etc). This enables an interpretation of the sedimentary environment that was present at the time of deposition. Further information regarding the application of these ecological classification schemes can be found in sections 6.2 and 8.3.

10.3.3.1 Classification of diatom species in typecore GVJ43

Figures 10.9a and 10.9b classify the diatoms preserved in GVJ43 according to their lifeform; the stratigraphy of GVJ43 is included within the diagrams to enable comparisons of changing diatom assemblages with changing sedimentary horizons. Figure 10.9a indicates the abundance of individual diatom species within the typecore, whilst Figure 10.9b shows the dominant diatom salinity groups present in each diatom assemblage. Table 10.5 summarises the diatom lifeform variations throughout typecore GVJ43. The table indicates the relative contributions of both epiphytic/benthic species and planktonic species, enabling an understanding to be achieved of the influence of autochthonous and allochthonous species respectively. The optimal autochthonous diatom group (regarding lifeform) has been calculated, indicating the dominant salinity conditions present at the time of deposition. The influence of those autochthonous species to the freshwater and marine ‘side’ (as a ratio) of the optimal group (see section 8.3.4 for methodology) have also been calculated, indicating the changing influence of freshwater and marine conditions through the core profile.

Diatoms within the typecore were reclassified according to their lifeform (planktonic, tychoplanktonic, epipelic, epiphytic, aerophilous) and salinity. The ten LDAZs are reassessed according to the classification scheme. Figures 10.10a and 10.10b summarise the diatoms preserved in GVJ43 according to the lifeform classification of Vos and deWolf (1993); the stratigraphy of GVJ43 is included within the diagrams to enable comparisons of changing diatom assemblages with changing sedimentary horizons. Figure 10.10a indicates the abundance of individual diatom species within the typecore, whilst Figure 10.10b shows the dominant diatom salinity groups presenting each diatom assemblage according to Vos and deWolf (1993). Table 10.6 summarises the lifeform assemblages present within each diatom sample (as a percentage of TDV), along with the inferred depositional environment from these assemblages according to the classification scheme of Vos and deWolf (1993). The overall summary of diatom assemblages within the typecore are provided in the analysis of allochthonous and autochthonous diatoms; only key species and lifeform variations will be described below.

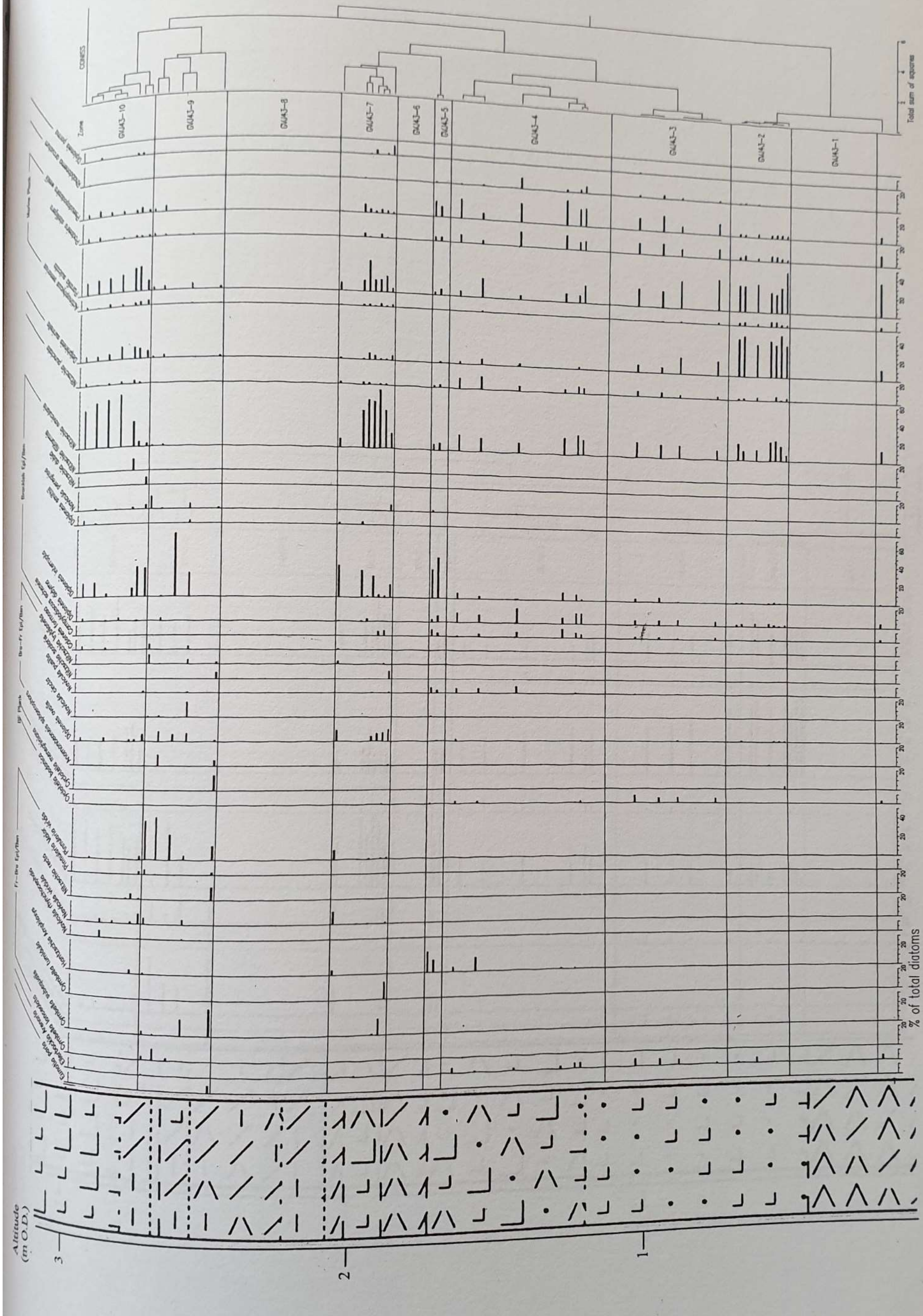


Figure 10.9a Ecological classification of epiphytic/benthic *vs* planktonic diatom species present in Typecore GVJ43

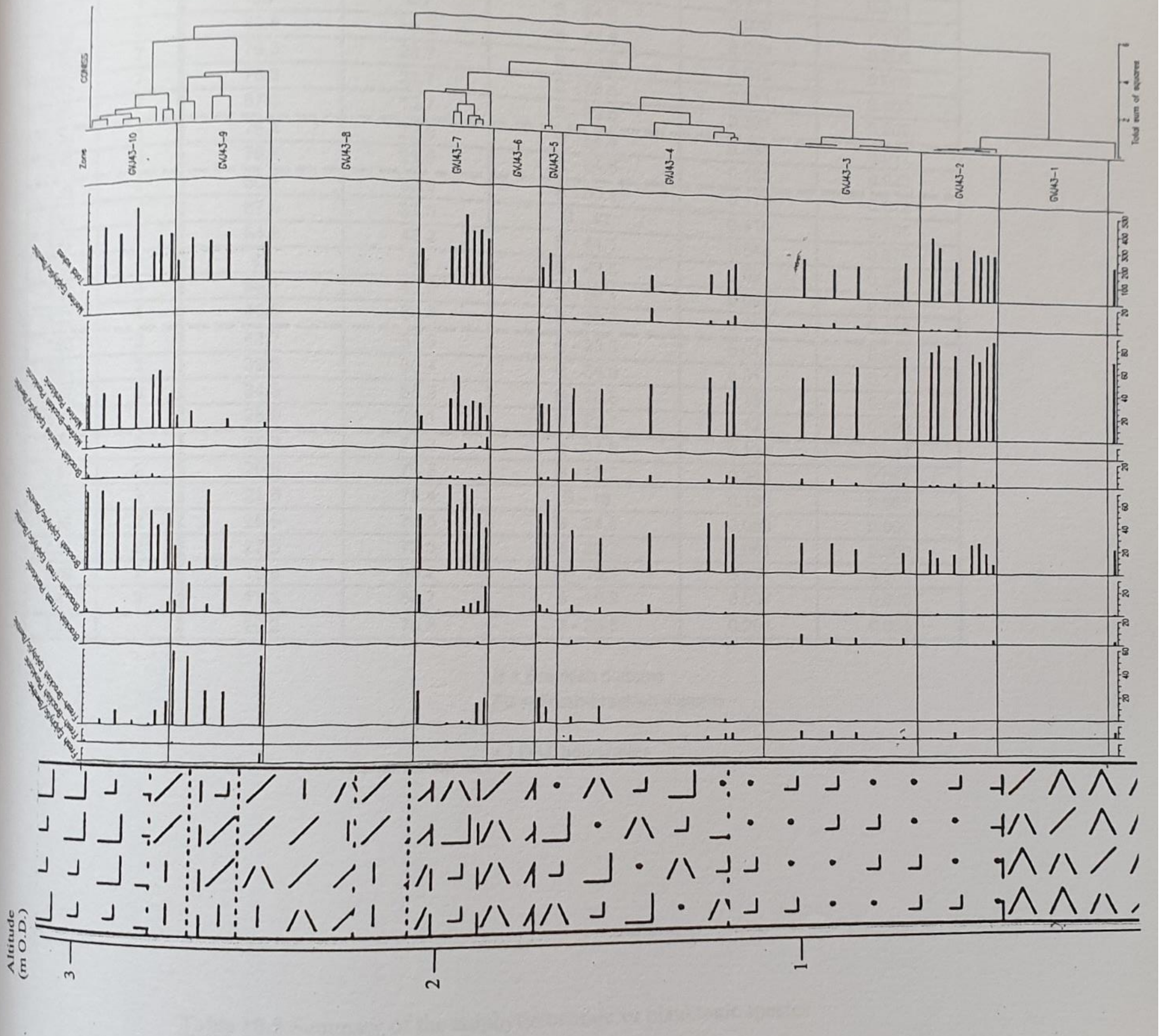


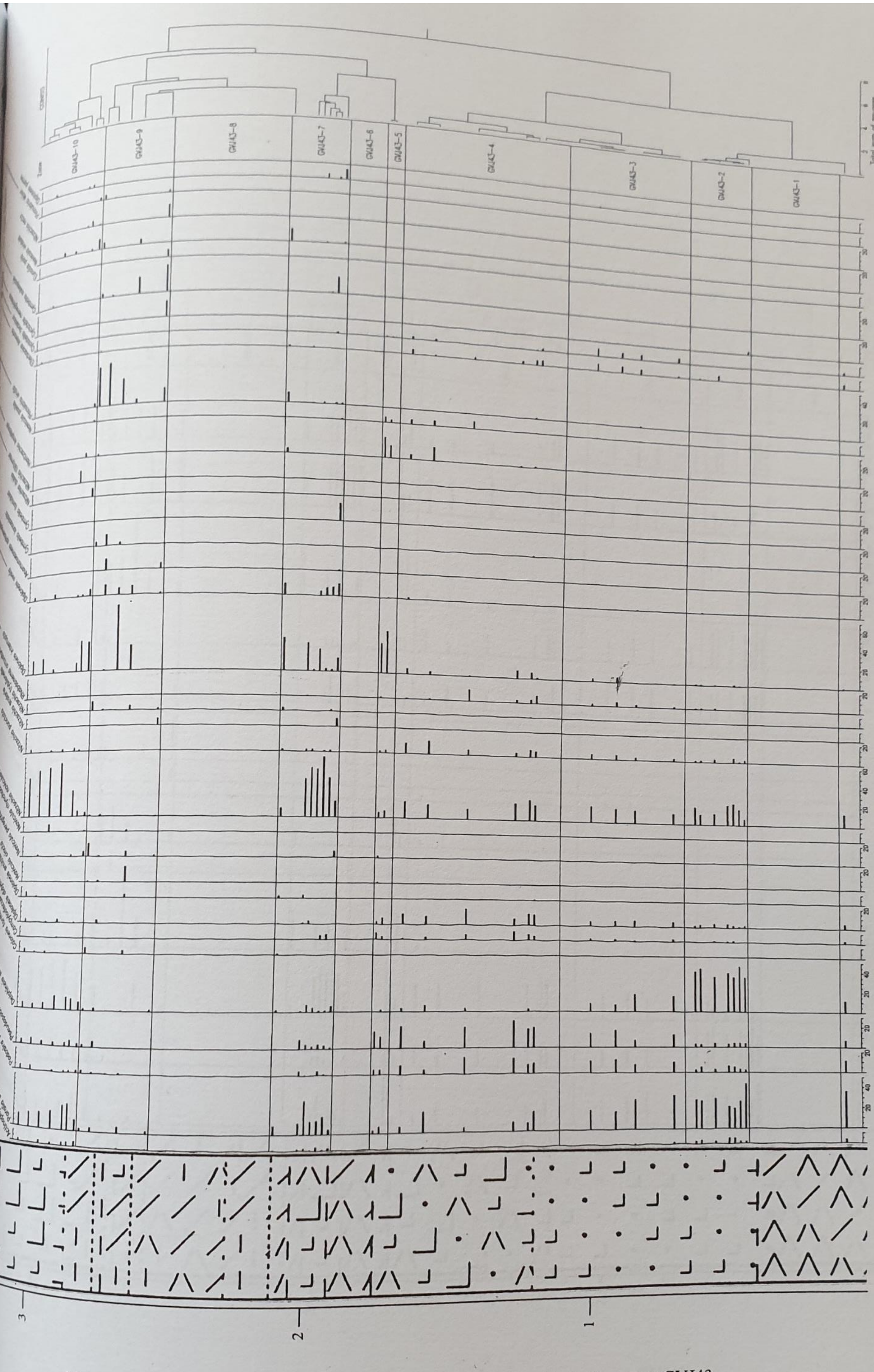
Figure 10.9b Ecological classification of epiphytic/benthic *vs* planktonic diatom groups present in Typecore GVJ43

Altitude (m OD)	LDAZ	Total diatoms % epiphytic/benthic	Total diatoms % planktonic	% Autochthonous diatoms (optimal epiphytic/benthic group)	Autochthonous diatoms (fresh ratio)	Autochthonous diatoms (marine ratio)
3.04	10	69.6	30.4	B - 67.5	0.021	0.007
2.99	10	71.6	28.4	B - 65	0.063	0.009
2.94	10	72.4	27.6	B - 59.9	0.204	0.005
2.89	10	61.8	38.2	B - 57.9	0.050	0.000
2.84	10	57.1	42.9	B - 53.7	0.020	0.011
2.82	10	54.2	45.8	B - 40.8	0.275	0.000
2.79	10	73	27	B - 48.1	0.435	0.000
2.77	9	87.5	12.5	FB - 66.7	-	0.313
2.73	9	82	18	FB - 73.2	-	0.120
2.68	9	98.7	1.3	B - 71	0.390	0.000
2.63	9	93	7	B - 66.2	0.405	0.000
2.53	9	83.4	16.6	FB - 81.8	-	0.020
2.11	7	88.5	11.5	B - 61.3	0.444	0.000
2.03	7	73.1	26.9	B - 71.1	0.014	0.014
2.01	7	55	45	B - 54.5	0.000	0.000
1.99	7	80.8	19.2	B - 74.8	0.024	0.000
1.97	7	76.3	23.7	B - 74.6	0.013	0.009
1.95	7	78.3	21.7	B - 58.5	0.311	0.000
1.93	7	87.3	12.7	B - 58.6	0.331	0.000
1.78	5	76.4	23.6	B - 54.4	0.388	0.017
1.76	5	78.1	21.9	B - 64.6	0.183	0.023
1.69	4	60.1	39.9	B - 50.4	0.175	0.018
1.61	4	67.4	32.6	B - 42	0.410	0.195
1.47	4	54.8	45.2	B - 41.1	0.046	0.278
1.3	4	47	53	B - 43.5	0.021	0.060
1.25	4	59.1	40.9	B - 50.1	0.090	0.090
1.23	4	49.5	50.5	B - 38.7	0.057	0.222
1.03	3	42.7	57.3	B - 38.3	0.013	0.081
0.94	3	39.6	60.4	B - 34.9	0.017	0.117
0.87	3	34.8	65.2	B - 28.8	0.139	0.069
0.73	3	28.9	71.1	B - 23.7	0.127	0.093
0.65	2	25.2	74.8	B - 21.5	0.135	0.037
0.63	2	20.5	79.5	B - 15.7	0.248	0.057
0.58	2	21.6	78.4	B - 18	0.133	0.067
0.53	2	25.5	74.5	B - 24.5	0.053	0.000
0.51	2	27.5	72.5	B - 29.7	0.061	0.000
0.49	2	19.8	80.2	B - 18.1	0.094	0.000
0.47	2	11.3	88.7	B - 10.9	0.037	0.000
0.11		29.2	70.8	B - 23.5	0.204	0.038

B = Brackish diatoms
FB = Fresh-brackish diatoms

= LDAZ boundaries

Table 10.5 Summary of the epiphytic/benthic vs planktonic species present within typecore GVJ43.



<u>Figure 10.10a</u> Ecological classification of diatom species present in Typecore GVJ43 according to Vos & deWolf (1993)

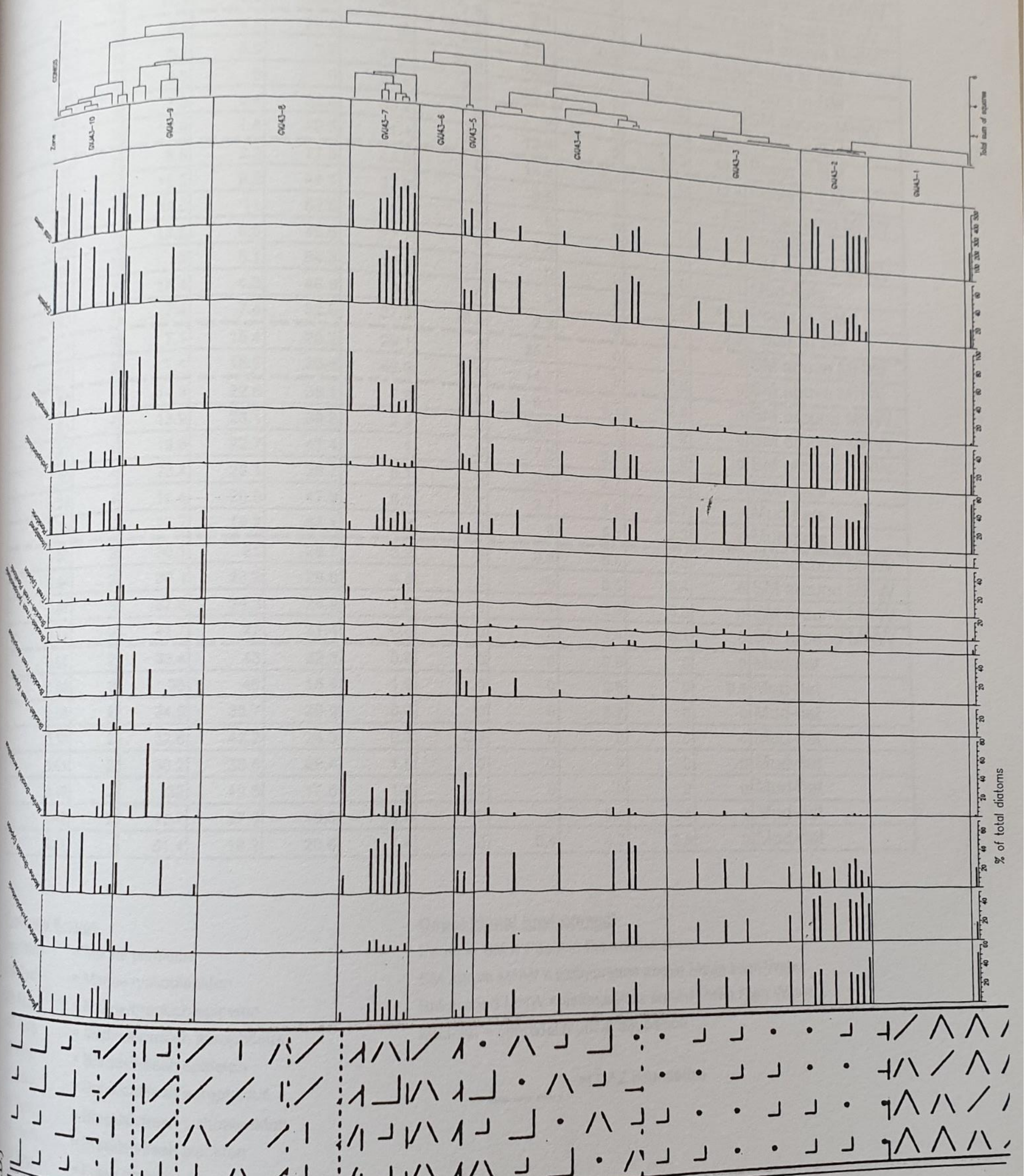


Figure 10.10b Ecological classification of diatom groups present in Typecore GVJ43 according to Vos & deWolf (1993)

Altitude (m O.D.)	LDAZ	Mar Plank	Mar Tych	MB Epip	MB Aero	BF Epip	BF Aero	BF Tych	BF Plank	Fr Epip	Depositional Environment
3.04	10	18.8	9.9	53.1	16.9	0	0	1.4	0	0	SM around MHW
2.99	10	18.7	10.6	50	14.5	0.3	1.3	0	0	2.6	SM around MHW
2.94	10	18.5	10.4	59.6	7.4	0	0	0	0	4.1	Mud-flats
2.89	10	21	16.5	59.3	0.2	0	0.2	0	0	2.7	Mud-flats
2.84	10	28	15.9	30.5	10.4	12.2	0	0	0	1.2	SM around MHW
2.82	10	30.1	16.9	6.8	32.5	0	4	0	0	7.2	SM above MHW
2.79	10	17.1	10.9	8.9	36.2	7.8	5.1	0	0	14	SM above MHW
2.77	9	5.6	4.6	29.6	0	3.7	40.7	0.9	0	14.8	Pools in SM
2.73	9	5.1	8.9	7.7	11.1	22.6	42.6	0	0.4	1.7	Pools in SM
2.68	9	0.5	0	0	71.8	2.3	25.4	0	0	0	SM above MHW
2.63	9	7.3	0.4	32.8	33.2	0	5	0	0	21.4	Pools in SM
2.53	9	2.9	1.4	10.5	1.4	5.7	13.9	0	15.3	48.8	Pools in SM
2.11	7	8.6	2.2	17.3	43.8	0	14.6	1.1	0	12.4	Pools in SM
2.03	7	16.2	9.8	44.1	27.9	0	0.5	1	0	0.5	SM around MHW
2.01	7	33.5	11	53.6	1.4	0	0	0	0	0	Mud-flats
1.99	7	12.8	6.5	49.6	27.7	0	1.3	0	0	0.8	SM around MHW
1.97	7	19	5.1	64.3	10.5	0	0	0	0	1	Mud-flats
1.95	7	18.4	4.3	46.9	10.5	0	1	0	1.3	16.1	Pools in SM
1.93	7	7.4	7.4	32.6	27.3	19.5	2.3	0	0	2.3	Pools in SM
1.78	5	7.1	15.4	20.2	29.1	0	25.2	0	1.1	0	SM above MHW
1.76	5	7.4	15.7	20.4	42.6	0	14.7	0	0.5	0	SM above MHW
1.69	4	14.3	22.6	38.1	7.8	0	9.1	4.7	2.9	0	SM around MHW
1.61	4	13.9	23.1	38.9	2.9	0	18.6	1	2	0	SM around MHW
1.47	4	19.6	22.7	47.4	1	0	7.2	2.1	0	0	SM around MHW
1.30	4	23.4	26.1	38.7	8.1	0	0.9	2.7	0	0	Mud-flats
1.25	4	16.4	20.5	47.9	6.2	0.7	2.7	4.8	0.7	0	Mud-flats
1.23	4	27.7	19.2	44.1	1.7	0	0	5.1	2.3	0	Mud-flats
1.03	3	30.1	21	29.7	3.2	0	0.5	6.8	7.8	0	SM around MHW
0.94	3	30.4	23.2	29.8	4.8	0	0	6.5	5.4	0	SM around MHW
0.87	3	37.6	24.3	24.9	1.6	0	1.1	3.3	5.3	0	SM around MHW
0.73	3	44.7	27	21.4	0.5	0	0	1.4	5.1	0	SM around MHW
0.65	2	33.4	43	22.2	0.8	0	0	0.5	0	0	Mud-flat
0.63	2	36	46	15.4	1.9	0	0	0.3	0	0.3	Mud-flat
0.58	2	34.8	38.7	20.9	0.4	0	0	5.2	0	0	Mud-flat
0.53	2	32.6	42.2	24.3	0.7	0.3	0	0	0	0	Mud-flat
0.51	2	30.2	38.5	29.4	1.9	0	0	0	0	0	Mud-flat
0.49	2	32	49.5	17.5	1.1	0	0	0	0	0	Mud-flat
0.47	2	47.7	37.6	10.5	0.8	0	0	0.4	3	0	Mud-flat
0.11		51.4	18.2	20.6	1.4	0	0.9	4.7	2.8	0	Mud-flat

Ecological Groups

Mar Plank = Marine plankton
Mar Tych = Marine tychoplankton
MB Epip = Marine/brackish epipelon
MB Aero = Marine/brackish aerophilous
BF Epip = Brackish/fresh epipelon
BF Aero = Brackish/fresh aerophilous
BF Tych = Brackish/fresh tychoplankton
BF Plank = Brackish/fresh plankton
FR Epip = Fresh epipelon

Depositional Environment

Pools in SM = Pools in the saltmarshes
SM above MHW = saltmarshes above Mean High Water
SM around MHW = saltmarshes arounf Mean High Water
Mud-flat = intertidal mudflat deposition

=LDAZ boundaries

Table 10.6 Summary of the diatom assemblages in typecore GVJ43 (% TDV) according to the ecological classification of Vos & deWolf (1993)

GVJ43 - 1: 0.13 to 0.46m OD

No diatoms were present within this zone

GVJ43 - 2: 0.46 to 0.69m OD

Dominant species: *Nitzschia navicularis, Delphineis surirella, Paralia sulcata*

Marine and marine-brackish planktonic species dominate the zone at the lower boundary (c. 55% TDV and 35% TDV respectively). Marine planktonic species gradually decrease in frequency upwards through the zone (from 55% TDV at base to 35% TDV), due primarily to fluctuations of *Paralia sulcata*. Marine-brackish planktonic species (e.g. *Delphineis surirella*) increase from 35% TDV to 40% TDV to the top of the zone.

Planktonic species are an important group within this zone. Up to 80% TDV are allochthonous diatom species, whilst epiphytic/benthic species are in low abundance. From the epiphytic/benthic species, the brackish diatoms are the optimal group, achieving a maximum of 25% TDV.

Marine planktonic and tychoplanktonic diatoms (Vos and deWolf, 1993) dominate the assemblages, with *Paralia sulcata* and *Delphineis surirella* the respective abundant species. Marine-brackish epipelon species also contribute up to 20% TDV within the zone, predominantly via *Nitzschia navicularis*.

GVJ43 - 3: 0.69 to 1.13m OD

Dominant species: *Nitzschia navicularis*, *Delphineis surirella*, *Paralia sulcata*, *Podosira stelligera*, *Pseudopodosira westii*.

Marine planktonic diatoms become increasingly dominant within the zone, although there is a gradual decline in abundance with height (from 55% to 45% TDV). *Paralia sulcata*, once again, contributes to the dominance of the marine planktonic group, declining in frequency with height from 30% to 17% TDV. *Paralia sulcata* counts decline, but *Podosira stelligera* and *Pseudopodosira westii* oppose this trend, with an overall increase in frequency with height to 12% and 15% TDV respectively. Brackish epiphytic/benthic species increase in frequency through the zone from 15% to 25% TDV.

Planktonic species contribute over *c*. 70% TDV at the base of the zone, decreasing to *c*. 60% towards the upper boundary. The optimal diatom group remains brackish epiphytic/benthic, with an increasing influence through the zone from *c*. 23% to 38% TDV. The freshwater autochthonous ratio is higher than the marine autochthonous ratio at the base of the zone, decreasing in influence with height.

An overall fall in the contribution of marine planktonic (45%-30%TDV) and marine tychoplanktonic (30%-20%TDV) diatoms occurs with height through the zone. Marine brackish epipelon species show an overall increase from 20% to 30% TDV.

GVJ43 - 4: 1.13 to 1.73m OD

Dominant species: *Diploneis didyma*, *Nitzschia navicularis*, *Paralia sulcata*, *Podosira stelligera*, *Pseudopodosira westii*.

The zone is characterised by the continued dominance of marine planktonic species, an increase in brackish epiphytic/benthic species and a reduction in marine-brackish planktonic species. *Pseudopodosira westii* (*c*. 25% TDV) and, to a lesser extent, *Podosira stelligera* (*c*. 15% TDV) dominate the marine planktonic species. Brackish epiphytic/benthic species increase in frequency in comparison with the underlying zone, though they fall from 40% to 30% TDV with height. *Diploneis didyma* and *Nitzschia navicularis* dominate this ecological group.

With height through LDAZ 4, the epiphytic/benthic species component of the TDV increases from *c*. 49% to *c*. 60%. Brackish epiphytic/benthic species is the optimal diatom group, increasing in TDV from c. 38 to 50% with height through the zone. An increase in the fresh autochthonous ratio occurs towards the upper zonal boundary.

There is a continued, but fluctuating, decline in the marine planktonic and tychoplanktonic species through the zone. Marine-brackish epipelon species dominate, contributing up to 48% TDV in the zone, primarily through the increases in *Diploneis didyma*, and *Nitzschia navicularis*. Marine-brackish and brackish-fresh aerophilous species increase in abundances through the zone, represented by *Diploneis interrupta* and *Hantzschia amphioxys* respectively.

GVJ43 - 5: 1.73 to 1.79m OD

Dominant species: *Hantzschia amphioxys*, *Diploneis interrupta*, *Pseudopodosira westii*.

Brackish epiphytic/benthic species dominate, decreasing in frequency with height from 60% to 45% TDV. *Diploneis interrupta* typifies this trend, contributing 40% TDV at the lower zone boundary and dropping to 27% TDV with height. Marine planktonic species (e.g. *Pseudopodosira westii*) are found in lower frequencies in contrast to the underlying zone. Fresh-brackish species, primarily *Hantzschia amphioxys*, increase in frequency with height through the zone, from 13% to 20% TDV.

LDAZ 5 is dominated by epiphytic/benthic species, contributing *c*. 75% TDV. Brackish species provide the optimal diatom group, which decreases in influence from 65% to 55% TDV with height. In contrast, the fresh autochthonous ratio increases from 0.183 to 0.388 through LDAZ 5, whilst the marine autochthonous ratio experiences a subtle decline with height.

Marine-brackish aerophilous species dominate through the abundance of *Diploneis interrupta*. Whilst there is an overall decline in marine-brackish aerophilous species with height (*c*. 40% to 30% TDV), an increase in brackish-fresh aerophilous species occurs (*c*. 15% to 25% TDV) with *Hantzschia amphioxys* and *Navicula pusilla* dominating.

GVJ43 - 6: 1.79 to 1.92m OD

No diatoms were present within this zone.

GVJ43 - 7: 1.92 to 2.12m OD

Dominant species: *Diploneis ovalis*, *Diploneis interrupta*, *Nitzschia navicularis*, *Paralia sulcata*.

Brackish epiphytic/benthic species once again dominate, increasing from 35% to 70% TDV towards the centre of the zone, only to drop to 40% TDV up-zone. *Nitzschia navicularis* reflects this trend, rising from 15% to 55% TDV, only to decline in abundance to 10% TDV at the top of the zone. Frequencies of *Diploneis interrupta*, in contrast, increase with height, from 12% to 30% TDV. Brackish-fresh and fresh-brackish epiphytic/benthic species attain their highest frequencies at the zone margins, decreasing in abundance towards the centre.

The influence of epiphytic/benthic species on the diatom assemblages is greater than in LDAZ 5, contributing up to *c*. 88% TDV. Brackish epiphytic/benthic species are the optimal diatom group throughout the zone. The influence of the fresh autochthonous species shows an increase towards the zonal boundaries.

Marine-brackish epipelon and aerophilous species dominate the zone, primarily through the presence of *Nitzschia navicularis* (up to *c.* 55% TDV) and *Diploneis interrupta* (up to *c*. 30% TDV) respectively. Aerophilous species are found in increasing frequencies towards the zonal margins, decreasing towards the centre.

GVJ43 - 8: 2.12 to 2.52m OD

No diatoms were present within this zone

GVJ43 - 9: 2.52 to 2.78m OD

Dominant species: *Cymbella subequalis, Pinnularia viridis, Diploneis interrupta*.

Fresh-brackish epiphytic/benthic species fluctuate between dominance at the base of the zone (50% TDV), a decline to 30% TDV mid-zone, and a recovery to *c*. 60% TDV towards the upper zone boundary. The initial decline is characterised by species such as *Cymbella subequalis* (22% - 0% TDV). *Diploneis interrupta* almost solely dominates the brackish epiphytic/benthic ecological group, rising from 0% TDV at the zone base, to 65% TDV towards the centre and returning to 0% TDV at the top of the zone.

Epiphytic/benthic species increase from *c.* 84% to 87% TDV through the zone, reaching optimum abundances of *c*. 98% TDV towards the centre. Fresh-brackish is the optimal group at the lower zone boundary (81.8% TDV), but changes to brackish species towards the centre (*c.* 71% TDV). Fresh-brackish species retain their dominance towards the upper zone boundary (66.7% TDV).

Marine-brackish aerophilous species once again dominate, initially contributing *c*. 60% TDV towards the upper boundary. However, brackish-fresh species increase in abundance with height to *c*. 40% TDV (predominantly through *Pinnularia viridis*). Freshwater epipelon species contribute *c*. 50% TDV at the lower boundary, decreasing with height. Towards the centre of the zone, aerophilous species contribute c. 90% TDV, declining to *c*. 35% TDV with height.

GVJ43 - 10: 2.78 to 3.04m OD

Dominant species: *Diploneis interrupta, Nitzschia navicularis, Delphineis surirella, Paralia sulcata.*

Brackish epiphytic/benthic species once again dominate, increasing in frequency with height from 45% to 60% TDV. *Nitzschia navicularis* increases from 5% to 50% TDV, but declines to 37% towards the upper zone boundary. Similarly, *Diploneis interrupta* maintains c. 30% abundance at the base of the zone, before a decline to 15% TDV with height. Marine planktonic species initially rise from 25% to 35% TDV, but decline and stabilise at 30% TDV for the rest of the zone. *Paralia sulcata* typifies this trend.

Epiphytic/benthic species once again dominate the diatom assemblages in LDAZ 10, contributing 55-70% TDV. Brackish species provide the optimal diatom group, increasing in TDV from 48-67% TDV towards the upper boundary. The fresh autochthonous ratio decreases from 0.435 to 0.021 towards the upper boundary.

The zone is characterised by high frequencies of *Nitzschia navicularis*, making marine-brackish epipelon species the most dominant. Aerophilous species dominate toward the lower boundary, but are replaced by epipelon species that significantly increase towards the upper boundary.

10.3.4 Radiocarbon dating

The stratigraphy of typecore GVJ43 indicated that three phases of organic peat development were interbedded within predominantly (bluey-) grey clayey silts. Six samples were therefore extracted for radiocarbon analysis, at the lower and upper stratigraphic boundaries of each of the three peat units. Table 10.7 summarises the radiocarbon dates for typecore GVJ43, and Figure 10.11 places the dates within the context of the full core.

Sample Code	Sample depth	Altitude (O.D.)	Sample description	Conventional radiocarbon age	Radiocarbon date (1 sigma AMS - 68% confidence)	Radiocarbon date (2 sigma AMS - 95% confidence)
Beta-189681	3.21m	2.78m	Very dark brown well humified peat	3470 +/- 40yrs BP	3820-3680 Cal. yrs BP	3840-3640 Cal. yrs BP
Beta-189682	3.95m	2.04m	Medium red-brown herbaceous humified peat	4650 +/- 40yrs BP	5460-5380 and 5340-5310 Cal. yrs BP	5470-5300 Cal. yrs BP
Beta-189683	4.07m	1.92m	Medium red-brown herbaceous peat	4900 +/- 40yrs BP	5650-5600 Cal. yrs BP	5710-5590 Cal. yrs BP
Beta-189684	4.22m	1.77m	Medium red-brown herbaceous peat	5270 +/- 40yrs BP	6100-6070, 6020-5980 and 5970-5950 Cal. yrs BP	6180-5930 Cal. yrs BP
Beta-189685	5.51m	0.48m	Dark brown woody peat	5950 +/- 40yrs BP	6790-6730 Cal. yrs BP	6870-6670 Cal. yrs BP
Beta-189686	6.3m	-0.31m	Very dark brown herbaceous humified peat	6340 +/-40yrs BP	7290-7250 Cal. yrs BP	7320-7220 Cal. yrs BP

Table 10.7 Summary of radiocarbon results for typecore GVJ43.

The initiation of organic sedimentation (Unit 6a) overlying the basal sediment (Unit 1) occurred between 7,320-7,220 Cal. yrs BP (in the early Holocene). This first phase of biogenic accumulation ceased at 6,870-6,670 Cal. yrs BP, after which minerogenic sedimentation of fine sands and clayey-silts occurred (Unit 7a). Between 6,180-5,930 Cal. yrs BP, a return to organic accumulation occurred (unit 6b), which lasted only for a brief period of *c.* 400yrs, returning to minerogenic deposition (Unit 7b) after 5,710-5,590 Cal. yrs BP. This period of sedimentation was also short-lived, after which organic accumulation re-started between 5,470-5,300 Cal. yrs BP (Unit 6c). Peat development continued until 3,840-3,640 Cal. yrs BP, after which the accumulation of (blue) grey clayey-silts (Unit 7c) is likely to have continued until the Saxon period (*c.* 11th Century) when coastal reclamation, in the form of sea-defence construction, is believed to have occurred.

Estimations for sediment accumulation once again assume that constant rates of deposition occurred and that there were no periods of erosion. The possible influence of autocompaction could not be taken into account for reasons explained in section 12.2. Consequently, the accumulation rates, especially regarding the peat units (most prone to autocompaction), are somewhat tentative. The lower peat unit developed during the early Holocene over a *c.* 500yr period, accumulating at a rate of 15.8cm/100yrs. The overlying sand-rich minerogenic layer developed at a rate of 18cm/100yrs. The development of the thin second peat horizon occurred at a much slower rate of 3.7cm/100yrs, whilst the thin minerogenic horizon above accumulated at 4.5cm/100yrs. The final peat sequence began development in the mid-Holocene and continued for about 1,600yrs, developing also at 4.5cm/100yrs. If it is assumed that Saxon sea-defence construction and land reclamation occurred *c*. 11th Century, minerogenic sedimentation would have occurred for *c*. 2,800yrs after the last phase of peat development. The sedimentation would have therefore occurred at a rate of 11.5cm/100yrs.

Table 10.8 provides a summary of the multiproxy analysis of typecore GVJ43, combined with the relevant radiocarbon dates to infer the timescale involved in the sedimentary evolution of the site.

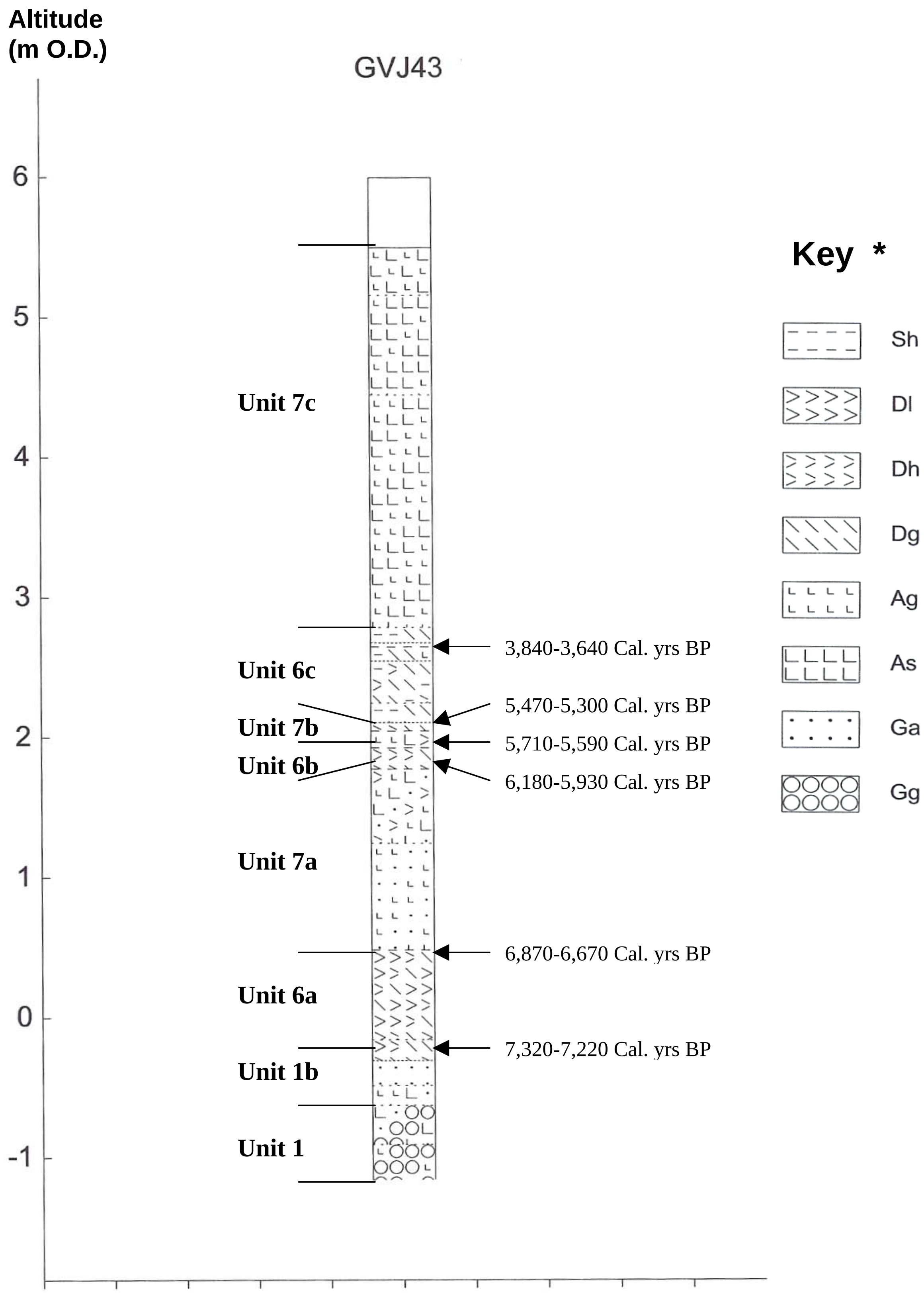


Figure 10.11 Stratigraphic profile of typecore GVJ43 indicating the position of AMS radiocarbon dates.
* Refer to Troels-Smith classification scheme (Table 8.1) for key interpretation.

Altitude (m O.D.)	Sediment Type	Particle Size Analysis	Predominant diatoms	Predominant Pollen	^{14}C Age (Cal. yrs BP, 2 sigma)
5.99-2.78m	Unit 7c: Light (bluey) grey-brown clayey-silt	Decrease in mean grain size with height from 5Ø to 6Ø, poorly sorted, negatively skewed, mesokurtic.	Marine-brackish epipelon and aerophilous species dominate, especially *Nitzschia navicularis* and *Diploneis interrupta*.	*Chenopodiaceae* and *Callitriche* increase in abundance with height. *Pteridium* dominant throughout.	2.78m (O.D.) 3,840-3,640
2.78-2.04m	Unit 6c: Dark brown herbaceous humified peat	N/S	Marine-brackish and brackish-fresh aerophilous species dominate, especially *Diploneis interrupta* and *Pinnularia viridis*.	*Poaceae* dominates at upper and lower unit boundaries, with *Filicales* abundant towards the centre of the unit. *Cyperaceae* and *Corylus* also contribute.	2.04 m (O.D.) 5,470-5,300
2.04-1.92m	Unit 7b: Light grey-brown clayey-silt	Mean grain size 5.5Ø, poorly sorted, negatively skewed, mesokurtic.	Marine-brackish epipelon and aerophilous species dominate, especially *Nitzschia navicularis* and *Diploneis interrupta*.	*Chenopodiaceae* dominant towards centre of unit, whilst *Poaceae* abundant at upper and lower boundaries.	1.92m (O.D.) 5,710-5,590
1.92-1.77m	Unit 6b: Dark brown herbaceous humified peat	N/S	Marine-brackish and brackish-fresh aerophilous species dominate, especially *Diploneis interrupta* and *Hantzschia amphioxy*s.	*Alnus* declines in abundance with height, replaced by increasing frequencies of *Filicales. Cyperaceae* and *Poaceae* also influential.	1.77m (O.D.) 6,180-6,670
1.77-0.48m	Unit 7a: Light grey silty sand	Mean grain size decreases with height from 4Ø to 5.5Ø, poorly sorted, positively skewed, mesokurtic.	Marine planktonic and marine-brackish epipelon species dominate, including *Paralia sulcata* and *Nitzscia navicularis*.	*Filicales, Pteridium* and *Chenopodiaceae* dominant throughout. *Coryus, Poaceae* and *Cyperaceae* also contribute.	0.48m (O.D.) 6.870-6,670
0.48 to -0.31m	Unit 6a: Dark brown woody peat	N/S	N/S	*Alnus* dominates, especially at the centre of the basal peat unit. *Filicales* and *Corylus* abundant at upper and lower boundaries respectively.	-0.31m (O.D.) 7,320-7,220
-0.31 to -0.49m	Unit 1b: Grey-brown sand	Mean grain size 2.5Ø, poorly sorted, positively skewed, leptokurtic.	N/S	Unit dominated by increasing frequencies of *Corylus* and decreasing frequencies of *Bryophytes* with height. Stable *Pteridium* abundance throughout.	N/S
-0.49 to -1.16m	Unit 1: Orange-brown pebbly sand	Mean grain size 1-2Ø, very poorly sorted, negatively skewed, very leptokurtic.	N/S	N/S	N/S

Table 10.8 Summary of proxy results for typecore GVJ43

10.4 Typecore GVF23

Figure 10.12 is a profile of the sedimentary content of the third typecore, GVF23, derived from TSPPlus (Waller *et al.*, 1995). Typecore GVF23 was extracted to validate the presence of the ridge in the Gordano Valley discovered by Jefferies *et al.* (1968). Confirmation was vital because the ridge had a significant influence on the development of the two separate depositional environments present within the valley. The typecore was levelled into a local benchmark, providing an altitude of 4.92m OD for the ground surface of the typecore site. As the origin of this feature is not part of the project objectives, no detailed analysis of the sediments took place

Table 10.9 summarises the stratigraphy of typecore GVF23. An orange-brown clast-dominated sediment was encountered at 3.03m O.D., overlain by dark brown, well-humified fen peat and grey silty-sands. Similar sediments were present throughout the typecore profile, although variations between clast-dominated and matrix-dominated horizons were found. Although bedrock had not been encountered, coring was halted at 4.2m depth (0.74m O.D.) as the ridge had been encountered and penetrated to some depth, and thus the objective of the typecore extraction had been achieved.

Initial analyses of the clasts within the orange-brown sediments indicated that the majority of these were of low sphericity, angular to sub-angular, and commonly varying in size from 1-6cm in diameter (-4ϕ to -6ϕ). Although detailed grain size analysis was not undertaken, the sediments were observed to be very poorly sorted. The abundance of clasts increased with height through the orange brown sediments, indicative of a coarsening upwards sequence. The majority of the clasts were composed of micritic limestone, with oolitic limestone, sandstone and some flint also contributing. When

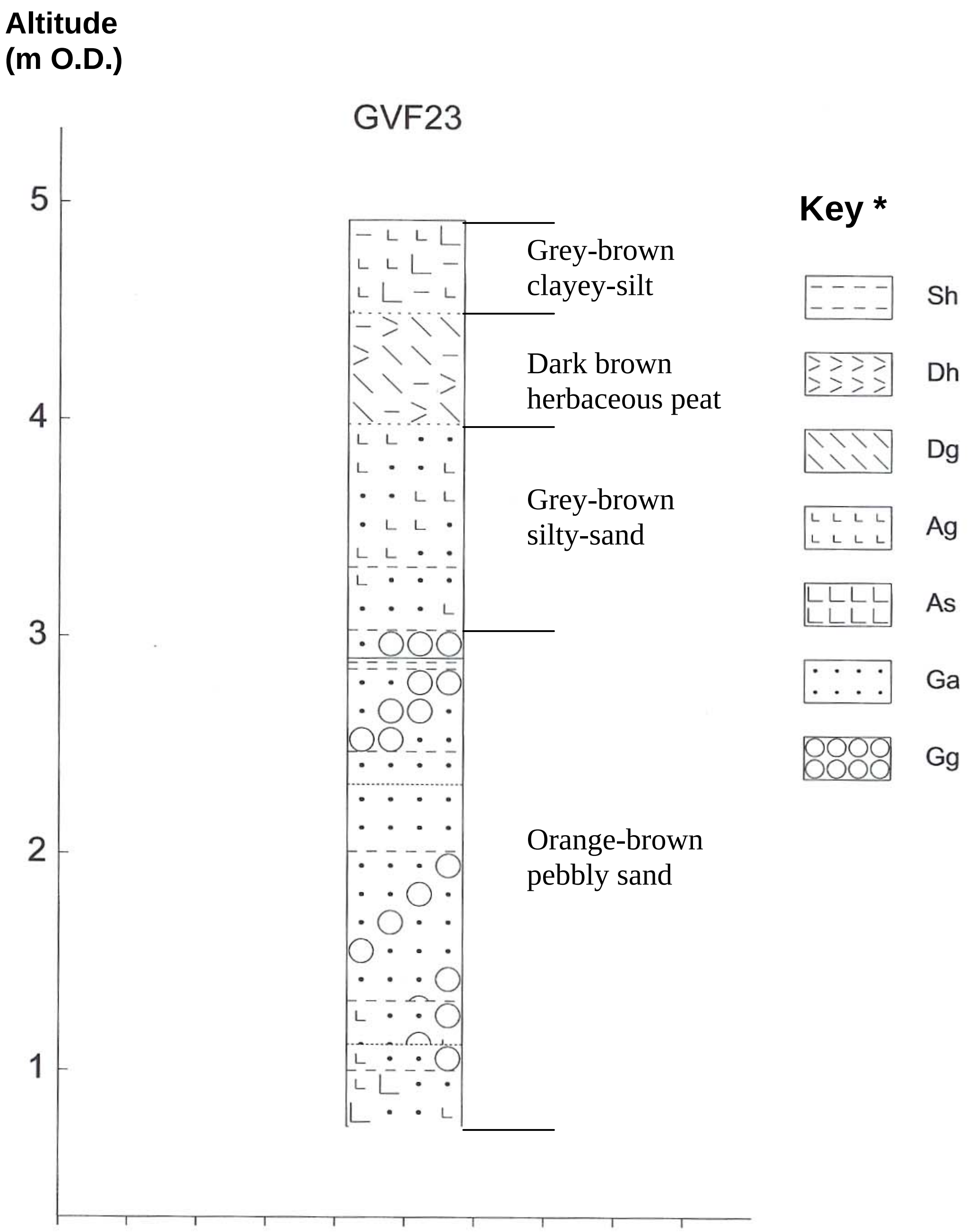


Figure 10.12 Stratigraphic profile of typecore GVF23.
* Refer to Troels-Smith classification scheme (Table 8.1) for key interpretation.

horizons of matrix-dominated sediments were encountered, coarse sands (*c.* 1ϕ) were in abundance and the levels of sorting were improved due to the reduction in clast content.

Altitude	Stratigraphy
4.92-4.49m O.D.	Ag2, As1, Sh1, Th+, Lf+, Dh+ Medium grey-brown organic clayey silt
4.49-3.98m O.D.	Dg2, Dh1, Sh1, Dl+, Th+ Dark brown herbaceous well-humified peat
3.98-3.32m O.D.	Ga2, Ag2, Sh+, As+, Th+, Th+ Medium grey-brown silty sand
3.32-3.03m O.D.	Ga3, Ag1, Gg(min)+, Gg(maj)+, As+, Th+, Dh+ Yellow brown silty sand
3.03-2.9m O.D.	Gg(maj)2, Gg(min)1, Ga1, Ag+ Orange-brown pebbly horizon
2.9-2.88m O.D.	Ga4, Ag+, Gg(min)+, Gg(maj)+ Orange-brown sand
2.88-2.85m O.D.	Ga3, Ag1, Gg(min)+, Gg(maj)+ Orange brown silty sand
2.85-2.47m O.D.	Gg(maj)2, Ga2, Gg(min)+, As+ Orange-brown pebbly sand
2.47-2.32m O.D.	Ga4, Ag++, As+, Gg(min)+, Gg(maj)+ Orange brown sand
2.32-2.01m O.D.	Ga4, Ag+, Gg(maj)+ Yellow-green sand
2.01-1.32m O.D.	Ga3, Gg(maj)1, Gg(min)+, Ag+ Orange brown pebbly sand
1.32-1.12m O.D.	Ga2, Ag1, Gg(maj)1, Gg(min)+ Orange brown pebbly-silty sand
1.12-1.0m O.D.	Ag2, Ga1, Gg(maj)1, Gg(min)+, Ag+ Grey-brown pebbly sandy silt
1.0-0.74m O.D.	Ga2, Ag1, As1 Grey-brown sandy-clayey silt

Table 10.9 Summary of typecore GVF23 stratigraphy

Part IV:

Interpretation of the Sedimentary Archive of the Gordano Valley.

Chapter 11: The Quaternary environmental history of the Gordano valley

11.1 Introduction

This chapter interprets the palaeoenvironmental evidence from each typecore. The results are then combined with the sedimentary archive of the Gordano Valley to construct a valley-wide model of evolution since late Quaternary sedimentation began.

11.2 The Quaternary sedimentary history of the Gordano Valley

11.2.1 Evolution of the basal sediments and ridge

Particle size analysis of the basal sediments (Unit 1) from the two main typecores, combined with the stratigraphy of the ridge preserved in typecore GVF23, allow certain conclusions to be made regarding the evolution of the basal sediments and the ridge respectively.

Analysis and interpretation of the basal sediments was not an aim of this research project due to access limitations around the ridge. However, the influence of these sediments and the ridge on the valley's late Quaternary sedimentary evolution justifies an interpretation of the available evidence. As multiproxy analyses of all the sediments in the cores were undertaken, including the basal sediments, some interpretations will be attempted regarding possible origins of these sediments.

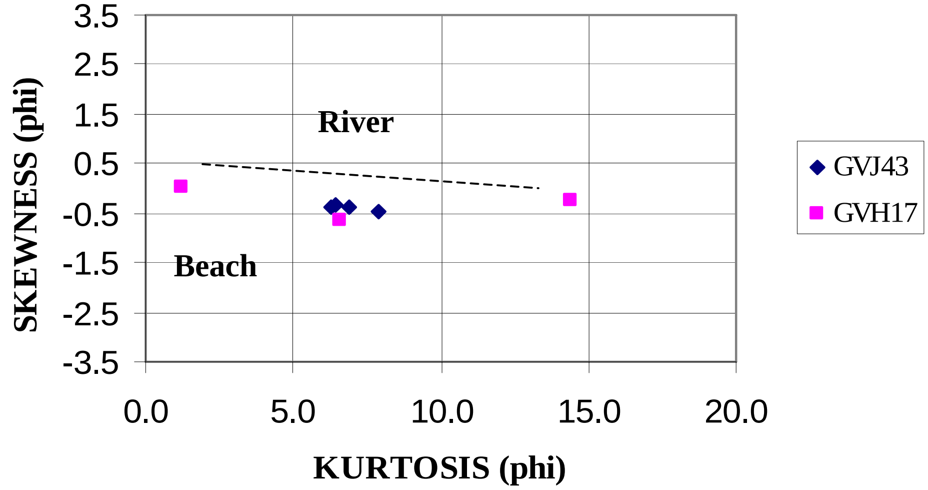
Particle size analysis was undertaken towards the upper sedimentary boundary between Unit 1 (orange-brown pebbly sands) and the overlying sediments in typecores GVH17 and GVJ43. This was attempted to assess whether Unit 1 had been deposited under different environmental conditions as suggested by Jefferies *et al.*

(1968) and Gilbertson *et al.* (1990), and thus to indicate a possible temporal between the deposition of Unit 1 and the overlying sediments.

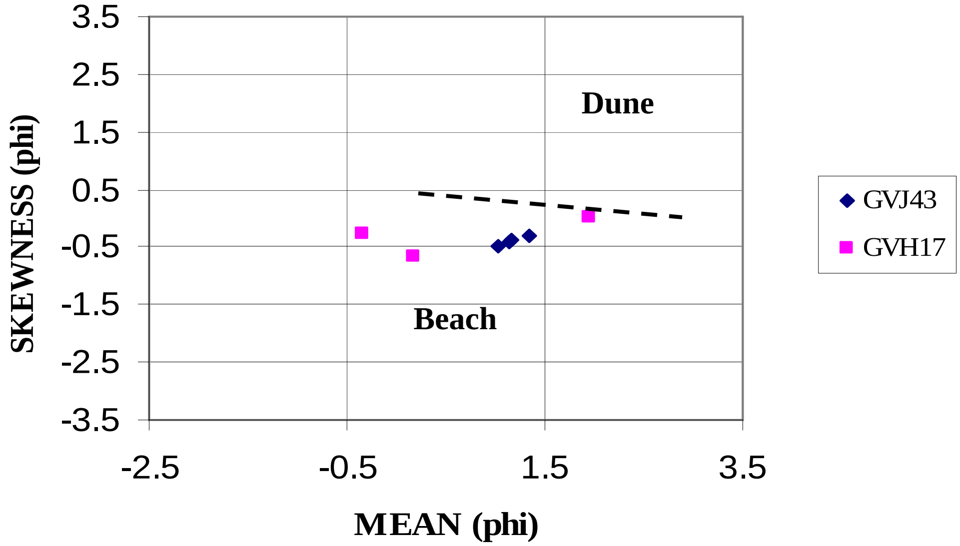
Upon analysis of the sediment samples extracted from Unit 1 in typecores GVH17 and GVJ43, the mean grain size was c. 1ϕ (coarse sand). Pebbles within Unit 1 varied between 9-22mm in size (c. –3ϕ to –4.5ϕ). The samples were all very poorly sorted (σ = 2-4ϕ), negatively skewed and extremely leptokurtic (K_G>3). Unit 1 is therefore characterised by poorly sorted, negatively skewed coarse sands. Certain depositional environments can be discounted via grain size analysis. For example, beach sands are well sorted and negatively skewed, river sands are less well sorted and positively skewed and dune sands are also positively skewed but have a finer mean grain size than beach sands (McManus, 1995). The overall grain size results of Unit 1 do not match any of these three general sedimentary characteristics, suggesting that none of these depositional settings could be the sole source of the basal unit.

Due to the limited data from Unit 1, samples from both typecores have been combined to identify potential depositional environments responsible for their development. Although the sedimentary characteristics do not correlate with the typical sedimentary characteristics found in coastal lowlands, Figure 11.1 compares the grain size parameters used by Friedman (1961) to differentiate between river, beach and dune sands. Figure 11.1A) compares the skewness and kurtosis of each sample from the two typecores, and indicates that the majority of samples have beach-derived characteristics. Similarly, Figure 11.1B) relates the skewness of the samples to mean grain size, and again implies that the majority of the samples were deposited in a beach setting. However, Figure 11.1C) compares the level of sorting against the skewness of each sample and plots almost all samples a considerable distance away from the divide between beach and river sands. In fact, the initial research by Friedman (1961) did not contain samples with levels of sorting poorer than 1.3ϕ

A)



B)



C)

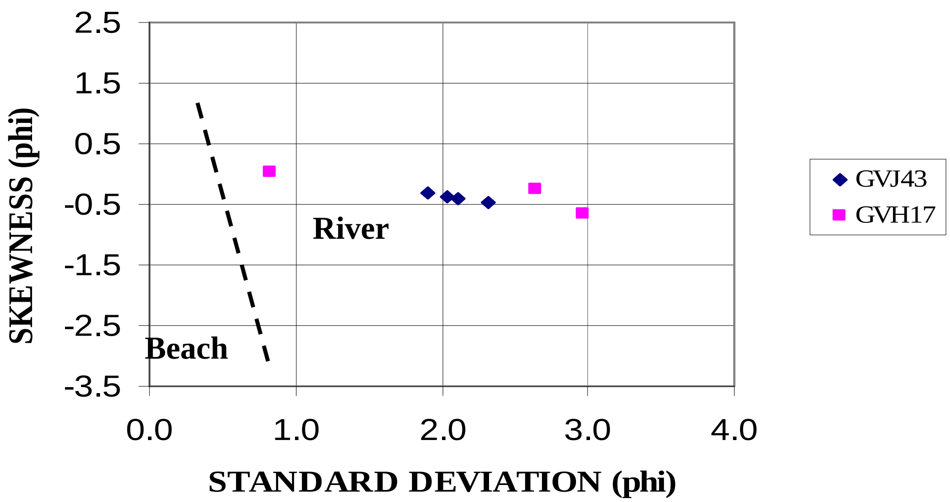
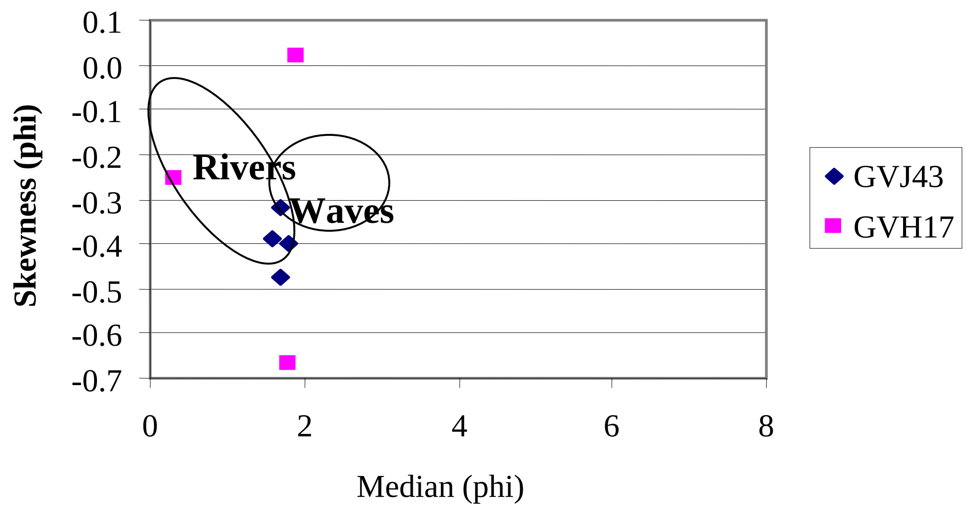


Figure 11.1 Bivariate plots of A) skewness against kurtosis, B) skewness against mean grain size and C) median grain size against skewness (based on the findings of Friedman, 1961).

D)



E)

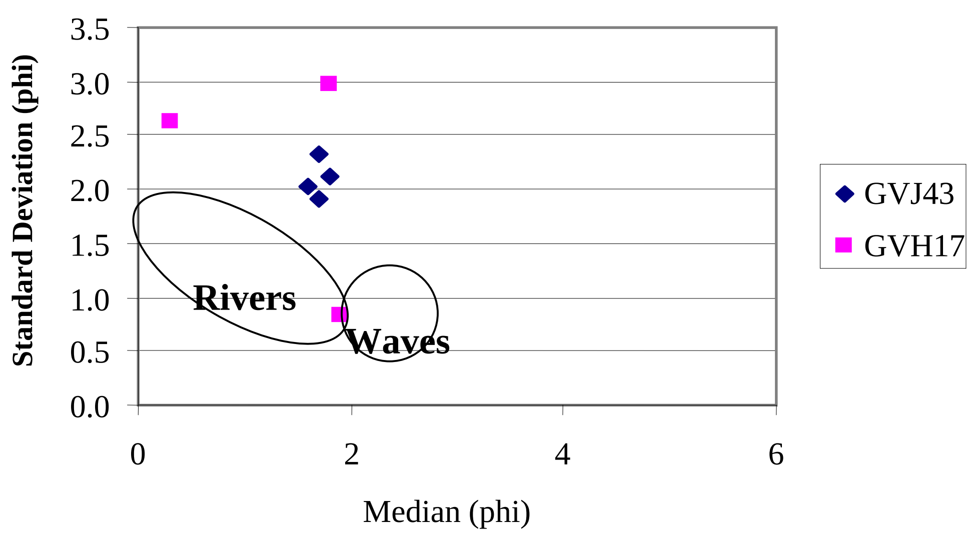


Figure 11.1 Bivariate plots of D) median grain size against sorting and E) median grain size against skewness (based on the findings of Stewart, 1958).

deviation, whereas six of the seven basal sand samples from the Gordano Valley have poorer levels of sorting than this limit. This does cast doubt over the assumption that the basal sediment was formed on a beach, especially as the level of sorting in such a depositional setting is normally very high (McManus, 1995). Figures 11.1D) and E) depict the variations in the samples' sorting and skewness against the median grain size (Stewart, 1958). Figure 11.1D) plots three of the sediment samples within the river sedimentation envelope, whilst the poor sorting of the deposits once again limit environmental interpretations from Figure 11.1E).

The considerable grain size variation and poor level of sorting, combined with the lack of correlation with typical environmental grain size parameters, suggests that river, beach and dune depositional environments cannot explain the origin of Unit 1. Considering that past research has suggested that shallow marine depositional conditions were responsible for its development (Jefferies *et al*., 1968; Gilbertson *et al*., 1990), alternative explanations based on the evidence available must also be considered.

11.2.2 Palaeoenvironmental interpretation

The orange-brown nature of Unit 1 and the ridge, combined with the dominance of limestone clasts within the stratigraphy of the ridge, indicate that the sediments are locally derived. The Devonian Old Red Sandstone found along the Clevedon-Portishead ridge to the north is likely to have contributed the majority of the sand matrix, whilst the Carboniferous Limestone present along the northern and southern valley sides was the source for the angular oolitic and micritic limestone clasts present throughout the sedimentary units.

Three theories regarding the possible origin of the ridge and basal sediments are described here, each based on the evidence provided during the initial stratigraphic survey of the valley and the subsequent analysis of the sediments. It must be stated however, that until further research is undertaken regarding the basal sediment and ridge, these conclusions remain tentative due to limited access and subsequent analysis achieved during this research.

(a) Ipswichian raised beach and ridge

Jefferies *et al.* (1968) tentatively concluded that the basal sediments and ridge were formed in either aeolian or shallow marine environments during the Ipswichian interglacial (*c*. 125,000 yrs BP). Aeolian conditions are unlikely to have been responsible for the evolution of these sediments due to the significant variation in grain size and abundance of coarse sands and clasts within the deposits (as discovered through the particle size analysis of typecores GVH17 and GVJ43, combined with the lithostratigraphy preserved in GVF23). However, as access limitations restricted analysis of the ridge to a site close to the northern valley side (where hillslope activity may have influenced stratigraphy), it cannot be assumed that the sediments from typecore GVF23 typify the feature, especially as Jefferies *et al.* (1968) stated that the ridge is composed primarily of well-sorted sands. Therefore, considering the proximity of the Gordano Valley to the Severn Estuary, combined with the abundance of Ipswichian sediments throughout the coastal lowlands of the region (Allen, 2001, 2002a), an Ipswichian origin must be considered.

During the Ipswichian interglacial, *c*. 125,000 yrs BP, the coastal environments of the Severn Estuary were wave-dominated, which favoured the accumulation of gravels and sands around the Ipswichian coastline (Allen, 2002a). The position and altitude of the ridge in relation to the contemporary coast could imply that similar depositional processes were also responsible for its development. The majority of the coarser Ipswichian sediments are found inland of the modern coastline, due to the higher position of MSL at the time, encouraging deposition at higher altitudes. For example, Ipswichian sediments can be found from *c*. 3-20km inland of the modern coastline in the Somerset Levels (Allen, 2002a) and *c*. 4km inland at Llanwern on the Gwent Levels (Haslett, 1997). The ridge in the Gordano Valley is positioned *c*. 5km inland from the Severn Estuary with its sediment surface at *c*. 3m O.D. along Weston Drove, which would require higher sea levels similar to that of the Ipswichian (5-10m O.D.) if developed by marine conditions.

The form of the ridge (Figures 3.4 and 3.5), its position in relation to the Gordano Valley and the Severn Estuary and the particle size results, suggest that the sediments may have developed as a result of wave activity. The sorting of the basal sediments from typecores GVH17 and GVJ43, combined with the lithostratigraphy of GVF23 however, discounts wave action as the sole cause of deposition. Hillslope processes may have contributed the coarser, angular and poorly sorted sediments within the archive.

Analysis of the core profiles from the Clapton Moor sequence shows that the basal sediments vary in form but are commonly found at *c*. 4m O.D. towards the valley sides, suggesting their association with the ridge is strong. A possible explanation for the theorised “Ipswichian” deposits may involve the occurrence of wave refraction around the Clevedon-Portishead ridge. Figure 11.2 shows the possible sediment transport and deposition that may have occurred in the Gordano Valley in response to the higher sea levels and wave dominance at this time. The Ipswichian sediments of the Severn Estuary lowlands (Allen, 2000c, 2001, 2002a) already indicate the presence of a wave-dominated coastal environment; thus it is reasonable to assume that wave activity was prevalent in the valley region at the time. This would allow erosion and transportation of the sediments from the Old Red Sandstone outcrops, which are well exposed on the coastline north of Portishead. As waves developed and advanced through the Severn Estuary, wave refraction around the Clevedon-Portishead bedrock ridge would introduce the transported sediments into the Gordano Valley (Figure 11.2). The development of a ridge transverse to the long axis of the valley could then have occurred at Weston Drove, accounting for the high level of sorting indicated by Jefferies *et al.* (1968).

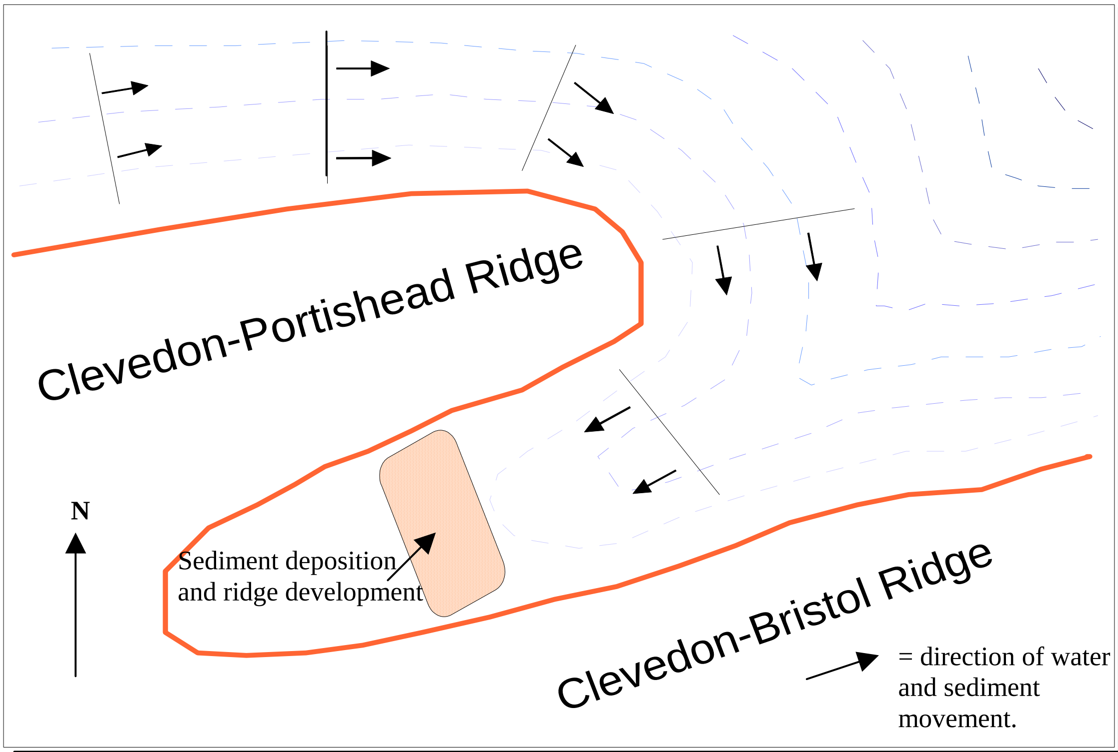


Figure 11.2 Theoretical influence of wave refraction during the Ipswichian interglacial on the evolution of the sediment ridge traversing the Gordano Valley. Dashed lines indicate water depth, increasing towards the northeast (not to scale).

If this interpretation is accurate, the considerable temporal gap between sedimentation in the Ipswichian and the onset of minerogenic sedimentation prior to *c*. 15,000 Cal. yrs BP must be accounted for. The sharp sedimentary boundary encountered in the typecores between the basal sands and the overlying sediments, combined with the considerable difference in grain size parameters, does suggest that an unconformity is present and that contrasting depositional environments were responsible for the deposition of the two sedimentary units. To account for this temporal gap, it is proposed that the basal sediments could have been preserved within the Gordano Valley prior to the re-initiation of sedimentation, primarily as a result of periglacial activity. The proximity of the Devensian ice sheet along the northern coast of the Severn Estuary around the LGM (Figure 2.10) would have had considerable influence on climate and sea level around the Gordano Valley, causing permafrost to dominate the region and preserve the basal sediments and ridge during the glacial period. The preserved Ipswichian topography would have allowed the two contrasting sedimentary basins to develop on either side of the ridge once climate began to improve towards the end of the Devensian glacial period.

(b) A glacial origin for the basal sediments and ridge

Whilst the above explanation into the origin of the basal sediments and ridge is one possible interpretation, a second explanation should also be considered. The majority of the literature discounts the possibility of any direct glacial activity south of the Severn Estuary during the LGM (summarised by Campbell *et al*., 1998), but there is an abundance of evidence for a glaciation in and around the Gordano Valley during the Quaternary (see sections 2.4 and 3.2.2). The orange-brown sediments could be accounted for if a small glacier was present towards the head of the Gordano Valley during a glacial period. Figure 11.3 indicates the likely position of the theorised glacier within the valley to account for the ridge and basal sediments encountered in the valley. Climatic amelioration during a glacial-interglacial transition would have caused the gradual melting of the ice mass. Subsequent melt-out of the glacial mass could have produced a ‘terminal moraine’ at the seaward ice margin which continued to accumulate sediment as the glacier down-wasted (Figure 11.4). Whilst the resultant terminal moraine could account for the ridge, subglacial

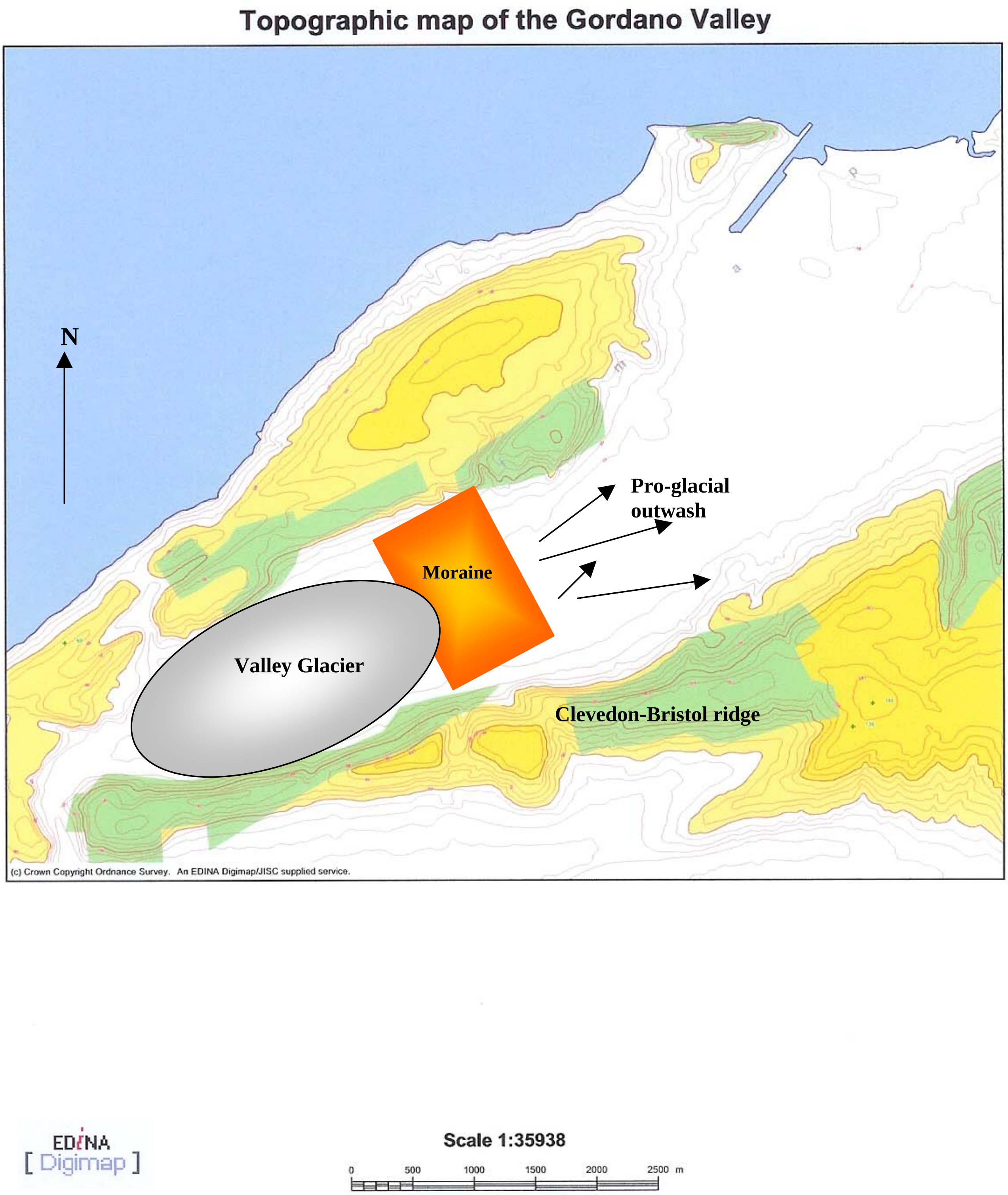


Figure 11.3 Topographic map of the Gordano Valley indicating the theorised position of a valley glacier to explain the development of the ridge and associated basal sediment (Digimap, 2004).

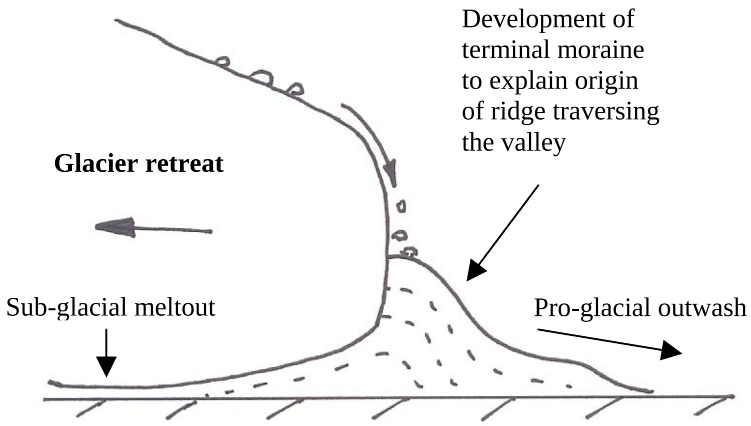


Figure 11.4 Diagram of the theorised glacial retreat and development of terminal moraine in the Gordano Valley (adapted from Benn & Evans, 1998 p.246).

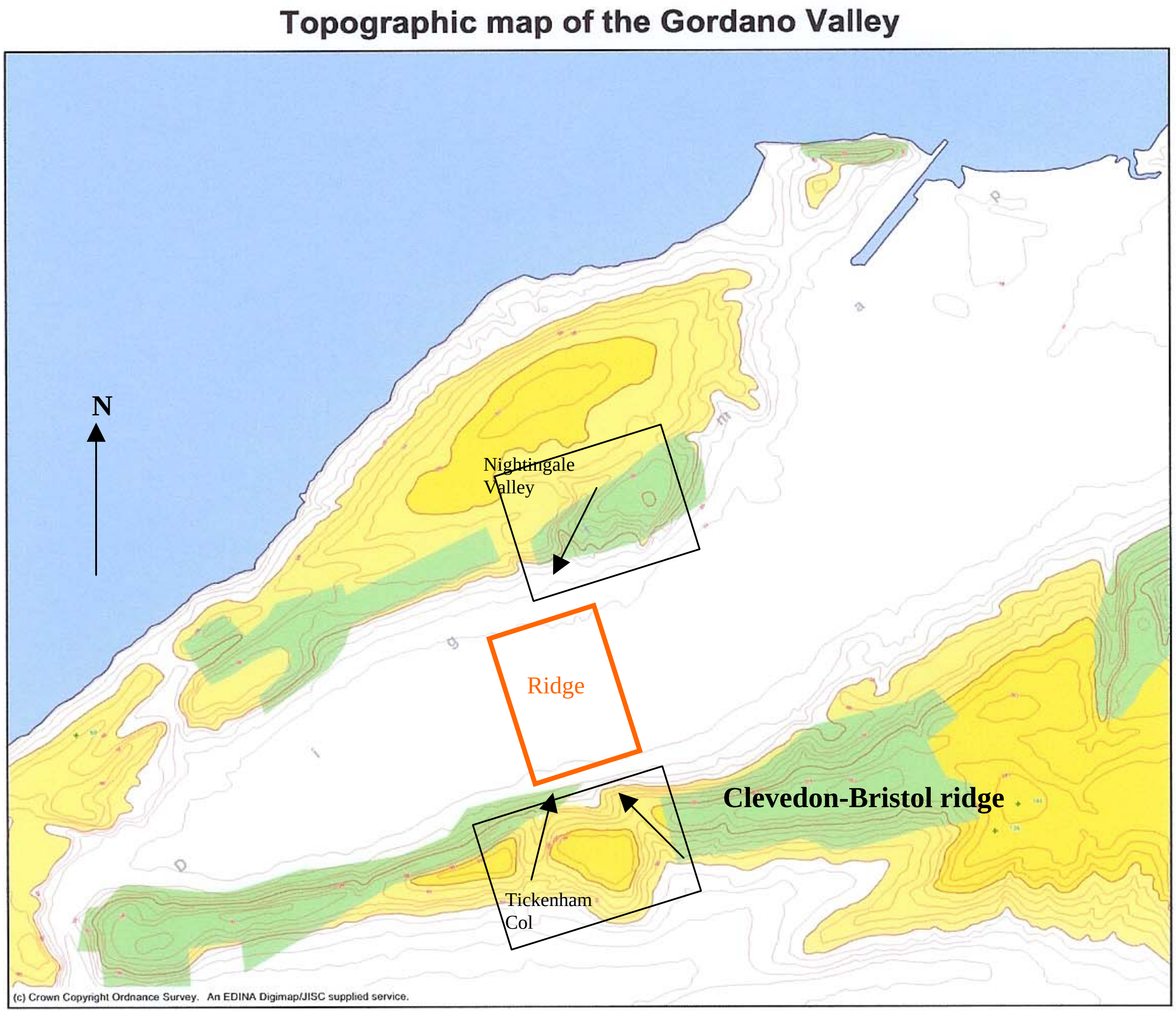
deposition would explain the basal sediments headward of the ridge, and pro-glacial outwash would account for the seaward basal sediments. The poorly sorted nature of the sediments, combined with the angular to sub-angular clasts that dominate typecore GVF23, would also be accounted for by glacial deposition. If glacial processes are responsible for the formation of the ridge and associated basal sands, it is unlikely that their origin dates to the Devensian due to the dominance of periglacial processes in southwest England at the time (see section 2.4). Glacial tills, as well as glacio-fluvial and glacio-lacustrine sediments have been found in the Gordano Valley (Hawkins & Kellaway, 1971; Gilbertson & Hawkins, 1978b; Hunt, 1998) and although undated, may relate to a theorised pre-Cromerian glacial event responsible for tills found at Kenn, *c*. 3km south of the Gordano Valley (Gilbertson & Hawkins, 1978a; Hunt, 1998). If such a glacial mass was positioned in southwest England *c*. 700,000 yrs ago, the majority of the sedimentological and geomorphological evidence that might once have been present throughout the coastal lowlands would have subsequently been destroyed by coastal processes in the Severn Estuary during the late Quaternary.

(c) Hillslope processes responsible for the deposition of the basal sediment and ridge

The final theory regarding the origin of the basal sediments seems the most likely explanation from the evidence available. Considering the poorly sorted nature of the basal sediments from typecores GVH17 and GVJ43, and if the sedimentology of typecore GVF23 is representative of the whole of the ridge (and not just localised lithostratigraphy), hillslope processes may have been responsible for the origin of the basal sediments and ridge.

Southwest England experienced periglacial conditions throughout the last glaciation due to the proximity of the Devensian ice mass (Campbell *et al*., 1998). Evidence for periglacial erosion in the southwest is present in the Axe Valley for example, in which solifluction and alluvial fan deposits accumulated during the glacial stage (Macklin & Hunt, 1988). Aeolian coversands dating to the Devensian have also been found in the Gordano Valley at Holly Lane and Court Hill Col (Gilbertson & Hawkins, 1974, 1978b). The sparse vegetation and extensive freeze-thaw activity that would have characterised the valley under periglacial conditions (Carson & Kirby, 1975) would have encouraged enhanced erosion of the valley sides (Selby, 1982). Gullying and alluvial fans would have developed as a result of the enhanced hillslope activity, especially in response to seasonal meltout of snow within the valley. This depositional environment would explain the spatial extent of the basal sediments found throughout the catchment and up to 4m O.D. on the valley sides.

Figure 11.5 shows a topographical map of the Gordano Valley (Digimap, 2004). A geological fault is present directly south of the ridge along the Clevedon-Bristol ridge (see Figure 3.1 for reference). Leeder (1999) states that the majority of ancient fan deposits are located at basin-margin positions adjacent to fault zones.



= Position of gully systems responsible for ridge development

= Movement of sediment through periglacial processes

EDINA [Digimap]

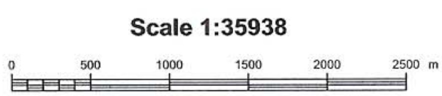


Figure 11.5 Topographic map of the Gordano Valley. Note the proximity of gully systems to the north and south of the ridge (Digimap, 2004).

Such a fault would have been susceptible to erosion through periglacial processes, encouraging enhanced gullying and alluvial fan development onto the valley floor. Periglacial deposits have been found around Tickenham Col by Gilbertson & Hawkins (1983a), proximal to the gullies and directly south of the ridge. To the northeast of the ridge another gully system is present in the valley side (Figure 11.5). This may also have encouraged similar depositional processes on this side of the valley floor. The Nightingale Valley opens into this gully feature and contains possible pre-Cromerian till deposits (Hunt, 1998), which would have been susceptible to erosion. This increased sediment supply could have contributed to the development of the ridge. Therefore, sedimentary accumulation could have been directed into the central region of the valley floor via localised gullying and alluvial fan development on the northern and southern valley sides, to cause the gradational development of a ridge which traverses the width of the valley. The coarsening upwards sequence evident in the ridge sediments from typecore GVF23 may reflect the gradual progradation of an alluvial fan onto the valley floor (Leeder, 1999). Similar depositional processes would have been responsible for the development of the basal sediments to the east and west of the ridge and account for their abundance on the valley sides. However, a lack of faults or topographic hollows prevented hillslope erosion from being concentrated into a small area (as with the ridge); thus a layer of talus formed on the valley sides and floor.

Such a theory can be considered more acceptable than that of the Ipswichian or glacial models. This is because periods of *c.* 110,000yrs and *c.* 700,000yrs without sedimentation do not need to be accounted for. The spatial distribution of the sediments can also be accounted for if hillslope activity is responsible for the development of the basal sediments and ridge.

This study has confirmed the presence of the ridge traversing the width of the Gordano Valley. A definitive explanation as to the mode and timing of the formation of the feature however, has not been achieved with the evidence available. Further research is required to assess the overall form and stratigraphy of the ridge. This could be achieved through increasing the coring resolution from the ridge region combined with subsequent analysis of the sediments.

11.2.3 Typecore interpretation: GVH17

(a) Lithostratigraphic summary

Unit	Altitude (O.D.)	Description
5	2.26-5.16m	Dark brown herbaceous well-humified peat
4	2.22-2.26m	Light grey organic silt
3	1.51-2.22m	Yellow-brown clastic rich herbaceous peat
2	1.00-1.51m	Light grey-brown sandy-clayey silt
1	0.31-1.00m	Orange-brown pebbly sand

(b) Palaeoenvironmental interpretation

Unit 1: 0.31-1.00m O.D.

Section 11.2.2 provides palaeoenvironmental interpretations for Unit 1.

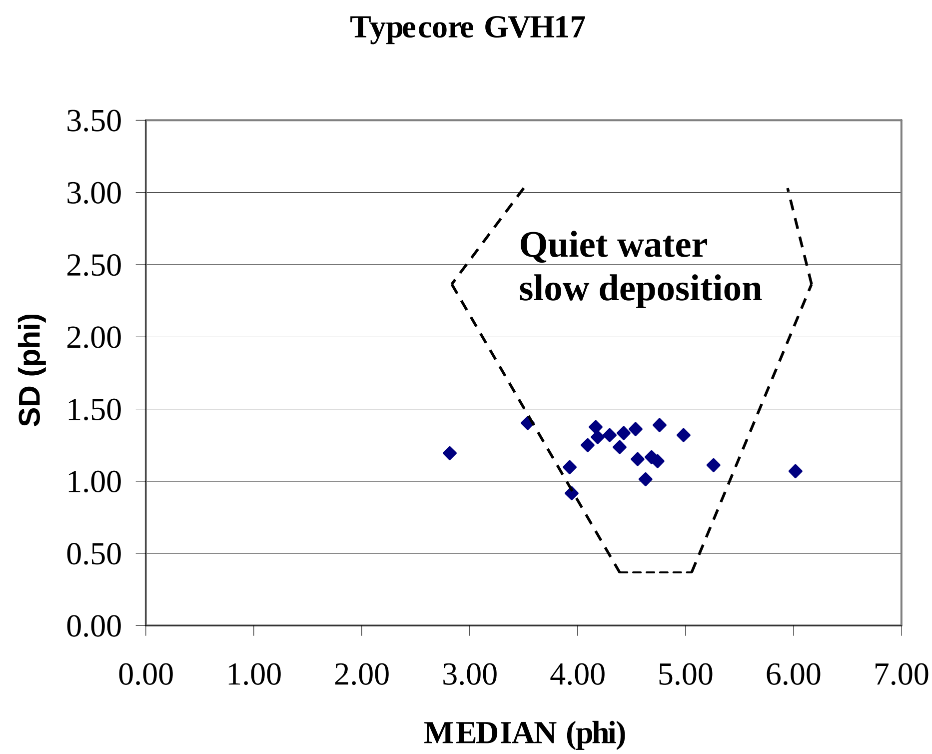
Unit 2: 1.00-1.51m O.D.

Unit 2 (the grey-brown sandy-clayey-silt) contains much finer sediments than Unit 1, indicative of a much lower-energy depositional environment. The radiocarbon date of the overlying clastic peat (Unit 3) indicates that the accumulation of this deposit occurred prior to *c*. 13,820-15,060 Cal. yrs BP. The mean grain size is relatively consistent throughout Unit 2, but an overall increase in size is evident with height (From 5ϕ at 1.16m O.D., to 4.25ϕ at 1.49m O.D.). Moderately sorted sediments are present towards the base of the unit (0.9ϕ size range at 1.22m O.D.), with the level of sorting decreasing with height.

Figure 11.6 is a comparison of grain size parameters based on Stewart (1958), in which the median grain size of the sample is plotted against the level of sorting and skewness of the sediment. Stewart (1958) suggested that defined envelopes representing certain depositional environments could be identified using this technique. The majority of the sediment samples from Unit 2 are positioned within the envelope identified as "quiet water, slow deposition" (Stewart, 1958). This indicates that the accumulation of the *c*. 0.5m of fines required a slow moving, if not stagnant body of water for deposition (through suspension) to occur. This is further supported by a comparison of mean grain size against standard deviation in Unit 2 on a logarithmic scale (Figure 11.7). This approach was first attempted as a palaeoenvironmental indicator by Tanner (1997), and further developed by Lario *et al*. (2002). Two of the analysed samples are positioned within the environmental envelope defined as "closed basin", whilst the remaining samples lie just outside of this zone. Those samples included within the closed basin section are found towards the base of Unit 2 (1.16-1.13m O.D.). Unfortunately, no environmental label is provided for the bivariate plot region where the majority of the samples lie, although the samples' proximity to the closed basin envelope suggests that similar depositional conditions were required.

The relative position of the majority of the Unit 2 samples within the "quiet water slow deposition" envelope described by Stewart (1958), along with the samples' overall proximity to the closed basin parameters described by Lario *et al*. (2002), does therefore suggest that deposition occurred within an enclosed basin. This

A)



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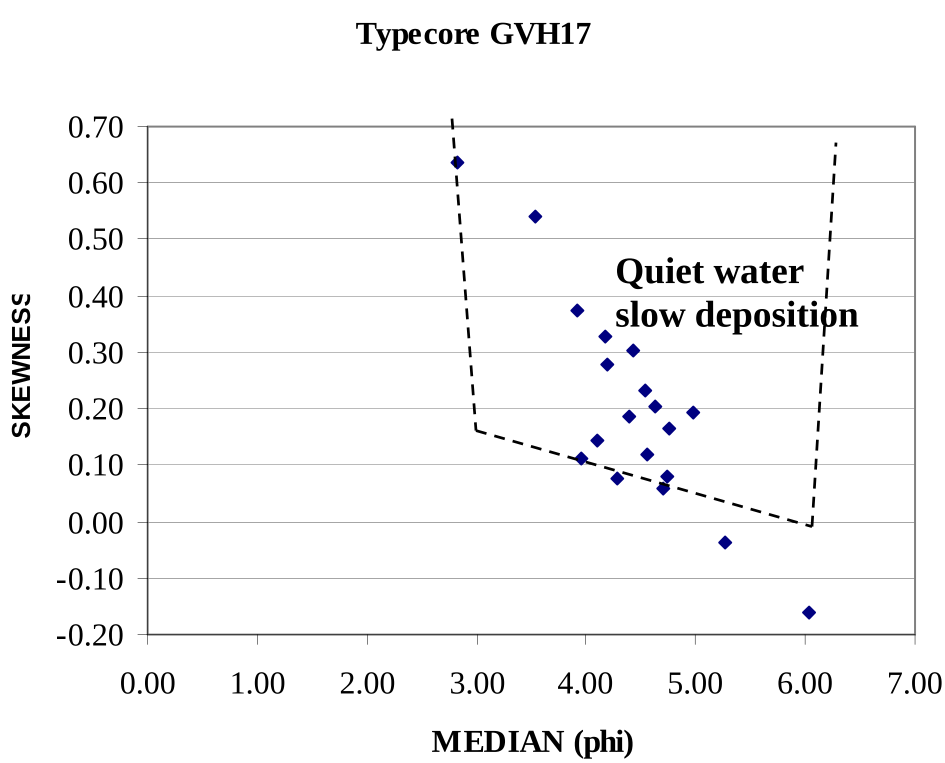

<u>**Figure 11.6**</u> Bivariate plot of grey-brown sandy clayey silt (Unit 2), A) median against sorting, B) median against skewness (based on the findings of Stewart, 1958).

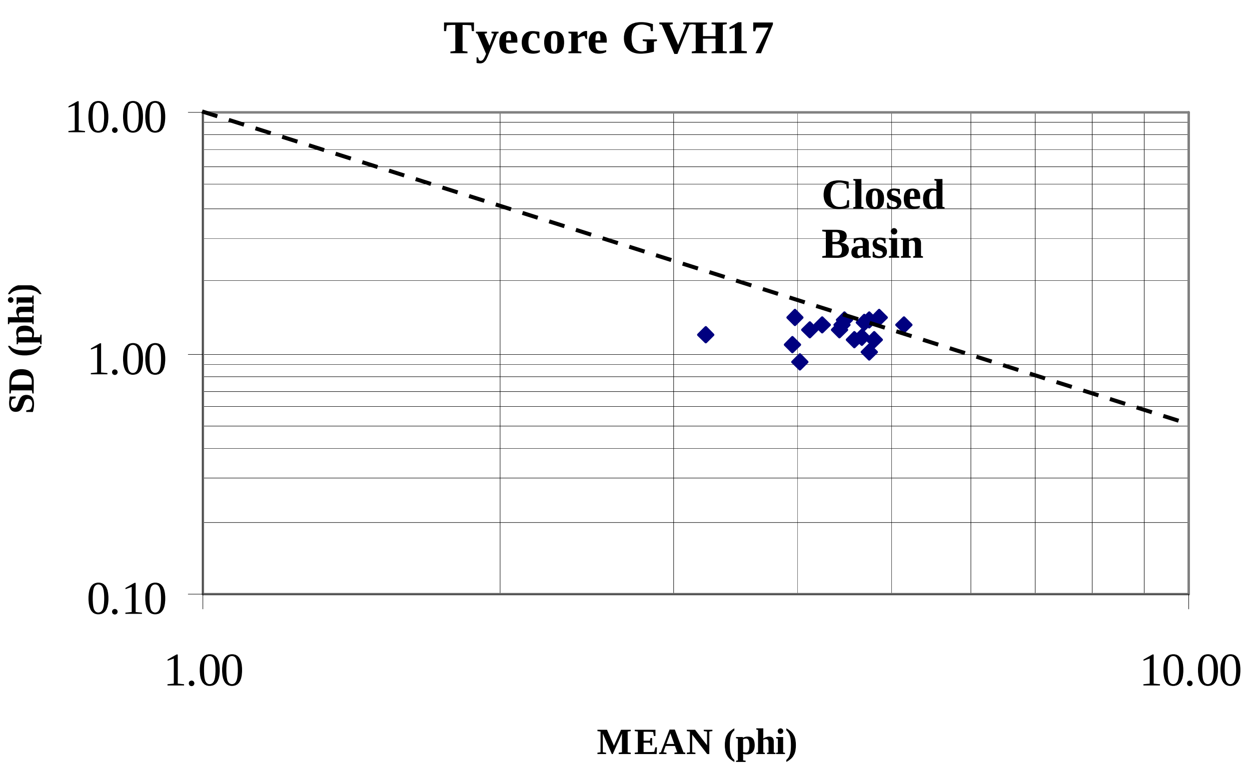

Figure 11.7 Logarithmic bivariate plot of mean grain size against sorting (phi) of Unit 2 in typecore GVH17 (adapted from Tanner, 1997).

is likely to have been a result of the combined influence of the valley sides and the ridge traversing the width of the valley, which would have prevented the drainage of water away from this basin after accumulation. Very thin laminations (<5mm) were present towards the base of Unit 2 in the typecore, which disappeared with height up the profile. Laminations are common within enclosed water basins such as lakes, in which the water depth is too great to enable wind and wave action from the surface to affect the gradual accumulation of sediments at the base of the water column (Sly, 1994). Gradual infilling of the enclosed basin and subsequent shallowing of the water body resulted in the turbulence within the water column reaching the floor of the basin, which disturbed the sediments and prevented the continued development of depositional laminations.

The pollen data from Unit 2 provides an insight into the environmental conditions that may have been present within the enclosed basin (refer to Figure 10.4). Although pollen preservation was relatively poor within the sedimentary unit (as with most clastic sediments; Moore *et al*., 1991), LPAZ 1, covering the majority of Unit 2, was dominated by *Artemisia, Pinus, Salix, Cyperaceae* and *Poaceae*. Contributions were also made by *Betula, Thalictrum, Trollius, Helianthemum* and *Ranunculus*. Species including *Poaceae*, *Artemisia*, *Helianthemum* and *Betula* are typical of northwest central European Oldest Dryas biozones (Litt *et al*., 2001). *Thalictrum* and *Helianthemum* are considered to be indicative of bare ground with unstable and immature soils (Walker *et al*., 2003), which is further supported by the relative abundance of broken and degraded unidentifiable pollen grains within the unit (which decreased in abundance with height). Broken and degraded grains are evidence for sediment reworking and re-deposition (Lowe & Walker, 1997). The dominance of open habitat taxa including *Poaceae*, *Artemisia* and *Cyperaceae* therefore suggests that relatively open bare ground surrounded the basin catchment, further supported by the abundance of herb species (*c*. 80% TLP) and low abundance of tree species throughout the unit (although *Betula* increased with height). The lack of salt tolerant species suggests that a freshwater enclosed basin was present. The similarity of species from the Gordano Valley with northwest and central European pollen sequences, along with the chronology provided from the overlying peat, indicates that the unit is likely to have developed prior to the Bølling/Allerød period, during the Oldest Dryas stadial (18,000-15,000 Cal. yrs BP; Roberts, 2000). The evidence therefore supports the proposition by Mills (1984) and Gilbertson *et al.* (1990) that the headward region of the Gordano Valley contained a lake during the late glacial period.

Unit 3: 1.51-2.22m O.D.

The yellow-brown clastic-rich peat horizon (Unit 3) overlying the sandy-clayey-silt unit began developing between 15,060 and 13,820 Cal. yrs BP. The unit's stratigraphy is characterised by herbaceous rooty-peat with very thin laminations of fine grained sediment throughout. The frequency of clastic laminations decreases with height, being replaced by increasingly humified organic remains within the peat content. The strong preservation of the leaf litter present, together with the layering of the organic remains towards the base of Unit 3, indicates deposition in a low-energy anoxic environment. Such conditions favoured the suspension deposition of the silts and clays present between the leaf layers. The presence of a stable stagnant water body is also indicated by the abundance of fine rootlets penetrating the horizontally layered leaf litter. Although the stratigraphic archive suggests a comparatively small water body was present in the Gordano Valley (*c*. 1km long, 0.5km wide), the palaeoenvironmental evidence indicates a stagnant, anoxic, freshwater depositional setting prevailed (see below). Consequently, to assist palaeoenvironmental interpretations, the term ‘lake’ will be utilised.

A decline in *Artemisia, Cyperaceae* and *Salix* throughout LPAZs 2-3, combined with the increase in tree species (to 55% TLP) suggests a reduction in bare ground cover in the surrounding catchment. The distinct increase in *Betula* through Unit 3, together with (to a lesser extent) *Anagallis* and *Pinus* are responsible for the gradational expansion of woodland cover over time. Within the overall transition from herb-dominated to tree-dominated species, short-term reductions in *Betula* are mirrored by increases in *Poaceae* in the lower and upper regions of LPAZ 2. This indicates that the onset of clastic-rich peat accumulation (LPAZ 2) occurred during the initial expansion of the grassland cover through the catchment. This was subsequently followed by a shift in vegetation (initiated within a thin 2cm minerogenic horizon) in which *Betula* woodland expanded, reducing the amount of open ground available for grasses. The *Betula* expansion is only short-lived, after which a brief re-expansion of grassland cover occurs by the end of LPAZ 2 before it is out-competed by *Betula* once again. During the Devensian late glacial between *c*. 15,000 and 13,000 Cal. yrs BP, *Betula* abundance is taken as a proxy of climate change, indicating the onset of higher, interstadial temperatures (Godwin, 1975; Popweb, 2004). The combination of peat development and expansion, along with the increased frequency of *Betula*, would indicate that a phase of climatic warming had begun around this time. Very low *Cyperaceae* levels, combined with the relative abundance of *Poaceae* within Unit 3, indicate that the typecore site was probably waterlogged. The inability of *Betula* to thrive in waterlogged conditions (Godwin, 1975; Popweb, 2004) suggests that its pollen was transported into the typecore site from elsewhere. Aquatic species (*Callitriche, Typha* and *Myriophyllum*), although relatively low in abundance, are present in LPAZs 2 and 3 and they support the continued presence of a freshwater body within the enclosed basin. Aquatic species have also been found in very low abundances at other lake sites including Star Carr, north Yorkshire (Dark, 1998).

The thickness of Unit 3 was greatest towards the centre of the Gordano Valley. Typecore GVH17 contained 71cm of the peat unit, whereas core GVE17, some *c*. 400m north of the typecore site, contained only 40cm of the same clastic-rich peat unit. With distance towards the valley sides (and towards the valley head and ridge) Unit 3 decreased in thickness. However, its upper surface was found to be relatively flat when compared to the form of the underlying grey-brown sandy-clayey-silt unit (see Figure 9.4). The peat unit therefore developed via gradual infilling of the basin that remained in the upper valley region. The timing of the transition from open water to peat deposition (dated between 15,030 – 13,820 Cal. yrs BP) appears to overlap with the transition from the last stages of the Oldest Dryas stadial (*c*. 18,000-15,000 Cal. yrs BP) and the onset of the Bølling-Allerød Interstadial (*c*. 15,000-13,000 Cal. yrs BP) (Roberts, 2000). As the pollen evidence suggests open water deposition during the Oldest Dryas stadial, it is proposed that onset of clastic-rich peat development occurred during the subsequent Bølling subinterstadial. A sudden climatic amelioration at the beginning of the Bølling subinterstadial provided temperatures similar to that of the early Holocene (Bjork *et al*., 1998). Bedford *et al*. (2004) calculated that the temperature in northwest England increased to 13.4°C at this time, comparable to the maximum temperature of 13.8°C at the start of the Holocene. This probably initiated the transition from open freshwater conditions to peat deposition.

Prior to the Bølling subinterstadial climatic amelioration, slope instability and catchment erosion had been responsible for a gradual infilling of the lake basin. The arrival of more favourable climatic conditions encouraged the establishment of *Betula* woodland and associated understory vegetation around the valley sides. This enhanced soil stability reduced the level of minerogenic input into the sedimentary basin. Catchment stability and the favourable climate initiated peat development at the lake margins, which then encroached into the lake basin as biogenic sedimentation exceeded the minerogenic input. The size of the lake began to decrease as peat development continued to advance into the freshwater body, and replaced the open water system with a terrestrial peatland. *Betula* pollen increased in abundance in typecore GVH17 before the onset of peat development (at the top of LPAZ 3), supporting the theory of a gradual infilling of the lake. The *Betula* woodland would have enhanced slope stability at the start of the Bølling subinterstadial, after which peat development began. But minerogenic sedimentation would have continued in the central lake region (where the typecore was extracted), transporting inwash deposits into the basin and elevating *Betula* abundances in the typecore. During the late glacial period, *Betula* pollen has been shown to be highly abundant in lake-centre deposits, compared to its sparsity at lake-margins (Dark, 1998), which suggests that lake-centre deposits reflect a regional pollen signal, probably from a radius exceeding several hundred meters around the lake (Jacobson & Bradshaw, 1991).

Unit 4: 2.22-2.26m O.D.

Prior to 9,580-9,520 Cal. yrs BP, the 4cm thick upper minerogenic unit that overlies the clastic peat was deposited (Unit 4). Although thin minerogenic laminations were common within the underlying peat, few were of greater thickness than a few millimetres and Unit 4 was the only horizon found consistently during fieldwork. The unit is characterised by very fine silts and a sharp upper boundary with the overlying dark brown peat (Unit 5). The pollen preserved within Unit 4 maintained the trend evident prior to the shift from biogenic to minerogenic sedimentation. A continued rise in *Betula*, combined with the gradual reduction in *Poaceae*, suggests the continued expansion of birch woodland during the deposition of Unit 4. *Corylus* also becomes more abundant within the unit, whilst *Artemisia* is not abundant beyond this horizon. Godwin (1975) states that the reduction in abundance of *Artemisia* from the pollen record was a common occurrence during the early Holocene. In the Gordano Valley, this transition is indicated at 9,580-9,520 Cal. yrs BP. Immediately above Unit 4, *Betula* percentages, along with *Poaceae* fall to almost 0% TLP, and are replaced by *Filicales*, *Cyperaceae* and *Corylus*. The change in vegetation, combined with the detrital sedimentation, is evidence for temporary catchment instability resulting from the retreat of birch woodland. This would have enhanced the potential for hillslope erosion to occur, which was responsible for depositing the in-washed minerogenic horizon. The abundance of *Betula* within the silt unit, however, suggests the presence of birch woodland during the unit's deposition. This could be explained through enhanced catchment instability and erosion, which caused older pollen grains to be transported and re-deposited at the typecore location. The minerogenic unit is at its thickest towards the northern valley side and within the valley centre, and is shown to have infilled hollows within the palaeosurface (Figure 9.6A and B), possibly through sediment accumulation from catchment runoff.

Unit 5: 2.26-5.16m O.D.

The development of dark brown well-humified peat marks the establishment of herb, shrub and spore species in place of birch woodland and the remaining open grassland, which occurred between 9,580 and 9,520 Cal. yrs BP. *Cyperaceae* and *Filicales* show contrasting trends in abundance. The drastic reduction in *Poaceae* abundance, and its replacement by *Cyperaceae* and *Filicales*, also point to a drier depositional environment when compared to the underlying clastic-rich peats. LPAZ 4 is characterised by this sudden change from closed birch woodland to open fern, sedge and hazel scrub vegetation. *Filicales* spores found at the base of Unit 5 were commonly corroded on the surface. This is indicative of possible chemical damage through variations in oxidation (Lowe & Walker, 1997), which may be associated with seasonal water table fluctuations in rapidly accumulating (and hence no longer anaerobic) fen peats (Walker *et al*., 2003). The much higher levels of humification within Unit 5 in contrast to the underlying clastic-rich peats further supports a change from an anaerobic setting within a stationary water basin into a depositional system characterised by water table fluctuations. Spore exine corrosion, increased levels of humification and dry-indicator pollen species all suggest that the lake basin had now experienced complete infilling through biogenic activity. The palaeosurface is likely to have been positioned around or above the water table, favouring the decomposition of biogenic sediments, corrosion of pollen grains and the establishment and expansion of vegetation that thrive in drier environmental conditions.

The expansion of *Corylus* around the onset of LPAZ 4 (9,580-9,520 Cal. yrs BP), coincides well with the typical Holocene *Corylus* rise in southwest England, dated to between *c*. 9,500-9,000 Cal. yrs BP (Birks, 1989), and is believed to be due to the lack of competition from other taxa and no environmental constraints (Popweb, 2004). *Corylus* arrived in the coastal lowlands of Wales and southern Ireland via water transport from the Irish Sea before c. 9,500 Cal. yrs BP (Birks, 1989), and the proximity of the Gordano Valley to these areas may explain why *Corylus* was also established in the valley prior to 9,500 Cal. yrs BP. Huntley (1993) concludes that the rapid expansion of *Corylus* was primarily due to the species' greater climatic tolerance of the more seasonally extreme climate in the early Holocene compared to thermophilous species such as *Quercus* and *Ulmus*.

The *Corylus* expansion was short-lived. The onset of LPAZ 5 (2.57m O.D.) is characterised by the arrival of *Alnus, Quercus* and *Tilia*, whilst *Poaceae* increased in abundance to c. 10% TLP. The initial colonisation and domination of the site by ferns and sedges was also relatively short-lived. Declining *Filicales* and *Cyperaceae* frequencies are compensated for by other spore producers including *Polypodium, Pteridium* and *Sphagnum* which cannot tolerate waterlogged conditions. There is a gradual expansion of herb, shrub and tree species in place of the fluctuating spore frequencies. The arrival of tree species including *Tilia, Quercus* and *Alnus* in Britain occurred around 8,500 Cal. yrs BP (Godwin, 1975; Chambers & Price, 1985; Popweb, 2004). Although based on relatively limited pollen evidence, their arrival into southwest England shows some temporal variation, with *Quercus* arriving at *c*. 9,250 Cal. yrs BP, *Alnus* at *c*. 7,250 Cal. yrs BP and *Tilia* at *c*. 6,750 Cal. yrs BP (Birks, 1989). As *Corylus* is not shade-tolerant, its corresponding reduction towards the centre of LPAZ 5 (*c*. 3.56m O.D.) is likely to be in response to woodland expansion, limiting *Corylus* development to woodland margins and clearings (Birks, 1989). The relatively low tree pollen counts in contrast to the overall dominance of herb, shrub and spore species suggests that, whilst the valley floor was inhabited by scrub and grassland vegetation, tree species thrived on the valley sides. Indeed, *Tilia* and *Quercus* prefer soils that have developed on limestone bedrock (found on the southern slope of the Gordano Valley), whilst *Alnus* is commonly found on the margins of fen and bog sites where it can tolerate thin and nutrient poor soils (Popweb, 2004).

Tree, herb, shrub and spore frequencies remain relatively constant through Unit 5. Towards the upper zone boundary of LPAZ 5 however, a decline in shrub vegetation primarily through *Corylus* is indicated, which is replaced by subtle increases in tree species. A radiocarbon date of 6,530-6,390 Cal. yrs BP in LPAZ 5 at 3.59m O.D. marks the initiation of an *Alnus* recovery together with a period during which *Tilia* frequencies reach their maximum within the pollen profile. *Pteridium* and *Filicales* abundances also rise within the zone. The thermophilous nature of *Tilia* suggests a period of relative climatic warming (Birks, 1989), although the presence of aquatic species (*Typha, Callitriche, Elodea*) suggests a relatively wet environment. Woodland expansion on the valley sides is likely to be responsible for the reduction in *Corylus* scrub, whilst herbs and spores including grasses, sedges, ferns and bracken spread into the remaining open ground and woodland margins. The peak in *Tilia* frequencies coincides with the climatic optimum that is believed to have occurred *c*. 7,000-5,000 Cal. yrs BP (Godwin, 1975) and is marked by the northward expansion of such thermophilous species.

The increased frequency of shrubs and trees in LPAZ 6 is primarily caused by *Corylus* and *Alnus* respectively. The dominance of grasses and sedges in the underlying pollen zones are seen to decline gradually with height through the zone. The continued expansion of mixed woodland dominated by *Alnus* seems a likely interpretation, whilst *Corylus* continued to expand at the margins of the woodland in the place of herb species. Artificial drainage of the Gordano Valley is likely to have provided more suitable environmental conditions and encouraged woodland expansion onto the valley floor during the late Holocene. The final zone, LPAZ 7, must be interpreted with caution because present-day agricultural activity (such as ploughing) is likely to have considerable disturbance in the upper *c*. 25cm of the profile (if not deeper). There is, however, a distinct decline in tree and shrub species recorded, again driven by reductions in *Alnus* and *Corylus* frequencies. These are replaced by herbs and spores, primarily *Poaceae* and *Filicales*, whilst towards the typecore surface, *Ericaceae* and *Sphagnum* are increasingly influential. The subsequent rapid decline in tree pollen is due to anthropogenic woodland clearance to open up land for agricultural purposes within the typecore region. The colonisation of

Poaceae and expansion of *Ericaceae* indicates the respective implementation of grazing and drainage of the valley floor.

(c) Summary of the evolution of the upper valley region

Table 11.1 summarises the results of the multiproxy analysis of typecore GVH17. Landward of the ridge, sedimentary accumulation began (at the latest) during the Oldest Dryas Stadial, *c.* 18,000-15,000 Cal. yrs BP (Roberts, 2000). A small freshwater lake developed in a basin that was enclosed by the ridge that crossed the width of the Gordano Valley. Minerogenic sedimentation dominated in the basin during this period of late glacial climatic recovery, during which catchment instability encouraged the erosion of the sparsely vegetated valley sides. The enclosed nature of the basin accounts for the absence of testate amoebae and diatom assemblages within the archive, as calcareous-rich runoff from the valley sides would have accumulated in the lake and caused enhanced biogenic silica dissolution, thus preventing preservation (Barker *et al*., 1994).

The development of the ridge during the Devensian glacial period (see section 11.2.2(c)) is likely to have stripped the valley sides of sediments through periglacial processes. This brings into question the origin of the lacustrine sediments. One explanation could relate to the accumulation of loess in southwest England during the late glacial period. Most British loess was deposited during the transition from the Devensian glacial into the present interglacial, between *c*. 18,000 and 13,000 Cal. yrs BP (Catt, 2001). Deposits are found in abundance directly north and south of the Gordano Valley (see Figure 11.8) and are also present in the valley at Holly Lane (Gilbertson & Hawkins, 1974) and Court Hill (Gilbertson & Hawkins, 1978b). Wind blown slits and clays could have accumulated on the valley sides during this period, only to be eroded, transported and redeposited within the lake during the Oldest

Altitude (m O.D.)	Sediment Type	Particle Size Analysis	Predominant Pollen	Environment of deposition	^{14}C Age (Cal. yrs BP, 2 sigma)
5.16-2.26m	Unit 5: Dark brown herbaceous well-humified peat.	N/S	*Alnus, Corylus, Poaceae, Cyperaceae* and *Filicales* . Increasing levels of *Alnus* and *Corylus* with heigh through unit, whilst *Cyperaceae* and *Filicales* decrease.	Transition from basin fen to valley fen conditions prevailed.	3.69m (O.D.) 6,530-6,390 2.26m (O.D.) 9,580-9,520
2.26-2.22m	Unit 4: Light grey organic silt.	Mean grain size 5.5phi, poorly sorted, negatively skewed, mesokurtic.	*Betula, Pinus, Corylus* and *Poaceae.* Highest tree pollen frequencies in whole archive within unit, primarily due to *Betula* and (to a lesser extent) *Pinus* . Introduction of *Corylus* and decreasing levels of *Poaceae* with height.	Catchment instability during a period of climatic deterioration caused hillslope erosion to occur and deposit fine grained in-wash deposits onto the valley floor.	N/S
2.22-1.51m	Unit 3: Yellow-brown clastic rich herbaceous peat.	N/S	*Betula, Artemisia* and *Poaceae.* Continued decline in *Artemisia* with height, compensated by increasing *Betula* . *Poaceae* fluctuates through unit.	Climatic amelioration initiated the terrestrialisation of the enclosed lake, encouraging the encroachment of peat into the basin.	1.51 m (O.D.) 13,820-14,840 14,260-14,220 15,060-14,840
1.51-1.00m	Unit 2: Light grey-brown sandy-clayey silt.	Mean grain size 4.6phi, moderately sorted, positively skewed, mesokurtic.	*Pinus, Artemisia, Poaceae* and *Cyperaceae* . Overall decreases of *Artemisia* and *Pinus* with height, whilst *Poaceae* and *Cyperaceae* remain constant. Appearance of *Betula* and *Ranunculus* towards upper boundary.	Minerogenic deposition occurred within an enclosed lake basin which gradually became infilled with time.	N/S
1.00-0.31m	Unit 1: Orange-brown pebbly sand.	Mean grain size 0-3phi, very poorly sorted, varying skewness, extremily leptokurtic.	N/S	Sedimentation possibly occurred within a coastal back-barrier environment, through sub-glacial meltout or a result of hillslope deposition.	N/S

Table 11.1 Summary of proxy results for typecore GVH17

Dryas. Indeed, ApSimon and Donovan (1956) described a sedimentary unit overlying periglacial solifluction deposits in Weston in Gordano as a “hillwash” layer with aeolian constituents. This would explain the similarity between the mean grain size of the lacustrine sediments (30-50µm) and that of loess across southern England (25-45µm; Shotton, 1977).

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Figure 11.8 Distribution of loess around England and Wales (from Catt, 2001 p.222)

Sedimentation within the lake occurred predominantly through suspension deposition in the stagnant freshwater body. Initial sedimentation enabled fine drapes to develop, possibly in response to seasonal variations in palaeohydrology (Sly, 1994). Continued sedimentation caused shallowing of the water body and increased turbidity at the lake bed which gradually restricted the continued formation of the drapes. The gradual infilling of the lake system culminated in a shift in depositional processes at the onset of the Bølling subinterstadial (15,000 Cal. yrs BP), at which point sudden climatic amelioration encouraged vegetation expansion on the valley sides. Subsequent catchment stability and favourable climatic conditions initiated biogenic sedimentation at the lake margins, which gradually encroached into the freshwater body. Initial clastic-rich peat accumulation occurred in anoxic conditions around the periphery of the lake, and continued peat accumulation caused the terrestrialisation of the lake by the early Holocene.

A short period of catchment instability encouraged a return to minerogenic sedimentation on the valley floor, filling surface hollows towards the northern and central valley regions. These silt rich sediments were thickest around the northern valley side, suggesting that this region was the source of catchment runoff into the terrestrialised basin. As radiocarbon dating was not carried out on the clastic-rich peat directly below this unit, it is unclear at present when this period of sedimentation took place. The sharp boundary between Unit 4 and the overlying fen peat suggests an unconformity and it is suggested that the minerogenic unit was deposited some time before 9,580-9,520 Cal. yrs BP, when fen peat began to develop. A Younger Dryas age is hypothesised due to the climatic deterioration that occurred during this period, but this cannot be confirmed until further radiocarbon dating is undertaken. By 9,580-9,520 Cal. yrs BP, fen peat was accumulating in the central valley region and it is likely to have begun on the valley sides before encroaching into the valley over time in a similar way as the clastic-rich peat sequence. The remaining *c*. 3m of highly-humified dark-brown peat indicates the maintained development of fen peat in the upper valley since the early Holocene. Surface runoff, groundwater and stream flow would have maintained the region's high water table close to the valley surface (Charman, 2002), although annual water table fluctuations are likely to have supported the high level of humification present in the valley archive.

The sedimentary sequence preserved landward of the ridge is typical of a hydroseral succession, thereby preserving the gradual transition from freshwater to terrestrial depositional conditions during the late Quaternary (Figure 11.9). The stratigraphic characteristics within the valley archive compare favourably with the concept of hydroseral succession proposed initially by Tansley (1939), in which “a gradual change from open water to aquatic macrophytes, followed by colonisation by rooted aquatics, emergent plants, a terrestrial fen with a further transition to raised bog (conditions)” occurs (Charman, 2002, p.146). Radiocarbon dating suggests that the transition from open water to shallow aquatic conditions at the Gordano Valley occurred around the onset of the Bølling subinterstadial (*c*. 15,000 Cal. yrs BP) and this is further supported by Charman (2002) who states that, although it is possible for such a transition to occur under stable climatic conditions, the likelihood of this is small and that climatic influences probably affect the timing of such transitions.

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Figure 11.9 Typical basin mire development and stratigraphy (Charman, 2002, p.12)

Given that the *c*. 70cm lake peat sequence covers a timescale of some *c*. 4,000yrs, rates of organic accumulation were low (1.4-1.7cm/100yrs) in relation to the rest of the sedimentary archive (c. 2.3-4.6cm/100yrs). The aquatic phase of a typical hydroseral succession commonly experiences higher rates of accumulation than later phases due to the combination of autogenic and allogenic input (Charman, 2002). It must be stressed, however, that limited radiocarbon dating applied to the sedimentary archive of the Gordano Valley limits reliable analysis of the temporal evolution of the hydroseral sequence. Based on the dating carried out so far, the clastic-rich peat unit and the overlying thin minerognic unit (Unit 4) covers the Bølling/Allerød interstadial, the Younger Dryas stadial and the onset of the Holocene. Whilst there are distinct changes in pollen assemblages which may relate to these climatic periods (especially in relation to the fluctuations in arboreal and non-arboreal pollen ratios), based on accumulation rates alone no significant correlations can be made. This is likely to be a result of enhanced autogenic sedimentation that occurred during periods of climatic amelioration (e.g. the Bølling and Allerød subinterstadials) and reduced sedimentation during periods of climatic deterioration (e.g. the Older Dryas substadial and Younger Dryas stadial). Consequently, it is difficult to infer accurate accumulation rates and chronological comparisons from only two radiocarbon dates.

The climatic deterioration that probably encouraged the development of the thin minerogenic unit (Unit 4; through catchment instability and erosion) marks a distinct shift in valley ecology and appearance. The final phases of recovery from the Devensian glaciation were characterised by birch woodland around the valley sides and open grassland on the waterlogged valley floor. In contrast, the onset of fen peat development supported sedge, fern and hazel scrub expansion and the disappearance of most arboreal species from the catchment. Initial hazel expansion, tolerant of the early Holocene climate extremes, assisted the valley soils in a return to relative stability, and enabled gradual recovery and vegetation expansion. Accumulation rates of the dark brown peats are higher during the early-mid Holocene (4.6cm/100yrs) in comparison to the late Holocene archive (2.3cm/100yrs). It must be stressed once again that these rates are estimates from limited radiocarbon dates and the influence of anthropogenic activity (e.g. peat cutting) is unknown in the region. Charman (2002) notes that fen peat growth rates are typically higher than the later bog phases, possibly due to the gradual reduction in the influence of the water table over time, which encourages enhanced decomposition of the standing biomass. Whilst the initial phase of peat accumulation would have been within a basin fen setting (due to the continued presence of the ridge), the eventual overtopping and submergence of the ridge led to the development of a valley fen setting into which the upper and lower valley regions were incorporated.

11.2.4 Typecore interpretation: GVJ43

(a) Lithostratigraphic summary

Unit	Altitude (O.D.)	Description
7c	2.78-5.49m	Light (bluey) grey-brown clayey-silt
6c	2.04-2.78m	Dark brown herbaceous humified peat
7b	1.92-2.04m	Light grey-brown clayey-silt
6b	1.77-1.92m	Dark brown herbaceous humified peat
7a	0.48-1.77m	Light grey silty sand
6a	-0.3 to 0.48m	Dark brown woody peat
1b	-0.49 to -0.3m	Grey-brown sand
1	-1.16 to -0.49m	Orange-brown pebbly sand

(b) Palaeoenvironmental interpretation

Unit 1: -1.16 to –0.49m O.D.

Section 11.2.2 provides palaeoenvironmental interpretations for Unit 1.

Unit 1b: -0.49 to –0.30m O.D.

Pollen was extracted from the grey-brown sand horizon (Unit 1b) that overlies the orange-brown pebbly sand (Unit 1). Spores dominate the pollen assemblages, primarily through *Bryophytes* and *Pteridium*, whilst *Corylus* contributes *c*. 30% TLP with height through the horizon (refer to Figure 10.8). There is also a gradual increase in arboreal species with height through the profile towards the overlying woody peat horizon. Low levels of *Chenopodiaceae* would suggest that the site was in relative proximity to saltmarsh conditions. However, similar frequencies of *Typha* and *Callitriche* could imply that a coastal freshwater reedswamp was present (Waller *et al.*, 1994). The initial dominance of *Bryophyte* spores suggests the colonisation of pioneer moss species in the region, which require wet conditions for part of their life cycle at least (Carrington, 1997). Drier conditions are likely to have prevailed on the valley sides as *Corylus* and *Tilia* frequencies reach their maxima within the profile (30% and 10% TLP respectively) towards the overlying peat boundary. The particle size results for Unit 1b suggest that the unit may have been deposited in a fluvial setting. The positive skewness, relatively poor level of sediment sorting and leptokurtic nature of grain size distribution indicates that a river system may have been present initially within the seaward region of the valley, which drained the catchment's runoff into the Severn Estuary. Like that of Unit 1, this is a tentative conclusion due to limited palaeoenvironmental knowledge of the unit. The unconsolidated nature of the sediment (and that of Unit 1) limited its extraction during fieldwork and thus it is inappropriate to suggest the presence of a river system on the basis of one core alone. The coarse nature of the sediment, which limits the potential for frustule deposition and preservation (Lowe & Walker, 1997), meant that no diatoms were present in Unit 1b and freshwater or marine conditions could not be determined.

Unit 6a: -0.30 to 0.48m O.D.

The lower peat unit (Unit 6a) is dominated by high frequencies of *Alnus* (up to 65% TLP) which contributes up to 85% of the arboreal pollen. The greatest *Alnus* frequencies are recorded towards the centre of the peat unit, decreasing in abundance towards the unit boundaries. Fragments of *Alnus* wood were common throughout unit 6a, suggesting the development of woodland on the valley floor at this time. Significant contributions are also made by *Tilia* and *Quercus*, whilst *Corylus* is present throughout (though decreasing in frequency with height). A warm fen carr environment began to develop *c*. 7,320-7,220 Cal. yrs BP, indicated by the initially high frequencies of *Tilia*, which is replaced by *Alnus* with height, and the very low influence of *Poaceae* and *Cyperaceae* (Waller *et al*., 1994). *Tilia* cannot tolerate the high water tables within which peat accumulates (Waller *et al*., 1994), and thus declined as the fen carr developed. Although alder dominated the woodland, a mixed forest was likely, with oak contributing, lime present towards the peatland margins and hazel scrub present towards the woodland margins where the canopy was thinner. The rapid expansion of alder-dominated woodland occurred within only *c*. 250yrs. At the upper and lower peat boundaries, trees were replaced by *Filicales* and *Pteridium*. The initiation of peat deposition at the site would have therefore resulted in the initial colonisation by ferns and bracken, which were out-competed after a short period of time by the encroachment of the woodland as the water table fell. A subsequent rise in relative sea level produced environmental conditions less suitable for tree and shrub species, and encouraged the re-establishment of *Filicales* and *Pteridium*.

The only sample within Unit 6a found to contain diatom frustules (0.11m O.D.) was dominated by marine and marine-brackish planktonic species such as *Paralia sulcata* and *Delphineis surirella*, with minor occurrences of fresh and brackish species. Considering the relative lack of minerogenic sedimentation within the peat unit, combined with the abundance of fen carr vegetation, the species preserved within the sediment sample do not appear to match the depositional environment inferred through pollen interpretation. If the assemblage is a fair representation of the environmental conditions that were present at the time of deposition, a storm episode may have been responsible for depositing the diatom frustules within the alder carr sequence.

Unit 7a: 0.48 – 1.77m O.D.

The upper boundary of the lower peat unit was dated to *c*. 6,870-6,670 Cal. yrs BP, at which point a change to deposition of light grey silty-sands occurred. The lower boundary of Unit 7a represents a change in vegetation from tree and shrub-, to herb- and spore-dominated taxa. *Filicales* and *Pteridium* dominate the minerogenic unit, and are in greatest abundance towards the unit boundaries. These species are, however, commonly over-represented in marine sediments due to allochthonous input (Alderton & Waller, 1994). *Chenopodiaceae* contributes up to 15% TLP through the unit, whilst *Lactuceae* increases in frequency with height (*c*. 5% TLP), which indicates a strong influence from marine conditions (Waller & Kirby, 2002).

The evidence for marine deposition is further supported by the diatom assemblages, where brackish species are the optimal autochthonous group throughout the sedimentary unit. Some caution, however, must be exercised when interpreting the lower LDAZs within the minerogenic deposits due to the low percentage of autochthonous species present within zones GVJ43-2 and (to a lesser extent) GVJ43-3 (see Table 10.5). This may be due to the preferential preservation of more resistant diatom frustules, as research has shown that diatom species experience differential susceptibility to dissolution over time (Ryves *et al.,* 2001). The relatively sandy nature of the sediment towards the base of the unit would further support this, as higher depositional energy conditions were likely to be required and would explain the disarticulation commonly found within the diatom assemblages (Lowe & Walker, 1997).

The optimal autochthonous diatom group commonly only accounts for *c*. 20% TDV, as up to *c*. 80% of the species are planktonic in GVJ43-2. At the transition into GVJ43-3, towards the centre of Unit 7a, there is an increase in the fresh autochthonous ratio, which indicates an increased influence of freshwater conditions proximal to the site. This is further supported by the environmental interpretations achieved through Vos & deWolf (1993). The diatom assemblages indicate a change from deposition predominantly on mud-flats at the start of minerogenic sedimentation, to deposition on salt marshes around MHW higher up the tidal frame. Although pollen analysis does not indicate significant vegetation changes in response to this, the increased influence of marine-brackish aerophilous, brackish-fresh planktonic and tychoplanktonic species within GVJ43-3 (see Table 10.6) does suggest a reduction in marine influence for a short period (Vos & deWolf, 1993). The diatom assemblages preserved in GVJ43-4 are interpreted as being deposited on the mud-flat towards the base of the zone, primarily due to the continued dominance of marine-brackish epipelon and marine planktonic species (including *Nitzschia navicularis* and *Paralia sulcata* respectively). Towards the upper zonal boundary, deposition occurred on the salt marsh around mean high water (MHW), indicated by the substantial increase in brackish-fresh aerophilous species (mainly *Hantzschia amphioxys* and *Navicula pusilla*).

Reduced exposure to marine conditions is indicated within GVJ43-5 where, although brackish species remain the dominant autochthonous component, the fresh autochthonous ratio rises to 0.388 towards the boundary with Unit 6b, and indicates an increased freshwater influence. Autochthonous species also contribute over 75% TDV, and provide representative environmental interpretations. GVJ43-5 is dominated by marine-brackish and brackish-fresh aerophilous species, namely *Diploneis interrupta* and *Hantzschia amphioxys* respectively. Such species are reliable indicators of salt-marsh conditions (Denys, 1994). This is further supported by the environment of deposition being interpreted though Vos & deWolf (1993) as a salt marsh above MHW.

Intertidal and salt-marsh depositional conditions were occurring within the typecore site during the accumulation of Unit 7a, and these are indicated by pollen and diatom assemblages. The most significant characteristic identified through particle size analysis was the gradual decrease in mean grain size from *c*. 4ϕ to *c*. 5.5ϕ throughout the unit. This could be explained by a change in sea level relative to surface elevation during sedimentation. The diatom assemblages indicate that the transition from Unit 6a (lower peat unit) into Unit 7a must have resulted from rapid marine inundation due to the immediate deposition of mud-flat diatom assemblages. In contrast, a gradational transgression of marine conditions would have resulted in the presence of salt-marsh indicator species such as *Diploneis interrupta* and *Hantzschia amphioxys* prior to mud-flat sedimentation (Vos & deWolf, 1993). Deposition lower down the estuarine tidal frame would result in the accumulation of coarser sediments in response to higher energy conditions, thus explaining the deposition of sandy-silts. Diatom analysis indicates a reduction in exposure to marine conditions with height through the sedimentary unit as aerophilous species increase in influence along with the fresh autochthonous ratio, and this reduction in marine influence coincides with the decline in mean grain size. If such a shift in marine conditions occurred, minerogenic deposition would take place towards the upper limits of the tidal frame, where energy levels within the tidal waters are much lower and current velocities drop to 0cm/sec^{-1} at the transition from the flood to the ebb currents (Dyer, 1994). This could consequently explain the variation in grain size with height through the profile.

Unit 6b: 1.77 – 1.92m O.D.

The middle peat unit (Unit 6b) began to accumulate 6,180-5,930 Cal. yrs BP and is characterised by an initial peak in *Alnus*, *Cyperaceae* and *Poaceae*. The fall in

Chenopodiaceae and rise in *Alnus* and *Cyperaceae* frequencies at the lower boundary of Unit 6b suggests a reduced exposure to marine conditions, which encouraged the expansion of open alder-dominated woodland nearby, whilst hazel and sedges dominated the woodland and coastal margins respectively. The woodland did not establish itself at the site due to the relatively short period of peat deposition (and hence poor soil development), although the increase in *Cyperaceae* in place of *Poaceae* with height is indicative of a gradual drying out of the environment as the local water table fell (Long & Innes, 1993). *Chenopodiaceae* frequencies then increase from 0% to 5% TLP towards the upper peat boundary, suggesting an increase in marine influence with height. Peat accumulation ends at 5,710-5,590 Cal. yrs BP, at which point ferns dominate as the influence of tree, shrub and herb species decline. This is likely to be due to the increasing influence of sea level on the lowland environment, which would have caused a rise in the local water table.

Unit 7b: 1.92 – 2.04m O.D.

The change in the level of the water table as a result of the increased exposure to marine conditions encouraged the initial expansion of *Poaceae*, which was then replaced by *Chenopodiaceae* (up to 25% TLP) as light grey-brown clayey-silts (Unit 7b) began to accumulate on top of the thin peat unit. Rising levels of *Corylus* and fluctuating frequencies *Quercus* and *Alnus* within Unit 7b indicates the continued presence of open woodland close to the site (Alderton & Waller, 1994). *Diploneis interrupta* and *Nitzschia navicularis* dominate the diatom assemblages throughout the sedimentary unit in zone GVJ43-7, representing deposition near to the upper salt marsh at the unit boundaries, and upper mudflat towards the centre of the unit (Denys, 1994). Brackish species maintain the optimal autochthonous diatom group, whilst autochthonous species contribute over 80% TDV within the unit. Fresh-brackish and brackish-fresh species are also more abundant towards the unit margins, supporting a depositional setting close to HAT.

The environment of deposition inferred from Vos & deWolf (1993) is indicative of surface pools on the salt marsh towards the upper and lower unit boundaries of GVJ43-7; samples from the centre of the unit were deposited on mud-flats or around MHW. The grain size within Unit 7b is finer than that of Unit 7a, but again could be explained through variations in the tidal frame and its associated current velocities (Dyer, 1994). The size of the sedimentary unit (only *c*. 12cm thick), combined with the diatom assemblages which indicate deposition towards the upper mudflat and salt-marsh regions, suggests that the energy levels responsible for the development of the minerogenic unit would already be very low as deposition was occurring towards the upper limit of the tidal frame.

Unit 6c: 2.04 – 2.78m O.D.

After clastic sedimentation for *c*. 250yrs, peat deposition began again between 5,470-5,300 Cal. yrs BP. Unit 6c, divided into LPAZ 7 and 8, shows differences in vegetation when compared to the two underlying peat units. The low abundance of arboreal pollen, combined with a lack of wood fragments in LPAZ 7, suggests a continued absence of woodland at the typecore site after the retreat of the sea. Grasses and hazel scrub initially colonised the site as the influence of marine conditions declined, but these were out-competed over time by ferns and (to a lesser extent) sedges. *Chenopodiaceae* is wholly absent from LPAZ 7, whilst *Callitriche, Typha* and *Hydrocharis* indicate freshwater deposition (Long & Innes, 1995). An increase in tree species is evident in LPAZ 8, with *Alnus*, *Fraxinus* and *Quercus* all contributing (*c*. 5% TLP). The zone is also characterised by a decline in *Cyperaceae* and *Poaceae* and associated increases in the abundance of *Pteridium*. The fluctuating presence of grasses and sedges, combined with maximum ash abundances, suggest human activity within the region. Mid-late Holocene forest disturbance or clearance may have enabled the colonisation of ash onto disturbed ground (Birks, 1989; Popweb, 2004). The advance of open woodland close to the typecore site was relatively brief and is likely to have been restricted to the valley sides. Soon after, an increase in the local water table in response to exposure to marine conditions (indicated through the re-introduction of *Chenopodiaceae*) caused the expansion of bracken along the coastal margin.

Diatom assemblages towards the upper boundary of Unit 6c are grouped into zone GVJ43-9. Fresh-brackish species are the optimal autochthonous diatom group through much of the peat unit, with up to *c*. 87% TDV being autochthonous. There is a shift to brackish dominated assemblages within the unit where silt is present within the peat (2.64-2.54m O.D.), before a return to fresh-brackish dominated assemblages with height. Palaeoenvironmental interpretation through Vos & deWolf (1993) indicates that the majority of the organic deposition was occurring in pools on a salt marsh, supported by the dominance of aerophilous species (primarily *Diploneis interrupta* and *Pinnularia viridis*) and fresh epipelon species (e.g. *Cymbella subaequalis*).

Unit 7c: 2.78 – 5.49m O.D.

The final phase of peat deposition ended at *c*. 3,840-3,640 Cal. yrs BP, after which estuarine conditions prevailed. The initial dominance of *Pteridium* and the subsequent rise in *Chenopodiaceae* through the upper minerogenic unit indicates a gradual increase in marine influence (Long & Innes, 1995). Arboreal species are at their lowest when compared to the whole of the typecore profile (*c*. 10% TLP), indicating their absence from the immediate region around the core site. The tree species, as with most of the shrubs (with similar low abundances at *c*. 5% TLP) would have been found on the valley sides away from the estuarine setting. Aquatic pollen types contribute up to 20% TLP via *Callitriche* and indicate the continuation of influence of freshwater conditions during the environmental transition (Waller *et al*., 1994). The dominance of brackish autochthonous diatom species shows a return to brackish estuarine conditions. The fresh autochthonous ratio declined with height through Unit 7c, indicating a reduced freshwater influence in an increasingly marine-dominated environment. High levels of marine-brackish aerophilous species indicate that the initial depositional environment was a salt marsh above MHW (Vos & deWolf, 1993). However in response to the increased marine influence, a transition to salt marsh around MHW occurred, followed by mud-flat sedimentation (indicated by increasing frequencies of marine-brackish epipelon species; see Table 10.6).

(c) Summary of the evolution of the lower valley region

Table 11.2 summarises the results of the multiproxy analyses of typecore GVJ43. Sedimentation in the Gordano Valley on the seaward side of ridge appears not to have begun until at least *c*. 7,500 yrs after the initiation of lacustrine deposition further inland. This does not necessarily mean that sediment accumulation was not occurring prior to *c*. 7,200 Cal. yrs BP. Allen (2000c) states that earlier, rapid marine transgressions may have prevented accumulates from being preserved, as the majority of marine-estuarine deposits in Severn Estuary region date from after 7-9,000 Cal. yrs BP.

Underlying the basal peat unit is a thin layer of grey-brown sand which may have developed under fluvial conditions prior to the onset of freshwater peat accumulation. A sparsely vegetated lower valley was present, into which runoff from

Altitude (m O.D.)	Sediment Type	Particle Size Analysis	Predominant diatoms	Predominant Pollen	Environment of deposition	^{14}C Age (Cal. yrs BP, 2 sigma)
5.99-2.78m	Unit 7c: Light (bluey) grey-brown clayey-silt	Decrease in mean grain size with height from 5-6phi, poorly sorted, negatively skewed, mesokurtic.	Marine-brackish epipelon and aerophilous species dominate, especially *Nitzschia navicularis* and *Diploneis interrupta* .	*Chenopodiaceae* and *Callitriche* increase in abundance with height. *Pteridium* dominant throughout.	Initially deposition occurred on lower saltmarsh, although marine influence increases through unit.	2.78m (O.D.) 3,840-3,640
2.78-2.04m	Unit 6c: Dark brown herbaceous humified peat	N/S	Marine-brackish and brackish-fresh aerophilous species dominate, especially *Diploneis interrupta* and *Pinnularia viridis* .	*Poaceae* dominates at upper and lower unit boundaries, with *Filicales* abundant towards the centre of the unit. *Cyperaceae* and *Corylus* also contribute.	Sub-aerial exposure initiates peat deposition in a freshwater reedswamp environment with saltmarsh conditions at margins.	2.04 m (O.D.) 5,470-5,300
2.04-1.92m	Unit 7b: Light grey-brown clayey-silt	Mean grain size 5.5phi, poorly sorted, negatively skewed, mesokurtic.	Marine-brackish epipelon and aerophilous species dominate, especially *Nitzschia navicularis* and *Diploneis interrupta* .	*Chenopodiaceae* dominant towards centre of unit, whilst *Poaceae* abundant at upper and lower boundaries.	Deposition on lower saltmarsh and upper mud-flats prevailed.	1.92m (O.D.) 5,710-5,590
1.92-1.77m	Unit 6b: Dark brown herbaceous humified peat	N/S	Marine-brackish and brackish-fresh aerophilous species dominate, especially *Diploneis interrupta* and *Hantzschia amphioxy* s.	*Alnus* declines in abundance with height, replaced by increasing frequencies of *Filicales. Cyperaceae* and *Poaceae* also influential.	Mudflat becomes sub-aerially exposed, allowing freshwater reedswamp to prevail with saltmarsh at the margins.	1.77m (O.D.) 6,180-6,670
1.77-0.48m	Unit 7a: Light grey silty sand	Mean grain size decreases with height from 4-5.5phi, poorly sorted, positively skewed, mesokurtic.	Marine planktonic and marine-brackish epipelon species dominate, including *Paralia sulcata* and *Nitzscia navicularis* .	*Filicales* , *Pteridium* and *Chenopodiaceae* dominant throughout. *Coryus, Poaceae* and *Cyperaceae* also contribute.	Intertidal mudflat conditions with marine influence.	0.48m (O.D.) 6.870-6,670
0.48 to -0.31m	Unit 6a: Dark brown woody peat	N/S	N/S	*Alnus* dominates, especially at the centre of the basal peat unit. *Filicales* and *Corylus* abundant at upper and lower boundaries respectively.	Dry alder carr environment prevailed with sedge fen at margins.	-0.31m (O.D.) 7,320-7,220
-0.31 to -0.49m	Unit 1b: Grey-brown sand	Mean grain size 2.5phi, poorly sorted, positively skewed, leptokurtic.	N/S	Unit dominated by increasing frequencies of *Corylus* and decreasing frequencies of *Bryophytes* with height. Stable *Pteridium* abundance throughout.	Possible river floodplain environment prevailed	N/S
-0.49 to -1.16m	Unit 1: Orange-brown pebbly sand	Mean grain size 1-2phi, very poorly sorted, negatively skewed, very leptokurtic.	N/S	N/S	Sedimentation possibly occurred within coastal beach environment, pro-glacial meltout or a result of hillslope deposition.	N/S

Table 11.2 Summary of proxy results for typecore GVJ43

the valley sides would have been transported to the Severn Estuary by a palaeo-river. The initiation of peat development between *c*. 7,320-7,220 Cal. yrs BP occurred during relatively stable, warm climatic conditions, favouring the development of alder carr with secondary lime and hazel scrub (Unit 6a). The strong alder pollen signal, combined with the abundance of wood fragments, supports the presence of alder-dominated woodland in the lower valley floor region. Unlike the enclosed basin landward of the ridge, a reduction in the local water table enabled the establishment of woodland on the valley floor during the early Holocene.

A rise in sea level relative to land elevation resulted in the onset of estuarine sedimentation between c. 6,870-6,670 Cal. yrs BP (Unit 7a). The influence of this transgressive marine phase can be seen in transect J-2 (Figure 9.8). Although possible marine sediments were found towards the base of some of the core profiles in transect 28 (Figure 9.9), their absence throughout the valley stratigraphy suggests these are not associated with the marine transgressions present in the region surrounding typecore GVJ43, and therefore may originate from an alternative environment of deposition. The stratigraphic profile indicates that marine inundation only reached *c*. ½ km inland from the site of typecore GVJ43. Estuarine conditions within the lowland valley region remained until *c*. 6,180-5,930 Cal. yrs BP, after which a reduction in the influence of marine conditions encouraged the re-establishment of a freshwater depositional environment. A short phase of peat accumulation occurred (Unit 6b), although the close proximity of the estuary restricted biogenic sedimentation to the upper salt marsh and prevented the return of woodland communities. The rate of peat deposition did not exceed that of relative sea-level rise, and estuarine sedimentation replaced the freshwater environment between 5,710-5,590 Cal. yrs BP (Unit 7b). Once again, as indicated by transect J-2 (Figure 9.8), the marine transgression only reached *c*. ½ km inland from the typecore site. The brief period of estuarine sedimentation lasted *c*. 250yrs, after which the final phase of peat accumulation replaced the marine conditions (Unit 6c). Although peat development continued for *c*. 1,500yrs, the influence and close proximity of the estuary (as indicated by the stratigraphy preserved seaward of the typecore site; Figure 9.8) prevented woodland from establishing on the valley floor.

Peat accumulation was finally halted by a continued rise in apparent sea level and estuarine conditions were re-established in the valley between *c*. 3,840-3,640 Cal. yrs BP (Unit 7c). The transgressive overlap is recorded throughout the valley stratigraphy seaward of the ridge and is indicative of an increase in the influence of sea level relative to land elevation (in contrast to the previous transgressive phases). The rate at which sea-level rise inundated the valley is unknown, due to the paucity of dating on the same upper peat-clay unit boundary further inland. Estuarine conditions remained in the lower valley region until medieval times, at which point lowland reclamation prevented the continued marine inundation of the valley from *c*. 11th Century onwards.

Whilst local variations in environmental conditions are clear from the interpretation of typecore GVJ43, changes in sedimentary processes in the Severn Estuary are indicated during the Holocene. Particle size analysis of the three minerogenic units in typecore GVJ43 indicates fining-upwards sequence from fine sands to clayey-silts. The variation in grain size could be explained through varying energy levels present within the palaeo-tidal frame. For example, the current velocities in an estuarine environment are greater closer to MSL than at HAT, and this enables varying grain sizes to be transported and deposited at different sites (Dyer, 1994). However, instead of deposition occurring at different heights within a tidal frame, the overall reduction in the grain size within the typecore could be in response to a reduction in energy levels or even a change in the sediment regime within the Severn Estuary as a whole. Diatom assemblages from the base of the core indicated that sand-rich sediments were related to mud-flat assemblages deposited lower down the tidal frame. However, with height through the typecore, similarly inferred mud-flat assemblages were found to be present within clayey-silt sediments, thus indicating that the grain size was not necessarily only controlled by tide-level. Therefore, if grain size is decreasing over time in the depositional archive, and changes in sedimentation in relation to the varying tidal frame are not the cause; a different control must be responsible.

Allen (2002a) stated that during the Ipswichian Interglacial (*c.* 125,000 yrs BP), when sea-levels were 5-10m higher than present due to the warmer climate, the larger width and depth of the Severn Estuary resulted in wave-dominated coastal processes occurring within the region (in comparison to the tidal-dominated processes present throughout much of the Severn Estuary today). This resulted in the deposition of coarse sands and pebbly-sands that typify the Ipswichian lithostratigraphy (Allen, 2001). However, a wave-dominated depositional environment could not be seen as a viable explanation for the deposition of coarser sediments within the valley archive after 7,320-7,220 Cal. yrs BP. This is because sea level at that time was lower than the present day (Lambeck, 1995; Peltier *et al*., 2002), which reduces the width and depth of the Severn Estuary relative to the Ipswichian period, and thus decreases the ability for wave generation to occur. The more likely reason for coarser sedimentation towards the base of the profile is that such sediments were available in abundance in the early-mid Holocene, but diminished as time passed. Fine silts and clays may dominate the modern-day depositional sequences because all the coarser sediments initially within the catchment system are preserved in sedimentary archives that accumulated in the past.

11.3 The Quaternary sedimentary evolution of the Gordano Valley

Figure 11.10 reconstructs the depositional environments of the Gordano Valley between the Mid Devensian glacial period and *c*. 3,000 Cal. yrs BP. The diagrams show long-axial cross-sections of the Gordano Valley, facing towards the northern valley side (and the Severn Estuary). Key stages in the evolution of the Gordano Valley are presented: a) the Mid-Devensian, b) the Devensian LGM, c) 16,000 Cal. yrs BP, d) 14,000 Cal. yrs BP, e) 7,000 Cal. yrs BP, and f) 3,000 Cal. yrs BP.

The majority of the sedimentary evolution of the Gordano Valley has occurred since the Devensian glacial. There is however evidence for direct glacial activity within the valley that may relate to the known pre-Cromerian glacial event that affected the surrounding region (see section 2.4). The onset of the Quaternary sedimentation within the valley therefore may to date to *c*. 700,000 yrs ago, when an ice mass deposited glacial tills in and around the valley. Since then, except for possible raised beach deposits at Weston-in-Gordano, a hiatus in sedimentation occurred, resulting in much of the evidence for glacial activity being removed by erosion. The timing of ridge development is unknown but, it has been assumed from the evidence available, a Devensian timescale is likely. Once the ridge had been emplaced through the progradation of alluvial fans from the north and south valley sides (Figure 11.10a & b), the headward region of the valley became enclosed and catchment runoff began to create a small isolated lake. By *c*. 16,000 Cal. yrs BP (Figure 11.10c), the enclosed lake had grown, accumulating fine-grained minerogenic sediments through catchment runoff. Continued minerogenic sedimentation, however, began to reduce the depth of the lake. By *c*. 14,000 Cal. yrs BP, the climatic amelioration of the Bølling/Allerød interstadial caused terrestrialisation of the lake to

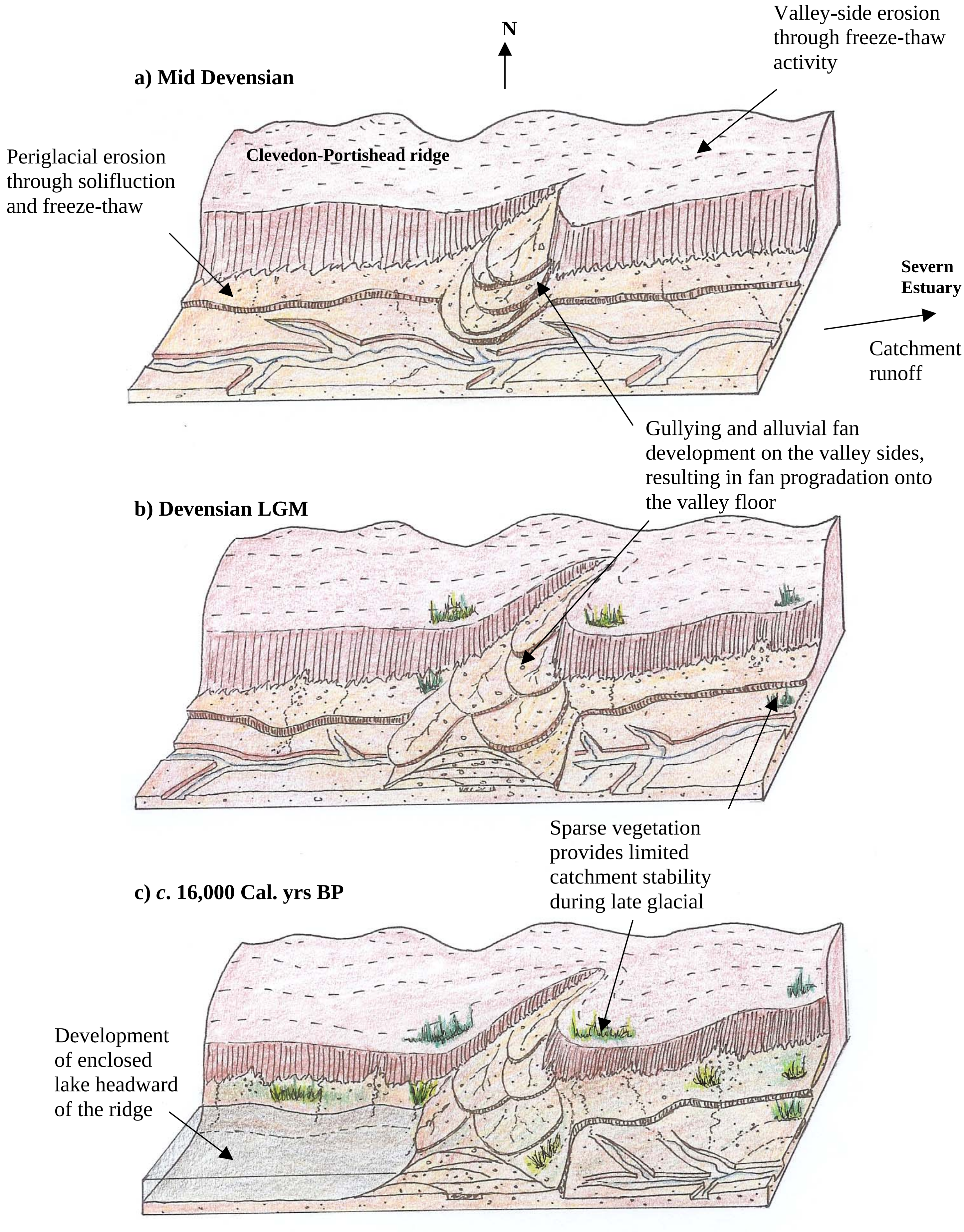


Figure 11.10 Palaeoenvironmental reconstructions of the Gordano Valley at various stages during the late Quaternary period (- - - - - = contours. Not to scale).

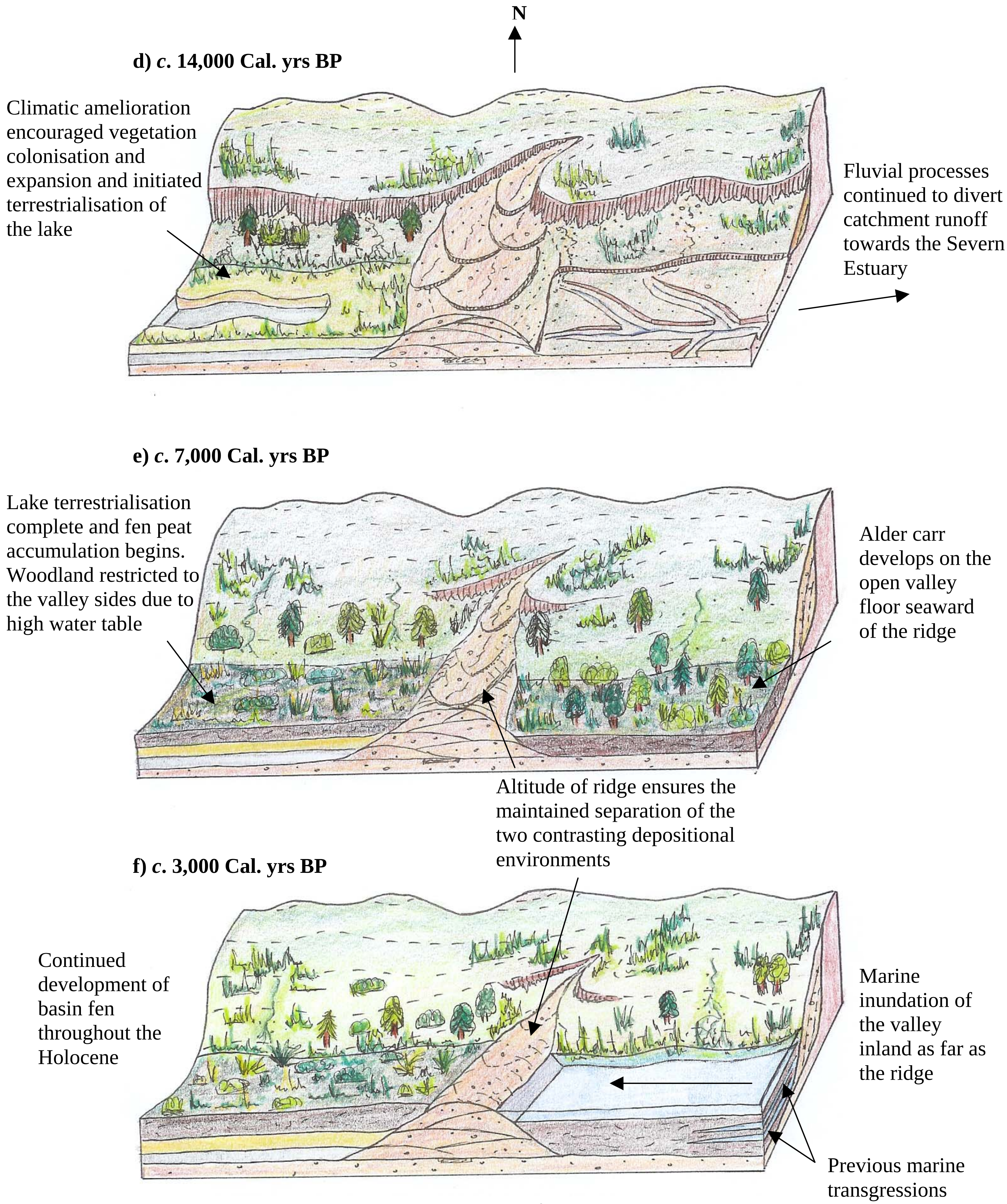


Figure 11.10 Palaeoenvironmental reconstructions of the Gordano Valley at various stages during the late Quaternary period (- - - - = contours. Not to scale).

occur (Figure 11.10d). By c. 9,500 Cal. yrs BP, a basin fen environment prevailed in the headward valley region.

Throughout the transition from the Devensian late glacial to the Holocene, seaward of the ridge, sedimentation occurred via hillslope processes. Catchment runoff probably continued to be diverted into the palaeo-Severn Estuary via fluvial processes. However, by c. 7,000 Cal. yrs BP, peat accumulation had begun within the lower valley and this supported an alder carr system (Figure 11.10e). In response to apparent sea-level rise throughout the Holocene, short-term marine transgressions occurred within the valley from *c*. 6,800-6,100 Cal yrs BP and *c*. 5,650-5,400 Cal. yrs BP. Continued organic sedimentation prevented these marine incursions from entering further than c. ½ km inland from the site of typecore GVJ43. Sea-level rise finally exceeded terrestrial sedimentation c. 3,700 Cal. yrs BP. As a result, marine inundation occurred up to the ridge (Figure 11.10f).

Chapter 12: Reconstruction of Holocene sea-level change in the Gordano Valley

12.1 Introduction

Sedimentary coring, multiproxy analyses and radiocarbon dating of key unit boundaries have revealed clear transgressive and regressive overlaps within the valley stratigraphy seaward of the ridge. Attempts to reconstruct past sea level have been made by determining SLIPs using the diatom-based sea-level transfer function, applied to typecore GVJ43. In addition, a qualitative reconstruction of sea-level change was also achieved through the diatom ecological classification scheme of Vos and deWolf (1993).

Changes in the tidal range during the Holocene are known to have occurred but could not be accurately quantified from the evidence available (see section 2.3.2). The inability to quantify autocompaction of the valley sediments has also restricted the accurate interpretation of past sea levels within the Gordano Valley over the last *c*. 7,000yrs. Particular difficulties have arisen during attempts to account for autocompaction which reduces the altitude of the sedimentary units preserved in the valley archive. A summary of the impact of autocompaction is first provided, before qualitative and quantitative reconstructions of palaeo sea level from typecore GVJ43 are evaluated.

12.2 The influence of autocompaction on sea-level reconstructions within the Gordano Valley

Autocompaction has been shown to influence stratigraphic archives through the vertical displacement of sedimentary boundaries from their original altitudes

(Kidson & Heyworth, 1973; Haslett *et al*., 1998; Crooks, 1999; Allen, 2000b, 2001). The difficulty in estimating accurately the impact of autocompaction has limited attempts to a) understand the processes and subsequent altitudinal impact of autocompaction and b) apply such knowledge to reassess the effect of autocompaction on sea-level reconstructions. For the Gordano Valley, autocompaction will affect sea-level reconstructions achieved through the application of the diatom transfer function. The *c*. 3m of estuarine overburden above the upper peat unit preserved in the Gordano Valley (see transect J-2; Figure 9.8) reduces the thickness of each underlying sedimentary unit, and consequently lowers each unit from its original altitude at the time of deposition. As interpretations of past sea level incorporate the present altitude of the sedimentary samples, the lowering of altitude caused by autocompaction suppresses any subsequent reconstruction (Allen, 2000b). Therefore, any attempts to reconstruct sea level which ignore autocompaction result in considerable underestimations of the position of true sea level.

Whilst autocompaction is commonly mentioned in palaeo sea-level studies, it is not always accounted for in the subsequent reconstruction. For example, Zong & Horton (1999) did not take into account the potential impact of autocompaction when using a diatom transfer function to reconstruct sea level from a sedimentary archive from Kentra Moss, west Scotland. Shennan (1986, p.156) admitted that “the majority of the materials dated…. for use as sea-level index points (were) not presently at the altitude at which they were deposited”, and a standardised method of estimating the impact of autocompaction was not provided when applying indicative meaning to SLIPs. Techniques to account for compaction have been developed, as summarised in section 2.3.2, but as of yet, a standardised and universal procedure is unavailable, resulting in those reconstructions in sea level which do assess autocompaction (commonly through different methodologies) providing potentially variable results.

The role of autocompaction in the vertical build-up of sedimentary sequences was assessed by Allen (2000b) via the application of growth models that attempt to account for all forcing factors that influence coastal deposition. However, this approach required an extensive and in-depth understanding of the geotechnical and sedimentary properties of all depositional units within a sedimentary sequence. Considering the complexity involved in the evaluation of autocompaction when only a *single* peat unit was present within the stratigraphic archive under analysis (Allen, 2000b), the presence of *three* interbedded peat units within the Gordano Valley archive further exacerbates the difficulty in accounting for autocompaction. It is likely that the influence of autocompaction on an interbedded sedimentary archive would be greatest towards the surface due to the combined effects of autocompaction on the underlying units (Figure 12.1). Insufficient sedimentological and geotechnical information was available to adopt such an approach within the deposits of the Gordano Valley.

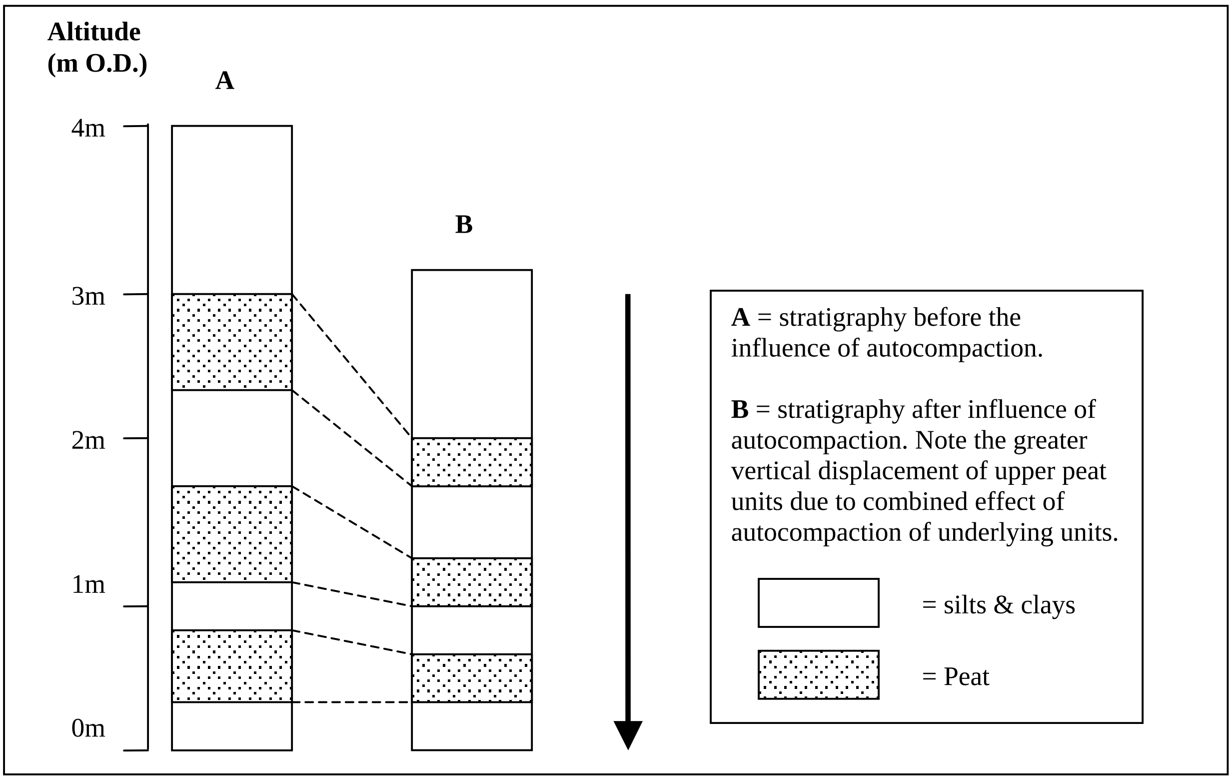


Figure 12.1 The influence of autocompaction on the Gordano Valley stratigraphic archive (not to scale).

An alternative technique was applied by Haslett *et al*. (1998) to coastal deposits in the Nyland Hill region of the Somerset Levels with success, and was summarised in section 2.3.2. The presence of an upper peat boundary on bedrock provided an uncompacted surface from which corrected altitudes could be applied to create reliable SLIPs. The known presence of the ridge within the Gordano Valley provided a potential surface from which similar inferences could be made with respect to the main peat unit within the valley stratigraphy. The lack of access to the ridge (imposed by the tip site and private land ownership) prevented the application of this technique to account for autocompaction. Access limitations also prevented stratigraphic surveys from being achieved along the valley sides where the peat horizons may have overlain bedrock.

The similarity in the ages of the upper peat-clay boundary in the Gordano Valley (3,840-3,640 Cal. yrs BP) and Nyland Hill (3,725-3,465 Cal. yrs BP; Haslett *et al*., 1998), combined with the similar levels of overburden thickness at both sites (*c*. 3metres) implies that, if both sites experienced marine transgressions at a similar time in the Late Holocene, sea level would have been at a similar altitude at both sites at the time. Therefore, the altitude of the uncompacted Gordano Valley peat would have also been at a similar altitude to the uncompacted peat of Nyland Hill. However, considering that the variation in tidal range between Avonmouth and Weston-Super-Mare (the two closest tidal stations to the Gordano Valley and Nyland Hill respectively) is 1.2m at present, and that tidal range variations would have been similar in the past, the position of MSL responsible for the development of the Gordano Valley peat-clay boundary would have been different to that of the Nyland Hill peat-clay boundary. Consequently, such an attempt to account for autocompaction also could not be applied to the Gordano Valley archive.

Shennan & Horton (2002) compiled all known SLIPs for the Bristol Channel region and this provided another opportunity to account for autocompaction within the Gordano Valley. This could be achieved by comparing the altitudes of basal index points from the regional data set with compaction susceptible index points from the study site (see section 2.3.2). If the ages of the compaction susceptible index points created by the diatom-based sea-level transfer function were between the mean weighted age of two basal peat index points from the Shennan & Horton (2002) data set, then linear regressions could be performed and the scale of autocompaction could be accounted for (Gehrels, 1999). However, the youngest basal peat index point from the data set was *c*. 6,149 Cal. yrs BP (see Table 2.4) and only one of the five diatom transfer function SLIPs from the typecore GVJ43 was older than this (see section 12.7). Therefore, only one diatom transfer function SLIP from the Gordano Valley archive was suitable for this compaction correction technique. As the influence of autocompaction is strongly dependent on the age of the unit in question, each index point would require older and younger basal peat index points to accurately infer vertical displacement. It could not be assumed that the amount of autocompaction experienced by this index point could be applied to the younger compaction susceptible index points. Until more basal peat index points are found within the Severn Estuary lowlands that are younger than those present in the Shennan & Horton (2002) data set, such a compaction correction technique will not be applicable to the Gordano Valley. Consequently, this autocompaction method could also not be utilised.

In summary, attempts to account for autocompaction within the Gordano Valley sedimentary archive were unsuccessful and it was not possible to quantify its impact on typecore GVJ43 during this study. Consequently, absolute sea-level curves relating to the Holocene evolution of the Gordano Valley could not be created due to the likely underestimation of sea level caused by autocompaction. Age-altitude plots for changes in palaeo-surface height could, however, be produced based on the creation of SLIPs using the diatom-based sea-level transfer function. Whilst the results will not provide an account of absolute sea-level change, they do allow for the spatial and temporal interpretation of past sea level. This contributes significantly to an area hitherto unresolved with respect to the evolution of the Gordano Valley.

12.3 Age-depth model of typecore GVJ43

Figure 12.2 is an age-depth model for typecore GVJ43. Table 12.1 summarises the stratigraphic boundary data utilised in Figure 12.2. It is assumed that constant rates of sedimentation have taken place during the development of each sedimentary unit (no erosive contacts were visible upon analysis of the typecore). Based on the age of the deposits alone, it is clear that variations in the rate of sedimentation have occurred during the development of the stratigraphic sequence. The rate of accumulation is higher during the development of the lower peat and lower minerogenic unit, indicated by the steep gradient on the age-depth model. This contrasts to the middle peat, middle minerogenic and upper peat units, all of which experienced lower rates of accumulation during their development. In addition, autocompaction will have affected the stratigraphic elevation and subsequent accumulation rates indicated by Figure 12.2. For example, the true rate of sedimentation for the lower peat unit would have been much higher than indicated by Figure 12.2, but autocompaction would have reduced the thickness of the unit, affecting the subsequent age-depth model.

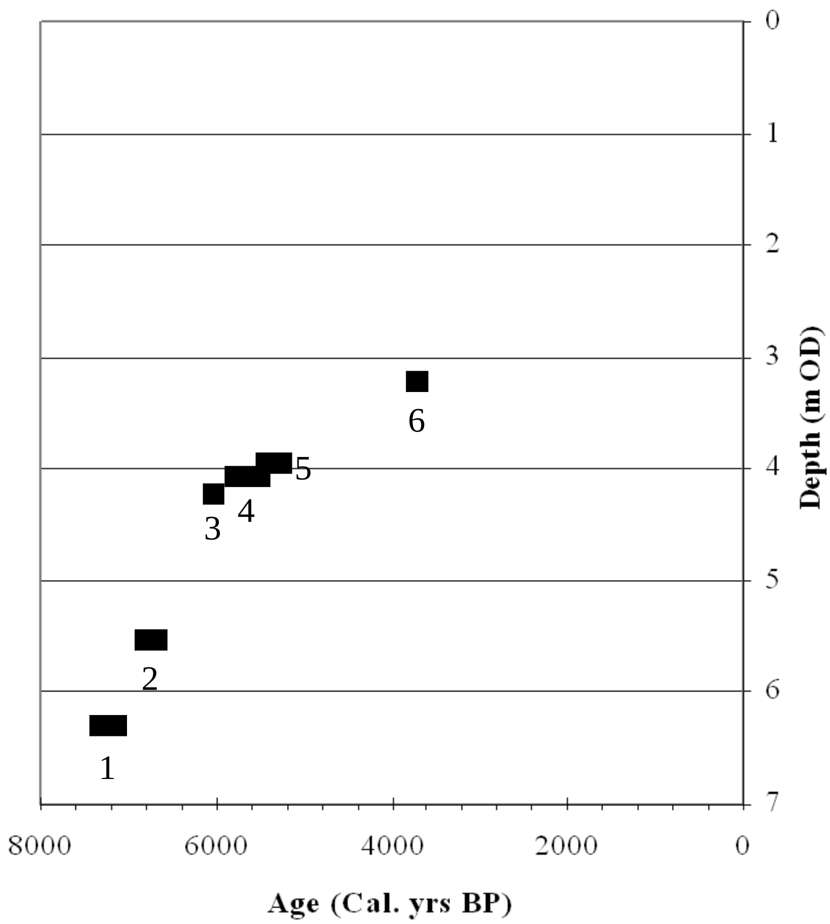


Figure 12.2 Age-depth model of typecore GVJ43 to indicate variations in accumulation rates. The size of each box reflects the age errors that occurred through radiocarbon dating. Numbers relate to each dated unit boundary (see Table 12.1 for reference).

Unit Boundary	Depth (m OD)	Altitude (m OD)	Age (Cal. yrs BP)
6	3.21	2.78	3840-3640
5	3.95	2.04	5470-5330
4	4.07	1.94	5710-5590
3	4.22	1.77	6180-5930
2	5.51	0.48	6870-6670
1	6.3	-0.31	7320-7220

Table 12.1 Summary of sedimentary boundaries used to create Figure 12.2

12.4 Interpretation of sea-level change through the application of Vos & deWolf (1993)

Figure 12.3 indicates the altitude of each sedimentary surface within typecore GVJ43, based on the interpretation of diatoms using Vos and deWolf (1993). The reconstruction estimates the position of the palaeo-ground surface relative to the level of the tide at the time of deposition, and provides a qualitative indicator of positive and negative sea-level tendencies. Consequently, no attempt has been made to apply a time scale to the reconstruction, as this would suggest that quantitative rates of sea-level change are (incorrectly) being interpreted from qualitative data. Although not explained directly by Vos and deWolf (1993) it has been assumed in this study that, within the supratidal area, the interpreted sedimentary environment at the highest altitude relative to MSL is “pools within the saltmarshes”, primarily due to the enhanced freshwater diatom influence, followed by “saltmarshes above MHW” and “saltmarshes around MHW”. The intertidal and subtidal areas follow with decreasing altitude. In Figure 12.3, higher palaeo-ground surfaces are indicated towards the left of the diagram and lower palaeo-ground surfaces lie to the right. The inferred sea-level trend generally follows the expected change in altitude, with higher depositional surfaces toward the peat units, while lower depositional surfaces are commonly present within the centre of the estuarine sandy-silts and clayey-silt units. The only diatom sample extracted from the lower peat unit (Unit 6a, at 0.11m O.D.) is strongly indicative of a mud-flat setting. This is unlikely due to the position of the sample in the centre of an alder carr peat sequence combined with the palaeoenvironmental interpretations in section 11.2.4 (b). Mud-flat sedimentation is indicated immediately after peat deposition ceased, when estuarine sandy-silts began to accumulate (Unit 7a). With increasing height through the profile, autochthonous input into the assemblages increased rapidly, suggesting that much more reliable interpretations of

				Intertidal	Supratidal		
Altitude (m O.D.)	LDAZ	Sediment		Mud-flats	around MHW	above MHW	pools in SM
3.04	10	clayey-silt					
2.99	10	clayey-silt					
2.94	10	clayey-silt					
2.89	10	clayey-silt					
2.84	10	clayey-silt					
2.82	10	clayey-silt					
2.79	10	clayey-silt					
2.77	9	peat					
2.73	9	peat					
2.68	9	peat					
2.63	9	peat					
2.53	9	peat					
2.52-2.12	8	PEAT	NO DIATOMS				
2.11	7	clayey-silt					
2.03	7	clayey-silt					
2.01	7	clayey-silt					
1.99	7	clayey-silt					
1.97	7	clayey-silt					
1.95	7	clayey-silt					
1.93	7	clayey-silt					
1.92-1.79	6	PEAT	NO DIATOMS				
1.78	5	sa-cla-silt					
1.76	5	sa-cla-silt					
1.69	4	sa-cla-silt					
1.61	4	sa-cla-silt					
1.47	4	sa-cla-silt					
1.3	4	sa-cla-silt					
1.25	4	sa-cla-silt					
1.23	4	sandy-silt					
1.03	3	sandy-silt					
0.94	3	sandy-silt					
0.87	3	sandy-silt					
0.73	3	sandy-silt					
0.65	2	sandy-silt					
0.63	2	sandy-silt					
0.58	2	sandy-silt					
0.53	2	sandy-silt					
0.51	2	sandy-silt					
0.49	2	sandy-silt					
0.47	2	sandy-silt					
0.46-0.12	1	PEAT	NO DIATOMS				
0.11		peat					
0.10 to -0.30		PEAT	NO DIATOMS				

Figure 12.3 Qualitative reconstruction of ground surface altitude relative to the palaeo-tidal frame from the diatom assemblages of Typecore GVJ43.

depositional environments could be attained. A negative sea-level tendency is then evident through the onset of peat accumulation (Unit 6b).

When clayey-silt sedimentation replaced peat deposition (Unit 7b), a marine transgression occurred, evident through the shift in diatom assemblages that are representative of deposition in salt-marsh pools to mud-flats respectively. This transgression was short-lived, after which the sea retreated again, or terrestrial sedimentation increased, causing accumulation of mud-flat and salt marsh above MHW and finally salt-marsh pool diatom assemblages before peat deposition was restarted (Unit 6c).

There was a final transgressive phase as marine influence gradually increased towards the transition from the upper freshwater peat unit into the overlying clayey-silt unit (Unit 7c). The diatom assemblages within the peat unit indicate deposition within salt-marsh pools towards the limits of marine influence, to be replaced by assemblages that developed further down the tidal frame as the sea transgressed into the valley. At 3.04m O.D., the diatom assemblage indicates deposition around MHW, after which point diatom preservation was too poor to infer further variations in the influence of relative sea level.

12.5 Interpretation of sea-level change via the diatom-based sea-level transfer function

12.5.1 The application of the diatom-based transfer function to the Gordano Valley archive

Chapter 7 summarised the construction of the diatom-based sea-level transfer function using the contemporary diatom assemblages from a Severn Estuary coastal transect. During the derivation of the transfer function, several regression techniques were assessed for validity.

The WA-Tol transfer function, using classic deshrinking and jack-knifed cross-validation, was developed from the contemporary coastal data set (see section 7.3). This was applied to the fossil diatom data from typecore GVJ43 to reconstruct variations in altitude (relative to MSL) during the timeframe represented by the core. To ensure a suitable overlap between the modern and fossil assemblages, the diatom samples where analysed via unconstrained correspondence analysis (CA). Figure 12.4 shows that the overlap between the fossil and contemporary data is generally good, confirming the ability to apply the transfer function to the fossil diatom assemblages. There is a small offset present within the diagram, with a group of fossil samples positioned to the left of the modern samples. This however does not indicate the incompatibility of the modern and fossil assemblages. It is primarily the result of the linearity of the sampling strategy for the modern data set, which resulted in the arrangement of plots on Figure 12.4 into an arch; this is known as the '*horseshoe*' effect. This problem is common when creating diagrams to visualise CA results. Such an effect is particularly pronounced when a long environmental gradient has been sampled, so that samples from one end are considerably different in composition to those at the other (Kovach, 1995). The overall proximity of modern and fossil diatom samples within the CCA diagram however, supports the use of the transfer function to investigate the relationship between the fossil diatom assemblages and inferred depositional altitude.

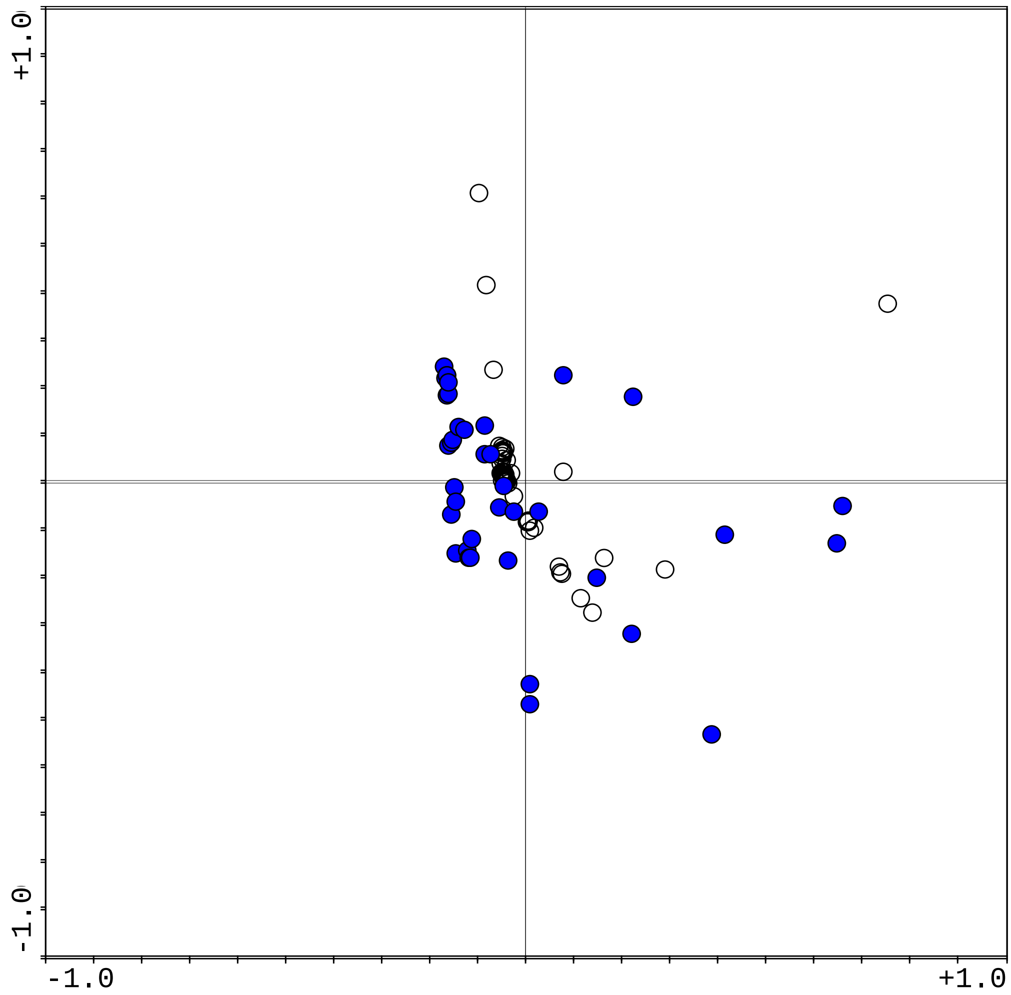
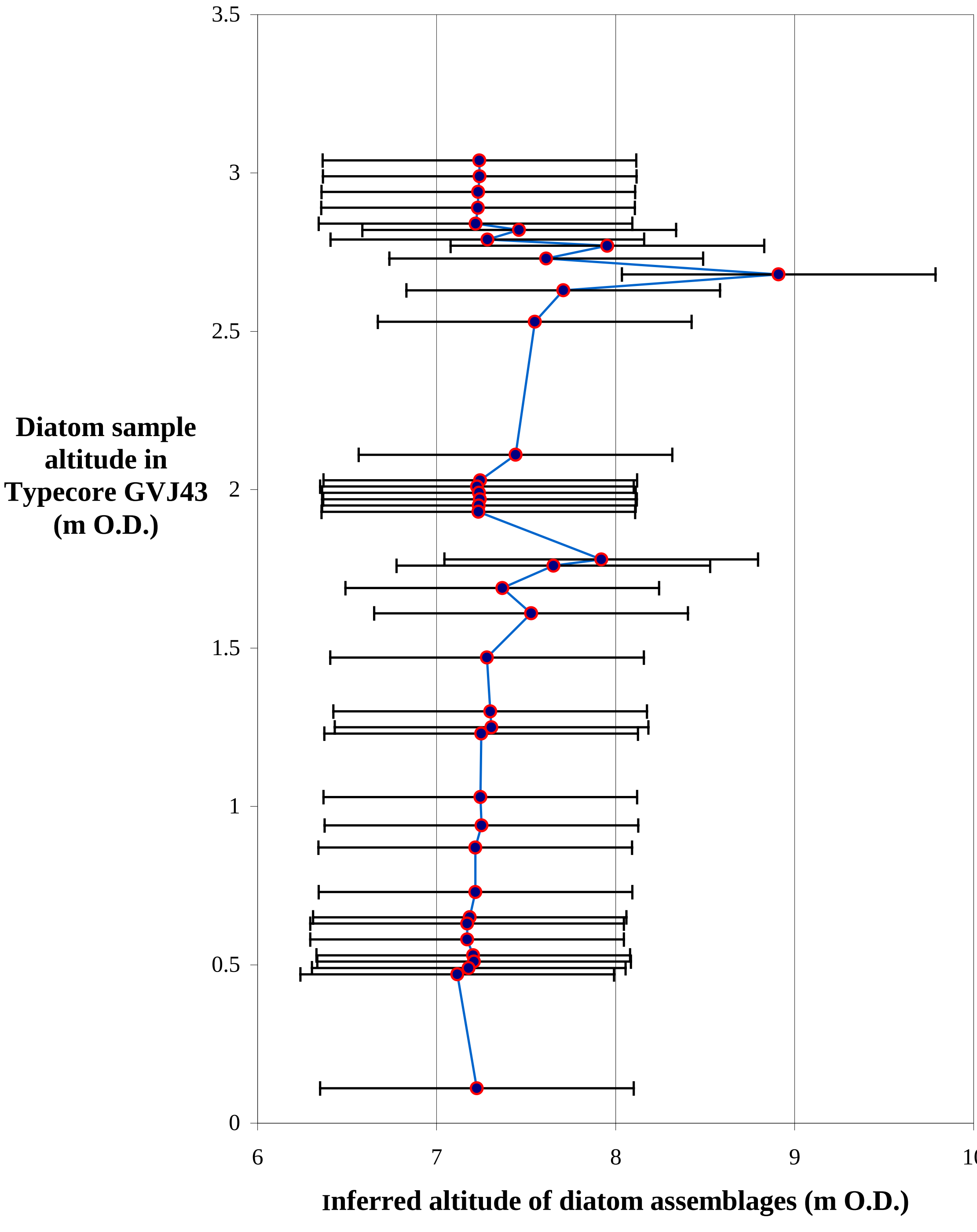


Figure 12.4 Correspondence analyses of modern diatom samples from the contemporary data set and fossil samples from the Gordano Valley. Empty circles represent modern samples; filled circles represent fossil samples. Note the arch-shaped distribution of the modern diatom samples, which is a common occurrence during CA analysis.

Species present within both data sets were used to quantitatively infer the position of the archive sample in relation to the tidal frame at the time of deposition. Figure 12.5 shows the predicted altitude that was inferred for each diatom assemblage analysed in the valley archive. Jack-knifed cross-validation in the computer programme C2 (Juggins, 2003), produced a margin of error for the data set (see section 7.3), which indicated the possible altitudinal range of error calculated during calibration analyses; this was 0.876m.



<u>Figure 12.5</u> Inferred depositional altitudes for each diatom assemblage from typecore GVJ43 analysed with the diatom-based sea-level transfer function.

The radiocarbon dates attained from the six peat boundaries provided a chronology for the altitudinal reconstructions. An equation was developed in order to calculate the position of MSL in relation to each diatom assemblage. By applying uniformitarianism, the position of MSL was found from each calibrated archive horizon by the equation:

$$MSL = (S_D - WAT_{inv}) + 0.4$$

where S_D is the sample depth of the archive diatom assemblage (m O.D.), WAT_{inv} is the predicted altitude inferred through calibration of that sample (m O.D.) and 0.4 is the position of MSL in relation to the modern-day tidal frame (m O.D.).

Figure 12.6 shows the diatom assemblages and stratigraphy from typecore GVJ43 combined with the inferred MSL produced during calibration. The six radiocarbon dates were taken from the peat horizons that were interbedded within the fine clayey silts under analysis. Therefore, estimations were required of the rates of minerogenic accumulation that occurred between each dated horizon. As a result, it was assumed that accumulation occurred at a constant rate and that there were no periods of erosion during the development of the sedimentary archive (refer to Figure 12.2). Figure 12.7 is a plot of age against the inferred altitude of MSL from the archived diatom assemblages during the time period covered by the typecore. Table 12.2 summarises the results of the application of the transfer function to typecore GVJ43 and subsequent position of relative sea level inferred from each diatom assemblage.

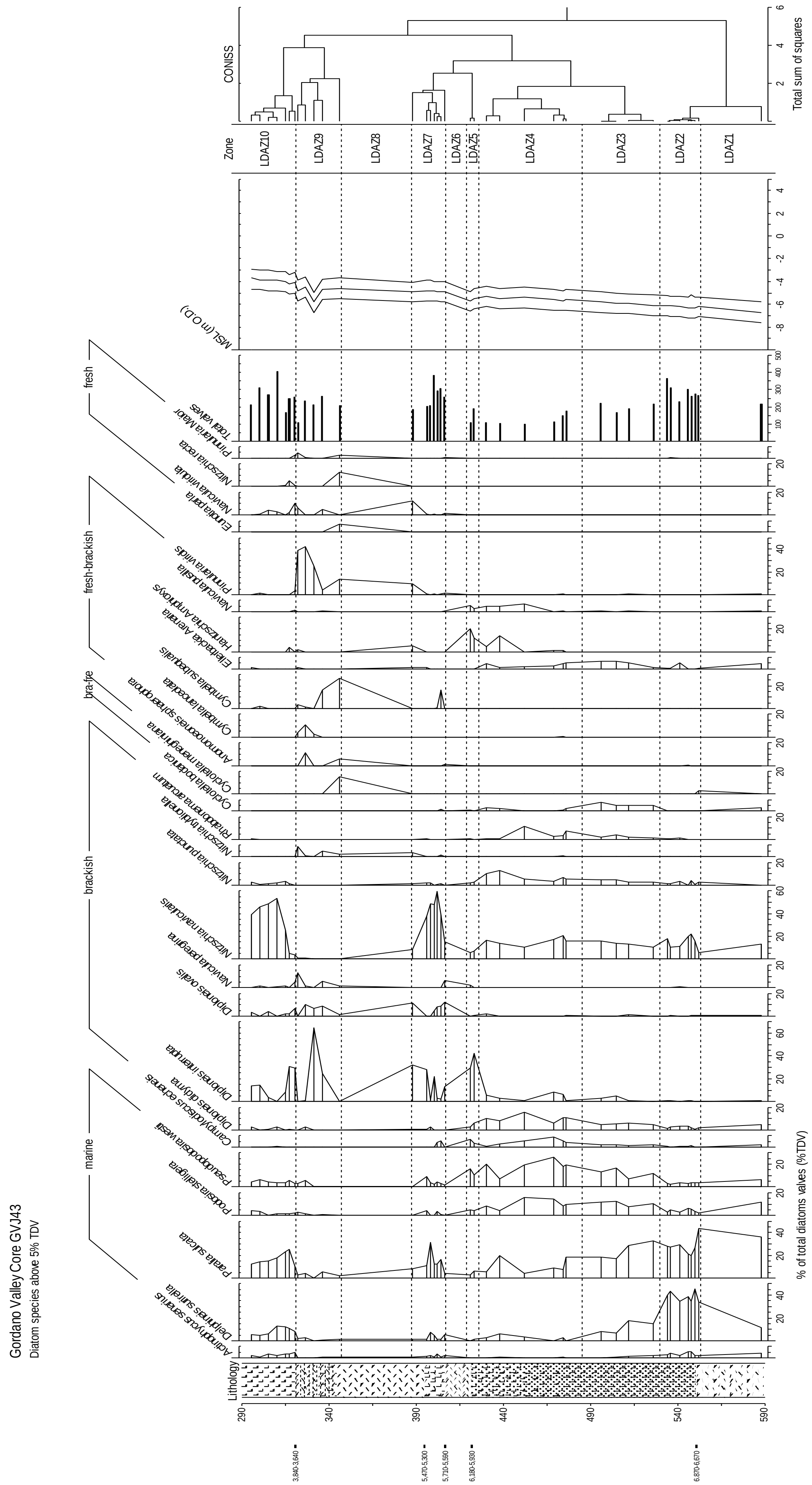


Figure 12.6 Diatom assemblages from Typecore GVJ43, combined with inferred depositional altitude from diatom-based sea-level transfer function

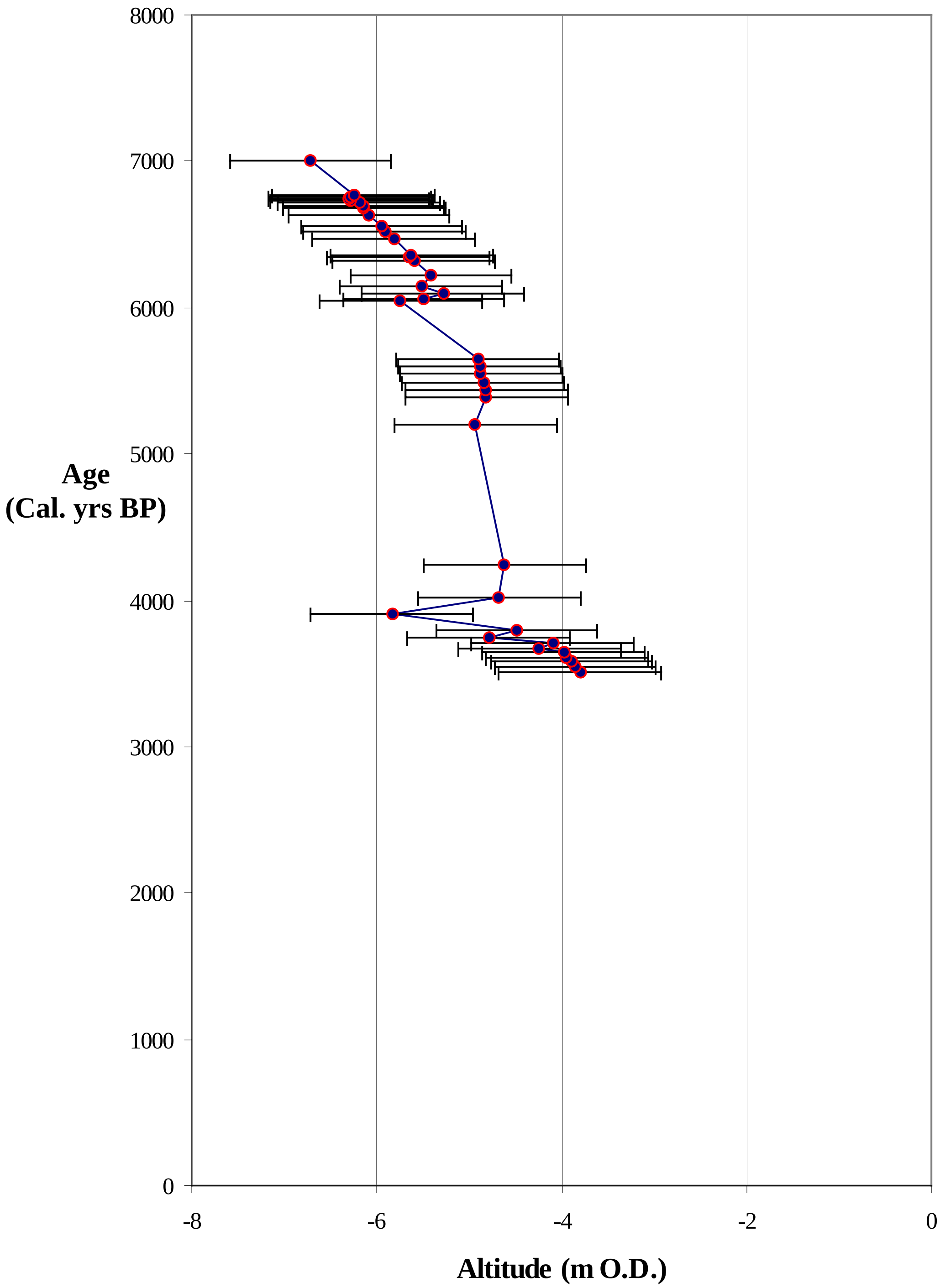


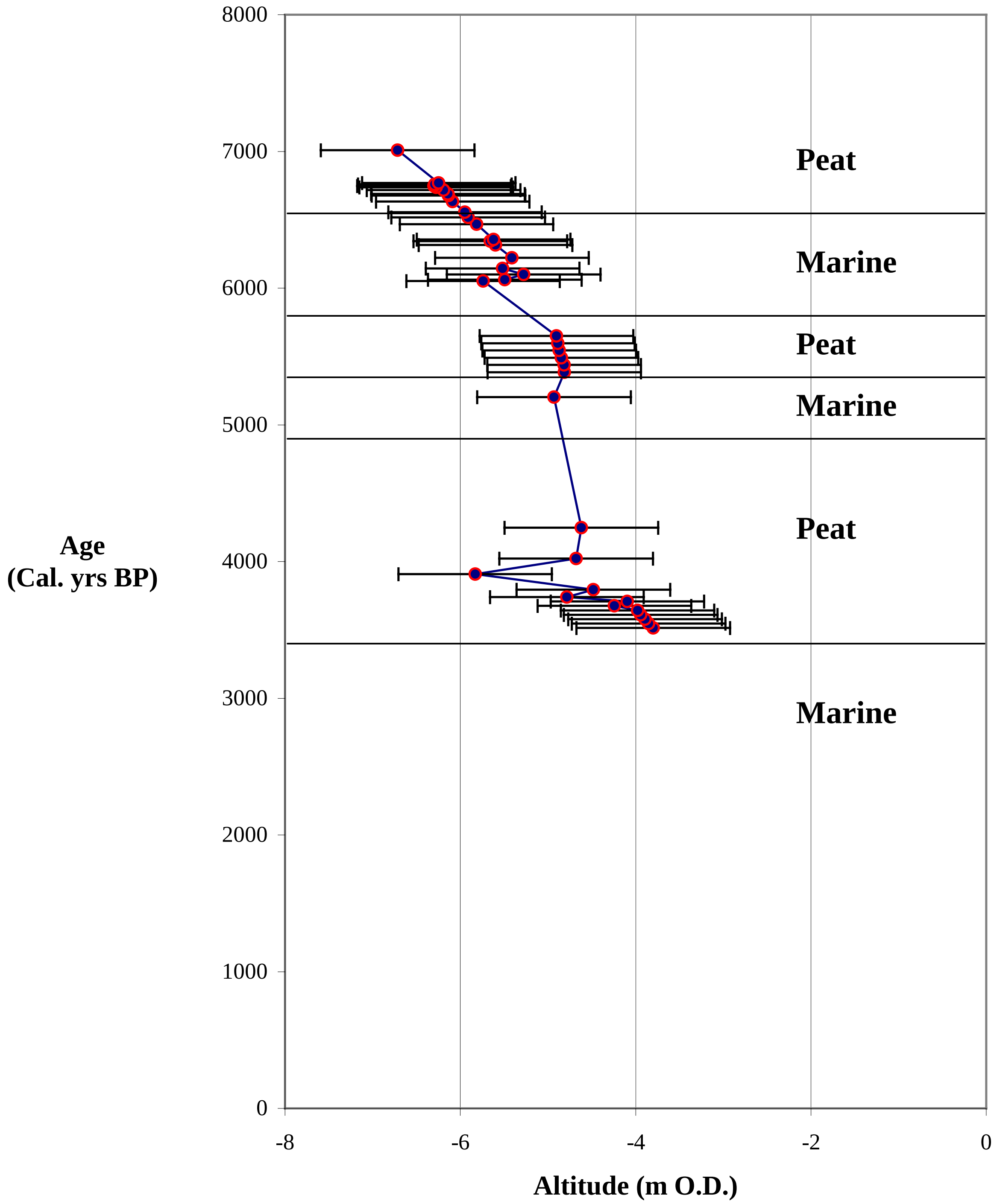
Figure 12.7 A plot of age against predicted altitude of MSL from the archived diatom assemblages.

Sample depth (m)	Altitude (m O.D.)	Sample age (Cal. yrs BP)	Inferred depositional altitude (m O.D.)	Lower tolerance	Upper tolerance	Inferred MSL (m O.D.)	Lower tolerance	Upper tolerance
2.95	3.04	3514	7.239	6.362	8.116	-3.799	-4.676	-2.922
3.00	2.99	3546	7.241	6.364	8.118	-3.851	-4.728	-2.974
3.05	2.94	3579	7.233	6.356	8.110	-3.893	-4.770	-3.016
3.10	2.89	3611	7.232	6.355	8.109	-3.942	-4.819	-3.065
3.15	2.84	3643	7.218	6.341	8.095	-3.978	-4.855	-3.101
3.17	2.82	3676	7.461	6.584	8.338	-4.241	-5.118	-3.364
3.20	2.79	3708	7.284	6.407	8.161	-4.094	-4.971	-3.217
3.22	2.77	3740	7.954	7.077	8.831	-4.784	-5.661	-3.907
3.26	2.73	3794	7.612	6.735	8.489	-4.482	-5.359	-3.605
3.31	2.68	3908	8.911	8.034	9.788	-5.831	-6.708	-4.954
3.36	2.63	4021	7.707	6.830	8.584	-4.677	-5.554	-3.800
3.46	2.53	4249	7.549	6.672	8.426	-4.619	-5.496	-3.742
3.88	2.11	5203	7.442	6.565	8.319	-4.932	-5.809	-4.055
3.96	2.03	5385	7.244	6.367	8.121	-4.814	-5.691	-3.937
3.98	2.01	5438	7.226	6.349	8.103	-4.816	-5.693	-3.939
4.00	1.99	5491	7.237	6.360	8.114	-4.847	-5.724	-3.970
4.02	1.97	5544	7.242	6.365	8.119	-4.872	-5.749	-3.995
4.04	1.95	5597	7.236	6.359	8.113	-4.886	-5.763	-4.009
4.06	1.93	5650	7.234	6.357	8.111	-4.904	-5.781	-4.027
4.21	1.78	6052	7.920	7.043	8.797	-5.740	-6.617	-4.863
4.23	1.76	6061	7.653	6.776	8.530	-5.493	-6.370	-4.616
4.30	1.69	6100	7.367	6.491	8.244	-5.277	-6.154	-4.401
4.38	1.61	6145	7.528	6.651	8.405	-5.518	-6.395	-4.641
4.52	1.47	6222	7.282	6.405	8.159	-5.412	-6.289	-4.535
4.69	1.3	6317	7.299	6.423	8.176	-5.599	-6.476	-4.723
4.74	1.25	6344	7.307	6.430	8.184	-5.657	-6.534	-4.780
4.76	1.23	6356	7.250	6.373	8.127	-5.620	-6.497	-4.743
4.96	1.03	6467	7.245	6.368	8.122	-5.815	-6.692	-4.938
5.05	0.94	6517	7.251	6.374	8.128	-5.911	-6.788	-5.034
5.12	0.87	6555	7.216	6.339	8.093	-5.946	-6.823	-5.069
5.26	0.73	6633	7.217	6.340	8.094	-6.087	-6.964	-5.210
5.34	0.65	6678	7.185	6.308	8.062	-6.135	-7.012	-5.258
5.36	0.63	6689	7.171	6.294	8.048	-6.141	-7.018	-5.264
5.41	0.58	6716	7.171	6.294	8.048	-6.191	-7.068	-5.314
5.46	0.53	6737	7.204	6.327	8.081	-6.274	-7.151	-5.397
5.48	0.51	6748	7.209	6.332	8.086	-6.299	-7.176	-5.422
5.50	0.49	6759	7.180	6.303	8.057	-6.290	-7.167	-5.413
5.52	0.47	6770	7.116	6.239	7.993	-6.246	-7.123	-5.369
5.88	0.11	7008	7.225	6.348	8.102	-6.715	-7.592	-5.838

Table 12.2 Summary of the application of the transfer function to typecore GVJ43 and the subsequent inferred position of relative sea level.

12.5.2 Analysis of the transfer function results

By applying the known environmental tolerances of contemporary diatom assemblages to those preserved in the sedimentary archive, changes in relative sea level were indicated that related well to stratigraphy, supporting the theory that uniformitarianism can be applied to such reconstruction techniques. At the simplest level of interpretation, diatom assemblages preserved in the freshwater peat sequences indicated the position of relative sea level (in relation to the sample altitude) as being lower than that of assemblages preserved in marine sediments. For example, the diatom assemblage extracted below the boundary between the lower minerogenic unit (Unit 7a) and middle peat unit (Unit 6b, 1.76m O.D.) was calculated as being positioned at an altitude of *c.* 7.65m O.D. at the time of deposition, which indicates that relative sea-level was at *c*. –5.49m O.D. (taking into account the sample altitude and the position of relative sea level in relation to the contemporary tidal frame). In contrast, the next sample extracted from the core profile within the overlying peat unit (1.78m O.D.) contained diatom assemblages that were calculated to have been deposited at *c.* 7.92m O.D., positioning relative sea level at *c*. –5.74m O.D. Therefore, a drop in relative sea-level of almost 0.25 metres at the transition from estuarine to freshwater sedimentation was estimated by the calibration of species assemblages between the contemporary diatom data set and the sedimentary archive. This trend continues throughout the sea-level reconstruction, with higher relative sea levels in relation to estuarine sedimentation and lower relative sea levels during organic accumulation. Figure 12.8 reproduces the age-altitude plot created from the transfer function and includes a breakdown of the position of freshwater (peat) and marine sedimentation, to clarify the differences in reconstructed relative sea level between the different sediment types.



<u>Figure 12.8</u> A plot of age against predicted depositional altitude of the archived diatom assemblages.

Sea-level trends are also present within the reconstructions. The most distinct trend relates to the position of relative sea level during the development of the lower minerogenic layer (Unit 7a) which overlies the lower peat (Unit 6a). This transition from freshwater peat to marine sedimentation occurred *c*. 6,870-6,670 Cal. yrs BP. There is a clear increase in relative sea level with height through the Unit 7a prior to the initiation of the second phase of peat development (Unit 6b) *c*. 6,180-5,930 Cal. yrs BP (relative sea-level rises from *c*. –6.24m to –5.49m O.D.). Considering the uniform rate at which relative sea level is calculated to have changed during the deposition of the lower minerogenic unit, estuarine sedimentation kept pace with sea-level rise during the unit's evolution. This is supported by the age-dept model of typecore GVJ43 (Figure 12.2), in which the rate of accumulation is highest during the deposition of Unit 7a. However, the position of relative sea level declined towards the upper unit boundary prior to the onset of organic sedimentation. This was derived from the increased influence of freshwater species with height through Unit 7a. The transfer function predicted that these diatom assemblages would have accumulated at altitudes higher than the underlying assemblages within the unit, thus indicating a decline in relative sea level with height. The cause of the change in altitude predicted by the transfer function may be attributable to a real change in the rate of sea-level rise or, alternatively, a change in the rate of sedimentation at the site. By taking into consideration the age-depth model (Figure 12.2), there is a distinct reduction in the accumulation rates within the Gordano Valley at *c*. 6,180-5,930 Cal. yrs BP, which continues for *c*. 700 yrs. Consequently, enhanced terrestrial sedimentation is unlikely to have caused the shift from estuarine to peat deposition. The evidence therefore suggests that an actual reduction in the rate of sea-level rise encouraged the establishment of freshwater sedimentation and peat expansion within the lowlands at this time.

A similar sea-level trend is present within the middle minerogenic unit (Unit 7b) which, although subtle, indicates a gradual increase in relative sea level before freshwater peat accumulation returns (relative sea level increased from *c*. -4.9 m to -4.8m O.D.). Although diatom assemblages were low in number within the upper peat unit (Unit 6c), the assemblages towards the lower unit boundary predicted a decline in relative sea level (by –0.2m) in relation to the onset of peat accumulation. With height through Unit 6c, diatom assemblages do not follow the trends of continued relative sea-level rise recognised within the minerogenic units. Reconstructed relative sea level fluctuates throughout the unit, with an overall inferred rise in sea level prior to the return of minerogenic sedimentation (Unit 7c). The transfer function indicated that a rise in relative sea level of only *c*. 0.15m occurred during peat development over *c*. 1,600yrs, whilst the overlying estuarine sediments infer a rise in relative sea level of *c*. 1m over a period of *c*. 250yrs.

Variations in relative sea level reconstructed from the diatom transfer function correlate well with the typecore stratigraphy and the prevailing environmental conditions at the site during its evolution (section 11.2.4 (b)). A fall in relative sea level is predicted by the transfer function at the transition from estuarine to peat deposition. From the diatom assemblages preserved in the peat units, gradual rises in relative sea level are inferred before marine sedimentation replaces freshwater deposition. Therefore, the application of the contemporary diatom species from the Severn Estuary, to the diatom assemblages within the sedimentary archive of the Gordano Valley, was successful. The fact that shifts in diatom assemblages within the typecore profile indicated changes in relative sea level which a) coincide with changes in stratigraphy and b) correlated with known sea-level change interpreted through multi-proxy analysis of the core, indicates that the diatom species on the contemporary coastal transect require environmental conditions similar to those that were present during the earlier Holocene.

The reconstruction of age-altitude plots of MSL through the application of the transfer function supports the evidence for an overall rise in MSL throughout the time period covered by the diatom assemblages. Whilst a shift in sedimentation from estuarine silts to terrestrial peat may indicate that a drop in relative sea level has occurred, it is likely that this is in fact in response to localised factors such as enhanced terrestrial sedimentation and a reduction in the rate of sea-level rise. This is explained in section 12.7.

12.6 Limitations within the reconstruction of sea level using the diatom-based sea-level transfer function

12.6.1 Autocompaction

Autocompaction has already been highlighted as a major limitation in sea-level reconstructions derived from sedimentary analysis (section 12.2). Autocompaction will lower the altitude of each sediment boundary and diatom sample analysed in typecore GVJ43, and the predicted position of relative sea level of that sample will consequently be underestimated. Therefore, the results of the study could not be interpreted as a true sea-level reconstruction. However, although the altitude of reconstructed relative sea level is likely to be vertically lowered, the transfer function provides a clear chronological interpretation of the trend in changing sea level over time. Furthermore, the low compactability of minerogenic sediments (Allen, 2000b) means that the rates of changing sea level in the sandy and clayey-silt units (utilised by the transfer function due to the abundance of diatom assemblages) are more reliable. Consequently, whilst it is acknowledged that the vertical displacement of the sedimentary archive has prevented a true reconstruction of sea level, the overall *trends* in sea level, especially within the minerogenic units, can be analysed with confidence. If future studies could account for autocompaction, their application to the late Quaternary archive from the Gordano Valley would provide a detailed record of sea-level history in the region.

12.6.2 Palaeo-tidal range

Variations in the tidal range of the Severn Estuary must also be considered when attempting to interpret past sea level through the diatom-based sea-level transfer function. In this study, it was necessary to assume that the past tidal range was similar to that of the contemporary range in order to infer the position of MSL relative to the typecore stratigraphy. Whether there have been any significant variations in the tidal range of the Severn Estuary during the Holocene period is unclear and, as with autocompaction, there is limited evidence to support or refute this. As a result, the potential exists to over- or underestimate the position of MSL if an incorrect tidal frame is applied to each diatom assemblage.

The rise in relative sea level throughout the Holocene means that it is reasonable to assume that, if any change in tidal range was to occur, it would be an increase as sea levels increased over time (caused by the increase in width and depth of the Severn Estuary; Allen 2002a). Research by Austin (1991), however, suggested that a *larger* tidal range was present within the Bristol Channel *c*. 7,000-9,000 Cal. yrs BP. This study modelled Holocene tides for the whole of northwest Europe based on variations in continental shelf edge boundaries, and consequently detailed bathymetric studies of the Severn Estuary were not included within the palaeo-tidal model. Without taking into account such localised variations in basin width and configuration, the accuracy of the tidal predictions must be questioned. This assumption is supported by research into tidal amplification in the Bay of Fundy, Canada (Gehrels *et al*., 1995). Site-specific bathymetric adjustments were incorporated into the tide model, and the predicted tidal range is shown to have increased during the Holocene. The study suggests that only *c*. 60% of the site's current tidal range was present at *c*. 7,000 Cal. yrs BP. The present-day tidal regime was only achieved by *c.* 2,000 Cal. yrs BP. Shennan & Horton (2002) have also applied a tidal adjustment model to the sea-level reconstructions from the Humber Estuary. This has consequently improved the similarity between glacio-isostatic model predictions and observed SLIPs. A similar tide model needs to be applied to the Severn Estuary in order to accurately account for palaeo-tidal variations during the Holocene. Until such a study has been undertaken, it can only be suggested that the tidal range has varied during the Holocene, and no quantitative assessment of this change can be applied to subsequent sea-level reconstructions. It was therefore not possible during this study to recreate the palaeo-tidal conditions of the Severn Estuary in order to understand the scale of the change in tidal influence in the past. As a result, as with most reconstructions of sea level in the UK, it is common for the contemporary tidal parameters to be applied to SLIPs (Shennan, 1986).

12.6.3 Contemporary and fossil diatom assemblages

Diatom valves are light-weight and they are commonly transported considerable distances away from their original source (Spencer, 1996, Zong & Horton, 1999). Diatoms can also be transported by the wind creating the potential for unrepresentative contemporary and fossil assemblages (containing diatoms that are *ex-situ*). The isolated nature of the Gordano Valley however, does minimise this risk when compared to an exposed system such as the surrounding estuary. The valley sides restrict the influence of coastal winds and would limit any diatom transportation to local environs. Preferential diatom preservation can also be a limiting factor, with the less robust and weakly silicified forms experiencing dissolution, consequently biasing the diatom assemblages in favour of the stronger silicified forms (Lowe & Walker, 1997). Another problem that has been observed within diatoms is the influence of local water tables on the frustules (Mayer *et al.*, 1991). In an environment that experiences continual water table fluctuations (brought on especially as a result of the seasonally varying temperature regimes), sediments will be subjected to repeatedly changing redox levels. Such action results in the accumulation of iron oxides which initiate silicate dissolution within the sediment (Mayer *et al.*, 1991). Consequently, much of the diatom assemblages within the upper and lower limits of the present day water table would be dissolved and diffused away into the porewater, and this proved to be the case in the upper *c*. 3m of the Clapton Moor sequence.

The relationship between the contemporary and fossil diatom assemblages must be also considered. Diatom species were abundant in both data sets and this enabled the creation of the diatom transfer function and the assessment of sea-level change during the valley's evolution. However, certain species that were abundant in the contemporary assemblages were found in very low frequencies in the fossil deposits, and vice versa. Examples include the relative dominance of *Diploneis interrupta* in the typecore assemblages, which was present in abundances <5% TDV (and thus statistically insignificant in the subsequent quantitative reconstructions) along the contemporary coastal transect. *Pseudopodosira westii, Diploneis ovalis* and *Cymbella subaequalis* also followed this trend. In contrast, *Gyrosigma spencerii, Gyrosigma wansbeckii, Navicula fasciculata* and *Rhaphoneis amphiceros* were all found in varying abundances in the contemporary assemblages, but were not present above 5% TDV within the typecore. Similar problems regarding the variation in diatom assemblages have been experienced in other research. Zong (1997) highlighted the variability of species between the two data sets, and noted a similar problem with the influence of *Diploneis interrupta* when assessing sea-level change in Roudsea Marsh, northwest England. Zong & Horton (1999) also found that species including *Diploneis incurvata*, *Diploneis smithii* and *Diploneis Didyma* were present in the sedimentary archive of Kentra Moss, west Scotland, but absent from the contemporary data set. It is therefore a common occurrence for the modern and archived deposits to yield different assemblages. It has been suggested that such variations may be the result of changes in sediment type, water salinity and acidity between the ancient and modern depositional environments (Zong, 1997).

The variability between modern and archived deposits can result in certain species dominating samples from one data set but, because they are absent from the second data set, being excluded from the final analyses. This can impact upon those species that are found in both the modern and archived deposits, by potentially decreasing their percentages and thus decreasing their eventual weighting through regression analysis. For example, if a species such as *Diploneis interrupta* contributed *c*. 40% TDV in a diatom assemblage, but was only found in one data set, those species present in the remaining *c*. 60% TDV (and present in both modern and archived data sets) would consequently be undervalued due to abundance of *Diploneis interrupta*. However, whilst weighting of species may be affected, the Gaussian model will not (see section 4.2). Diatom species will still have environmental tolerances beyond which they cannot survive and therefore, even if frequencies of individual species are affected by partial representation in the data sets, their presence or absence in response to changes in the environment (in this case altitude) will not be affected. Therefore, those species that are present at >5% TDV in both the contemporary coastal data set and the Gordano Valley archive provide reliable environmental information regarding the variation of altitude (and thus the position of relative sea level at this location). The application of such a technique is also supported by the interpretation of past sea level using the ecological classification of Vos and deWolf (1993).

12.7 Summary of sea-level reconstruction

The two methodologies described above recovered a strong sea-level signal from the sedimentary archive of the Gordano Valley. Whilst each method carried advantages and disadvantages, the combination of the two sea-level interpretations was mutually beneficial. The techniques indicate that relative sea level has risen throughout the Holocene. Contrasting rates of relative sea-level rise during this period, combined with the variation in the rate of sedimentation within the study site, is likely to be responsible for three phases of relative sea-level rise being recorded in the sedimentary archive over the last *c*. 7,300 Cal. yrs (reflected through estuarine sedimentation). These episodes of rising sea levels are separated by periods during which, as discovered by Allen (1990), the slower rate of relative sea-level rise enabled salt-marsh growth to emerge above highest astronomical tide (HAT) due to the constant supply of organic sediments. Consequently, freshwater peat accumulation occurred.

The qualitative interpretation obtained through Vos & deWolf (1993) indicated that the diatom assemblages varied accordingly as the influence of freshwater and marine conditions changed over time, thus reflecting fluctuations in land elevation in response to the influence of sea level. Whilst the ecological classification scheme of Vos & deWolf (1993) only provides a qualitative interpretation of sea level, the diatom-based sea-level transfer function provides a quantitative sea-level reconstruction through its ability to infer change throughout sedimentary units (diatoms permitting). Although margins of error are present which relate to the predicted position of relative sea level for each diatom assemblage, the quantitative reconstruction supports the evidence for sea-level rise within the typecore region.

Figure 12.9 is a reproduction of the predicted altitude of MSL derived from the transfer function. The majority of the transfer function's altitudinal predictions cannot be classified as 'real' SLIPs due to the absence of direct dating on each sediment sample. As only six radiocarbon dates were available for typecore GVJ43, the majority of the diatom samples required estimations of age to be calculated (see section 12.5.1). However, when both radiocarbon dating and quantitative diatom analysis were undertaken on the same sample, all the characteristics required to classify a sample as a SLIP were achieved: location, age, altitude, indicative meaning and tendency (see section 2.3.1). Consequently, five 'real' SLIPs were created using the diatom-based sea-level transfer function. These SLIPs are summarised in Table 12.3 and shown in green on Figure 12.9.

SLIP	Depth (m)	Altitude (m OD)	Age (Cal. yrs BP)	Predicted MSL (m OD)	+/- (m)	Tendency
1	3.22	2.77	3740	-4.784	0.876	positive
2	3.96	2.03	5385	-4.814	0.876	negative
3	4.06	1.93	5650	-4.904	0.876	positive
4	4.21	1.78	6052	-5.540	0.876	negative
5	5.52	0.47	6770	-6.246	0.876	positive

Table 12.3 Summary of the five 'real' SLIPs created using the diatom-based sea-level transfer function

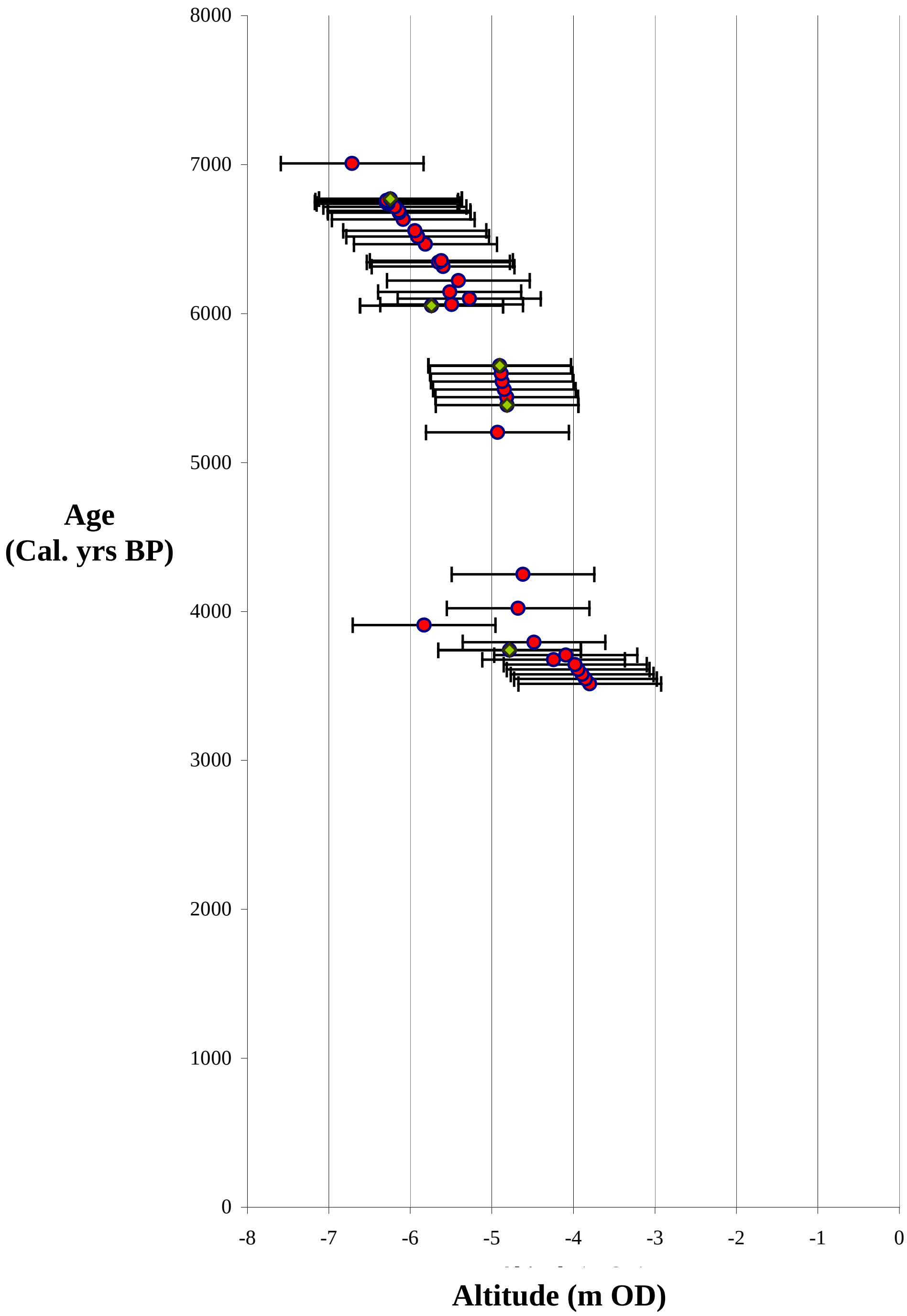


Figure 12.9 Age-altitude plot of MSL created by the diatom-based sea-level transfer function. Note that the 'real' SLIPs are shown in green. Refer to Table 12.3

The first period of Holocene marine inundation within the Gordano Valley occurred at the latest *c*. 6,700 Cal. yrs BP, evident through estuarine sediments (Unit 7a) overlying the basal peat (Unit 6a). Although poor diatom preservation renders it difficult to establish whether marine conditions were present at the typecore site prior to peat accumulation, the influence of sea level is limited between c. 7,300 and 6,700 Cal. yrs BP. After this period of terrestrial peat deposition, a rise in relative sea level is suggested by the transfer function between *c.* 6,700 and 6,000 Cal. yrs BP, indicating an overall increase in marine influence from –6.24 to –5.74m O.D.

The diatom assemblages within the lower minerogenic unit (Unit 7a) indicate a shift in deposition from mud-flats (in closer proximity to MSL) to deposition on saltmarshes above MHW (closer to HAT) towards the upper unit boundary. The evidence therefore suggests that an initial rise in sea level occurred at *c*. 6,700 Cal. yrs BP, which initiated mud-flat sedimentation soon after the transition from peat to minerogenic deposition. This marine inundation is believed to have transgressed *c*. ½ km inland from the typecore site, indicated by the lack of similar minerogenic deposits within the valley archive further inland.

The enhanced freshwater input (which caused the diatom assemblages to indicate a drop in relative sea-level) eventually resulted in recommencement of peat accumulation at *c*. 6,000 Cal. yrs BP (Unit 6b). Peat development lasted until *c.* 5,700 Cal. yrs BP, after which a re-establishment of marine conditions then occurred. The transfer function calculated that a rise in relative sea level of –5.74 to –4.9 m O.D. occurred over the *c*. 300yr period.

Sea level fluctuated marginally within the thin middle minerogenic unit (Unit 7b), with an overall rise indicated by the transfer function from –4.9 to –4.8m O.D. from *c*. 5,700 to 5,400 Cal. yrs BP. The valley's sedimentary archive also suggests that this period of marine sedimentation occurred in response to marine inundation of the valley reaching *c*. ½ km inland from the typecore site. The final phase of peat accumulation began *c*. 5,400 Cal. yrs BP (Unit 6c), at which point the transfer function infers that a drop in relative sea level of–0.12m O.D occurred during the transition from estuarine to peat accumulation. Fen peat continues to develop for *c.* 1,600 Cal. yrs, during which time the transfer function indicates a fluctuating but overall increase in relative sea level from –4.93 to –4.78m O.D. The diatom assemblages support a gradational rise in sea level with increasing abundances of marine and marine brackish species with height. When estuarine sedimentation returns at *c.* 3,700 Cal. yrs BP (Unit 7c), the transfer function calculates relative sea level at –4.09m O.D. Relative sea level then rises to –3.79m O.D. within the lower sediments of the upper minerogenic unit, above which diatoms were not preserved, thus limiting the ability to infer changing sea levels through the application of the transfer function or the ecological classification scheme of Vos & deWolf (1993). Estuarine sedimentation in response to the final rise in relative sea level affected the whole of the lower valley region seaward of the ridge.

The presence of the overlying clayey-silt sediment unit indicates that estuarine conditions prevailed at the site until land reclamation occurred, possibly around the 11th Century. Although reclamation may have occurred prior to this (for example during the Roman occupation), the clayey-silt unit contained no evidence for a break in sedimentation (which would indicate such an event). Sea-level rise has occurred at a rate of *c*. 0.9mm/yr since estuarine sedimentation recommenced at *c*. 3,700 Cal. yrs BP, reaching its present position of 0.4m O.D. This, however, is likely to be an overestimation of the actual sea-level rise due to the influence of autocompaction on the vertical displacement of the sedimentary units.

Chapter 13: Quaternary environmental change in the Gordano Valley

13.1 Introduction

In this chapter, the results obtained from the Gordano Valley archive will be integrated with regional studies and presented in a wider context. Comparisons will be made with research that has been undertaken throughout the Severn Estuary lowlands to identify whether, during the late Quaternary period, the evolution of the Gordano Valley followed a regional trend, or whether the valley's sedimentary basin developed out of context with other lowland coastal sites. The two separate sedimentary archives preserved within the valley allow a regional comparison of the site's evolution with the Severn Estuary since *c*. 15,000 Cal. yrs BP. Attempts can also be made to link the basal sediments and ridge to the regional picture of past climate and sea-level change.

Table 13.1 provides a summary of the evolution of the Gordano Valley, focusing on the Quaternary palaeoenvironmental change that has been discovered in this study.

13.2 Comparisons relating to the basal sediments and ridge

The Gordano Valley contains a unique sedimentary archive due to the influence of the ridge that traverses its width. No other coastal lowland site along the Severn Estuary is known to contain such contrasting depositional environments that evolved in unison since the LGM. The feature acted as an environmental barrier, favouring the

<table>
<tr><th></th><th></th><th>Weston Moor Stratigraphy</th><th>Age (Cal. yrs BP)</th><th>Clapton Moor Stratigraphy</th></tr>
<tr><td rowspan="16">Quaternary</td><td rowspan="9">Holocene</td><td>Peat-cutting at Weston-in-Gordano?</td><td>700</td><td></td></tr>
<tr><td rowspan="7">maintained development of fen peat, protected from marine influence by valley ridge</td><td>900</td><td>land reclamation by Saxons?</td></tr>
<tr><td>3,700</td><td>marine inundation up to valley ridge</td></tr>
<tr><td>5,400-3,700</td><td>peat accumulation, proximity to coast preventing woodland development</td></tr>
<tr><td>5,650-5,400</td><td>marine inundation 1/2km inland from typecore site</td></tr>
<tr><td>6,100-5,650</td><td>peat accumulation, proximity to coast preventing woodland development</td></tr>
<tr><td>6,750-6,100</td><td>marine inundation 1/2km inland from typecore site</td></tr>
<tr><td>7,250-6,750</td><td>peat accumulation, expansion of alder dominated woodland</td></tr>
<tr><td>Onset of fen peat development</td><td>9,560</td><td rowspan="5">River network active within the region seaward of the ridge, draining the catchment's runoff into the Severn Valley</td></tr>
<tr><td rowspan="7">Pleistocene</td><td>Short-term catchment instability initiated clastic sedimentation</td><td>Younger Dryas?</td></tr>
<tr><td>Terrestrialisation of lake in response to Bølling/Allerød interstadial climatic amelioration</td><td>15,000</td></tr>
<tr><td>Accumulation of sediments within ridge, possibly eroded loess originally deposited on valley sides</td><td rowspan="2">18,000-15,000</td></tr>
<tr><td>Development of small lake within enclosed basement behind ridge</td></tr>
<tr><td colspan="3">Mid-Devensian?
Formation of ridge in response to periglacial activity within the Gordano Valley, acting as an environmental barrier between the Weston & Clapton Moor</td></tr>
<tr><td colspan="3">Development of periglacial deposits throughout valley lowlands; interbedded breccias and coversands at Holly Lane, soliflucted keuper marl, ice wedge clasts & widened rock joints on Clevedon-Bristol Ridge</td></tr>
<tr><td colspan="3">Pre-Cromerian?
Direct glacial activity within the Gordano Valley, depositing glacio-lacustrine, glacio-fluvial and till deposits at Nightingale Valley and Court Hill Col</td></tr>
<tr><td>Pre-Quaternary</td><td></td><td colspan="3">Deposition of Triassic Marl

Formation of valley geomorphology present today

Intra-palaeozoic folding, faulting and subsequent erosion

Deposition of Devonian sandstone and Carboniferous limestone</td></tr>
</table>

Table 13.1 Summary of the evolution of the Gordano Valley

evolution of a freshwater lake within the headward region of the valley during the late glacial climatic amelioration that preceded the Holocene interglacial.

Considering the significant archive of Ipswichian sedimentary deposits scattered throughout the lowlands of the Severn Estuary (Haslett, 1997; Allen, 2001, 2002a), the regional evidence could suggest that the basal sediments and ridge originated from the previous interglacial. The analysis and subsequent interpretation of the data available however, suggests that the ridge did not develop as a result of higher sea levels during the Ipswichian interglacial (see Section 11.2.2). The theorised presence of a small glacier within the landward region of the valley to account for the ridge was also assessed. The glacial sediments that are present within the Gordano Valley at Nightingale Valley (Hunt, 1998) and Court Hill Col (Gilbertson & Hawkins, 1978b) are of an unknown age but are found on the valley sides to the north and south of the ridge, suggesting a potential chronostratigraphic association. Glacial tills dating from the pre-Cromerian period are present at Kenn and Yew Tree Farm (Gilbertson & Hawkins, 1978a; Hunt, 1998), *c*. 3km south of the valley and this proximity may suggest a similar age for the glacial deposits. Whether a pre-Cromerian glacial period can explain the development of the ridge is still open to debate, but a *c*. 700,000 yr gap in sedimentation between ridge formation and the accumulation of late Devensian and Holocene sediments within the valley, suggests it is not the most likely explanation. Although the sedimentary boundary between the basal sediments and overlying younger sediments was often very sharp, there was no evidence for any palaeosols having developed that would suggest a lengthy hiatus in sedimentation had occurred.

Devensian periglacial features are present in southwest England (Macklin & Hunt, 1988), but the majority of sedimentary deposits preserved within the coastal lowlands of the Severn Estuary either date from the Ipswichian or the Holocene (Allen, 2000c, 2001, 2002a). Consequently, few comparisons can be made regarding the preferred theory that the basal sediment and ridge was formed by the infilling of the valley by periglacial hillslope processes during the late Devensian. However, the abundance of periglacial features within the valley around Holly Lane (Gilbertson & Hawkins, 1974) and Tickenham Col (Gilbertson & Hawkins, 1983a) that date from the Devensian, suggest that intense periglacial processes were occurring within the valley during the last glaciation. The presence of a major fault directly south of the feature on the Clevedon-Bristol ridge (proximal to Tickenham Col), combined with gullying features to the north (see Figure 11.5), would have provided sedimentary sources from which the ridge could have formed (Carson & Kirkby, 1975; Selby, 1982; Leeder, 1999). There is also an abundance of unconsolidated material available in these regions due to the presence of glacial sediments in Court Hill Col and Nightingale Valley (Gilbertson & Hawkins, 1978b; Hunt, 1998). The coarsening upwards sequence within the ridge sediments of typecore GVF23 could be indicative of a prograding alluvial fan that originated from the northern valley side (Leeder, 1999). The basal sediments throughout the valley catchment would also have developed as a result of similar hillslope processes that were active during the Devensian period. The environmental interpretations of this study, as with those of Jefferies *et al.* (1968), are still hypothetical due to the limited access available to assess the ridge further.

13.3 Comparisons relating to the sedimentary sequence landward of the ridge

Whilst the origin of the basal sediment remains open to interpretation, multi-proxy analysis of the contrasting depositional environments that evolved on either side of the sub-topographical feature has provided more robust interpretations regarding the valley's late Quaternary evolution. The hydroseral succession preserved landward of the ridge began during the Oldest Dryas stadial (Unit 2) *c*. 18,000-15,000 Cal. yrs BP (Roberts, 2000). The initial accumulation of minerogenic sediments within the basin occurred in response to catchment instability caused by the climate stadial. The deposition of loess in the surrounding region during the late Devensian may account for the fine-grained nature of the lake sediments (see Section 11.2.3(c)). As wind-blown sediments were accumulating throughout England at the same time the lake was experiencing sedimentation (Catt, 2001), the loess from the surrounding catchment could have then experienced subsequent erosion and redeposition in the lake basin.

Radiocarbon dating of the overlying clastic-rich peat unit (Unit 3; 15,060-13,820 Cal. yrs BP) combined with the interpretation of the pollen assemblages within typecore GVH17, indicated that the onset of clastic-rich peat accumulation occurred around the Bølling subinterstadial, *c.* 15,000 Cal. yrs BP. Gilbertson *et al*. (1990) dated the onset of lake peat accumulation to 11,020 ± 120 yrs BP, but relied upon the stratigraphic sequence reconstructed by Jefferies *et al.* (1968), and no further assessment of the valley's sedimentary archive was attempted. This contrasts with the valley-wide investigation undertaken in this study. Consequently, this study has discovered that the timescale involved during the evolution of the lake system spans a further *c*. 4,000 Cal. yrs when compared to the initial studies of Gilbertson *et al.* (1990).

A further benefit of the research into the landward valley archive is that very few studies of similar depositional environments from southwest England cover a similar timescale. It is therefore possible that the hydroseral succession sequence covering the late glacial transition is the oldest discovered in the region. Hawks Tor on Bodmin Moor preserves an infilled lake sequence from the late glacial period (Brown, 1977, 1980; Campbell & Davey, 1998), with sedimentation beginning during the Older Dryas period (*c*. 13,088 ± 300 yrs BP). Comparisons between the palaeoenvironmental reconstructions from Hawks Tor and the Gordano Valley reveal very similar results. At Hawks Tor, solifluction of minerogenic sediments occurred into a still water environment during the Older Dryas. Pollen analysis indicated the presence of a treeless, sparsely vegetated landscape during clastic deposition (Brown, 1980), similar to the environmental conditions present in the Gordano Valley at the same time. A shallowing of the water body then occurred at Hawks Tor, with a transition to sedge mire taking place *c*. 12,600 yrs BP. By *c*. 11,500 yrs BP, woody sedge peat with tall herb fen and birch carr had developed. In the Gordano Valley, the lake sequence began infilling through biogenic sedimentation between *c*. 15,060 and 13,820 Cal. yrs BP. Pollen analysis correlates with Hawks Tor, with increasing tree species and the expansion of birch woodland in response to climatic amelioration (Campbell *et al*., 1998). Whilst radiocarbon dating at Hawks Tor suggests the shift from minerogenic to biogenic sedimentation occurred during the Allerød subinterstadial, this change in deposition may have occurred earlier in the Gordano Valley, during the Bølling subinterstadial.

A return to minerogenic deposition occurs at Hawks Tor from *c*. 11,000 to *c*. 9,650 yrs BP and pollen analysis indicates its development during the Younger Dryas period. Minerogenic sedimentation also returns in the Gordano Valley after the initial terrestrialisation of the lake. Although the onset of minerogenic sedimentation in the Gordano Valley was not dated, its cessation correlates with Hawks Tor, having occurred before *c*. 9,550 Cal. yrs BP. Until radiocarbon dating of the lower minerogenic boundary is achieved, it can only be suggested that Unit 4 in the Gordano Valley also developed during the Younger Dryas. The similarities in pollen assemblages between this unit and that of Hawks Tor however, combined with both sites recording a sharp unconformity at the upper minerogenic boundary supports a chronological correlation. The onset of fen peat accumulation at Hawks Tor (*c*. 9,650 yrs BP) and the Gordano Valley (*c*. 9,550 Cal. yrs BP) are both too young for the opening of the Holocene, but the unconformities between the minerogenic unit and peat at both sites suggest a period of erosion to account for the delay in peat accumulation. The Holocene peat unit at Hawks Tor for example, has been found to overlie the Allerød peat and even bedrock in places (Brown, 1980).

The similarities between the Gordano Valley and Hawks Tor suggest that a regional trend in climate change influenced southwest England during the transition from the Devensian glaciation into the Holocene. A similar depositional environment was discovered by Walker *et al.* (2003) at an infilled kettle-hole from Llanilid, south Wales, which dated as far back as 16,350-14,812 Cal. yrs BP. Comparison of the pollen results between Llanilid and the Gordano Valley reveal that similar palaeoenvironmental conditions were present during the glacial-interglacial transition, supporting the evidence from Hawks Tor that suggests the Gordano Valley followed a regional trend in vegetation evolution. Bare ground and immature soils, populated by open habitat taxa such as grasses, sedges and *Artemisia*, initially dominated the regional topography. In response to climatic amelioration, favourable environmental conditions enabled the establishment of woodland vegetation as the catchment stabilised and the valley lake reduced in size through peat deposition.

Chapter 2 identified the known fluctuations in climate during the glacial-interglacial transition (Figure 2.2), and these variations are believed to be primarily in response to variations in oceanic circulation in the North Atlantic. Clarke *et al.* (2001) stated that a prolonged period of glacial freshwater input into the Atlantic Ocean from the North American Laurentide ice sheet was responsible for the Oldest Dryas stadial (*c*. 18,000-15,000 Cal. yrs BP). This is believed to have ceased around the time of the onset of the Bølling/Allerød interstadial (*c.* 15,000 Cal. yrs BP). Enhanced ocean circulation brought warmer waters to the coastline of northwest Europe, raising the temperature to levels comparable with the start of the Holocene (Bedford *et al*., 2004). The onset of terrestrialisation in the Gordano Valley, Hawks Tor and Llanilid during the Bølling/Allerød interstadial, suggests that the reduction in meltwater input from the Laurentide ice sheet (North America) into the North Atlantic Ocean at the end of the Oldest Dryas period could have been responsible for the transition from detrital sedimentation to organic sedimentation within lake environments around southwest Britain. This is further supported by Charman's (2002) view that a change in climate is the most likely cause for the initiation of terrestrialisation. The temporary return to minerogenic sedimentation in the Gordano Valley and at Hawks Tor during the Younger Dryas is also believed to have been caused by variations in North Atlantic Ocean circulation. Recent studies suggest that the continued downwasting and northerly retreat of the Laurentide ice sheet caused the rerouting of glacial meltwaters from the

Mississippi River into the North Atlantic via St Lawrence River (Nesje *et al*., 2004). The subsequent introduction of cold freshwater would have significantly affected thermohaline circulation, reducing the movement of warm waters by ocean circulation to northwest Europe, and resulting in climatic deterioration.

Fen peat accumulation has occurred in the upper Gordano Valley region since terrestrialisation of the lake system was completed, *c*. 9,580-9,520 Cal. yrs BP. Some similarities can be seen between the results of this study and the past research undertaken in the valley regarding vegetation change. For example, Jefferies *et al*., (1968), Mills (1984) and Gilbertson *et al*, (1990) encountered the distinct abundance of fern and sedge species at the onset of fen peat development within the valley. The decline in birch woodland and the subsequent initial expansion of hazel scrub during the early Holocene identified during this study was also found by Jefferies *et al.* (1968). However, the abundance of certain tree species within the work of Jefferies *et al*. (1968), Mills (1984) and Gilbertson *et al.* (1990) contrasts with their relatively low frequency in this study. For example, oak, pine and elm are all found to contribute the majority of the arboreal vegetation in past research, whilst these species were found in very low numbers during this study. One explanation could be the positioning of the typecores in relation to one another. The typecores extracted by Jefferies *et al*. (1968; which subsequently influenced the core location for Mills, 1984 and Gilbertson *et al.,* 1990), were positioned closer to the valley head (see Figure 3.4) than typecore GVH17 in this study (see Figure 10.1). Their closer proximity to the valley sides could have encouraged enhanced accumulation of tree pollen from the surrounding valley-side woodland. In contrast, the position of typecore GVH17 would have to some degree restricted the pollen sources for the subsequent vegetation reconstruction to the localised valley floor vegetation community due to the increased distance to the woodland valley sides. The highest tree pollen frequencies discovered during this study were within the lake sequence, when pollen grains were likely to have been transported into the lake basin from the valley-sides through runoff. Dark (1998) explained that considerable spatial variation in pollen assemblages is evident when comparing lake-centre cores to those taken from a lake-edge. This was found to be due to the influence of localised pollen input on lake-margin assemblages, whilst lake-centre pollen profiles were influenced to a greater extent through regional pollen input from the surrounding catchment. The fen peat sequence also attains its highest tree pollen frequencies towards the core surface where, prior to anthropogenic activity, the mature fen system began to be colonised by trees migrating onto the valley floor.

13.4 Comparisons relating to the sedimentary sequence seaward of the ridge

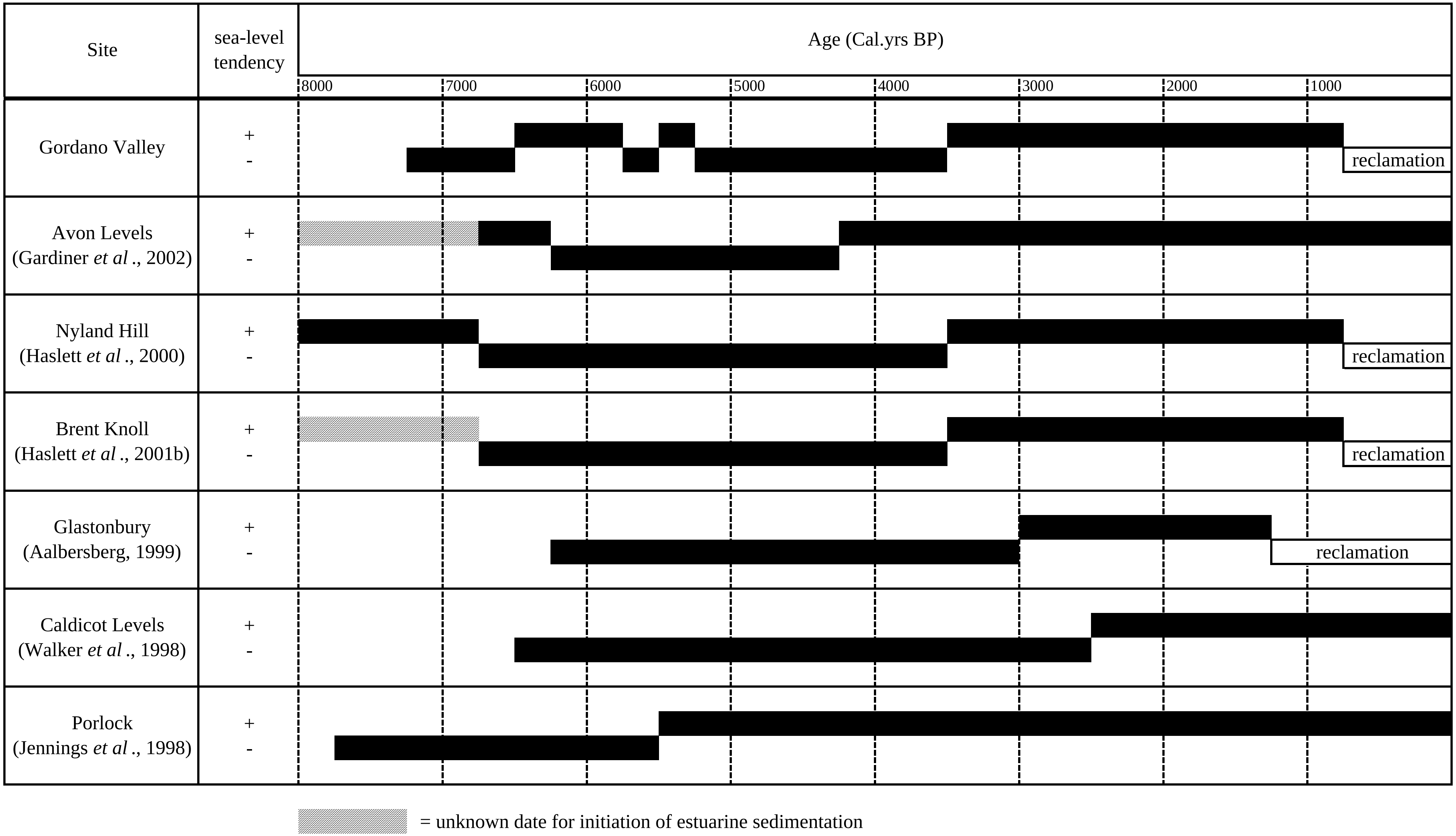
In contrast to the relatively unique sedimentary archive present towards the head of the Gordano Valley, the sequence of interbedded peats and silts preserved seaward of the ridge reflect the deposits more typically found throughout the Severn Estuary coastal lowlands. Allen (2000c) summarised the typical sedimentary sequence present throughout much of the Severn Estuary Levels that developed during the Holocene and many similarities can be seen. The initiation of sedimentation (expressed by peat accumulation) occurred between c. 7,320-7,220 Cal. yrs BP in the Gordano Valley, whilst the majority of the known deposits from the Severn Estuary Levels date from after 9,000-7,000 Cal. yrs BP (e.g. Gwent Levels; Allen, 2000c). The increase in the thickness of the freshwater peat deposits discovered with distance inland in the Gordano Valley, follows the trend found throughout the coastal lowlands and is thought to be due to the spatial variations in estuarine influence (Kidson & Heyworth, 1973).

The site of typecore GVJ43 was chosen due to the presence of three distinct periods of marine inundation into the Gordano Valley. Whilst the stratigraphy enhanced the potential for quantitative reconstructions of past sea level with the diatom-based transfer function, the site location also reflected the lower valley's susceptibility to marine inundation during the Holocene. The interbedded estuarine sequence also supports the findings of Allen (1995) confirming that, whilst the underlying trend in sea level was that of an overall increase throughout the Holocene, high frequency, short-term fluctuations in the rate of sea-level rise were also superimposed onto the upward trend. Comparisons of typecore GVJ43 with the sedimentary sequence further inland confirms fluctuating sea levels on a scale of a few decimetres, due to the two earliest short-term rises in apparent sea level (occurring from *c*. 6,800-6,100 Cal. yrs BP and *c*. 5,650-5,400 Cal. yrs BP) that transgressed only *c*. ½ km inland from the typecore site.

Whilst three phases of relative sea-level rise resulted in marine transgressions and estuarine sedimentation within the Gordano Valley, only one of these phases resulted in marine inundation as far as the ridge. Between 3,840 and 3,640 Cal. yrs BP, the rate of sea-level rise exceeded the rate of vertical growth of organic sedimentation that had been responsible for the development of the underlying peat unit for the previous *c*. 1,600 Cal. yrs. The resulting marine transgression submerged much of the lower Gordano Valley until land reclamation around the 11th Century. Comparisons can be made with the surrounding coastal lowlands of the Severn Estuary (Figure 13.1). The Panborough area of Glastonbury (Somerset Levels) experienced a gradual increase in apparent sea level, culminating in marine conditions dominating the lowlands by 3,100 Cal. yrs BP (Aalbersberg, 1999). Nyland Hill, also in the Somerset Levels however, experienced a return to marine conditions earlier than at Panborough and at a similar time to the Gordano Valley, between *c*. 3,725 and 3,465 Cal. yrs BP (Haslett *et al*., 1998). This can be explained by the closer proximity of Nyland Hill to the coastline compared to Panborough, which meant that it thus experienced marine inundation at an earlier date.

Along the south Wales coastline, dates for the end of peat formation vary considerably however, from *c*. 5,350 Cal. yrs BP to 2,975 Cal. yrs BP (Bell, 2000), and these sites are all in close proximity to one another relative to the coast. There is therefore considerable spatial and temporal variability in the last regional transition from freshwater peat to estuarine deposition which occurred during the late Holocene. It is unlikely that these variations are the result of contrasting relative sea levels because the sites are all within close proximity (especially along the south Wales coastline). This is further supported by sea-level reconstructions within the Severn Estuary/Bristol Channel region, where the rise in relative sea level has been the most stable over the last 8-6,000 Cal. yrs (Lambeck, 1995; Peltier *et al*., 2002). Also, as crustal movements in response to glacio-isostatic influences have been shown to be similar throughout the southwest since the mid Holocene (Shennan & Horton, 2002), therefore such a forcing mechanism could not explain localised changes in relative sea level.

It is therefore likely that, whilst continued rise in sea level in the Severn Estuary region was the underlying control on lowland evolution, the overriding factor that



= unknown date for initiation of estuarine sedimentation

Figure 13.1 Comparisons of inferred sea-level change from the Gordano Valley with sites from the Severn Estuary lowlands Radiocarbon dates have been rounded to the nearest 250 Cal. yrs for inclusion in the diagram.

influenced individual site development was autogenic (organic) deposition (Shennan, 1994). For example, at sites such as Goldcliff, south Wales, where a return to marine estuarine sedimentation is dated as early as *c*. 5,330-4,650 Cal. yrs BP (Bell, 2000), the supply of organic sediments was not sufficient for peat accumulation to keep pace with that of sea-level rise. As a result, marine inundation and a return to estuarine deposition occurred. In contrast, at sites where peat accumulation outpaced rates of relative sea-level rise, the return to estuarine sedimentation was delayed. Consequently, the Gordano Valley supported freshwater peat development until 3,840-3,640 Cal. yrs BP, after which the continued relative sea-level rise culminated in a marine transgression. The rate at which this transgression submerged the valley is at present unclear, due to a lack of radiocarbon dating of the upper peat boundary inland of the typecore site. Considering the spatial extent of the return to marine conditions *c*. 5-3,000 Cal. yrs BP throughout the Severn Estuary lowlands (and the comparative size of the Gordano Valley in relation to the Severn Estuary), it is possible that the transgressive phase was complete within a few hundred years.

With respect to the coastal evolution of the Gordano Valley during the historical period, the lack of archaeological evidence and historical records from the study site limits comparisons with the surrounding regions. It is likely, however, that lowland coastal reclamation did not occur in the Gordano Valley until medieval times (*c*. 11th Century) (Rippon, pers. comm.), which is later than reclamation experienced in much of the Severn Estuary lowlands. For example, evidence of Roman mining and coastal reclamation in the Somerset Levels is dated to *c*. 1,776 ± 46 Cal. yrs BP (Haslett *et al.*, 2000), which correlates well with archaeological evidence from the region. This typifies much of the Severn Estuary during the Romano-British period, which experienced extensive drainage and sea-wall construction (Bell, 2000). A number of coastal sites did experience initial land reclamation during the Roman occupation, only for the sea walls to fall into disrepair and result in the late Roman marine transgression (Rippon, 1997). However, evidence from the valley's seaward stratigraphy (via a lack of possible unconformities within the upper clay unit, or buried palaeosols) did not indicate temporary reclamation prior to the 11th Century. Consequently, the dating for the eventual reclamation of the valley's coastal lowlands to around the 11th Century relied on the nature of the field boundary patterns and the place names present within the Gordano Valley (Rippon, 1997). It is possible that the proximity of the extensive reclaimed land around the Somerset Levels, combined with the relatively small size of the valley's palaeo-saltmarshes and tidal flats, meant that there was no demand for reclamation of the lowlands until the medieval period.

The coastal sedimentary sequence preserved in the Severn Estuary can also be compared favourably to the stratigraphic models of coastal evolution described by Long *et al*. (2000) and Streif (2004). Long *et al*. (2000) suggested a tripartite model of estuary evolution, characterised by estuarine expansion during the early and late Holocene and separated by a period of estuarine contraction and peat development during the mid Holocene. The Wentlooge Formation of south Wales and the Somerset Levels Formation both correlate well with this model (section 2.4). Estuarine expansion and minerogenic sedimentation occurred throughout the lowlands during the early Holocene, only to be replaced by peat accumulation as organic sedimentation outpaced the rate of sea-level rise. Terrestrial sedimentation and estuarine contraction characterised the mid Holocene, until a return to estuarine sedimentation occurred, in response to a rise in apparent sea level. The stratigraphic model of Streif (2004) follows a similar trend to that of Long *et al*. (2000), although a number of transgessive and regressive overlaps are present during the period of estuarine contraction described by Long *et al*. (2000). Both models can be applied successfully to the stratigraphy of the Gordano Valley. The basal peat unit is indicative of an initial rapid rate of sea-level rise during the estuarine expansion experienced during the early Holocene. This resulted in high groundwater levels in the coastal lowlands, encouraging organic preservation and bog growth. The maintained rise in sea level resulted in a transgressive boundary and estuarine sedimentation replacing the basal peat. Short-term fluctuations in apparent sea level then resulted in transgressive and regressive overlap boundaries within the Gordano Valley, comparative to the mid-Holocene estuarine contraction described by Long *et al*. (2000) and Streif (2004). The final marine transgression then occurred, inundating the valley with estuarine sedimentation at *c*. 3,700 Cal. yrs BP, in correlation with the models' estuarine expansion during the late Holocene.

13.5 Comparisons relating to the sea-level history of the Gordano Valley

Although autocompaction prevented the reconstruction of an absolute sea-level curve during this study, the spatial and temporal impact of sea level on the valley's evolution has been elucidated. The interbedded peats and marine silts indicate an overall rise in sea level since sedimentation began in the seaward region of the valley between *c*. 7,320-7,220 Cal. yrs BP. This upward trend was interrupted by minor short-term fluctuations in the rate of sea-level rise superimposed onto the general trend, evident through the valley stratigraphy and the Severn Estuary as a whole (Allen, 2000c).

Comparisons of the sea-level reconstructions from the Gordano Valley with the most recent sea-level models for the Severn Estuary region (Lambeck, 1993, 1995; Peltier *et al*., 2002) are difficult due to the inability to account for autocompaction during this study. The sea-level models created by Lambeck (1993, 1995) and Peltier *et al*. (2002) took into account all the known external influences believed to control changes in relative sea level at any point along a continent's coastline. The models were then compared with known SLIPs created through sedimentary and morphological features to ensure accuracy. Glacio-isostasy, the most influential control on relative sea level in the UK, is believed to have resulted in crustal subsidence occurring within the Severn Estuary region at a rate of c. 0.76mm yr^{-1} over the last c. 4,000 yrs (Shennan & Horton, 2002). Whether this rate of subsidence has been uniform during this period is unknown. In addition, considering the stratigraphic archive of the Gordano Valley spans over *c*. 7,000 Cal. yrs, its glacio-isostatic activity prior to 4,000 Cal. yrs BP is unclear. Consequently, the relative sea-level curve created for the Gordano Valley does not take into account factors such as glacio-isostasy and autocompaction. Models of Holocene tidal variations within the Severn Estuary, another factor that affects sea-level reconstructions, also could not be applied with accuracy due to the limited evidence available at present (see section 12.6). Consequently, contrasting results would be expected when comparing the sea-level models of Lambeck (1995) and Peltier *et al*. (2002) with the sea-level data set from this study.

The basal peat regressive overlap boundary can be interpreted to indicate that there was a reduction in the rate of relative sea-level rise in the valley between 7,320-7,220 Cal. yrs BP. Considering this, the model of Peltier *et al.* (2002) provides the most accurate interpretation of sea level for the Severn Estuary region. This is due to the model's calculations indicating that such a reduction in the rate of sea-level rise occurred at *c*. 8,000 Cal. yrs BP (Figure 2.5), in contrast to Lambeck's (1993,1995) model which indicated maintained rates of sea-level rise until *c*. 6,000 Cal. yrs BP (Figure 2.4). Figure 13.2 overlays the age-altitude plots and 'real' SLIPs achieved from the diatom-based sea-level transfer function with the sea-level curve of Peltier *et al.* (2002).

As the onset of peat accumulation at a lowland coastal site is interpreted as an indicator of a relative reduction in the rate of sea-level rise (Allen, 1995), the basal peat unit supports the sea-level model of Peltier *et al.* (2002), which assumed that thinner ice was present at the LGM, combined with a lower mantle viscosity and a thinner lithosphere in comparison to the model of Lambeck (1993, 1995). The overall trends in sea level show a continued reduction in the rates of sea-level rise through the Holocene, again in agreement with the sea-level models of Lambeck (1993, 1995) and Peltier *et al.* (2002). There is a strong correlation between the two sea-level studies (Figure 13.2). However, the model of Peltier *et al.* (2002) reconstructs MSL rising at a faster rate than predicted by the transfer function during the mid- to late-Holocene. Whilst tidal amplification during the Holocene may be a contributing factor, this deviation between the two data sets is likely to be due to autocompaction in the Gordano Valley, which increased in influence with height through the sedimentary archive (see Section 12.2). Consequently, the age-altitude plots that were derived from diatom assemblages in the upper sedimentary horizons of the Gordano Valley were vertically offset to a greater extent than those underneath (see Figure 12.1 for reference), thus underestimating the position of MSL during the mid- to late-Holocene.

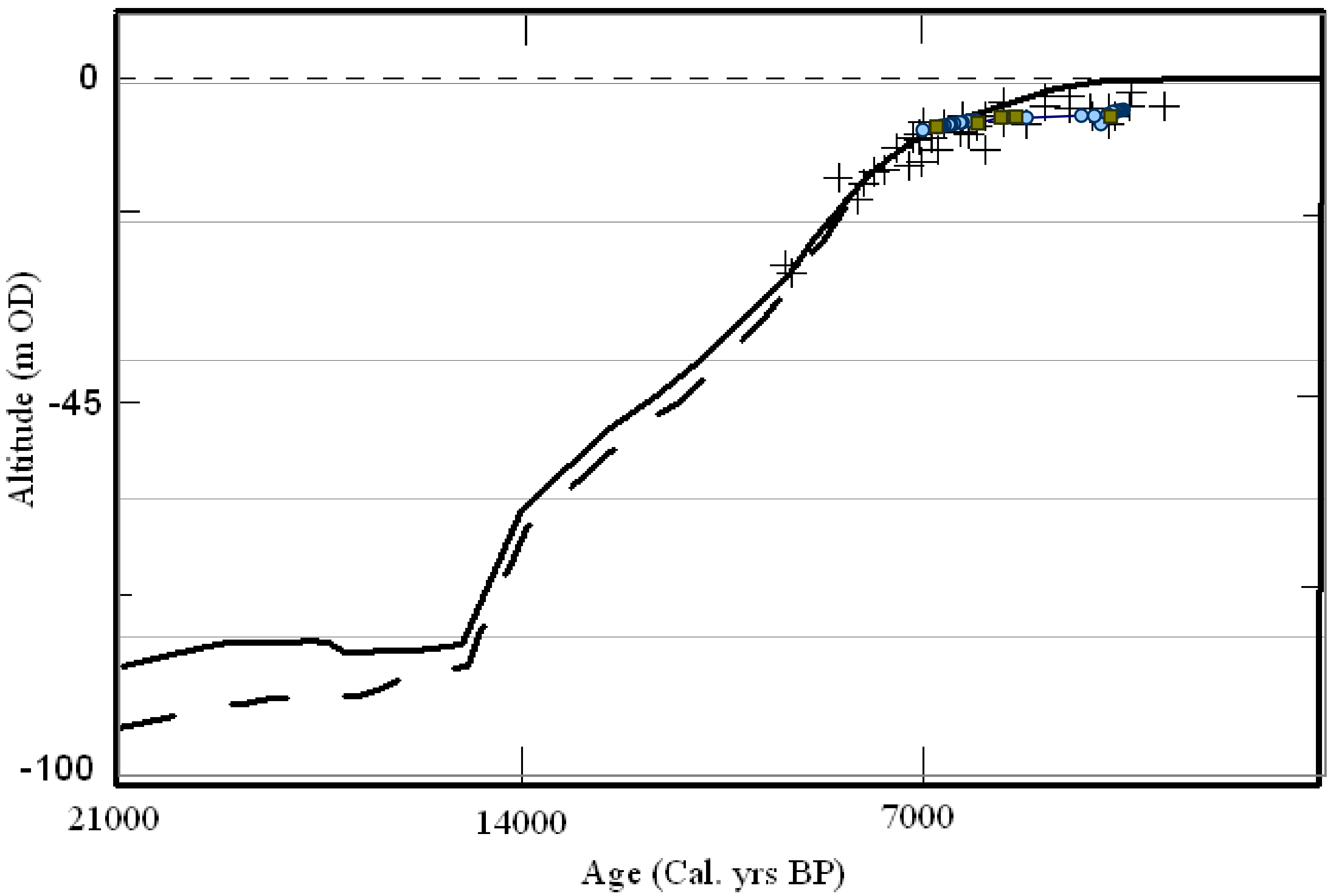


Figure 13.2 Overlay of the diatom-based age-altitude plots (blue circles) and the 'real' transfer function SLIPs (green squares) onto the modelled sea-level curves of Peltier *et al.* (2002). Due to the large scale, error bars have not been included. Figure 2.5 explains the origin of the two contrasting sea-level curves created by Peltier *et al.* (2002).

Comparisons can also be made between the results obtained during this study and the latest sea-level data set compiled by Shennan & Horton (2002) for the Severn Estuary (Figure 13.3). The results follow the same trend as the Peltier *et al*. (2002) model (Figure 13.2), as a similar glacio-isostatic model is used in both data sets. However, Shennan & Horton (2002) incorporate a larger data set of observed SLIPs and subsequently does not rely primarily on glacio-isostatic model predictions.

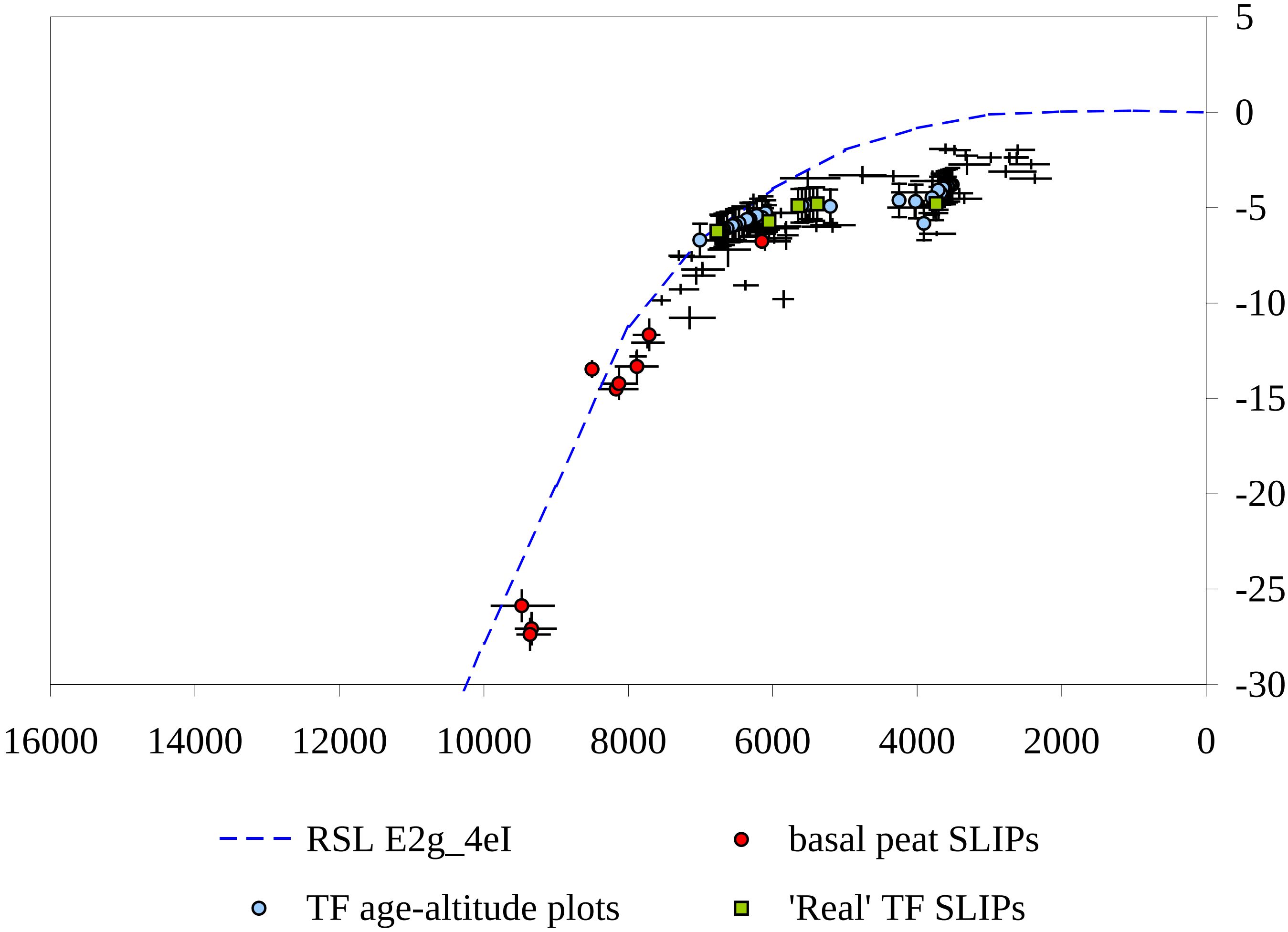


Figure 13.3 Overlay of diatom-based age-altitude plots and SLIPs from the Gordano Valley onto the sea-level data set of Shennan & Horton (2002).

The observed SLIPs from the Shennan & Horton (2002) data set and those from the Gordano Valley all follow a similar trend. The basal peat SLIPs from previous studies in southwest England plot close to the glacio-isostatic model of sea-level change, confirming the reliability of basal peat units as a source of sea-level information due to their resistance to autocompaction. In contrast, the five transfer function SLIPs obtained from interbedded peat units, combined with the remaining age-altitude plots from the data set, all plot below the model-predicted sea-level curve. The observed index points also deviate away from the modelled sea-level curve during the Holocene, similar to the results from the comparisons with the Peltier *et al*. (2002) sea-level model. This is also likely to be a consequence of autocompaction and varying tidal ranges during the Holocene. Shennan & Horton (2002) were able to model changes in Holocene tidal range for the Humber Estuary. The tidal adjustment model was able to quantify the variation in tidal influence on the SLIPs, and the subsequent age-altitude plots provided a stronger correlation to the glacio-isostatic sea-level model.

The application of a diatom-based sea-level transfer function to fossil assemblages has been achieved for the first time in southwest England. The highly accurate predictions of altitude provided by the transfer function during the regression analyses of the contemporary diatom data set (RMSEP = 0.876) confirms the transfer function's ability to reliably reconstruct past depositional altitudes from fossil diatom assemblages. The construction of the transfer function for this study however, only included one contemporary data set. In comparison, Zong & Horton (1999) and Gehrels *et al*. (2001) incorporated six and three contemporary data sets respectively. This is likely to explain the increased accuracy of palaeoenvironmental predictions over past studies, as increasing the number of data sets incorporated into the construction of a transfer function would subsequently reduce a transfer function's predictive potential (see section 7.2). Only one attempt has been made within the UK to develop a diatom-based transfer function and to apply this to a fossil archive (Zong and Horton, 1999) and this was applied to a sedimentary archive in Scotland. The application of such a technique to a coastal setting with a tidal range as high as the Severn Estuary has consequently never been attempted before. Therefore comparisons with research of a similar nature are limited. Difficulties such as preferential diatom preservation (Ryves *et al*., 2001) and diatom dissolution (Mayer *et al*., 1991) hindered the ability to infer sea-level change throughout the full sedimentary sequence of the Gordano Valley. However, considering the vast sedimentary archive preserved within the Severn Estuary coastal lowlands (*c*. $8km^3$; Allen, 2000c), numerous potential sites could provide the opportunity for further research into this method of sea-level reconstruction.

Chapter 14: Conclusions

14.1 Advances in the understanding of the evolution of the Gordano Valley

This chapter considers the contribution of this study to current knowledge. Each of the study objectives will be revisited in order to indicate the contribution made to the existing knowledge of the Gordano Valley during the late Quaternary. The palaeoenvironmental reconstructions from the Gordano Valley, combined with the reconstruction of Holocene sea-level change, underpin the contribution of knowledge from this thesis. Consequently, this study has resolved a number of issues regarding the evolution of the Gordano Valley.

14.2 To log the Quaternary stratigraphy of the Gordano Valley and reconstruct the sedimentary environments

Detailed stratigraphic analysis of the sedimentary archive preserved in the Gordano Valley provided a deeper understanding of the spatial and temporal variations in lithostratigraphy than that achieved by earlier studies. Whilst the majority of fieldwork undertaken by Jefferies *et al.* (1968) extracted cores from the ridge region of the valley, and the research of Mills (1984) and Gilbertson *et al.* (1990) extracted only one core for proxy analysis, this project applied a high resolution coring grid to ensure that a precise understanding of the sedimentary archive was achieved on a spatial and temporal scale. Although access limitations did restrict a full valley-wide stratigraphic survey, an enhanced understanding of both the hydroseral succession sequence (landward of the ridge) and the interbedded freshwater peat and estuarine clay sequence (seaward of the ridge) has been achieved.

The sedimentary archive of the Gordano Valley was further elucidated by the creation of both two-dimensional and three-dimensional stratigraphic images which have facilitated reconstructions of the evolution of the isolated basin. Even with the access restrictions around the Weston Drove region of the valley, the position of the basal sediments could be extrapolated from the available data to produce a reconstruction of the basal sediments and ridge (Figure 9.10) not wholly dissimilar to that of Jefferies *et al.* (1968).

Despite further access restrictions seaward of the ridge, the implementation of a single core transect running parallel with the axial trend of the valley was achieved. Although a stratigraphic survey of the lower valley region had been undertaken before, subsequent laboratory analysis was restricted to a single sedimentary boundary (Jefferies *et al.*, 1968). The multiproxy analysis of the typecore extracted from the lower valley region during this study therefore constitutes the first attempt to reconstruct palaeoenvironmental changes that have occurred since sedimentation began.

14.3 To determine the influence of sea-level change on the Gordano Valley's Quaternary sedimentary sequence

An attempt was made to apply a diatom-based sea-level transfer function to the Gordano Valley archive during this project. The creation of a contemporary data set from the coastline of the Severn Estuary was required as no attempt to apply such a quantitative technique had occurred in a) southern England and b) a coastal site with one of the largest tidal ranges in the world. Although the collation of two separate coastal transects was required to achieve a full record of diatom assemblages from MSL to HAT, subsequent analysis indicated that this approach created a reliable data set. The contemporary coastal data set also provided an opportunity to assess the validity of the ecological classification scheme of Vos and deWolf (1993) in a macro-tidal setting.

Regression analyses of the fossil diatom assemblages from the interbedded coastal sequence of the Gordano Valley indicated that the quantitative approach to diatom analysis was successful. By calculating the depositional altitude (relative to MSL) for each diatom assemblage in the valley archive, freshwater peat deposits were found to have developed at higher altitudes than the marine minerogenic sediments. A number of improvements could be applied to this quantitative technique, including the expansion of the environmental variables which are used to explain species variability, and the application of the transfer function to other sites within the Severn Estuary. However, the construction and subsequent application of the diatom-based sea-level transfer function has created very useful palaeoenvironmental reconstructions using a quantitative technique which is in its relative infancy in the UK.

14.4 To determine ecological and vegetation change within the Gordano Valley's Quaternary sedimentary sequence

The palynological results indicated the relative influence of climate on vegetation during the transition from the late glacial into the Holocene. The colonisation and expansion of vegetation in response to climatic amelioration around *c.* 15,000 Cal. yrs BP enhanced catchment stability and prevented the continued input of detrital sedimentation into the enclosed lake basin. Subsequent biogenic activity encouraged the terrestrialisation of the lake, leading to the creation of a fen peat environment in the early Holocene (c. 9,580-9,520 Cal. yrs BP). Variations in vegetation on a localised scale were also evident upon comparison of the results with past research. An abundance of arboreal pollen was discovered by Jefferies *et al.* (1968) and Gilbertson *et al*. (1990) landward of the ridge in contrast to its relative absence in the terrestrialised sequence during this study. The location of typecore sites could explain this variation; the study sites of Jefferies *et al.* (1968) and Gilbertson *et al*. (1990) were in close proximity to the valley sides, whilst typecore GVH17 was extracted from the centre of the valley. Woodland establishment on the valley sides would have resulted in enhanced input of arboreal pollen on a localised scale, explaining the pollen sequences discovered by Jefferies *et al*. (1968) and Gilbertson *et al*. (1990). The valley floor, however, was unsuitable for woodland colonisation due to the high water table (maintained by the enclosed nature of the headward valley region). Consequently, the representation of arboreal pollen was restricted and the herbs and shrubs that colonised the valley floor dominated the pollen profile. It is unlikely that woodland expansion occurred on the valley floor until drainage of the fen peat began in the historic period.

Seaward of the ridge, considerable variations in vegetation were present during the Holocene, primarily reflecting variations in the influence of sea level. Unlike the enclosed basin headward of the ridge, the water table in the lower valley region was low enough during the Early Holocene to allow the establishment of alder-dominated woodland on the valley floor from between *c*. 7,300 and 6,800 Cal. yrs BP. Subsequent rising sea levels prevented the re-establishment of woodland on the site during the mid to late Holocene. Coastal reedswamp and upper saltmarsh conditions prevailed in the lower valley as maintained sea-level rise and terrestrial sedimentation combined to develop the lithostratigraphy typical of the Severn Estuary lowlands.

14.5 To integrate the sea-level, vegetation and sedimentological data to reconstruct the Quaternary environmental history of the Gordano Valley, and to place the archive and its interpretation within the contexts of established work in the Severn Estuary region and of frameworks for climate change.

14.5.1 Chronostratigraphic analysis of the Gordano Valley

Significant advances have also been achieved regarding the timescale of evolution in the Gordano Valley. Although the age and origin of the basal sediments and ridge are still open to interpretation, the application of radiocarbon dating to the terrestrialised peat sequence and interbedded coastal sequence has improved the temporal context of the site. Radiocarbon dating of the onset of lake peat development, combined with multiproxy analysis of the hydroseral succession, indicated that organic accumulation began in the enclosed basin *c*. 15,000 Cal. yrs BP, in response to the climatic amelioration occurring at the onset of the Bølling/Allerød interstadial.

Although radiocarbon dating of the lacustrine peats was undertaken by Gilbertson *et al.* (1990), their limited understanding of the valley stratigraphy and the positioning of their typecore resulted in a date for peat initiation of *c*. 11,020 Cal. yrs BP, some *c*. 4,000 Cal. yrs later than discovered during this research. This research has therefore indicated that not only was minerogenic sedimentation occurring within an enclosed lake basin, but that this was probably taking place during the Oldest Dryas period, prior to the climatic amelioration responsible for the initiation of peat development.

This study marks the first radiocarbon dating of the interbedded coastal sequence, seaward of the ridge. This enabled the evolution of the Gordano Valley to be compared to the known histories of the many coastal lowland sites that have been analysed throughout the Severn Estuary region (Allen, 2000c; Bell, 2000). In addition, the valley archive correlated well with stratigraphic models of coastal evolution (Long *et al*., 2000; Streif, 2004), and confirmed how variations in the rate of sea-level rise influenced lowland development during the Holocene. The initiation of organic deposition within the lower valley region has been dated to between 7,320-7,220 Cal. yrs BP, whilst the final phase of marine inundation occurred between 3,840-3,640 Cal. yrs BP. Jefferies *et al.* (1968) suggested that this final phase of marine inundation occurred around the Romano-British period, *c*. 2,000 Cal. yrs BP, but this has been demonstrated as incorrect.

14.5.2 Hydroseral succession sequence within the Gordano Valley

The sedimentary evolution of the upper valley region, in which a lake developed during the transition from the Devensian glacial period, was the focus of the majority of past research into the palaeoenvironmental evolution of the Gordano Valley (Jefferies *et al.*, 1968; Mills, 1984; Gilbertson *et al.*, 1990). The current study attempted to further enhance the understanding of the valley's evolution. Three-dimensional reconstructions of the stratigraphy, combined with radiocarbon dating, have provided a considerable improvement in the spatial and temporal understanding of the late Quaternary deposits. In addition, a thin minerogenic layer separating the lacustrine peat from the overlying fen peat was also discovered throughout much of the upper valley's stratigraphic archive. It is suggested that the Younger Dryas Stadial may have been responsible for the return to minerogenic sedimentation, but further radiocarbon dating is required to confirm this.

The hydroseral succession preserved in the upper valley appears to be the oldest of its kind in southwest England; few other records of postglacial lacustrine environments of a similar age have been discovered in this region (see section 13.3). The stratigraphy preserved in the valley therefore provides an ideal source to uncover the region's response to environmental and climate changes that occurred during the transition from the late glacial to the present interglacial (*c*. 18,000-11,500 Cal. yrs BP). Whilst valuable information regarding the valley's response to these changing conditions has been uncovered during this research, further studies into this archive should be undertaken to allow comparisons with independent records from elsewhere in the UK and the North Atlantic region.

14.5.3 Reconstruction of Holocene sea level

One of the most significant aspects of this research project involved the multiproxy analysis of the stratigraphic archive preserved seaward of the ridge in the Gordano Valley. Such an investigation had never before been undertaken within the valley. The interbedded peats and marine silts provided the ideal opportunity to elucidate the response of valley sedimentation to sea-level change. The interbedded coastal sediments were shown to relate well to reconstructions of coastal evolution throughout the Severn Estuary lowlands, and comparisons have been made to the Wentloodge and Somerset Formations that dominate the region. The thickness of the peat units preserved in the valley archive was found to decrease with distance towards the present-day coastline. One main peat unit was evident towards the ridge within the valley and this became interbedded with marine sediments towards the coast. Typecore GVJ43 contained three interbedded freshwater peat and marine minerogenic units, indicative of fluctuations in sea level in relation to land elevation. Subsequent multiproxy analysis of these sediments confirmed the influence of marine conditions on sedimentary deposition. Two of the three periods of marine inundation encountered at typecore site GVJ43 transgressed only a further *c.* ½ km inland, lending support to Allen's (1995) observation that the sea-level history of southwest England was characterised by an overall rise in sea level during the Holocene, onto which high-frequency, short-term fluctuations in the rate of sea-level rise were superimposed. This is further supported by the comparisons made between the results from this study and those of past research into the sea-level history of southwest England (Shennan & Horton, 2002; Peltier *et al.*, 2002). Distinct similarities can be seen relating to the observed position of relative sea level estimated through the transfer function and past studies, supporting the evidence for an overall reduction in the rate of sea-level rise during the Holocene.

The most influential period of relative sea-level rise occurred in the Gordano Valley *c.* 3,840-3,640 Cal. yrs BP, during which the whole of the valley seaward of the ridge was submerged. Estuarine conditions resulted in the deposition of clayey-silts until coastal reclamation during *c.* 11th Century. Similar dates for a shift from freshwater to marine conditions are found throughout the Severn Estuary coastal lowlands (Figure 13.1). Sea-level change is concluded to be the underlying control in the evolution of the sedimentary archive in the seaward region of the Gordano Valley. However, the proximity of the Gordano Valley to south Wales, combined with the contrasting dates for the onset of marine deposition, suggests that variations in the rates of terrestrial sedimentation was another significant factor on inter-site variability. Organic sedimentation would have enabled the vertical growth of the sediment surface within the Gordano Valley to keep pace with or exceed sea-level rise until *c.* 3,700 Cal. yrs BP. Rising sea levels exceeded organic accumulation in the coastal lowlands of south Wales at a much earlier date (e.g. Goldcliff, *c.* 5,350 Cal. yrs BP; Bell, 2000).

The influence of factors such as glacio-isostasy, autocompaction and variations in tidal range, have been assessed in order to understand their influence on reconstructions of past sea level. The combined influence of crustal subsidence and sediment consolidation would have caused the vertical displacement of the Gordano Valley sedimentary sequence, which resulted in subsequent sea-level reconstructions underestimating the actual position of relative sea level. In addition, the application of the contemporary tidal frame to sea-level reconstructions would also underestimate the position of relative sea level due to the likely increase in tidal range during the Holocene. It was not possible to accurately quantify the influence of these factors and consequently they were not incorporated into the reconstructions of sea level achieved from the Gordano Valley stratigraphic archive. However, this study has developed a large sea-level data set created by the diatom-based sea-level transfer function to contribute to the growing understanding of sea-level change in southwest England.

It can be concluded, therefore, that this study has made a significant contribution to current knowledge of the evolution of the Gordano Valley during the Quaternary period. A spatial and temporal understanding of the influence of Holocene sea-level change in the valley has also been achieved for the first time. In terms of palaeoenvironmental methodologies, multiproxy analysis of the stratigraphic archive enhanced the accuracy of environmental interpretations through the application of pollen, diatom and particle size analysis. The quantitative reconstruction of sea level through diatom analysis indicated that this technique could be applied to a site such as the Gordano Valley.

Chapter 15: Suggestions for further research

15.1 Introduction

A number of questions have arisen from this study. The time constraints placed on the project meant that subsequent investigations into these areas of interest could not be conducted. Considering the range of analytical methods available to the Quaternary researcher, this section summarises the potential areas in which our understanding of the Quaternary evolution of the Gordano Valley could be enhanced in the future.

15.2 Palaeoenvironmental analysis of the basal sediments and ridge

It was made clear during this study that the ridge and the associated basal sediments were responsible for influencing the evolution of two contrasting depositional environments in the Gordano Valley. These sediments were therefore deposited, at the latest, during the late glacial period (*c*. 18,000-15,000 Cal. yrs BP). Access limitations (in terms of permission by land-owners and the presence of the tip site) restricted the potential for any significant research to be undertaken on the processes and timescale involved in ridge deposition. During the initial fieldwork, when the basal sediments or ridge were encountered, the presence of material too coarse for extraction or the unconsolidated nature of the sediment prevented full stratigraphic sequences from being extracted with the gouge corer. Consequently, although alternative suggestions have been made in this study regarding the mode of deposition for the sediments, a robust interpretation has yet to be found. It is suggested, however, that periglacial hillslope activity is the most likely cause for the development of the basal sediments and ridge.

If access was granted to land overlying the ridge, detailed sedimentary analysis could be conducted to produce more reliable interpretations of the processes responsible for ridge formation. An estimation of the ridge's age could be achieved through foraminiferal analysis, whereby an abundance of temperate-water species assemblages would confirm whether the feature did indeed develop during the Ipswichian interglacial period. An alternative approach would be to use luminescence dating to provide an estimate for the onset of sedimentation within the ridge. The benefit of luminescence dating is there is no need for organic remains (as required for radiocarbon dating).

15.3 The terrestrialised lake sequence

The identification of a sedimentary sequence that spans the last glacial-interglacial transition provides an opportunity for further research into the palaeoenvironmental history of southwest England. There is the potential for the application of a number of proxy analytical techniques to the archive that have not been utilised before, including chironomid and coleopteran analyses. Gatropoda were found within the lake peat in some cores during the initial stratigraphic survey, the analysis of which could also contribute to the developing palaeoenviromental understanding of the Gordano Valley. In addition, further radiocarbon dating of the terrestrialised peat sequence is required. Enhancing the dating resolution within the typecore would allow the available palaeoenvironmental evidence to be correlated with know climatic events during the transition to the Holocene epoch. The dating of the upper boundary of the clastic-rich peat unit is also required in order to establish the age of the theorised Younger Dyras minerogenic unit. Also, by extracting and dating new typecores from the sedimentary sequence, it may be possible to understand the timescale involved with the terrestrialisation process, This would prove useful considering the large time period covered by the radiocarbon dating of the base of the clastic-rich peat unit (*c*. 15,060-13,820 Cal.yrs BP). If the initiation of biogenic sedimentation does indeed date to the Bølling subinterstadial, the terrestrialised sequence may be the oldest of its kind in southwest England.

15.4 The diatom-based sea-level transfer function

The success in developing a diatom-based transfer function from the contemporary Severn Estuary coastline, combined with its application to the fossil diatom archive within the Gordano Valley, has been a promising outcome from this study. A lack of quantitative reconstructions by similar means throughout southwest England (and indeed most of the UK) restricts inter-site comparisons and hence an assessment of the technique's robustness. Whilst considerable success was achieved with the contemporary data set, the transfer function should be applied to other sedimentary archives from the Severn Estuary region for validation. Similar results to those obtained through analysis of the Gordano Valley archive would validate the technique as a reliable indicator of palaeo sea level. Contrasting results, however, could suggest that the application of such a technique to the coastal lowlands of the Severn Estuary requires further development and refinement.

The transfer function could be further improved through the introduction of new environmental variables into the data set. To enable comparisons, this study incorporated the environmental variables that were analysed during the creation of the only similar diatom-based transfer function by Zong & Horton (1999). The known relationship between diatom assemblages and sea level (Zong & Horton, 1999; Gehrels *et al*., 2001), combined with the creation of the transfer function primarily as a means to understand palaeo sea-level conditions, meant that further environmental variables were not considered to be necessary during this study.

During the regression analyses of the contemporary data set, it was discovered that *c*. 75% of the variation in diatom distribution could not be accounted for by the environmental variables analysed. Although this is an improvement over the diatom-based transfer function created by Zong & Horton (1999), it is likely that the additional scrutiny of extra environmental variables would enhance the understanding of contemporary diatom distribution. Through the use of twelve variables, Ng and Sin (2003) explained 60.8% of the total diatom variance discovered during the analysis of sea-level change in the coastal waters off Hong Kong. Charman *et al.* (2002) explained between 41% and 69% of the total variance in testate amoebae distribution on contemporary saltmarshes with eight environmental variables. It is therefore possible that by increasing the number of environmental variables present within the contemporary data set, more accurate interpretations of past environmental conditions could be achieved. These could include pH, salinity, water depth, temperature and conductivity.

15.5 Autocompaction and sea-level reconstructions

Autocompaction was the most significant problem encountered with respect to palaeo sea-level reconstruction. It was initially hoped that an accurate sea-level curve could be created from the development of the diatom-based transfer function. However, autocompaction could not be accounted for and consequently the reconstruction of sea level was restricted to age-altitude plots (see section 12.2). Given the impact of autocompaction on all lowland coastal sequences, a standard technique is required to solve this. Present techniques for assessing autocompaction either require a detailed understanding of sedimentological and geotechnical properties of the depositional archive (Allen, 2000b), which are not available to most researchers, or an uncompacted peat surface overlying bedrock (Haslett *et al*., 1998). If access was granted to the ridge, it could be possible to ascertain whether the main peat unit within the interbedded estuarine sediments overlies the ridge. This would provide an uncompacted surface which could be dated and enable autocompaction to be accounted for. Access permission to the valley sides would also provide a similar opportunity to discover if the interbedded coastal sequence overlaps the valley's bedrock. This would subsequently contribute to the creation of a true sea-level curve for the Gordano Valley which can be compared with confidence to other reconstructions. Irrespective of which approach is chosen, or whether a new study is undertaken, the benefits of future research into quantifying autocompaction would have far-reaching benefits within sea-level studies.

15.6 Variations in the tidal range of the Severn Estuary during the Holocene

This research assumed that the tidal range has remained constant in the Severn Estuary throughout the Holocene. Sea-level reconstruction using the diatom-based transfer function required the Severn Estuary's tidal range to be applied to each potential SLIP to estimate MSL during the evolution of the Gordano Valley (Shennan, 1986; Gehrels *et al*., 2001). The modern-day tidal range has been commonly applied to sea-level reconstructions (Shennan, 1989) due to the assumption that tidal variations over the last *c.* 6,000 Cal. yrs has been minimal, and prior to this any changes would have been slight (Heyworth & Kidson, 1982). However, as described in section 12.6.2, it is possible that the tidal range has increased during the Holocene in response to the increasing width and depth of the Severn Estuary. Previous research into tidal variation within the Severn Estuary does not support this theory (Austin, 1991), although this study did not take into account localised variations in basin width and configuration. Research by Gehrels *et al*. (1995) developed a model for tidal amplification for the Bay of Fundy, Canada, which indicated that only *c*. 60% of the contemporary tidal range was present *c*. 6,000 Cal. yrs BP. Shennan & Horton (2002) also modelled tidal amplification in the Humber Estuary and were able to apply the results to observed SLIPs. If a similar model is applied to the Severn Estuary, by taking into account the detailed bathymetry of the site, a better understanding of variations in tidal range during the Holocene will be achieved. This, in turn, will enhance the accuracy of subsequent sea-level reconstructions.

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