DOCTOR OF PHILOSOPHY

Late Devensian and Holocene relative sea level changes on the Isly of Skye, Scotland

Selby, Katherine

Award date:
1997

Awarding institution:
Coventry University

Late Devensian and Holocene Relative Sea Level Changes on the Isle of Skye, Scotland

Katherine Selby

A thesis submitted in fulfilment of the University's requirements for the degree of Doctor of Philosophy

August 1997

Volume I: Chapters 1-11 and References

Declaration

This dissertation is the result of the author's own work. Data or information from other authors, which are referred to or quoted in the text, are acknowledged at the appropriate point in the text.

Abstract

Five coastal sites have been studied on the Isle of Skye to investigate Late Devensian and Holocene relative sea level changes. In the field, detailed stratigraphical work, geomorphological mapping and levelling were undertaken and representative cores were sampled. Detailed pollen and diatom analyses were undertaken in the laboratory and samples were submitted for radiocarbon assay where distinct pollen, diatom or lithostratigraphical changes were recorded. Loss on ignition analysis was also undertaken to ascertain the carbon content of the samples.

The investigations have revealed that during the Late Devensian marine transgressions were experienced at two sites in southern Skye. These are thought to relate to readvances of the ice that arrested the isostatic recovery of the land, caused renewed isostatic depression and upon deglaciation, allowed marine waters to penetrate the sites. At Inver Aulavaig the transgression is thought to relate to the Wester Ross Readvance recorded in Wester Ross, Coll and Tiree and at Point of Sleat the transgression is thought to relate the Loch Lomond Readvance recorded extensively in Scotland. Relative sea level at Point of Sleat (southern Skye) then fell below an altitude of 4.13mOD at 10460±50 BP and remained low during the early Holocene until the Main Postglacial Transgression occurred. This transgression is recorded at three of the sites: at Inver Aulavaig (southern Skye) at 8850±70 BP where it had attained an altitude of at least 5.10mOD, at Peinchorran (eastern Skye) where it is thought to have been underway by 7980±70 BP and attained an altitude of 4.49mOD and at Talisker Bay (western Skye) at 7790±100 BP where it had attained an altitude of -2.18mOD. At Ardmore Bay (northern Skye), it is thought that the Main Postglacial Transgression did not reach an altitude of 3.34mOD. It is possible that barrier formation at some of the sites accompanied the early stages of the Main Postglacial Transgression.

It is thought that regression of the sea occurred between *circa* 6600 BP and *circa* 5400 BP and remained low until *circa* 4200 BP when a later rise in relative sea level took place at Peinchorran attaining a maximum altitude of 4.90mOD. A late Holocene transgression is also recorded at Point of Sleat at between *circa* 3800 BP and *circa* 2900 BP where it attained an altitude of greater than 4.13mOD and at Inver Aulavaig after *circa* 3200 BP where it attained an altitude of between 5.10-6.01mOD. It is unclear whether this episode of high relative sea level represents the diachronous nature of one late Holocene transgression or several fluctuations in relative sea level during the late Holocene. Following the late Holocene transgression, relative sea level fell until the present day.

Comparison of the data obtained from Skye with the isobase maps and rheological models suggests that the isobases for the Main Lateglacial Shoreline (Firth *et al.*, 1993) show a good fit in age and altitude but the rheological model of Lambeck (1993b) for 10500 BP requires modification. The isobases for the Main Postglacial Shoreline appear to lie *circa* 4m too high for the sites studied on Skye and the isobases produced for a late Holocene shoreline appear to be greatly in error (Firth *et al.*, 1993). It is possible that the build up of ice during the Loch Lomond Stadial may have had a greater effect on crustal movements than previously thought and this may account for discrepancies identified in the isobase maps. The study of isolation basins and back-barrier environments has allowed an assessment of their potential in recording relative sea level changes. The use of isolation basins in areas devoid of estuarine sedimentation has been particularly demonstrated.

The vegetation reconstruction undertaken, suggests that variations do occur in coastal locations compared to sites further inland, although these are subtle. The dates obtained for the increase in taxa such as *Corylus avellana* and *Alnus* and the recording of anthropogenic indicators on the vegetation, agree with those previously obtained for Skye. The use of pollen analysis in verifying the radiocarbon dates obtained, particularly for the Late Devensian, has been recognised and combined with diatom analysis has provided a comprehensive data base from which to reconstruct past relative sea levels.

Acknowledgements

I wish to extend my gratitude to Professor David Smith and Dr. Alastair Dawson for providing me with the opportunity to undertake this research. I have acquired many skills and had the opportunity to visit and study a spectacular island whose beauty was a constant inspiration. None of this would have been possible without the commitment of David and Alastair. I would also like to thank Dr. Timothy Mighall and Dr. Andrew Haggart for their supervisory contribution to this research.

Funding for this research was provided by the European Commission on relative sea level changes and extreme flooding events around European coasts (PL910044).

Many people have assisted me with fieldwork on Skye, often providing essential bodymass to push down the coring equipment. They remained good-natured despite the inevitable Scottish west coast downpours and infamous midges and their help was invaluable. They are Hazel and Brian Bird, Jim Campbell, Robin Cullingford, Alastair Dawson, Chris Gleed-Owen, Siân Hender, James Lewis, David Smith and James Wells. David's reserve in this department must also be acknowledged as several pieces of coring equipment now "rest in peace" beneath a peat moss in southern Skye.

Several sites were studied in Skye and permission to work on the land was obtained from the following people; Neil Campbell at Talisker Bay; Roger and Georgie Bidwell at Point of Sleat; David Bryant at Ardmore Bay. My thanks are extended to these people for their interest and willingness to allow me to undertake research on their land.

Finally, I would like to thank my family and friends for their support, advice and encouragement with work in the field, in the laboratory and especially on the computers, which displayed logic several dimensions removed from mine at times.

Late Devensian and Holocene Relative Sea Level Changes on the Isle of Skye

Statement of copyright and declaration 2
Abstract 3
Acknowledgements 4
Contents 5
List of Tables 9

Section A Context of the research

Chapter 1.0 Introduction
1.1 Introduction 11
1.2 Objectives 11
1.3 Location of the Isle of Skye 12
1.3.1 Geology 12
1.3.2 Climate 13
1.3.3 Vegetation 13
1.4 Location of sites studied 14
1.5 Structure of the dissertation 15
1.6 Glossary of abbreviations and terms 16

Chapter 2.0 Literature review
2.1 Introduction 17
2.2 The Late Devensian in Scotland 17
2.3 The Late Devensian on Skye 20
2.4 Relative sea level changes in Scotland 24
2.5 Late Devensian relative sea level changes in Scotland 25
2.5.1 Late Devensian relative sea level changes in eastern Scotland 26
2.5.2 Late Devensian relative sea level changes in western Scotland 27
2.6 Late Devensian relative sea level changes on Skye 29
2.7 Holocene relative sea level changes in Scotland 31
2.7.1 Holocene relative sea level changes in eastern Scotland 31
2.7.2 Holocene relative sea level changes in western Scotland 33
2.8 Holocene relative sea level changes on Skye 35
2.9 Isobase maps and shoreline diagrams 36
2.10 Rheological models of isostatic rebound 38
2.11 Vegetational history of the Isle of Skye 39
2.11.1 Late Devensian vegetational history 40
2.11.2 Holocene vegetational history 42
2.12 Conclusions 44

Chapter 3.0 Methodology and techniques of analysis
3.1 Introduction 45
3.2 Fieldwork 45
3.2.1 Determining the stratigraphy and sampling the site 46
3.2.2 Geomorphological mapping 47
3.2.3 Levelling 47
3.3 Laboratory analyses 47
3.4 Palynology and its use in this research 49
3.4.1 Pollen preparation methods 49
3.4.2 Pollen counting methods and identification 50
3.4.3 Notes on taxa 50
3.4.4 Pollen percentage diagrams and zonation 51
3.4.5 Pollen taphonomy and errors in palynology 51
3.5 Diatom analysis and its use in sea level studies 53
3.5.1 Diatom preparation methods 54

3.5.2 Diatom counting methods and identification........................... 55
3.5.3 Diatom percentage diagrams and zonation............................ 56
3.5.4 Errors in diatom analysis.. 56
3.6 Foraminifera, Mollusca and fish bone analyses.............................. 57
3.7 Radiocarbon dating and its use in sea level studies........................ 57
3.8 Relative sea level index points.. 60
3.9 Loss on ignition.. 62
3.10 Methodology employed in the study of isolation basins and its context..... 63
3.11 Methodology employed in the study of barriers and tombolos and its context... 65
3.12 Conclusions.. 68

Section B Presentation of Results

Chapter 4.0 Inver Aulavaig

4.1 Introduction.. 70
4.2 Geomorphological mapping, borehole location and stratigraphy............ 70
4.3 Loss on ignition.. 74
4.4 Pollen analysis.. 74
4.4.1 Borehole 36.. 74
4.4.2 Borehole 3a... 76
4.4.3 Borehole 15.. 77
4.5 Diatom analysis... 78
4.5.1 Borehole 36.. 78
4.5.2 Borehole 3a... 80
4.5.3 Borehole 15.. 81
4.6 Mollusca analysis of borehole 3a.. 81
4.7 Foraminifera analysis of borehole 36... 82
4.8 Fish bone analysis.. 83
4.9 Radiocarbon dates.. 83
4.10 Interpretation of pollen assemblages... 84
4.10.1 Borehole 36.. 84
4.10.2 Borehole 3a.. 91
4.10.3 Borehole 15.. 92
4.11 Interpretation of diatom assemblages.. 93
4.11.1 Borehole 36.. 93
4.11.2 Borehole 3a.. 97
4.11.3 Borehole 15.. 99
4.12 Interpretation of the molluscan assemblages from borehole 3a............. 99
4.13 Interpretation of fish bone analysis.. 100
4.14 Environmental interpretation of Inver Aulavaig.............................. 101
4.15 Conclusions... 105

Chapter 5.0 Peinchorran

5.1 Introduction.. 107
5.2 Geomorphological mapping, borehole location and stratigraphy............ 107
5.3 Loss on ignition.. 108
5.4 Pollen analysis.. 109
5.5 Diatom analysis... 111
5.6 Radiocarbon dates.. 111
5.7 Interpretation of pollen assemblages... 112
5.8 Interpretation of diatom assemblages.. 116
5.9 Environmental history of Peinchorran.. 117
5.10 Conclusions... 121

Chapter 6.0 Talisker Bay

6.1 Introduction.. 122
6.2 Geomorphological mapping, borehole location and stratigraphy............ 122

6.3 Loss on ignition.... 124
6.4 Pollen analysis.... 125
6.4.1 Borehole A5.... 125
6.4.2 Borehole S1.... 126
6.5 Diatom analysis.... 127
6.5.1 Borehole A5.... 127
6.5.2 Borehole S1.... 128
6.6 Radiocarbon dates.... 129
6.7 Interpretation of pollen assemblages.... 130
6.7.1 Borehole A5.... 130
6.7.2 Borehole S1.... 135
6.8 Interpretation of diatom assemblages.... 137
6.8.1 Borehole A5.... 137
6.8.2 Borehole S1.... 138
6.9 Environmental history of Talisker Bay.... 138
6.10 Conclusions.... 141

Chapter 7.0 Point of Sleat
7.1 Introduction.... 143
7.2 Geomorphological mapping, borehole location and stratigraphy.... 143
7.3 Loss on ignition.... 145
7.4 Pollen analysis.... 145
7.5 Diatom analysis.... 146
7.6 Mollusca analysis.... 147
7.7 Radiocarbon dates.... 148
7.8 Interpretation of pollen assemblages.... 149
7.9 Interpretation of diatom assemblages.... 153
7.10 Interpretation of the molluscan assemblage.... 155
7.11 Environmental history of Point of Sleat.... 155
7.12 Conclusions.... 159

Chapter 8.0 Ardmore Bay
8.1 Introduction.... 161
8.2 Geomorphological mapping, borehole location and stratigraphy.... 161
8.3 Loss on ignition.... 162
8.4 Pollen analysis.... 162
8.5 Diatom analysis.... 163
8.6 Radiocarbon date.... 164
8.7 Interpretation of pollen assemblages.... 164
8.8 Interpretation of diatom assemblages.... 166
8.9 Environmental history of Ardmore Bay.... 167
8.10 Conclusions.... 169

Section C Conclusions of Research

Chapter 9.0 Relative sea level changes on the Isle of Skye
9.1 Introduction.... 171
9.2 Inver Aulavaig.... 171
9.3 Peinchorran.... 172
9.4 Talisker Bay.... 172
9.5 Point of Sleat.... 173
9.6 Ardmore Bay.... 173
9.7 Relative sea level index points and age-altitude plots.... 174
9.8 Late Devensian relative sea level changes on Skye.... 174
9.9 Implications for the Late Devensian isobase map and rheological model.... 174
9.10 Early-middle Holocene relative sea level changes on Skye.... 178
9.11 Implications for the isobase map and rheological model for the

middle Holocene.... 180
9.12 Middle-late Holocene relative sea level changes.... 181
9.13 Implications for the late Holocene isobase map.... 182
9.14 Barrier formation.... 182
9.15 Comparison of isolation basin and barrier sites for the recording of relative sea level changes.... 183
9.16 Conclusions.... 187

Chapter 10.0 Late Devensian and Holocene vegetation changes on the Isle of Skye
10.1 Introduction.... 188
10.2 Late Devensian vegetational changes.... 188
10.3 Early Holocene vegetational changes (10000-7000 BP).... 191
10.4 Middle Holocene vegetational changes (7000-4000 BP).... 194
10.5 Late Holocene vegetational changes (4000 BP-present).... 196
10.6 Anthropogenic effects on the vegetation.... 197
10.7 Conclusions.... 198

Chapter 11.0 Conclusions
11.1 Relative sea level changes on the Isle of Skye.... 199
11.2 Methodological conclusions.... 200
11.3 Recommendations for future work.... 201
11.4 Overview of the research.... 202

References.... 203

List of Tables

Table 2.1:	Definition of terms and associated sea level features	17
Table 3.1:	Definition of terms used in diatom identification	54
Table 3.2:	Quantification of errors used in the construction of relative sea level index points	62
Table 4.1:	Stratigraphy of borehole 36 (NG 6050 1240)	73
Table 4.2:	Stratigraphy of borehole 3a (NG 6055 1238)	73
Table 4.3:	Stratigraphy of borehole 15 (NG 6052 1230)	73
Table 4.4:	Pollen zone descriptions for borehole 36	75
Table 4.5:	Pollen assemblage description for borehole 3a	76
Table 4.6:	Pollen zone descriptions for borehole 15	77
Table 4.7:	Diatom zone descriptions for borehole 36	79
Table 4.8:	Diatom zone descriptions for borehole 3a	80
Table 4.9:	Diatom assemblage description for borehole 15	81
Table 4.10:	Frequency chart of molluscan identified	82
Table 4.11:	Radiocarbon dates for borehole 36	84
Table 4.12:	Radiocarbon dates for borehole 3a	84
Table 5.1:	Stratigraphy of borehole F (NG 5280 3320)	108
Table 5.2:	Pollen zone descriptions for borehole F	110
Table 5.3:	Diatom zone descriptions for borehole F	111
Table 5.4:	Radiocarbon dates for borehole F	112
Table 6.1:	Stratigraphy of borehole A5 (NG 3138 3015)	124
Table 6.2:	Stratigraphy of borehole S1 (NG 3128 3013)	124
Table 6.3:	Pollen zone descriptions for borehole A5	125
Table 6.4:	Pollen zone descriptions for borehole S1	127
Table 6.5:	Diatom zone descriptions for borehole A5	128
Table 6.6:	Diatom assemblage description for borehole S1	129
Table 6.7:	Radiocarbon dates for borehole A5	129
Table 6.8:	Radiocarbon dates for borehole S1	129
Table 7.1:	Stratigraphy of borehole 3 (NG 5645 0030)	144
Table 7.2:	Pollen zone descriptions for borehole 3	146
Table 7.3:	Diatom zone descriptions for borehole 3	147
Table 7.4:	Results of molluscan analysis	148
Table 7.5:	Radiocarbon dates for borehole 3	148
Table 8.1:	Stratigraphy of borehole 3 (NG 2195 6100)	162
Table 8.2:	Pollen zone descriptions for borehole 3	163
Table 8.3:	Diatom assemblage description for borehole 3	164
Table 8.4:	Radiocarbon date for borehole 3	164
Table 9.1:	Radiocarbon dates, altitudes and indicative meaning of relative sea level index points	175
Table 9.2:	Summary of advantages and disadvantages of using isolation basins and back-barrier environments for the investigation of relative sea level changes	186

Section A: Context of the research

Introduction
Literature review
Methodology and techniques of analysis

"Wouldst thou.........
Learn the secret of the sea?
Only those who brave its dangers
Comprehend its mystery!"

from "The secret of the sea" by Henry Wadsworth Longfellow (page 341)

Chapter 1.0 Introduction

1.1 Introduction

The Isle of Skye lies off the west coast of Scotland and forms part of the Inner Hebrides (Figure1.1). It has a crenulate coastline formed by sea lochs and in the north and west of the island, steep cliffs fringe the coast. Raised marine terraces of sand and gravel are present in the landscape and represent Late Devensian and Holocene shorelines, but little work has been undertaken on the reconstruction of past sea levels. Richards (1969; 1971) described some of the coastal features in the north and west of the island and Walker *et al.* (1988) described some shorelines to the south of the Cuillin Hills. However, in contrast to other areas of Scotland no detailed systematic studies have been undertaken on sea level changes that occurred during the Late Devensian and Holocene. The aim of this research is, therefore, to remedy this deficiency and contribute further knowledge to the overall pattern of Scottish sea level changes.

1.2 Objectives

Four objectives of the research have been identified.

1.2.1 To reconstruct relative sea level changes for the Isle of Skye during the Late Devensian and Holocene. It is hoped that this will complement other sea level studies that have been undertaken in Scotland and work undertaken by Richards (1969; 1971) and Walker *et al.* (1988) on former sea level changes on Skye. It is intended that an age-altitude plot will be constructed with radiocarbon dated sea level index points of positive and negative marine tendencies.

1.2.2 To test the validity of provisional isobase maps for this area (Dawson, 1988; Lambeck, 1990; 1991; 1993a; 1993b; Firth *et al.*, 1993) . The maps are relatively well constrained on the eastern coast of Scotland, but data points are sparse on the west coast. Sites were chosen, therefore, to span across the provisional isobases that have been drawn for Skye for the Main Lateglacial Shoreline, the Main Postglacial Shoreline and a late Holocene Shoreline.

1.2.3 To compare the data and relative sea level record obtained from different geomorphological environments. It is intended to establish the advantages and deficiencies of working in areas where relative sea level changes are recorded behind barriers, tombolos and in isolation basins and to assess the preservation potential of these sites.

1.2.4 To establish patterns of vegetation change that have occurred during the Late Devensian and Holocene and compare them with previous studies that have been undertaken on Skye (Birks, 1973; Vasari, 1977; Williams, 1977; Birks and Williams, 1983; Walker *et al.* 1988; Walker and Lowe, 1990).

1.3 Location of the Isle of Skye

The Isle of Skye (57°00'-57°42'N; 5°58'-6°47'W) is the second largest island in western Scotland. The name Skye derives from the gaelic An t-Eilean-Sgitheanach literally meaning the sky (Forbes, 1923). It has a total area of 17000 hectares and has a deeply indented coastline of over 600 kilometres. Four major peninsulas constitute the island; the Sleat peninsula in the south and the Trotternish, Waternish and Duirnish peninsulas in the north (Figure 1.2). Skye has some of the most varied geological scenery of Great Britain and an extremely diverse vegetation, with some flora being recorded at their most northerly limits (Birks, 1973).

Skye is separated from the mainland by the Sound of Sleat and from Raasay by the Inner Sound, a glacially scoured trough over 700m deep containing thick Quaternary deposits. The island is separated from the Outer Hebrides by the Little Minch to the north-west and the Sea of the Hebrides to the west and south. Both basins are covered by a thin veneer of Late Quaternary sediments (Fyfe *et al.*, 1993) overlying Mesozoic bedrock (Scottish Natural Heritage, 1993; Little Minch Sheet 57°N-08°W).

1.3.1 Geology

The oldest rocks on Skye are the Lewisian gneisses of the Sleat Peninsula which are buried beneath Torridonian grits and arkoses (Scottish Natural Heritage, 1993). Sandstones, limestones and siltstones were laid down during the Cambrian and Ordovician periods on the continental shelf and these are present in north-west Sleat and the Broadford-Loch Eishort area (Figure 1.2). Folding during the Caledonian Orogeny formed the Moine Schists at the tip of the Sleat Peninsula while during the Jurassic period, fossiliferous sands and muds were laid down on the continental shelf. These sedimentary rocks occur in the Broadford area and in parts of the northern peninsulas. The calcareous rocks that formed beneath the sea during the Cretaceous period were all eroded, planating the Jurassic deposits (Scottish Natural Heritage, 1993).

At the beginning of the Tertiary period, intense volcanic activity built up the basalt ridges of northern Skye. The eastern slopes of the escarpment have been subjected to large rotational landslides. The Cuillins and the Red Hills represent the roots of the Palaeogene plutonic centre and are made of gabbros and peridotites (Scottish Natural Heritage, 1993). Gullies within these complexes are the result of weathered Tertiary basalt dykes. Tertiary sedimentary rocks were then deposited on top of and in between the lavas and faulting occurred. A major tectonic feature of this time is the great Camasunary fault which lies between Loch Scavaig and Loch Ainort in central Skye. The erosion of the next 50 million years shaped the scenery of Skye into its present form (Scottish Natural Heritage, 1993; Ballantyne and Benn, 1991a).

Quaternary glacial/interglacial cycles have modified the landscape, with each successive glaciation probably eroding most of the deposits of the previous one. The glacial deposits present on Skye primarily result from the Dimlington Stadial (26000 radiocarbon years BP to 13000 radiocarbon years BP) and Loch Lomond Stadial (*circa* 11000 radiocarbon years BP to *circa* 10000 radiocarbon years BP). Striae, erratics, hummocky moraine and till allow the reconstruction of the direction and dimensions of the last ice sheet (Ballantyne, 1988; 1989; 1990; Walker *et al.*, 1988; Walker and Lowe, 1990; Dahl *et al.*, 1996). Lying on top of these sediments are deposits that relate to fluctuating relative sea levels and terrestrial deposition since the retreat of the last ice sheet. These sediments are preserved in basins and behind coastal barriers.

1.3.2 Climate

The present climate of Skye is strongly maritime with high precipitation, relatively small temperature range, strong winds and much cloud cover (Birks, 1973). An east-west gradient appears to exist, with the coast exposed to Atlantic influences having decreased temperatures when compared to farther inland (Williams, 1977). There is also a latitudinal gradient with the north of the island cooler than the south and this has implications for vegetation patterns. Skye is influenced by the Gulf Stream and the associated atmospheric circulation which maintain the cool, oceanic climate despite its latitude. Local differences in the climate exist due to topographical controls and the predominant wind direction is north -west to south.

1.3.3 Vegetation

The present vegetation of the Isle of Skye has been studied and recorded extensively by Birks (1973) and a brief summary of the work is included here. Most woodland in Skye (excluding Forestry Commission plantations) is found on the Sleat Peninsula and in the Kyleakin area. This appears to result from the milder climate and particularly decreased wind exposure when compared to northern Skye. According to Williams (1977), the Sleat Peninsula represents an ecotonal area between the *Betula/Corylus* woods of Skye and the *Quercus* woods of the Morar Peninsula. It is also an area where McVean and Ratcliffe's (1962) three potential woodland zones, *Betula*, *Pinus* with *Betula* and *Quercus*, and *Quercus* with *Betula*, converge. Birks (1973) recognised two main associations of woodland; on the poorer soils *Betula pubescens-Vaccinium myrtillus* are present and on the richer soils *Corylus avellana-Oxalis acetosella*. In some of the northern areas a more 'open' scrub has developed with *Salix* and *Juniperus*. Grazing has a great influence on the understorey present and additionally, the pH of the soil is a determining factor. *Calluna vulgaris* grows only on acidic soils and cliff edges, but can withstand grazing and burning. *Pteridium* is found up to 350m in all areas of Skye.

Bogs and fens are common wherever there is impeded drainage and aquatic reedswamp communities are present, although the flora is affected by altitude and exposure. The flora of the freshwater lochs is related to the bedrock with basalts and gabbros having a more diverse flora than those on sandstones (Birks, 1973). Limestone areas have a rich flora and lowland cliffs often support a 'tall herb' vegetation. Coastal communities are greatly influenced by sea spray, salinity and exposure. Some cliff areas support wood and scrubland, but due to the instability of these communities, it is unlikely that woodland ever formed a major component. Many ruderal species are found in coastal areas and this could be due to man's preference to living in these locations and encouraging growth of these plants for food and medicinal uses. Saltmarsh vegetation is influenced by fluctuations in the water table, substrate, grazing and exposure. The alpine area is affected by a more severe climate with snow present for some months of the year. It is generally an area of thin, low pH soils and poor drainage. As a result, the richest montane flora is on the basalt soils of Trotternish and many upland areas are bare of vegetation (Birks, 1973).

1.4 Location of sites studied

Five coastal sites were studied on the Isle of Skye: Inver Aulavaig and Point of Sleat lie in the south on the Sleat peninsula, Peinchorran lies on the east coast, Talisker Bay lies on the west coast and Ardmore Bay is located on the Waternish peninsula in the north (Figure 1.1). Several sites were investigated, but these five were, after initial analyses, deemed to be the most suitable for this research. The sites were chosen to investigate different areas of the coast in order to identify any regional variations in relative sea level patterns and additionally, the spread of sites around the island allowed greater assessment of published shoreline isobase maps. Two sites, Point of Sleat and Inver Aulavaig, are basins that have been isostatically uplifted and subsequently cut off from marine influence, *i.e.* isolation basins and the remaining sites all possess coastal barriers.

1.5 Structure of the dissertation

The dissertation is divided into three major sections. The first section, **Section A**, contains **Chapters 1.0, 2.0** and **3.0** and provides a background to the study area, the nature of the project and the methodologies employed. **Chapter 1.0** outlines the aims of the project and gives an introduction to the environment of the Isle of Skye. Abbreviations or terms used within the text are outlined at the end of the chapter. **Chapter 2.0** is a literature review that summarises glacial events in Scotland and Skye during the Late Devensian and Holocene. Relative sea level changes associated with the changing ice loads since deglaciation are summarised for all areas of Scotland and Skye. Vegetation changes that have occurred on Skye over the last 13000 years are outlined with reference to other published pollen diagrams so that comparisons can be made with the findings of this research. The methodologies employed with justification for the techniques chosen are detailed in **Chapter 3.0**. Errors of the techniques are considered and the presentation of the results is described.

Section B contains **Chapters 4.0, 5.0, 6.0, 7.0** and **8.0** and each of these describes the findings of a particular site. The results of the fieldwork including the stratigraphical work, the geomorphological mapping and the levelling are presented and maps and diagrams used where appropriate to illustrate the results. The results and interpretations of the microfossil analyses are also presented and shown diagrammatically and a section at the end of each chapter brings together all the lines of evidence in a palaeoenvironmental history of the site.

Section C contains the concluding chapters that compare and contrast the sites studied in Skye. **Chapter 9.0** reconstructs past relative sea level change on Skye for the Late Devensian and Holocene and investigates how the geomorphology of the area affects the preservation of the relative sea level record. Aspects of coastal change are explored and age-altitude plots summarise the findings. The information obtained is then placed in a regional context and the accuracy of the isobase maps for this area of Scotland are assessed. The isostatic influence of the Loch Lomond Readvance upon Skye is also considered. **Chapter 10.0** collates all the information obtained on vegetational changes for Skye and compares and contrasts them with other pollen assemblages that are available for the island. Conclusions of the research are outlined in **Chapter 11.0**. and recommendations for future work, in view of the findings, are discussed. The **Appendices** contain photographs of the sites, an ecological list of the diatom species encountered and the borehole records of the sites.

1.6 Glossary of abbreviations and terms

Several terms and abbreviations are used within the text and these are defined below.

1.5.1 All dates quoted in the text are uncalibrated conventional radiocarbon years before present (BP) unless otherwise stated. They are quoted with a $\pm 1\sigma$, although it is common practice to use radiocarbon dates with $\pm 2\sigma$, sometimes calibrated, when constructing relative sea level graphs. BP is used as an abbreviation to represent years before present taking AD 1950 as the standard year of reference for all dates (Libby, 1955).

1.5.2 All altitudes quoted in the text are related to metres above Ordnance Datum (mOD) at Newlyn, Cornwall.

1.5.3 The indicative meaning of a horizon is defined as 'the relationship of the environment in which the sample accumulated to a reference water level' (Shennan, 1982; 1986; van de Plaasche, 1986). Tendencies of sea level movement are terms used to imply a change in marine influence as, for example, determined by microfossil analyses. A positive tendency of sea level movement is defined as an apparent increase in marine influence at the site and a negative sea level tendency is defined as the apparent removal of marine influence at the site (Shennan, 1983).

1.5.4 The abbreviation MHWOST represents the mean high water mark of spring tides and MLWOST represents the mean low water mark of spring tides.

Chapter 2.0 Literature review

2.1 Introduction

This chapter summarises present knowledge on the pattern of glacial events and relative sea level changes in Scotland during the Late Devensian and Holocene. Scotland has been the focus of much Quaternary research in recent years and as a result a wealth of knowledge exists on events since the start of the Late Devensian. The table below defines the terms and ages of the periods studied in this research and lists the associated sea level features.

Table 2.1: Definition of terms and associated sea level features

Period	Approximate C14 ages (BP)	Associated relative sea level feature
Holocene (Flandrian)	10000-present day	Main Postglacial Shoreline, Main Buried Beach, Low Buried Beach
Loch Lomond Stadial (Younger Dryas) — LATE DEVENSIAN	11000-10000	Main Lateglacial Shoreline (Buried Gravel Layer, Main Rock Platform) High Buried Beach
Lateglacial Interstadial — LATE DEVENSIAN	13000-11000	Angus and Kincardineshire Shorelines, East Fife Shorelines, Main Perth Shoreline, Main Wester Ross Shoreline, Jura shorelines

Numerical uplift models and provisional isobase maps have been constructed for Scotland that reconstruct the pattern of isostatic uplift of the land since deglaciation. These are described and their significance to the observed relative sea level patterns will be outlined. The vegetation history of Skye for the Late Devensian and Holocene has been well established and the patterns observed are summarised. Figures 1.2 and 2.1 show the location of all sites mentioned in the text.

2.2 The Late Devensian in Scotland

The last ice sheet to cover Scotland was centred in the Highlands and attained its maximum extent between *circa* 25000 BP-18000 BP (Sissons, 1967; 1976). It is generally accepted that much of the North Sea area was free of ice during the Late Devensian although an advance of ice, corresponding to the Dimlington Stadial, is thought to have been recorded in the eastern part of the North Sea (Sejrup *et al.*, 1994). The British ice sheet terminated off the east coast of Scotland at the Wee Bankie moraine and possibly the Bosies Bank Moraine (Sutherland, 1984; Bowen *et al.*, 1986) (Figure 2.2). End moraines of Late Devensian age are also believed to be present in the Minches where, the Greenstone Ridge, a large arcuate moraine 60 kilometres long, has been identified (Bishop and Jones, 1979; Chesher *et al.*, 1983). The last Scottish ice sheet moved south-westward across the north of the Irish Sea.

The Shetland Islands are believed to have been occupied by a separate ice cap during the maximum of the Late Devensian but it is unclear whether the Orkney Islands and the whole of Caithness were ice covered or affected by glacio-marine sedimentation during this period (Flinn, 1978; Sutherland, 1984; Bowen *et al.*, 1986; Sutherland, 1991). The Outer Hebrides may have supported its own ice cap and the extent of ice in the Sea of the Hebrides and Malin Sea is now generally considered to be less than previous models predicted (Boulton *et al.*, 1977; Andersen, 1981). The ice sheet is thought to have terminated at the north of Lewis (Sutherland, 1991). The evidence of independent ice caps on some islands together with ice free areas on the northern fringes imply that the Scottish ice sheet was limited in extent (Ballantyne, 1989; 1990; 1994; Ballantyne and McCarroll, 1995; McCarroll *et al.*, 1995; Dahl *et al.*, 1996). Boulton *et al.* (1977) in their maximum ice reconstruction indicate that the ice was over 1800m thick and all mountains were covered but trimlines and other geomorphological evidence point to nunataks having existed and a maximum thickness of not greater than 1300m (Sutherland, 1991; Ballantyne, 1994; Dahl *et al.*, 1996). Over-riding of the Highlands and western Southern Uplands is thought to have occurred based on the evidence of high altitude erratics in these areas (Sissons, 1967; Cornish, 1982) but some mountains in the northern Highlands are thought to have stood above the ice as nunataks (Ballantyne and Sutherland, 1987).

The Scottish ice sheet, centred in the Highlands, was elongated in a north-south direction from Sutherland to the Cowal Peninsula (Sissons, 1976; Boulton *et al.*, 1991). Ice flowed outwards from this area into the Central Highlands and the Southern Uplands and also flowed westwards (Figure 2.3). As glaciation progressed, the Southern Uplands ice increased in volume and deflected the Highland ice leading to a shift in the position of the main centre of accumulation, the northern centres being relatively weak at this stage. Sutherland (1984) has suggested two reasons for this; firstly, the North Atlantic Polar Front, which controlled cyclo- and frontogensis and dictated the position of the depressions, moved southwards and secondly, the presence of the ice sheet modified the climate in favour of anticyclonic conditions and excluded precipitation from many northern areas.

At some point after *circa* 18000 BP, deglaciation began, possibly with stillstands or readvances: for example, in Wester Ross a readvance has been recorded as marked by the Wester Ross moraine (Robinson and Ballantyne, 1979; Sissons and Dawson, 1981); in the south-west, a minor readvance or stillstand called the Otter Ferry Stage has been recorded (Sutherland, 1981); at Ardesier evidence of a glacial stillstand is present and a readvance is thought to have occurred at between 13000 BP and 13500 BP in Perth, Stirling and Strathmore and is known as the Perth Readvance (Sissons, 1967). A readvance has also been proposed in the western part of the North Sea at between 15000 BP and 14000 BP (Peacock, 1997). The Cromarty and Moray Firths were probably not ice free until 13500 BP (Peacock *et al.*, 1980) and most of the Southern Uplands and western Scotland are thought to have been ice free by 13000 BP (Bishop and Coope, 1977; Lowe and Walker, 1977). In coastal areas during deglaciation, glacio-marine sediments were deposited often in association with a high-arctic fauna as, for example, in the Errol Beds (Peacock, 1975; 1993). Isostatic rebound of the land occurred and as relative sea level fell, raised shorelines formed (Sissons *et al.*, 1966; Cullingford and Smith, 1966; 1980; Sissons, 1983b). In areas peripheral to the ice sheet, shorelines dating from deglaciation are now submerged.

From approximately 13000 BP until 11500 BP, a mild climate prevailed as the North Atlantic Polar Front migrated to the north of Scotland and the North Atlantic Drift reached the Scottish coast (Peacock and Harkness, 1990). Marine and atmospheric temperatures increased, possibly very rapidly, and relative sea level fell due to a rapidly rebounding land that outpaced the rate of regional glacio-eustatic sea level rise. Between 11500 BP and 11000 BP, when all or most of the mainland ice sheet had disappeared, the climate started to deteriorate as shown by vegetational and coleopteran records (Walker *et al.*, 1994). A return to arctic conditions signified the start of the Loch Lomond Stadial during which ice again built up on the land (Figure 2.3).

The pattern of glaciation at this time reflected different precipitation patterns, with the largest valley glaciers having a southerly aspect. Winds from the south and south-east brought precipitation and snow-blowing occurred as the winds blowing across warm or occluded fronts of depressions along the Polar Atmospheric front, veered south-west (Sissons, 1979; 1980). High snowfall occurred in the western Highlands and a large area of ice accumulation occurred over Rannoch Moor attaining a maximum thickness of over 400m (Sissons, 1979). Mean summer air temperatures are thought to have been 7-9°C below those at present (Walker *et al.*, 1994). Periglacial trimlines associated with the Loch Lomond ice are present in the Scottish Highlands (Sutherland, 1984).

Relative sea levels probably continued to fall through the Loch Lomond Stadial and the

Main Rock Platform (Main Lateglacial Shoreline) probably formed at this time (Dawson, 1988). It is possible that the mass of ice on the land during the Loch Lomond Stadial was of sufficient magnitude to redepress the land (Sutherland, 1984; Firth, 1986). In the western Forth valley relative sea level rose as the ice retreated and the High Buried Beach is reported to have formed seaward of the Menteith moraine (Sissons, 1966; 1983b; Sissons *et al.*, 1966; Sissons and Brooks, 1971). It is thought that deglaciation occurred sometime after 10300 BP when climatic amelioration began (Sissons, 1976; Sutherland, 1984).

2.3 The Late Devensian on Skye

Much work has been undertaken in recent years on reconstructing the glaciation of Skye (Ballantyne, 1988; 1989; 1990; 1994; Walker *et al.*, 1988; Ballantyne and Benn, 1991b; Benn *et al.*, 1992; Dahl *et al.*, 1996). However, views on the patterns of ice sheet movement have not changed substantially from the work undertaken at the beginning of the century (Harker, 1901; Clough and Harker, 1904; Peach *et al.*, 1910). The pattern of ice sheet glaciation on Skye established at this time is still considered to be correct for south and east Skye with a more northerly movement implied along the Trotternish Peninsula following the trend of the escarpment (Ballantyne, 1990) (Figure 2.4). Ballantyne and Benn (1991b) estimate the maximum extent of the Late Devensian glaciation to have occurred between 18000 BP-17000 BP on Skye.

The glacial history of Skye is usually considered in terms of three geological areas; the north, the central Cuillin mountain range and the south-east. South-east Skye was overwhelmed by the mainland ice sheet, striae in the landscape trending in a westerly or north-westerly direction (Ballantyne and Benn, 1991b). Mainland erratics are present in the Kyleakin Hills and also on the Sleat Peninsula and the shores of Loch Eishort. The northern confluence of the mainland ice sheet and the Skye ice mass occurred in the Sound of Raasay between the islands of Raasay and Scalpay (Harker, 1901).

The central Cuillin ice mass deflected the flow of the mainland ice sheet to the north and south, with the point of divergence occurring approximately at the site of Broadford as shown by mainland erratics that occur only in coastal localities (Harker, 1901) (Figure 2.4). The presence of these erratics and mainland erratics on Soay, indicates that the ice sheet came to within a few kilometres south of the Cuillins (Clough and Harker, 1904; Peach *et al.*, 1910; Ballantyne and Benn, 1991b). Conflicting evidence exists as to whether the ice cap over the Cuillins was almost encircled by the mainland ice sheet or whether a deflection to the east and along the Trotternish Peninsula occurred. Harker (1901) showed that locally-nourished ice moved southwards into Loch Slapin and Loch Scavaig, was deflected westward by mainland ice and became confluent with an ice stream that flowed through Glen Brittle. In the north of the Cuillins, Ballantyne and Benn (1991b) propose that Sligachan ice moved northwards across Scalpay and down Glen Varragill and ultimately along the Trotternish Ridge.

Little is known of the glaciation of the Duirnish and Waternish Peninsulas but on the Trotternish Peninsula the ice sheet was deflected along the trend of the escarpment with the ice in the west lying higher than that to the east. Evidence for north-easterly movement across the cols of the escarpment is in the form of roches moutonnées and ice-moulded bedrock (Ballantyne and Benn, 1991b). Anderson and Dunham (1966) noted that no evidence exists on the highest peaks of the Trotternish for glacial over-riding. Ballantyne (1990) identified a periglacial trimline on the escarpment from *in situ* weathered regolith, indicating that the maximum height of the last ice sheet descended from 580-610m in the south to 440-470m at its northern end. At the northern end of the escarpment all peaks over 500m support periglacially altered rock and some non-patterned ground in the form of earth hummocks (Ballantyne, 1990). The field evidence for the periglacial trimline is supported by studies on the gibbsitic content of samples above and below the trimline (Ballantyne, 1990; 1994). It was shown that samples above the trimline supported gibbsitic soils but those soils below were depleted in that mineral. Southwards extrapolation of the Trotternish ice surface indicates an altitude of 750-800m for south-central Skye ice (Ballantyne and Benn, 1991b). This would have been sufficient to overwhelm the Red Hills but nunataks would have existed in the Cuillins. Le Coeur (1994) calculated a maximum ice altitude of 750-780m in the Cuillins based on evidence of frost weathered rock pinnacles.

The trimline on Macleod's Tables in the north-west is thought to lie at 480m (Dahl *et al.*, 1996) (Figure 2.5). Dahl *et al.* (1996) have calculated the surface of mainland ice to have laid at approximately 750m and calculated basal shear stresses agree with this and are indicative of an ice mass moving over a rigid bed. The altitude at the centre of the Skye ice mass in the Cuillins, Blà Bheinn and Glamaig is thought to have been between 800-850m (Dahl *et al.*, 1996). The Skye ice mass between Blà Bheinn and the Cuillins radiated out northwards and north-westwards and the ice altitude on average decreases from 7.5-9.0mkm^{-1}. In the eastern Red Hills, it is also possible that a minor ice mass could have developed, for a considerable thickness of ice there implies deflection of the mainland ice.

It is possible that the mainland ice sheet was confluent with the Outer Hebridean ice cap based on calculations of altitude and gradient (Ballantyne, 1990; Dahl *et al.*, 1996) but the Skye ice mass did not overrun the Outer Hebrides. The mainland ice sheet is thought to have extended into the Minches and moved north with the Skye ice. An extensive glacial erosion surface of probable Late Devensian age is present in the South Minch and Sea of Hebrides (Dahl *et al.*, 1996). The mainland ice sheet is thought to have extended 25-40 kilometres north of the Trotternish Ridge, from calculations based on the gradient and altitude of the last ice sheet (Ballantyne and Benn, 1991b).

During the deglaciation of Skye, relative sea levels reached up to *circa* 30mOD as a result of the complex interplay between glacio-isostatic uplift and glacio-eustatic sea level rise (Clough and Harker, 1904; Peach *et al.*, 1910; Richards, 1971; Walker *et al.*, 1988). The presence of high raised beaches around Sleat and Kyleakin indicate that relative sea levels remained high until all mainland ice had disappeared (Walker *et al.*, 1988). Thereafter, a progressive fall in relative sea level occurred. The Loch Lomond Stadial is assumed to have been associated with low sea levels contrary to the views of Charlesworth (1956) who associated the Highland Readvance (generally considered to be the equivalent of the Loch Lomond Readvance) with a '100 foot shoreline' (Dawson, 1984).

Evidence for local glaciers on Skye during the Loch Lomond Stadial has been reported for over 150 years based on the presence of corrie moraines in the Cuillins and Red Hills (Forbes, 1846; Bonney, 1871). The presence of valley and corrie glaciers in the Cuillins was later recorded by Harker (1901) and Clough and Harker (1904) who noted end moraines that marked a radial movement outwards from this area and the presence of hummocky moraine in Kylerhea Glen.

Several authors have attempted to define the areal limits of the Loch Lomond Readvance. Charlesworth (1956) suggested the development of an independent icefield in the Cuillins and Red Hills during the Highland Readvance and proposed that small valley glaciers would have developed in the Kyleakin Hills and to the east of the Trotternish escarpment. Anderson and Dunham (1966) produced a map that indicated a more extensive readvance and Birks (1973) suggested two Lateglacial readvances. This involved an extensive local glaciation in the central mountain area prior to *circa* 12000 BP and regeneration of small Loch Lomond Stadial glaciers between *circa* 11000 BP and 10000 BP.

Mapping by Sissons (1977) showed the existence of twelve corrie glaciers, eight in the Black Cuillins, four in the Red Hills and a valley glacier at Coir'uisg. Walther (1984) proposed that the Loch Lomond Stadial ice occupied Glens Sligachan, Drynoch and Varragill implying that the glaciation was even more extensive. More recently, Ballantyne (1989; 1990) using detailed geomorphological mapping found that only one readvance had occurred, and Walker *et al.* (1988) estimated this to have occurred at between 11000 BP-

10000 BP on the basis of palynological evidence and radiocarbon dates. Additional evidence to establish the extent of the Loch Lomond glaciers exists in the form of Lateglacial raised marine features and *in situ* frost-shattered bedrock that are only present outside and above the proposed limits of the readvance (Walker *et al.*, 1988). It was found that a major icefield had existed in the Cuillins during the Loch Lomond Stadial and with 10 associated corrie glaciers, had occupied *circa* 155km^2 (Ballantyne, 1989; 1990). A smaller icefield of *circa* 10km^2 occupied the Kyleakin Hills and two corrie glaciers existed on the east of the Trotternish escarpment (Ballantyne, 1989; 1990).

Outlet glaciers from the central Cuillin icefield moved northwards down Glen Sligachan into Glen Drynoch, Glen Varragill and Loch Sligachan (Ballantyne and Benn, 1991b) (Figure 2.6). These glacier limits are marked by drift deposits, striae, ice-moulding, end and lateral moraines (*e.g.* at Sconser (NG 529317)) (Ballantyne and Benn, 1991b). The upper limits of the glaciers are marked by periglacial trimlines, although in the Red Hills trimlines are rare as a result of the resistant basic rocks and, therefore, a change from thick glacial drift to frost-shattered bedrock marks the ice sheet limit there (Ballantyne, 1989). North-south asymmetry is present in the Cuillin icefield with very low glacier surface gradients on outlet glaciers in the north (Ballantyne, 1989). The low gradients coincide with areas of thick streamlined subglacial deposits and deformable sediments at the base of the Varragill glacier may be responsible for this asymmetry (Ballantyne, 1989). The seven corrie glaciers on the western side of the Cuillin Ridge were originally mapped by Sissons (1977) (Figure 2.6).

In the eastern Red Hills, Sissons (1977) mapped the extent of the corrie glaciers, as delimited by end and lateral moraines which Ballantyne (1989) has confirmed. In the Kyleakin Hills, the Kylerhea Glacier moved eastwards to extend a short distance beyond the present coastline (Ballantyne, 1989). Periglacial trimlines mark the upper limits of the icefield. On the Trotternish Peninsula, evidence for only two locally nourished glaciers is present (Ballantyne, 1990); Coire Cuithir is marked by a lateral moraine (NG 475595) and Coire Scamadal is marked to the east by a moraine (NG 506554).

Ballantyne (1989) established mean equilibrium line altitudes (ELAs) for the Loch Lomond Readvance on Skye. The area weighted mean ELA for Skye is 319m and conforms to a general eastward rise in ELAs across the Inner Hebrides and western Highlands reflecting westerly airstreams during the Loch Lomond Stadial (Sissons, 1979; 1980). On a more local scale the trend for ELAs shows a decline in a north-easterly and easterly direction across the Cuillin and Kyleakin Hill icefields. This reflects the influence of westerly winds that blew snow across the ice-sheds (Ballantyne, 1989). Sissons (1979; 1980) proposed that snow-bearing winds during the Loch Lomond Stadial were southerly airstreams that preceded warm and occluded fronts but that south-westerly winds were dominant and responsible for blowing snow onto and across the ice fields. The reconstructed ELA for the Skye icefield at this time and comparable data from Norway enabled Ballantyne (1989) to predict the mean July sea surface temperature as approximately 6°C.

Deglaciation following the Loch Lomond Readvance appears to have occurred in two distinct phases (Benn *et al.*, 1992). The initial stage of glacier retreat was interrupted by stillstands and readvances that appear to reflect decreased snow accumulation as a result of decreased precipitation at this time. It is thought, from pollen-stratigraphic evidence, that the first stage of deglaciation occurred during the Loch Lomond Stadial. The second stage of glacier retreat is thought to have occurred relatively rapidly and was uninterrupted by readvances or stillstands. Local *in situ* ice stagnation occurred at this time and it is thought that the onset of Holocene thermal amelioration was responsible for this latter stage. Benn *et al.* (1992), however, report that increasing temperatures were not the primary forcing mechanism for glacier retreat and that increased aridity led to decreased snow accumulation and could have initiated the second stage of glacier retreat. The presence of high altitude source areas is thought to have been a factor enabling the ice to remain for so long.

2.4 Relative sea level changes in Scotland

Scotland has an extremely varied coastline that includes large estuarine areas in the east and south and deeply indented sea lochs in the west. During the Quaternary the shape and character of the coast has changed in response to ice sheet growth and decay and associated sea level changes. As a result of this glacial history, two components of sea level are present. The first is the glacio-eustatic change in sea level due to a range of factors, but particularly global changes in the volume of ice during the Quaternary. The second and more local factor is the isostatic response of Scotland due to the mass of its own ice sheet. Two components of isostasy are particularly important when considering sea level changes in glaciated areas. The first is glacio-isostasy, the concept of which was originally developed by Jamieson (1865) and refers to the state of equilibrium achieved by the lithosphere in response to glacial loading and unloading during glacial and interglacial cycles. The second component is hydro-isostasy and refers to the lithospheric response to water loading and unloading during the same glacial/interglacial cycles. All sea level changes recorded in Scotland are a combination of these components and, therefore, represent relative sea level changes.

At the maximum of the Devensian ice sheet (*circa* 18000 BP) regional sea level in north-west Europe, is thought to have been approximately 120m below present sea level (Mörner, 1971). In areas experiencing isostatic depression due to ice loading, however, relative sea levels were considerably higher than at present. For example, in Scotland during deglaciation of the Late Devensian ice sheet, isostatic rebound of the land occurred at broadly the same time as global sea levels were rising as the major world ice sheets melted. Transgressions occurred widely around the coastline, notably in formerly glaciated areas where the rate of sea level rise outpaced that of isostatic rebound of the land and relative regression occurred in formerly glaciated areas where the rate of land uplift was greater than that of sea level rise. Isostatic uplift of the land was greatest where the thickest ice had occurred. Shorelines are, therefore, progressively at a lower altitude, have a shallower gradient and extend further inland as they become younger *i.e.* are time -transgressive. The pattern of tilted shorelines in formerly glaciated areas is, therefore, due to differential isostatic uplift in conjunction with glacio-eustatic changes in sea level, for example, in the western Forth valley (Figure 2.7).

Scottish sea level studies utilise morphological or stratigraphical evidence or commonly a combination of both. Morphological work involves the mapping and surveying of shoreline features and the construction of shoreline-distance diagrams. Stratigraphical work involves detailed description and surveying of sediments complemented by micro- or macrofossil, geochemical or particle size analyses. Relative sea level graphs are constructed based on index points taken from tidal flat and lagoonal environments (*e.g.* Cullingford *et al.*, 1980; Haggart, 1986; Shennan *et al.*, 1993; 1995a; 1995b). Lambeck (1993a; 1993b) has additionally constructed relative sea level graphs based on different rheological earth models. Isobase maps have also been drawn, representing the patterns of land uplift indicated by the altitudes of particular shorelines.

2.5 Late Devensian relative sea level changes in Scotland

Relative sea level is thought to have fallen rapidly during the Late Devensian as a result of isostatic rebound of the land as deglaciation occurred. Some researchers believe the fall in relative sea level to have been continuous throughout the Late Devensian while others believe that the Loch Lomond Readvance was accompanied by renewed depression of the land that led to a minor transgression (Sutherland, 1984; Firth, 1986). Sissons (1981) believed this transgression to be of the magnitude of 6-7m and to have occurred at the end of the Loch Lomond Stadial and beginning of the Holocene. Relative sea level graphs extending back into the Late Devensian have been constructed for the western Forth valley and areas of western Scotland (*e.g.* Sissons, 1966; Sissons and Brooks, 1971; Sutherland, 1981; Peacock *et al.*, 1977; 1978; Shennan *et al.*, 1993; 1994; 1995a; 1995b).

Sea level features resulting from the Late Devensian consist of areas of sediments and erosional and depositional terraces. On the east coast of Scotland, shorelines relating to the Late Devensian include the Angus and Kincardineshire Shorelines, East Fife Shorelines, the Main Perth Shoreline, the Main Lateglacial Shoreline (Buried Gravel Layer) and the High Buried Beach. On the west coast the shorelines include the Main Rock Platform, a possible correlative of the Main Lateglacial Shoreline of the east coast and the Wester Ross Shoreline (*e.g.* Sissons, 1976; Gray, 1978; Robinson and Ballantyne, 1979; Sissons and Dawson, 1981; Gray and Ivanovich, 1988; Dawson, 1984; 1988). However, the extent of these shorelines and their ages are equivocal.

2.5.1 Late Devensian relative sea level changes in eastern Scotland

Some of the earliest marine features in Scotland have been recorded in Angus and Kincardine where eight Late Devensian shorelines have been recognised that relate to the westward retreat of the ice sheet (Cullingford and Smith, 1980). These terraces consist of sand and gravel occurring up to 40mOD and are often eastward extensions of glacial outwash. This sequence of terraces is also recorded in south-east Scotland in the East Fife shorelines (Cullingford and Smith, 1966). Six shorelines are present, each with a shallower gradient than its predecessor, the younger shorelines extending farther west as ice retreat continued. As these shorelines were reached, the Errol Beds, a deposit of red clays, silts and sands, characterised by a high arctic fauna, accumulated (Peacock, 1975; 1993). It is thought that the Errol Beds date from approximately 18000 BP until 13000 BP, the age range reflecting the different ice limits in different areas (Boulton *et al.*, 1991). Offshore equivalents of these may be recorded in the North Sea as characterised by the Fladen Member of the Witch Ground Formation (Long *et al.*, 1986).

Subsequently, the Perth Stage of deglaciation was marked by up to three raised shorelines in the Forth and Tay valleys (Sissons and Smith, 1965; Sissons *et al.*, 1966). The Perth shorelines slope eastwards with the higher shorelines sloping more steeply than the lower ones. The shorelines in the Forth valley and the highest in the sequence in the Tay valley merge into outwash and indicate significant pauses in ice retreat. It is estimated that whilst ice occupied the Forth valley, relative sea level at Stirling fell from 38mOD to 20mOD (Sissons *et al.*, 1966).

In the Moray Firth, Firth (1984) has identified a sequence of ten Lateglacial shorelines including shingle ridges which relate to a fall in relative sea level associated with south-westward retreat of the ice margin and are broadly similar to those in south-east Scotland. Relative sea level reached about 40mOD in the Ardesier-Inverness area and fell to 30mOD as the ice retreated (Firth, 1984). The Lateglacial shorelines must have formed before *circa* 11000 BP as the Main Lateglacial Shoreline cuts across deposits associated with them (Sissons, 1981; Firth, 1984). In contrast, Synge (1977) and Synge and Smith (1980) have attempted to explain this sequence by relating it to a readvance of the ice to Ardesier.

Continued isostatic uplift resulted in a low relative sea level and caused extensive marine erosion and the formation of the Buried Gravel Layer (Sissons, 1969). This shoreline is isostatically tilted and has been identified in the Forth valley and the Firth of Forth cutting across Lateglacial marine sediments (Figure 2.7). It is overlain by Holocene sediments and is thought to have formed towards the end of the Lateglacial (Sissons 1969; 1976). Sissons (1976) concluded that it had been formed during the severe conditions of the Loch Lomond Stadial and a similar feature has also been found in the Tay valley and Inner Beauly Firth (Cullingford, 1977; Sissons, 1981; Firth, 1984).

In the western Forth valley, the maximum of the Loch Lomond Readvance is considered by Sissons (1966; 1983b) to have coincided with a marine transgression which resulted in the deposition of a High Buried Beach at up to 12.2mOD. It occurs outside the limits of the Menteith moraine and probably formed across outwash as ice remained at the moraine (Sissons, 1966; 1983b). The relative rise in sea level was about 8m and is thought to have occurred due to renewed isostatic depression caused by the Loch Lomond Readvance glaciers (Sutherland, 1984; Firth, 1986).

2.5.2 Late Devensian relative sea level changes in western Scotland

On the western coast some of the earliest shorelines are recorded in Islay and Jura relating to ice sheet deglaciation (Dawson, 1982). The oldest terminates at the Central Islay moraine where it is found in association with outwash terraces. This shoreline declines south-westerly from 40m in north-west Jura to 15m in central Islay with a gradient of 0.59m km^{-1} which is similar to that of the highest East Fife shorelines. The second shoreline is about 2m lower, has a gradient of 0.56mkm^{-1} and is absent in western Jura indicating that the coastline was likely to have been ice-covered at this time (Dawson, 1982). In north-east Jura, the crest of a raised tombolo is recorded at 35mOD indicating formation after the Lateglacial shorelines and the high altitudes of these features indicate early deglaciation. Falling relative sea level, after deglaciation, is indicated by the formation of beach ridge staircases on the west coasts of Islay and Jura. A large beach ridge, the Colonsay Ridge at 19-20mOD, may mark a halt in deglaciation or a relative marine transgression (Dawson, 1982; Dawson *et al.,* 1997).

Raised shorelines occur in Wester Ross that are possible equivalents of the Main Perth Shoreline (Robinson and Ballantyne, 1979; Sissons and Dawson, 1981). The limit is marked by an end moraine, possibly marking a readvance of ice and reaches 24mOD with a gradient of 0.33-0.39mkm^{-1}. On Coll and Tiree, shorelines, with a gradient of 0.39mkm^{-1}, also appear to relate to this readvance (Dawson, 1994). In the Clyde estuary, the Clyde Beds, grey clays, silts and sands containing arctic-boreal marine fauna, occur up to 35mOD and suggest that deglaciation had occurred at the head of the Clyde by *circa* 13000 BP and in the Lower Clyde by *circa* 12600 BP (Bishop and Dickson, 1970; Peacock, 1971; Browne *et al.*, 1977; 1983). The formation of possibly eight shorelines in the south-west Highlands, that are clearly isostatically tilted, has been proposed in association with or just after the retreating ice sheet and prior to the disappearance of the Loch Lomond Readvance glaciers (Sutherland, 1981). The highest of these is thought to be correlated with the Main Perth Shoreline. At Otter Ferry, Sutherland (1981) proposes a rapid sea level fall from 13000 BP-12000 BP when relative sea level fell by 20-25m and a decelerating fall to 11000 BP of approximately 5-10m asssociated with a glacial readvance or stillstand.

A well-developed rock platform is found extensively on the western coast and has been called the Main Rock Platform (Gray, 1974a). The platform is part of a glacio-isostatically tilted shoreline that declines in altitude westward and is thought to be correlated with the Main Lateglacial Shoreline on the east coast. Dawson (1980b) estimated that the shoreline was associated with removal of rock of up to 1m^{3}m^{-1} of coast per year and that the severe conditions of the Loch Lomond Stadial, assisted by wave action, would have enabled this to occur (Sissons, 1974). Some researchers, however, believe that the platform is part of a composite feature (Brown and McMillan, 1984; Gray and Ivanovich, 1988). In northern Jura, the Main Rock Platform slopes from 6mOD to present sea level in northern Islay (Dawson, 1980a; 1988) and in Oban, the platform has an altitude of 10-11mOD and declines in altitude to the west and south-west so that in Ardnamurchan, north-east Islay, Kintyre, Colonsay and western Mull the platform passes below present sea level (Dawson, 1988). In the Loch Long/Loch Fyne area, the platform, backed by a cliffline, is tilted at 0.12mkm^{-1} and is frequently cut into Lateglacial river terraces (Sutherland, 1981).

In the area south of Loch Lomond, the deposition of the Clyde Beds was followed by the formation of a shore platform which has been correlated with the Main Rock Platform (Gray, 1974a; 1978; Sissons, 1974). In the south-west Highlands, the Main Rock Platform is tilted to the south and west (Gray, 1974a; 1978; Dawson, 1980a; 1988; Gray and Ivanovich, 1988) and is particularly prominent around the Firth of Lorn. In some areas of the south-west Highlands, the Main Rock Platform is absent and this could be due to eustatic sea level rise outpacing that of glacio-isostatic recovery (Gray, 1978). In the south

-west Highlands the scale of erosion that has occurred appears to be of a magnitude greater than in the north-west Highlands (Dawson, 1988). Relatively low sea level of not greater than 0mOD has been demonstrated at Redkirk Point on the Solway Firth between 12290±250 BP and 10300±185 BP (Jardine, 1975).

Shennan *et al.* (1993; 1994; 1995a; 1995b) have produced a relative sea level graph from the Late Devensian for the Arisaig area (Figure 2.8) based on isolation basin studies. They found relative sea level to have fallen from 17.8mOD at 11820±145 BP to 9.3mOD at 10755 BP, a fall of 8.5m in approximately 1000 years (Shennan *et al.*, 1993). A fall in relative sea level is recorded at 12040±110 BP at an altitude of 20.6mOD, at 11940±105 BP at 16.32mOD and at 11895±95 BP at 16.26mOD (Shennan *et al.,* 1996). At Loch nan Eala, relative sea level is reported to have fallen from 6.3mOD at 10500±90 BP to *circa* 5.2mOD at 10060±86 BP.

Studies in the Arisaig area show that during the Late Devensian no transgressive events are recorded, just a rapidly falling relative sea level (Figure 2.8). Peacock *et al.* (1977; 1978) also record this pattern of relative sea level. This is in contrast to studies undertaken on the Cowal Peninsula which indicate a possible transgression towards the end of the Loch Lomond Stadial (Sutherland, 1981) (Figure 2.9). Further evidence for this transgression exists in the Loch Lomond area where marine deposits are found overlying till deposited during the Stadial (Browne and McMillan, 1984). Relatively low sea level at the end of the Loch Lomond Stadial is proved by the altitudes to which outwash deposits descend at Loch Shiel, Mull, the Firth of Lorn and the southern end of Loch Lomond (McCann, 1966; Gray, 1975; Dickson *et al.*, 1978).

Lateglacial marine features on the southern islands of the Outer Hebrides are now submerged and it is thought that the ice was relatively thin and deglaciation took place early (Sissons, 1980). In the Shetland and Orkney Islands, marine features of Late Devensian age are also absent indicating that the archipelagoes have experienced submergence since deglaciation (Birnie *et al.*, 1993).

2.6 Late Devensian relative sea level changes on Skye

On the Isle of Skye there are several raised shorelines that relate to the Devensian: high rock platforms, low rock platforms and raised beaches (Richards, 1969; 1971). High rock platforms are present at several locations around the coast and lie between 17-30mOD. The platforms are thought to represent composite, isostatically uplifted features that may have been partially overridden by ice during fluctuations of the ice sheet margin. McCann (1968) argued that these platforms were interglacial in age due to evidence of glacial over-riding and were comparable to the platforms found on Mull, Jura and Islay at altitudes of between 25-51mOD. This interpretation was supported by Richards (1969, 1971) who observed that in northern and western Skye the platforms reach 150m in width and are overlaid with Lateglacial shingle up to 21mOD. In some locations, terraces cut into drift record the same altitude as the high rock platform. These platforms are best developed on the east coast of the Trotternish Peninsula and poorly developed on the west coast. Sissons (1982; 1983a) suggested that the high rock platforms were formed during the Devensian when parts of the coast were unglaciated. The platforms would, therefore, be associated with relatively restricted Devensian ice sheets that would have terminated in the Inner Hebrides (Sissons, 1982).

Low rock platforms at or close to present sea level are visible on several stretches of the coast and are particularly prominent around the Sleat Peninsula. Richards (1969; 1971) described a number of platforms between Portree and Staffin at altitudes of 2-7mOD. Cemented gravels are often present on the platform surface and within associated caves. In one cave (NG 523598) Richards observed till on top of the cemented gravels and assigned an interglacial age to them. They have a very fresh appearance and McCann (1968) suggested that these platforms could have formed during the Holocene. However, it is also possible that the platforms are the equivalent of the Main Rock Platform observed in other areas of Scotland and attributed to erosion during the Loch Lomond Stadial (Sissons, 1974; Gray, 1978; Dawson, 1983a). This is supported by the absence of these platforms in areas covered by Loch Lomond Readvance glaciers and agrees well with extrapolated isobases established for Ardnamurchan and Moidart (Dawson, 1988).

Raised Lateglacial marine terraces occuring up to 30mOD were first recorded by Clough and Harker (1904) between Kyleakin and Broadford and have been noted by other workers (Peach *et al.*, 1910; Richards, 1971; Walker *et al.*, 1988). The shorelines present over 15mOD are only present outside the mapped limit of the Loch Lomond Readvance glaciers and are mainly found on the outer coastlines and around the heads of the westernmost sea lochs (Walker *et al.*, 1988). These raised marine terraces slope westward from 30mOD at Kyleakin to approximately 15mOD at Loch Harport and are thought to represent the Lateglacial marine limit in this area (Walker *et al.*, 1988). In the area immediately east of Strollamus a distinct Lateglacial marine limit of beach sands and gravels occurs at altitudes over 23mOD only 250m beyond the margin of the Strath Beag glacier (Walker *et al.*, 1988). This clearly shows the relationship between the distribution of high raised shorelines and Loch Lomond glacier limits because within the margins of the Strath Beag glacier, the highest shoreline deposits are of Holocene age.

2.7 Holocene relative sea level changes in Scotland

During the Holocene, eustatic sea level rose due to the input of meltwater into the ocean basins, and in areas of Scotland less influenced by isostatic recovery this became the dominant component. Initially in the Holocene, isostatic recovery of the land led to a falling relative sea level, although areas with the greatest isostatic recovery initially experienced high sea level, *e.g.* in the western Forth valley (*e.g.* Sissons, 1966; Sissons and Brooks, 1971).

Ultimately, eustatic sea level rise overtook the isostatic rebound component and the Main Postglacial Transgression occurred. In the western Forth valley, the Tay estuary, the head of the Beauly Firth, the Solway Firth and the Firth of Clyde, this transgression was associated with the deposition of the 'carse clays' (*e.g.* Smith, 1968). The culmination of this transgression may have been time-transgressive and it was at this time that the Main Postglacial Shoreline was formed (Sissons *et al.*, 1966). A fall in relative sea level then occurred as a result of continued isostatic recovery of the land and a number of lower shorelines are found particularly in the carseland areas (*e.g.* Smith, 1968).

2.7.1 Holocene relative sea level changes in eastern Scotland

In the western Forth valley, Holocene relative sea level changes have been studied extensively (Sissons and Smith, 1965; Sissons, 1966; 1972; 1974; Smith, 1968; Sissons and Brooks, 1971; Smith *et al.*, 1978) and as such this area is often used as an informal model for other areas of Scotland. Isostatic recovery has been greatest in the western Forth valley and as a result an initially high relative sea level was experienced in the Holocene. The pattern of relative sea level changes are shown for the western Forth valley in a relative sea level graph (Sissons, 1966; Sissons and Brooks, 1971) (Figure 2.10). Two buried terraces have been identified within the morainic arc at the head of the Forth valley; the Main Buried Beach, which has formed on outwash and the Low Buried Beach indicated by the second and third index points on the relative sea level graph. They formed as relative sea level continued to fall from the Loch Lomond Stadial, reaching 11.5mOD and 8mOD and are dated to *circa* 9600 BP and *circa* 8700 BP respectively (Sissons, 1966; Sissons and Brooks, 1971).

The fall in relative sea level recorded by the Buried Beaches terminated at *circa* 8500 BP as indicated by the lowest altitude attained on the relative sea level graph. Equivalents of the Main Buried Beach have been found in the Tay area at 3.2mOD, the Beauly Firth at between 8.76mOD and 1.94mOD (Haggart, 1986) and in the Dornoch Firth at -2.1mOD and -1.7mOD (Smith *et al.*, 1992). An equivalent of the Low Buried Beach has also been found in the Tay area and its abandonment has been dated at *circa* 8800 BP (Cullingford *et al.*, 1989).

Subsequent to the Buried Beach deposition, the Main Postglacial Transgression is recorded during which extensive deposition of carse clays occurred and this is marked on all the relative sea level graphs as the highest points that relative sea level reached during the Holocene. The transgression was underway at most sites by *circa* 8500 BP and had ended by *circa* 6000 BP (Smith *et al.*, 1983). The shoreline formed at the culmination of the transgression is the Main Postglacial Shoreline and diachroneity of this shoreline is observed with shorelines closer to the centre of isostatic uplift forming earlier than those farther away. The highest altitudes attained for this shoreline are in the western Forth valley and the lower altitudes in other areas indicate that less isostatic recovery has been experienced there. In the western Forth valley, deposition of carse clays occurred up to 14.7mOD (Smith, 1968) and the transgression is thought to have culminated at *circa* 6800 BP (Robinson, 1993), in the Inner Moray Firth an altitude of 9.5mOD was attained (Haggart, 1982; 1986; 1987; Firth, 1984; Firth and Haggart, 1989), in the Dornoch Firth, 6mOD (Smith *et al.*, 1992), in the Lower Ythan valley, *circa* 4mOD with the culmination after 6100 BP (Smith *et al.*, 1991), in the Montrose Basin at 7mOD (Smith and Cullingford, 1985) and in the Wick River valley at 1.5mOD (Dawson and Smith, 1997).

At several locations around the coast a thin sand layer has been found within the deposit representing the Main Postglacial Transgression. This was originally thought to be a storm surge deposit (Smith *et al.*, 1983) but has subsequently been attributed to a tsunami deposit resulting from the second submarine Storegga Slide on the Norwegian Continental Slope, west of Norway (Dawson *et al.*, 1988; Long *et al.*, 1989). It has been dated at *circa* 7000 BP and has been recorded in the Forth valley, the Tay valley and the Moray Firth (Haggart, 1982; Dawson *et al.*, 1988; Smith *et al.*, 1985).

Following the Main Postglacial Transgression, later shorelines were formed, particularly in peripheral areas, as relative sea level fell. In the western Forth valley and on the Lothian coastline later Postglacial Shorelines have been identified as relative sea level fell intermittently (Smith, 1968; Robinson, 1982) (Figure 2.7) and in the Moray Firth four lower marine terraces are recorded representing stillstands in the regression of the sea as a result of continued isostatic recovery (Firth and Haggart, 1989). In the Philorth valley a brown silty clay is present at the top of the sequence and it is suggested that it started accumulating at 4760±60 BP due to a later rise of relative sea level (Smith *et al.*, 1982). It is believed that only in peripheral areas where isostatic recovery of the land was less than relative sea level rise, would later Holocene transgressions be recorded (Smith *et al.*, 1982). Rises in relative sea level have also been recorded in the Wick River valley at *circa* 4400 BP and *circa* 1200 BP (Dawson and Smith, 1997).

The trends in the relative sea level graph for the western Forth valley are also present in the relative sea level graph for Lower Strathearn (Cullingford *et al.*, 1980) (Figure 2.11). The lower altitude of the features indicates that less isostatic recovery had occurred in this area. Three relative sea level graphs are also shown for northern areas; one for the Inner Moray Firth (Haggart, 1982; 1986; 1987; Firth and Haggart, 1989), one for the Dornoch Firth (Smith *et al.*, 1992) and one for the Lower Ythan valley (Smith *et al.*, 1991) (Figure 2.12 and 2.13). The trends of the relative sea level graphs are similar with a falling limb to a minimum that is thought to have been reached in the Moray Firth between 9200 BP and 8748±100 BP (Peacock *et al.*, 1978; Haggart, 1982). A steep rising limb is shown, particularly in the Lower Ythan valley, until the time of the culmination of the Main Postglacial Transgression (Smith *et al.*, 1983). After the Main Postglacial Transgression, all sites show a fall in relative sea level, although in peripheral areas sea level may have stood at the maximum for longer.

2.7.2 Holocene relative sea level changes in western Scotland

In contrast to studies on the east coast, no high relative sea level has been recorded on the west coast in the early Holocene (Dawson, 1984). The Buried Beach sequences are not recorded and no tsunami deposits have been noted from the west coast. A rising relative sea level is recorded through the early Holocene that culminates in the formation of the Main Postglacial Shoreline. Vegetated shingle and beach ridges often mark the culmination of the Main Postglacial Transgression and terrace fragments are rare (Dawson, 1984). At some locations later Postglacial shorelines have also been recorded as relative sea level fell.

The early Holocene minimum is recorded at between 10060±86 BP and 8743±49 BP at Loch nan Eala, Arisaig (Shennan *et al.*, 1993; 1994; 1995a; 1995b; 1996) (Figure 2.8). At this site, a relative rise in sea level is first dated at approximately 8700 BP and in an upper basin at this site, at 8300 BP. This represents the Main Postglacial Transgression in this area and the maximum is constrained by the dates 6630±50 BP and 4010±50 BP and altitudes of 9.3mOD and 6.3mOD respectively. At Kentra Moss, Argyll, the Main Postglacial Transgression reached *circa* 7.7mOD although the timing of this is unclear (Shennan *et al.*, 1994). After the culmination of the Main Postglacial Transgression a number of regressive index points have been obtained from this area that indicate a falling relative sea level to the present day with no minor oscillations recorded (Shennan *et al.*, 1992; 1993; 1994; 1995a; 1995b).

The Main Postglacial Shoreline has been identified on eastern Mull at 12mOD (Gray, 1974b). Gray (1974b) reports that in Upper Loch Etive, the Main Postglacial Shoreline slopes from 14mOD to 11.5mOD at Salen on Mull with a gradient of 0.05m km^{-1} and reports that two later Postglacial shorelines are recorded at 8mOD and 4mOD there. In western Jura, most Holocene beach deposits overlie the rock surfaces of the Main Rock Platform and decline in altitude from north-west to south-west from 10mOD to 8.5mOD. Shingle ridges and shingle ridge staircases exist on south-west Jura that are related to the Main Postglacial Transgression and descend from 12.3mOD (Dawson, 1979; 1984; 1991). At Loch Gruinart in Islay, the Main Postglacial Transgression is thought to have been underway by *circa* 9100 BP and lasted until *circa* 2000 BP (Dawson and Dawson, 1997). It is thought that episodes of relative sea level rise after the Main Postglacial Transgression may be incorporated within this sequence. In Oronsay, Inner Hebrides, the Main Postglacial Transgression appears to have been in progress by *circa* 7420 BP and to have culminated between 6560-5660 BP (Dawson, 1984).

The sea is thought to have entered Loch Lomond at *circa* 6800-6650 BP, a date which coincides with the maximum of the Main Postglacial Transgression in the western Forth valley. In the area of Loch Long and Loch Fyne, the transgression was underway by 7800 BP and in the Clyde area, relative sea level began to rise until after about 7000 BP when sand and gravel ridges were built up to 12mOD (Sutherland, 1981). Relative sea level then fell allowing aeolian sands to be deposited on the ridges that then formed in the littoral zone. Sutherland (1981) identified five shorelines in the Clyde area that formed after the Main Postglacial Transgression in that area.

Jardine (1975) produced a relative sea level graph for the eastern Solway Firth (Figure 2.14) that shows a distinctly different shape from any others obtained for the Holocene suggesting that the isostatic and eustatic history of the area is somewhat different. The younger dates for the Main Postglacial Transgression indicate a more rapid relative sea level rise than in the Forth valley. It would have occurred in a shorter time interval, however, as the rate of isostatic rebound would have been less due to its location in relation to the centre of isostatic uplift (Haggart, 1989).

In south-west Scotland, the earliest record of the transgression is recorded at Carsethorn, Solway Firth, at 9400 BP and an altitude of -1.05mOD (Jardine, 1975) although doubt exists as to whether this represents a regressive or a transgressive contact (Haggart, 1982; 1989). At Redkirk Point, the Main Postglacial Transgression began at about 8100 BP and grey silts and clays, equivalent to the carse deposits of eastern Scotland overwhelmed areas of peat (Jardine, 1964; 1971; 1975; 1980). This is shown by the second index point on the relative sea level graph. At Newbie, the transgression is recorded at between 7500 BP-7200 BP at altitudes of 2.95mOD and -5.8mOD and this is thought to show the diachroneity of the transgression along the shores of the Solway Firth (Jardine 1975; 1980). It is thought that by 7200 BP the maximum lateral extent of relative sea level rise had been attained but not necessarily its greatest altitude. Regression of the sea from this area occurred at 6645±120 BP at Lochar Moss and at Midtown at 6470±280 BP although at both these sites the sea may have been excluded from the area due to the development of beach ridges (Jardine, 1975). At Moss of Cree, peat accumulation following withdrawal of the sea did not commence until 5010±80 BP and the Main Postglacial Transgression in this area did not cease until 5500 BP (Jardine, 1975). At West Preston, Solway Firth, at 1850±95 BP the sea stood about 1m above present mean sea level and this is shown by the final index point on the relative sea level graph (Jardine, 1975).

In the Outer Hebrides, Shetland and Orkney Islands submergence has prevailed and relative sea levels are, therefore, preserved in offshore or nearshore sediments. Ritchie (1966) found no raised Postglacial beaches on the Outer Hebrides and, therefore, concluded that the Main Postglacial Transgression reached no higher than present and occurred prior to 5700 BP. During the last 5000 years the development of sand dunes and machair systems has occurred in the Outer Hebrides (Ritchie, 1966; 1979). Submerged peat beds are frequent in the Outer Hebrides and indicate a rise in relative sea level in recent times but it is unclear whether these were formed before, during or after the Main Postglacial Transgression. At Borve (Lewis), between 8800 BP-5200 BP, relative sea level was 3-5m lower than at present (Ritchie, 1985) and has subsequently risen by 5m resulting in landward migration of the shoreline.

2.8 Holocene relative sea level changes on Skye

Little work has been undertaken on Holocene relative sea level changes on Skye, although some mapping of raised marine features has occurred (Richards, 1971; Walker *et al.*, 1988). Raised beaches that formed during or following the culmination of the Main Postglacial Transgression are, however, widespread. In exposed areas, vegetated shingle ridges are present and in areas such as Peinchorran, tombolos have formed. At The Braes, a low fossil spit representing the Main Postglacial Shoreline has an altitude of *circa* 7mOD and at Staffin Bay, the Main Postglacial Shoreline lies at *circa* 6-7mOD (Benn, 1991). Within the Loch Lomond Readvance limits, erosional terraces related to the Main Postglacial Shoreline are cut across moraines (Ballantyne and Benn, 1991). The Postglacial features recorded on Skye occur up to 10mOD and although the exact timing of the Main Postglacial Transgression on Skye is unknown, dates from other areas of western Scotland suggest that the transgression may have occurred between 7000 BP-5500 BP (Dawson, 1984). The gradient of the Main Postglacial Shoreline on Skye is also unknown, although generalised isobases for the shoreline in western Scotland suggest that it slopes westward from *circa* 10mOD near Kyleakin to *circa* 6mOD in Duirnish, Waternish and northern Trotternish (Sissons, 1983a).

2.9 Isobase maps and shoreline diagrams

Models have been constructed to enable shoreline altitudes to be correlated between different areas. Typically, a shoreline equidistant diagram is used, with a linear x-axis that is produced by projecting the altitude in a limited area into a plane drawn at right angles to the slope of the uplifted surface. The line of projection is rotated until the best statistical alignment of points is established. Shoreline displacement, however, occurs within three dimensions and isobase maps have been produced, the earliest ones being hand drawn and plotting the zero isobase of the '25 foot' raised beach (*e.g.* Wright, 1911; Movius, 1942). More recently trend surface analysis has been used to establish regional trends by fitting polynomial equations of a certain order to a least squares set of data (Gray, 1983). Isobase maps have been produced using trend-surface analysis for the Main Lateglacial Shoreline, Main Postglacial Shoreline and a later Holocene shoreline (Smith *et al.*, 1969; Gray, 1978; Cullingford and Smith, 1980; Firth and Haggart, 1989; 1991; Cullingford *et al.*, 1991; Smith *et al.*, 1992; Firth *et al.*, 1993) (Figure 2.15).

When the isobases for these shorelines are compared, it is possible to hypothesise about the movement of the centre of isostatic uplift. A movement of around 50km to the south-south-east for the Main Lateglacial Shoreline has been suggested as a result of the renewed growth of the Loch Lomond glaciers in the western Highlands (Gray, 1983). Tectonic movements in the North Sea Basin and differential hydro-isostatic loading could be reflected in the steeper gradients to the north and east (Gray, 1983; Firth *et al.*, 1993). A north-east movement of the centre of uplift has been suggested from the Main Postglacial Shoreline to a late Holocene Shoreline and a rotation of the dome of uplift to the west, again possibly reflecting the increased influence of hydro-isostatic loading on the continental shelves (Gray, 1983; Firth *et al.*, 1993). The ice dome as suggested by the quartic model (Gray, 1983; Firth *et al.*, 1993) could have divided into two, reflecting either two centres of accumulation in the Loch Lomond Stadial (Boulton *et al.*, 1991) or differential glacio-isostatic recovery of areas as a result of the development of the Loch Lomond Stadial ice mass. In contrast to previous studies, it has been suggested that the

Loch Lomond Stadial ice mass may have had a significant effect on the redepression of the lithosphere shifting the centre of uplift and slowing the rate of crustal rebound (Gray, 1983; Sutherland, 1984; Firth, 1986; Firth and Haggart, 1989; Boulton *et al.*, 1991).

Gradients of shorelines provide crude measurements of differential uplift since the formation of the features and can be compared to assess the isostatic impact of the Loch Lomond Stadial ice mass. The Main Lateglacial Shoreline has a steeper gradient than some earlier Late Devensian shorelines indicating that it has been subjected to increased differential uplift possibly due to a redepression of the earth's crust during the Loch Lomond Stadial (Sutherland, 1984). Distance from the uplift centre also is important in considering the gradients of individual shorelines (Firth *et al.*, 1993). Dislocations of shorelines have also been reported due either to reactivation of faultlines that are present or to block uplift that occurs in preference to tilting as in the Forth valley (Sissons, 1972; Sissons and Cornish, 1982). It is also suggested that shoreline dislocations may have occurred in areas approximately 15km from the margins of the Loch Lomond Stadial ice mass where continued uplift and renewed redepression occur in close proximity (Gray, 1974b).

There are several shortcomings of these models, the most obvious being the small number of data points used in constructing the isobase maps. Other errors include the different type of shore feature measured and the diachroneity of shorelines. These problems have been outlined by many authors (*e.g.* Tooley, 1978; Jardine, 1981; Haggart, 1989) and it is clear that these models need to be tested in the field and corrections made where appropriate. Gray (1972) also outlines three reasons why trend-surface analysis may not be wholly appropriate for shoreline correlation in Scotland: firstly, the data consists of clusters of heights; secondly the heights on a single fragment are automatically correlated with each other and, therefore, not independent and thirdly, the residuals are not normally distributed and this could lead to autocorrelation of altitudes. Gray (1972) attempted to overcome some of these shortcomings by ensuring that each shoreline fragment or group of altitudes is represented by a single altitude representing the mean of the heights.

Shennan *et al.* (1993; 1995a) have found significant differences between the altitudes observed in the field of marine sediments thought to relate to the Main Lateglacial Shoreline and the Main Postglacial Shoreline and those predicted from the empirical models, from studies in western Scotland. The isobase for the Main Lateglacial Shoreline in this area is predicted to lie at 5mOD (Firth and Haggart, 1989). Data from the sites investigated indicate that for the last 1000 years of the Lateglacial Interstadial relative sea level fell from 17.8mOD to 9.3mOD and continued to fall to 6.3mOD by 10500 BP (Shennan *et al.*, 1995). The altitudes obtained for relative sea level during the Loch Lomond Stadial fit reasonably well with the altitude predicted for the Main Lateglacial Shoreline but do not suggest a stable or slowly falling relative sea level during this time that may have been necessary for the formation of the Main Lateglacial Shoreline (Shennan *et al.*, 1993; 1995a). The Main Postglacial Shoreline in this area is predicted to lie between 10mOD and 12mOD according to the model of Sissons (1983b) but data from this area indicates a Holocene maximum relative sea level of between 6.3mOD and 9.3mOD (mean sea level) for the Arisaig area and 7.7mOD at Kentra Moss in Moidart.

2.10 Rheological models of isostatic rebound

Lambeck (1990; 1991; 1993a; 1993b) has also developed models of isostatic rebound, relative sea level change and mantle viscosity. The aim of these models is to provide constraints on the Earth's response to surface loading, determine the dimensions of the ice sheet and timing of deglaciation. They provide a method of testing hypotheses relating to each of these variables and discrepancies should be considered as ways to improve the models. A sea level equation is constructed that takes into account the ice distribution on the land and Earth's response to it, the time and rate of meltwater addition or subtraction to the oceans and ocean geometry. An equipotential factor is also included of gravitational self-attraction of the water and ice. Three fields of ice are considered; near, intermediate and far. Lambeck (1993a; 1993b) considered a maximal and minimal reconstruction of the ice sheet with the minimum representing 20% of the maximum (Boulton *et al.*, 1977; Boulton *et al.*, 1985) and only considered the upper mantle due to the relatively small size of the British ice sheet. The Loch Lomond Readvance is considered to be only 1% of the volume of the maximum Devensian glaciation in the United Kingdom. Lambeck (1993a) found that the minimum ice reconstruction by Boulton *et al.* (1985) did not contain sufficient ice to produce the observed raised shorelines in the landscape. The maximum reconstruction where the Fennoscandian and British ice sheets merge in the North Sea (Boulton *et al.*, 1977) appears to fit the observations better but also has problems. Lambeck (1993b) suggests that an ice sheet terminating at the Wee Bankie moraine could provide a suitable compromise.

In the maximum model, the centre of ice accumulation was initially situated over Aberdeen, and then migrated over Rannoch Moor, although field evidence suggests that since 15000 BP, the ice centre had been over the western Highlands (Sutherland, 1984). However, in the Forth and Tay areas there is good agreement between observed and predicted sea levels although in the Moray and Beauly Firth area there is a need to increase the ice load over Ross and Cromarty or alter the model. The predictions in the west of Scotland agree with observed heights and in the Outer Hebrides and Orkney the shorelines formed since the Late Devensian are predicted to lie below present sea level. Shennan *et al.* (1995a) have found the general trends of rebound to be consistent with Lambeck's (1991; 1993b) models although the timing of the Lateglacial fall in relative sea level appears to be in error, being recorded later at Rumach and Loch nan Eala. The observed and predicted gradients of the Main Postglacial Shoreline from the Solway Firth to Morecambe Bay also agree well with the models (Lambeck, 1991; 1993b). It can be concluded as a result of the close correlation between the observed and predicted values of shorelines that no major tectonic activity has occurred other than isostatic effects.

Several shortcomings of these models can be identified. Firstly the resolution is not sufficiently high to identify small scale fluctuations in relative sea level. Lambeck (1993a; 1993b) assumes ice thicknesses that Dahl *et al.* (1996) have now shown to be probably in error and this has serious implications for the accuracy of the models. Account should also be taken of previous glacial cycles as they could affect the isostatic régime of the lithosphere especially as equilibrium may not have been achieved. Lambeck (1993a) also acknowledges that at sites near to the margin of the ice sheet the water-load term is in error. An assumption is made that the ice sheet at the maximum of the Late Devensian is in dynamic equilibrium which is not necessarily true. The models of Lambeck (1991; 1993a; 1993b) are based on the use of radiocarbon dates which are affected by radiocarbon plateaux (a clustering af radiocarbon dates caused by reduced ^{14}C concentration in the atmosphere) in the Lateglacial (Lowe and Walker, 1997). Errors are also introduced when applying these models to the British Isles because the absolute amount of crustal uplift is considerably smaller than in Scandinavia where the models were developed. Errors in Scandinavia associated with measurement of shorelines do not, therefore, affect the rheological models that are produced but in Scotland, errors in the measurement of shorelines can greatly distort the results.

2.11 Vegetational history of the Isle of Skye

In recent years, the Isle of Skye has become the focus of intensive palaeoecological investigations and over 20 pollen diagrams now exist for the island. Vasari and Vasari (1968) published Holocene profiles for Loch Cuithir (NG 476597) and Loch Fada (NG 457697) and Birks (1973) produced pollen sequences for five sites, Loch Cill Chroisd (NG 610204), Loch Meodal (NG 657111), Loch Mealt (NG 505650), Lochan Coir' a' Ghobhainn (NG 417183) and Loch Fada spanning the Lateglacial and early Holocene. Williams (1977) completed the Holocene part of the Loch Meodal profile and published Holocene profiles from Loch Ashik (NG 691233) and Loch Cleat (NG 447672). Birks and

Williams (1983) synthesised this work and Walther (1984) investigated more sites from around the Cuillins. More recently, work undertaken by Walker and Lowe (1990) from Druim Loch (NG 493418) and Slochd Dubh (NG 403170) appears to suggest that some of the earlier profiles of supposed Lateglacial age (Birks, 1973) in fact are early Holocene (Lowe, pers. comm.). It is thought, however, that Lateglacial records are present from Loch Cill Chroisd, Loch Ashik and Lochan Coir' a' Ghobhainn (Birks, 1973; Walker and Lowe, 1991) (Figure 2.16).

Walker *et al.* (1994) have produced a synthesis of Late Devensian/Weichselian environmental changes for north-west Europe. This includes information on geomorphology, soils, vegetation history and climate for the Scottish Highlands and islands (Figure 2.17). These summary charts show that by 13000 BP most of Scotland was ice-free and the higher temperatures experienced between 13000 BP and 12000 BP allowed the expansion of vegetation and development of soils. A short-lived revertance to colder conditions is recorded at between 12000 BP and 11800 BP and this is marked by increased erosion and colonisation by open habitat, pioneering species. The Loch Lomond Stadial is marked by a decrease in temperature resulting in a periglacial régime with tundra vegetation recorded and gelifluction and solifluction processes leading to the break up of interstadial soils. The mean July summer air temperature during the stadial in Scotland has been calculated at 6°C. At the beginning of the Holocene, a rapid increase in temperature occurred and this resulted in pedogenesis, renewed fluvial activity and the melting of permafrost. Woodland became established in protected areas as a result of succession from grassland and heathland.

2.11.1 Late Devensian vegetational history

As the climate started to ameliorate following deglaciation of the Devensian ice sheet at approximately 13300 BP (Sutherland, 1984) open habitat, pioneer taxa colonised the skeletal soils (Birks, 1973; Birks and Williams, 1983; Walker *et al.*, 1988; Walker and Lowe, 1990). The families and genera included Poaceae, Cyperaceae, Caryophyllaceae, *Artemisia*, Asteroideae and Lactuceae. The low quantities of arboreal taxa recorded probably represent a long distance component although *Salix* was present (Walker and Lowe, 1990). After the initial stage in colonisation, some succession to dwarf shrub heath and open grassland occurred throughout Skye with *Juniperus* and acidophilous *Empetrum* and Ericaceae heathland becoming dominant (Walker and Lowe, 1990). The Cuillin mountain range afforded protection from the dominant south-westerly winds and sites in its lee record stands of *Betula* with continued presence of *Salix*. Differences at this time appear in the pollen assemblages and reflect exposure, aspect and to a lesser extent geology and topography. In exposed locations, therefore, *Betula* and *Juniperus* development was sparse in distribution and Poaceae and heath communities developed, *e.g.* at Loch Ashik and Loch Cill Chroisd the development of *Empetrum* and Ericaceae are recorded (Birks, 1973; Birks and Williams, 1983; Walker *et al.*, 1988; Walker and Lowe, 1990).

It is thought that between 13300 BP and 12500 BP, the average summer air temperature may have reached in the region of 17°C (Atkinson *et al.*, 1987) but by about 12000 BP cooling had occurred, marked in the pollen diagrams by a decline in *Juniperus* and *Empetrum* pollen. At the same time an increase is noted in families and genera that colonise disturbed soils such as *Rumex*, Caryophyllaceae, *Salix* and *Lycopodium* (Walker and Lowe, 1990). This may correlate with the observations of Atkinson *et al.* (1987) who suggest that between 12300 BP and 11800 BP a fall of up to 10°C in the mean air temperatures of the winter months may have occurred. This revertance period is noted at Loch Ashik and dated at 12550±280 BP and 12400±200 BP, although these dates may be affected by a hard water error (Walker *et al.*, 1988; Walker and Lowe, 1990). The profiles from Loch Cill Chroisd, Elgol and Slochd Dubh also record this disturbance in the succession suggesting that the revertance period was representative of regional environmental or climatic change (Birks, 1973; Birks and Williams, 1983; Walker and Lowe, 1990). At Slochd Dubh and at Loch Ashik, the revertance period is marked by an increase in deteriorated pollen that showed signs of exine damage.

During the Loch Lomond Stadial, a tundra-type vegetation, dominated by families such as Poaceae and Cyperaceae, replaced the heathland (Walker and Lowe, 1991). Increased erosion is thought to have occurred at this time and stratigraphical changes are recorded from organic to minerogenic sedimentation (Walker and Lowe, 1990). In the south and west, areas exposed to the onshore winds, tundra vegetation almost entirely dominated as a result of areas of bare and unstable soils. At Slochd Dubh and Elgol, species of *Artemisia*, *Rumex* and *Lycopodium*, *Selaginella selaginoides* and *H. selago* dominated and at Lochan Coir' a' Gobhainn, dwarf shrub pollen dominated (Birks, 1973; Birks and Williams, 1983; Walker *et al.*, 1988; Walker and Lowe, 1990). In the north and the east, in the lee of the Cuillins, during the Loch Lomond Stadial, a tundra vegetation existed alongside some heathland species. At Druim Loch, Poaceae, Cyperaceae and *Empetrum* dominated the pollen assemblage with other elements including Pteropsida, *Lycopodium* species, *H. selago* and *Salix* occurring. The presence of *Betula* in this assemblage is thought to represent long distance transport (Walker *et al.*, 1988).

It is possible that some areas of permanent or semi-permanent snow cover existed in the lee of the Cuillins and Red Hills, as shown by the relatively low frequencies of *Artemisia* and

Rumex pollen at Loch Cill Chroisd, Loch Ashik and Druim Loch (Birks, 1973; Birks and Williams, 1983; Walker and Lowe, 1990). An important feature of pollen diagrams representing the Loch Lomond Stadial is the increase in deteriorated pollen and the general sparsity of the pollen grains (Birks, 1973; Birks and Williams, 1983; Walker *et al.,* 1988; Walker and Lowe, 1990). Many of the pollen grains encountered show signs of exine damage suggesting that increased soil erosion occurred at this time as a result of climatic deterioration. Pollen was transported and underwent corrosion, breakage and crumpling. This is recorded at Loch Ashik, Druim Loch and Slochd Dubh and Birks (1973) records 88% deteriorated pollen, representing the Loch Lomond Stadial, at the base of the Loch Cill Chroisd assemblage.

2.11.2 Holocene vegetational history

The transition from the Loch Lomond Stadial to the early Holocene is marked by the succession from grass-sedge communities of the tundra landscape to birch and hazel woodlands (Walker and Lowe, 1990). High *Juniperus* frequencies are recorded at Druim Loch, at Loch Ashik between 10330±80 BP and 9540±70 BP (Williams, 1977) and at Loch Meodal prior to 9700 BP (Birks and Williams, 1983). Sites protected by the Cuillins developed birch woodland and *Juniperus* scrub but those sites in exposed locations developed open grassland and dwarf shrubland following the Loch Lomond Stadial.

During the early Holocene, Lowe and Walker (1991) report a short-lived revertance period from two sites on Skye which could have affected the vegetation patterns. At Glen Arroch (NG 753208), Lowe and Walker (1991) record a minor climatic revertance shown in the profiles by reductions in *Empetrum*, *Juniperus* and *Corylus* and their replacement with *Rumex* and *Lycopodium*. This pattern is also thought to be recorded in the lowermost sequences of the Varragil (NG 473349) profile at around 10220 ±150 BP and 9590±90 BP (Walker *et al.*, 1988) and would appear to reflect ice wastage from the Loch Lomond Stadial. Work undertaken on the Island of Mull (Walker and Lowe, 1987) also records this climatic oscillation.

Birks and Williams (1983) report that around 9700 BP, birch and hazel woodland developed with communities of ferns as the temperature again increased. At Loch Meodal, *Betula,* at this time, accounts for over 40% of the sum (total land pollen) and at Loch Ashik, between 25% and 30% of the total land pollen (Williams, 1977; Birks and Williams, 1983). Southern Skye would have been the most densely wooded, eastern Skye would have supported woodland that was confined to the steep slopes and northern Skye would have supported tree growth only in sheltered, rocky locations.

At Loch Meodal and Loch Cleat during the early Holocene, *Salix, Populus* and *Viburnum* are recorded with tall herb communities characterised by *Filipendula ulmaria, Angelica sylvestris* and *Rumex acetosa.* At about 9000 BP, *Quercus* and *Ulmus* pollen are recorded although at low frequencies and *Alnus* appears in the pollen assemblages at about 6500 BP. It is reported that *Alnus* often expanded at the expense of *Salix* and formed mixed birch -hazel-alder woodlands (Birks and Williams, 1983). At Loch Ashik, an age of 6360±80 BP has been obtained for the *Alnus* rise and at Loch Meodal at 6500 BP (Williams, 1977). *Pinus,* which is present throughout the Holocene, records a short-lived expansion at Loch Ashik and this is dated at between 4600 BP and 3900 BP (Williams, 1977; Birks and Williams, 1983).

Other woodland communities continued to thrive until about 5200 BP when anthropogenic activities affected sites in Skye. At Loch Meodal, forest clearance began at this time, characterised by the spread of grassland and heath (Williams, 1977). By 4200 BP, the environment was still mainly wooded although acid heathlands, grasslands and bogs had developed (Williams, 1977; Birks and Williams, 1983). At approximately 1600 BP, an increase in *Calluna vulgaris* occurred at Loch Meodal (Williams, 1977). Anthropogenic indicators, including *Plantago lanceolata*, Chenopodiaceae, Brassicaceae and *Trifolium*-type pollen, are also present in the northern sites from about 5000 BP onwards and suggest that the fertile soils were exploited for agriculture and habitation. Contemporaneous with these species is the decrease in *Betula* and *Corylus avellana*-type pollen indicating scrub clearance at this time. At Loch Ashik *Calluna* expansion occurred at approximately 4000 BP in asssociation with *Sphagnum* indicating acidification of the environment (Birks and Williams, 1983). By 2700 BP, bog and heath were dominant at Loch Ashik and stands of *Betula* were extremely sparse (Birks and Williams, 1983). There are no archaeological remains from the Neolithic or Bronze Age on Skye but abundant Iron Age remains are preserved in northern Skye (Lowe and Walker, 1991). In the last 700 years, the Trotternish Peninsula has been entirely cleared of trees and cereal-type pollen is recorded in high quantities from this time (Birks and Williams, 1983). At Loch Meodal, during the last 300 years, widespread forest clearance has led to a decrease in *Calluna* moor and a large increase in grassland (Williams, 1977; Birks and Williams, 1983).

This pattern of Holocene succession follows broadly the pollen assemblage zones established for northern Britain (Lowe and Walker, 1991). However, lower amounts of tree pollen are generally recorded on Skye and *Betula* and *Corylus* dominate the Holocene woodland. It also appears that forest clearance occurred earlier on the Trotternish Peninsula than in other areas of Skye due to the fertile basaltic soils that are present and, therefore, were conducive to early settlement. In the north and centre of the island open *Betula*-

Corylus forest dominated while in the south and south-east a closed *Quercus* forest dominated possibly reflecting climatic differences (Birks and Williams, 1983).

2.12 Conclusions

This chapter has summarised the wealth of literature that is available for Late Devensian and Holocene on glacial events and relative sea level changes for Scotland and in particular the Isle of Skye. Since the 1960s, much data has been generated on relative sea level changes around the coast of Scotland. Distinct patterns of shorelines and trends in relative sea levels have emerged from regions situated close to the centre of isostatic uplift and those in more peripheral areas. Differences have also emerged in data from the west and east coast suggesting that the western Forth valley may not reflect typical relative sea level changes since the Late Devensian. As increasingly more data for Scotland was generated, isobase models were developed relating to general patterns of isostatic uplift experienced since deglaciation. These took the form of trend-surface analysis of shoreline altitudes and theoretical models based on different earth models, ice thickness and areal extent. At present these models are still insufficient to explain all the patterns measured around the coast of Scotland and are constantly being tested.

On Skye, particularly in the last ten years, extensive work has been undertaken on mapping periglacial trimlines associated with the Late Devensian ice sheet and limits of the Loch Lomond Stadial, both horizontally to obtain areal dimensions and vertically to ascertain the ice thickness. These are both known in considerable detail now. Palynological studies were used to test the readvance limits of the Loch Lomond ice and as a result over 20 pollen diagrams now exist for this island and complement Birks' (1973) earlier studies. Unlike many areas of Scotland, however, Skye is still deficient in detailed patterns of Late Devensian and Holocene relative sea level changes. This study attempts to remedy this deficiency.

Chapter 3.0 Methodology and techniques of analysis

3.1 Introduction

The methodology employed in this research is one of determining sea level changes from detailed litho- and biostratigraphical investigations. This approach has been increasingly used in sea level studies in Scotland and is based on identifying the transitions in deposits from marine to terrestrial, and *vice versa,* that are preserved in a vertical sequence. Skye possesses a deeply indented, rocky coastline, characterised by high energy marine conditions and preservation of sediments is, therefore, largely confined to isolation basin and barrier sites.

Two main criteria were important in identifying sites for this study. The site had to occupy a low-lying coastal location, where preservation of marine sediments dating from the Late Devensian was likely. The isobase model for the Main Postglacial Shoreline predicts that the altitude on Skye of this shoreline should lie below 10mOD and this, therefore, provided some altitudinal constraint for the sites (Firth *et al.*, 1993). Secondly, the site had to preserve microfossils as these were to be utilised to identify environmental changes. A site with low microbial activity and anaerobic conditions, such as a peat bog or palaeo-lake environment, was, therefore, sought.

The aims of the research also required that the sites;

i) were situated to span the proposed isobases for the Isle of Skye in order to test the validity of the isobase models as fully as possible (Sissons, 1976; Lambeck 1991; 1993a; 1993b; Firth *et al.*, 1993);

ii) were located at varying distances from the central Cuillin mountain range to ascertain if any effects of the Loch Lomond ice mass that developed in this area could be identified;

iii) included different geomorphological settings so that their effect on the preservation of the sea level record could be investigated.

It was necessary to study several sites as the sea level record may be fragmentary at any particular site.

3.2 Fieldwork

Investigations were undertaken in the field to determine the lithostratigraphy of the site and to map and level the geomorphological features. It was essential to ascertain the nature and extent of stratigraphical horizons at the site in as much detail as possible to increase understanding of the sediments, origins and processes of deposition. Development and form of the deposits are the product of topography, erosion, deposition, consolidation and compaction as well as sea level (Devoy, 1977). Geomorphological mapping and levelling of all features was also essential to develop an understanding of the depositional environment.

3.2.1 Determining the stratigraphy and sampling the site

A 1m Eijelkamp gouge was used to determine the stratigraphy of the site. A grid system was established for larger sites on a 100m base with closer spaced borings where the stratigraphy was seen to change rapidly. A 40m grid system was used for smaller sites. At the isolation basin sites, intensive borings were undertaken around the sill of the basin to accurately establish its lowest altitude. The stratigraphy of each borehole was described and recorded in the field and stratigraphical diagrams drawn up using a modified version of Troels-Smith's (1955) symbols for unconsolidated sediments. Dashed lines are used to correlate the same stratigraphic units to aid interpretation. A representative borehole was sampled, often from the deepest part of the basin, in order to obtain the most complete record of environmental change. The borehole had to show no signs of sediment disturbance and be situated as far as possible away from the influence of fluvial activity and any slopewash. Sampling was undertaken using a Stitz powered corer (a vibracorer) which takes samples of 1.4m length and a Russian sediment sampler with a chamber of 0.50m or 0.30m length. Two parallel holes were cored to provide an overlapping sequence and to minimise any loss, contamination or compression of the sediment. A third hole was also sampled, where necessary, for radiocarbon dating. The cores were transferred to plastic guttering, covered in plastic sleeving and sealed. In the laboratory, the cores were stored frozen.

Errors

The main error in stratigraphical work is compaction of the organic sediment since the time of deposition. Factors that contribute to this include the composition and thickness of the sediment, the density of the material, the weight of the overburden, the sediment on which the deposit is resting and the amount of pore water and voids contained in the deposit (Devoy, 1977; van de Plaasche, 1982; Greensmith and Tucker, 1986). Compaction is not even and could be dependent on the sedimentation rate. In sands and gravels, the amount of compaction is low, but in peats the compaction could account for an 80-90% reduction in thickness (Greensmith and Tucker, 1986). Even within each stratigraphic unit, the amount of compaction of the lower sediments would be expected to be greater than the upper sediments. Additionally, sediment can be compacted using sampling equipment and this was particularly noted during the retrieval of cores from Talisker Bay using a Stitz powered corer. The compaction error obviously has serious implications for radiocarbon dating when it is vital that the vertical distance over which the sample is taken is kept to a minimum.

3.2.2 Geomorphological mapping

A geomorphological map, at a scale of 1:10 000, was drawn up of each area studied and all physical features of the sites were represented according to the approach used by Sissons (1966). The location of all the boreholes was transcribed onto geomorphological maps.

3.2.3 Levelling

Levelling of the surface height of all boreholes was undertaken using a 5m telescopic staff and a Zeiss Autoset level and each traverse was closed and tied into the nearest Ordnance Survey Bench Mark. Ordnance Datum at most places in the British Isles has been related to the Mean Sea Level at Newlyn, Cornwall, although on the Isle of Skye, some Bench Marks still relate to Ordnance Survey Liverpool Datum. The Liverpool Datum heights were, therefore, converted to relate to Newlyn Datum by adding 0.46m (Ordnance Survey, Southampton, pers. comm.). Errors that occurred in each circuit of levelling never exceeded 0.10m and were mainly 0.00-0.03m.

At two sites, Point of Sleat and Ardmore Bay, synchronous sea level measurements were taken because of the large distance of the sites from an Ordnance Survey Bench Mark (Gray, 1974b). At a prearranged time, the height of the sea surface was levelled at the site under investigation. At a nearby location along the coast where there was a Bench Mark, the sea surface was also levelled at this time. At the location with the known Ordnance Survey Bench Mark, the traverse was completed and the altitude of the sea surface could then be established. The sea surface at both locations was considered to lie at the same altitude on the assumption that the sites are in close proximity and would experience the same sea surface height at the same point in time.

3.3 Laboratory analyses

It was decided that a multi-disciplinary approach would provide the best data from which to reconstruct relative sea level changes. Pollen and diatom analyses are increasingly used in combination in sea level studies (*e.g.* Devoy, 1977; Haggart, 1982; Prince, 1988; Healy, 1993) and Prince (1988) concludes that a multiple indicator approach usually narrows the errors in the data set and would highlight any discrepancies. Pollen analysis alone would not allow an accurate assessment of saline conditions at a site as the response time of plants is often delayed and long-distance transport of pollen grains could affect the pollen assemblage at a site. Diatom analysis, although yielding very accurate information on the salinity of the environment does not always indicate unconformities in sedimentation as changes in diatom assemblages can alter abruptly within an environment, as in isolation basin sequences (Hafsten, 1983). Additionally, diatoms unlike pollen sequences cannot be used for relative dating.

Detailed stratigraphic descriptions of the sampled cores were undertaken in the laboratory. Subsamples were then extracted for pollen and diatom analyses to determine the biostratigraphy of the sites. At two sites, Talisker Bay and Peinchorran, detailed pollen analysis was undertaken and samples were extracted at 8, 4, 2 and 1cm intervals. This was in order to establish a detailed pattern of vegetational change for these coastal sites to compare with those that have already been established elsewhere on Skye (Birks, 1973; Williams, 1977; Birks and Williams, 1983; Walker *et al.*, 1988; Walker and Lowe, 1990). Samples were taken at intervals of 8cm through uniform stratigraphic units, where the depositional environment was assumed to be unchanging and at intervals of 4, 2 and 1cm through stratigraphic contacts and rapidly changing sedimentary units, where environmental changes were likely to have occurred. At three other sites, Ardmore Bay, Point of Sleat and Inver Aulavaig, samples were taken at 8cm and 16cm intervals to give a broad environmental context at the time the sediments were deposited and to act as a relative dating technique. Diatom samples were taken contiguously at 1cm intervals across stratigraphic boundaries and at wider intervals through uniform stratigraphic units where the same depositional environment was likely to have prevailed. These samples were then complemented by more intensive sampling where marine units were identified. Samples for the analysis of Mollusca were taken of 5cm thickness and analysed by Dr David Keen and for Foraminifera analysis, samples of 2cm thickness were extracted. At one horizon at Inver Aulavaig (4.77mOD, 1000cm), fish bones were found and these were submitted to Brian Irving for identification.

Samples for radiocarbon dating were only extracted when all microfossil work had been undertaken. In most cases the material submitted was peat or organic material in which a plug of sediment from the core, normally of no more than 2cm thickness, was extracted. Care was taken to remove all wood, visible plant stems and rhizomes as they may have been derived and to remove material smeared onto the outside of the core during the sampling. One shell was extracted for Accelerator Mass Spectrometry (AMS) dating and this was washed in distilled water before being submitted. The final samples that were taken from the core were for low and high level loss on ignition to establish the organic carbon and carbonate fractions of the sediment respectively (Bengtsson and Enell, 1986).

3.4 Palynology and its use in this research

Palynology is the study of pollen and spores and has been employed in this research to establish a broad environmental context and general time framework at the time the sediments were deposited. It is used as a technique for environmental reconstruction, especially to complement other pollen studies on Skye that have tended to concentrate on inland sites (Vasari and Vasari, 1968; Birks, 1973; Williams, 1977; Birks and Williams, 1983; Walther, 1984; Walker *et al.*, 1988; Walker and Lowe, 1990). The vegetation assemblages during the accumulation of biostratigraphic horizons can reflect changes in water level and sedimentary régime and indicator species can give information on specific aspects of environmental change. Pollen analysis is also used to act as an independent relative dating technique to assess the validity or otherwise of the radiocarbon ages.

3.4.1 Pollen preparation methods

Samples for pollen analysis were prepared using standard procedures (Barber, 1976). 1g of sediment was mixed in distilled water and a few drops of 2M HCl to break down any calcium carbonate. After effervesence had ceased, 10% KOH was added to dissolve humic acids and heated for 15 minutes (Fægri *et al.*, 1989; Moore *et al.*, 1991). The residue was washed with distilled water through a 106μm sieve to remove any macrofossils and coarser sediment that may have been present. Siliceous material was then removed by digestion in HF and a wash of HCl afterwards ensured that all silicofluorides had been removed. Erdtman's acetolysis then followed to remove cellulose and lignin (Erdtman, 1960). The residue was washed with alcohol and toluene to dehydrate the sample and the samples were mounted in silicone oil.

At two sites, Point of Sleat and Inver Aulavaig (borehole 36), in the lower levels of the cores, the pollen was found to be too sparse to count (less than one pollen grain per slide) or absent and an alternative preparation technique was employed. 1ml of the sample was mixed with distilled water and heated. 25ml of 1% sodium pyrophosphate was then added to deflocculate the sample and passed through a 5μm sieve. The sample retained on the sieve was then centrifuged, decanted and washed. The preparation then followed as in the previous method for dissolving the calcium carbonate and Erdtman's acetolysis. After this stage, 6ml of sodium polytungstate was added to float off the organic debris and the residue was washed in distilled water. The samples were then stored and mounted in glycerol (Cwynar *et al.*, 1979).

3.4.2 Pollen counting methods and identification

A Medilux 12 microscope was used for analysis with a x10 objective and x40 lens. It was necessary to count a representative sample of grains on the slide, as it was not possible to record all the grains present. The number of pollen grains counted is dependent on the aims of the project, the sample diversity, the time available to the analyst and to some extent a smaller total count can be compensated by a closer vertical sampling strategy (Moore *et al.*, 1991). It is generally accepted that in northern Europe a count of 300-500 pollen grains sufficiently represents the various components of the pollen assemblage and that the percentages of the taxa encountered have stabilised with this number counted (Peglar, pers. comm.). A count of 300 total land pollen, which included arboreal (trees) and non-arboreal pollen (shrubs and herbs), was, therefore, undertaken. All spores and aquatics were also recorded, but they did not form part of the total pollen sum. Where more than one traverse was counted, the traverses were distributed to cover the whole slide to account for the non-randomness of pollen distribution on the slide (Brookes and Thomas, 1967). Identification followed Andrew (1984), Moore *et al.* (1991) and utilised departmental modern reference slides at Coventry University. Nomenclature follows Stace (1991) and adopts changes recommended by Bennett *et al.* (1994). Most grains were only identified to genus level, although some species were identified. Additionally, any obvious signs of damage to the pollen grains was recorded on the count sheets.

3.4.3 Notes on taxa

Corylus avellana and *Myrica* were not differentiated (Edwards, 1981) and are commonly called *Corylus avellana*-type.
Plantago media and *Plantago major* were not differentiated.
Betula pollen has not been identified to species level.
Armeria and *Limonium* pollen have not been differentiated.
Typha angustifolia and *Sparganium* have not been separated and are represented as *Typha angustifolia* on the pollen diagrams.
Myriophyllum spicatum and *Myriophyllum verticillatum* have not been differentiated and are written as *Myriophyllum v/s* on the pollen diagrams.
Isoetes has been divided into *Isoetes echinospora* and *Isoetes lacustris* on the basis of size (Birks, 1973). The dimensions used are *Isoetes echinospora*, mean size 24.5μm and between 18μm and 32μm and *Isoetes lacustris*, mean size 34μm and between 28μm and 40μm.

3.4.4 Pollen percentage diagrams and zonation

All pollen percentage diagrams were drawn up using Tilia 1.08 and Tilia*graph 1.17 (Grimm, 1991). The pollen data is represented as relative pollen percentage frequency diagrams with the total pollen sum based on the sum of the trees, shrubs and herbs *i.e.* total land pollen. Taxa with a presence of less than 1% are shown with a cross on the diagrams. Spores and aquatics are not included in the total pollen sum, but are expressed as relative percentage frequencies of the total pollen sum on the diagrams.

Pollen assemblage zones as defined by Birks (1973, p273) as "a consistent and homogeneous fossil pollen and spore content that is distinguished from adjacent sediment bodies by differences in the kind and frequencies of its contained fossil pollen grains and spores," were constructed using the stratigraphically constrained CONISS sum of least squares in the Tilia*graph program and compared to zones constructed subjectively. Local pollen assemblage zones (LPAZs) were established for each site and follow West (1970). Tables have been constructed to describe the LPAZs and the characteristics of the LPAZs are described against the altitude at which they occur.

3.4.5 Pollen taphonomy and errors in palynology

The use of pollen analysis to study palaeoenvironments assumes that the physiological requirements of the plants have not altered considerably since their time of deposition. This assumption could be erroneous. Other errors inherent in pollen analysis include the differential pollen production by plants and the different dispersal mechanisms which introduces a bias towards some taxa at the expense of others (Prentice, 1988). Some wind-pollinated grains, such as *Pinus*, can be transported over long distances, and insect-pollinated grains are deposited close to where they are produced, for example, pollen of aquatic species (Traverse, 1988). Differential pollen production could mean that some elements are absent from the pollen assemblage (Prentice, 1988).

Taphonomic processes affect the spatial distribution of the pollen as well as the depositional sequence (Fægri *et al.*, 1989). The relative contributions of the local, extra-local and regional components, as well as being difficult to distinguish, may also change through time. However, the pollen component is largely local and extra-local in origin, although it is dependent on the size of the site, mode of transport to the site and pollen source area (Turner, 1964; Tinsley and Smith, 1974; Cundill, 1979; Jacobson and Bradshaw, 1981). Modern studies show that a rapid reduction in tree pollen is noted with distance from the woodland, especially after 100m (Tinsley and Smith, 1974; Cundill, 1979).

Coastal lakes and mires are often of considerable size and receive a large quantity of non-coastal pollen rain (Jones, 1988). An increase in the size of the lake adds a bias towards taxa that have the best dispersal mechanisms (Prentice, 1988). In water bodies the buoyancy of the pollen grain affects the spatial distribution of the grains. *Pinus*, with its bisaccate pollen grain, is extremely buoyant and is often well represented in marine sediments (Hoffmeister, 1954, West, 1980). Pteropsida spores and *Betula* pollen are also often overrepresented for the same reasons (Koreneva, 1966; Brush and Brush, 1972). *Salix* pollen in contrast sinks and is underrepresented (Fægri *et al.*, 1989). If the pollen becomes degraded this can also affect the buoyancy and, therefore, the preservation of the grains.

Movement of pollen grains can also occur after deposition in both vertical and horizontal directions so that the grains are no longer *in situ* (Birks and Birks, 1980; Moore *et al.*, 1991). In sediments that are not compacted some vertical downward movement could occur but after 5-10 years this is thought to be negligible (Moore *et al.*, 1991). In lake and nearshore sediments, bioturbation can disturb sediments (Moore *et al.*, 1991). Reworking of sediments can also occur particularly in Lateglacial environments where the break up of soils was common as a result of climatic deterioration prior to the Loch Lomond Stadial (Walker *et al.*, 1988). Runoff and slopewash are two other processes whereby pollen can be moved after deposition (Peck, 1973).

Pollen grains also have different abilities to withstand chemical and biological destruction and differential pollen preservation could occur as the death assemblage is converted to a pollen assemblage. Care must be taken when interpreting pollen diagrams where relative proportions of the pollen have been used instead of absolute amounts. A relative rise or fall in a particular species could be the result of another species increasing or decreasing and the absolute quantity could have remained the same.

Jones (1988) reviews some of the particular problems inherent in coastal pollen analysis. These include the difficulty of separating anthropogenic effects from coastal indicator species when the families are mutual to both environments. In sea level studies, indicator species and families such as Chenopodiaceae, *Plantago maritima* and *Armeria maritima* have been used to suggest saltmarsh growth. Jones (1988), however, reports that members of the Chenopodiaceae, Brassicaceae and Caryophyllaceae are also commonly quoted as indicators of disturbed land. It is especially difficult to differentiate between natural and anthropogenic effects when the herbaceous taxa are recording an open vegetation and in the absence of archaeological evidence. It is also reported that some areas of the coastal zone, for example, vegetated sand-dunes, are particularly suitable for grazing and could have been inhabited with the minimum of disturbance.

3.5 Diatom analysis and its use in sea level studies

Diatoms are unicellular, photosynthetic algae which have particular salinity preferences which make them ideal for studying changing coastal environments and isolation basins (Palmer and Abbott, 1986). Additionally, they are abundant in all aquatic environments. In coastal environments, it is common to have diatoms from each halobian category in varying quantities and the changes in their proportions can be used to interpret local changes in relative sea level (Palmer and Abbott, 1986). The lifeform of the diatom can be related to tidal exposure and used in the reconstruction of past tidal and energy régimes (Anderson *et al.*, 1992). It must be noted, however, that few taxa are found exclusively in any one lifeform (Battarbee, 1986). Benthic diatoms are of great importance in sea level studies as they live in littoral areas and are found at depths of up to 10m, although they can survive depths of up to 100m (Palmer and Abbott, 1986). Epiphytic diatoms which live on macro-algae and water plants, for example, are related to low energy régimes in permanently submerged environments such as lakes and lagoons. Sand flats, saltmarshes and mudflats can be differentiated using diatom analysis as a typical part of the benthic community on sand flats are epipsammic, while on mud flats and saltmarshes, epipelic diatoms are more important (van de Hoek *et al.*, 1979; Admiraal, 1984; Vos and de Wolf, 1988). Farther subdivision can occur between these groups as large numbers of aerophilous diatoms live on saltmarshes as compared to mudflats. Epipelic diatoms can live on both tidal and non-tidal water-logged soils (Vos and de Wolf, 1993) (Figure 3.1).

The table overleaf defines the terms associated with diatom analysis (Cox, 1996).

Table 3.1: Definition of terms used in diatom identification

Term used to describe diatom	Description of term
Benthic	Bottom-living, including on sediments and rocks
Dystrophic	Rich in organic matter usually in the form of suspended plant colloids, but usually of low nutrient content
Epilithic	Living on rock or stone
Epipelic	Living on or in fine sediments
Epiphytic	Living attached to plants or other algae
Epipsammic	Living attached to sand grains
Epontic	Free living in the water column
Eutrophic	Having high primary productivity; rich in mineral nutrients
Mesotrophic	Having intermediate levels of primary productivity, with intermediate levels of nutrients required by plants
Oligotrophic	Having low primary productivity, containing low levels of mineral nutrients required by plants
Planktonic	Living suspended in the water column
Tychoplanktonic	Organisms carried into the plankton by chance factors such as turbulence
Aerophilous	Transported by the wind
Halobian	Organism living in a saline environment

3.5.1 Diatom preparation methods

A small amount of sediment (approximately 0.2g) was mixed with 20 mls of 30% H_2O_2 and placed on a hot plate at 90°C for 6 hours (Battarbee, 1986). After this time, the samples were centrifuged at 1000rpm for 5 minutes. The supernatant was then decanted and the pellet resuspended in distilled water and centrifuged. This process was repeated up to eight times. A few drops of the solution were left on coverslips overnight to evaporate and when dry, were mounted onto slides using Naphrax and heated to 130°C. This preparation method was found to be suitable for most of the samples, although some of the samples had a high clay content that obscured the diatoms and NH_3 was added to deflocculate the samples. Additionally, in some samples after laboratory preparation, no diatoms were found and, therefore, Calgon, an industrial detergent and sodium pyrophosphate, were added to break up the clays and other sediment. This was to ascertain whether the sample was barren of diatoms due to chemical dissolution and mechanical degradation or whether they were merely obscured.

3.5.2 Diatom counting methods and identification

A Medilux 12 microscope was used to count the diatoms and a x10 objective was used with a x100 lens under oil immersion. A minimum of 200 diatom valves were identified per level and traverses were set up from the edge of the coverslip to allow for any non-random distribution of the diatoms. Identification of the diatoms followed Hustedt (1930-66), Patrick and Reimer (1966), Hendey (1976), van der Werff and Huls (1957-74) and Krammer and Lange-Bertalot (1986-91). Nomenclature follows Denys (1991/2; 1991/3).

Vos and de Wolf (1993) report on a method of palaeoenvironmental diatom research developed by the Geological Survey of the Netherlands to reconstruct coastal sedimentary environments. In this, only lifeform and salinity are considered as these are the only parameters of which sufficient knowledge is available. With this method they consider that only 200 diatom valves need to be counted to accurately ascertain information on relative sea level changes. In this project, it was considered important to count as many horizons as time allowed to ascertain and constrain as accurately as possible any changes in salinity. Statistical tests were carried out on samples from Borehole 36 from Inver Aulavaig, to establish whether a count of 200 valves was representative of the salinity of the assemblage. It was found that the salinity of the assemblage was established after 100 valves were counted even though with more valves counted, more species were encountered. However, these species only contribute to a very small proportion of the total assemblage, often only appearing once, and as such, not altering the ecology or the salinity of the sample in any significant way. Figure 3.2 shows the results of these tests for a freshwater, brackish and marine assemblage at Inver Aulavaig (borehole 36). All taxa for each salinity category have been summed and appear as one line on the graph.

It was found that in the freshwater deposit, the salinity of the environment was established with 100 valves counted. The salinity of the environment did not alter by more than 6% with counts up to 600 valves. A similar pattern is recorded in the marine deposit. A fluctuation of around 6% is seen within each category of diatoms with increased counts of 100 to 600 valves. In the mixed community deposit, a different pattern initially appears to exist. However, the scale of the diagram is larger and exaggerates the fluctuations and there is also a greater percentage of diatoms with unknown ecology in this sample that affects the percentage values. The freshwater communities and halophobous species do not fluctuate by more than 5% with 600 valves counted. The mesohalobous species show the greatest fluctuation, but if the cumulative sum of all species that tolerate saline conditions is taken *i.e.* mesohalobous, poly-mesohalobous and polyhalobous, the fluctuation is minimal throughout the counts. From the results of these tests it was, therefore, felt justified that

200 diatom valves were counted. This was exceeded on many occasions, however, and as with the pollen analysis, a closer sampling strategy was undertaken, particularly where the environment was seen to be changing rapidly (Moore *et al.*, 1991).

3.5.3 Diatom percentage diagrams and zonation

Diatom percentage diagrams were drawn up using Tilia 1.08 and Tilia*graph 1.17 (Grimm, 1991). The total diatom sum was based on all diatoms counted from every halobian class and included the diatoms with unknown ecology. The diagrams were zoned using the stratigraphically constrained CONISS sum of least squares in the Tilia*graph program and compared to zones constructed subjectively. The diatom percentage frequency diagrams show taxa with a presence of greater than 5%. Summary diagrams for each halobian class are also shown. The large number of species encountered made it inappropriate to display all the taxa on the diagrams. Lists of all the taxa are, therefore, included in Appendix 2. Diatoms assigned to the 'Ecology unknown' category either have not been identified beyond genus and, therefore, the halobian status cannot be established or information is not available on the salinity tolerances of the species. A halobian system of classification was considered to be most appropriate for this study and Hustedt's classification (1953) was adopted with minor modifications. The categories are as follows;
Polyhalobous (marine)
Polyhalobous-mesohalobous (marine-brackish)
Mesohalobous (brackish)
Mesohalobous-oligohalobous (marine-freshwater)
Oligohalobous-halophilous (freshwater, slightly salt tolerant)
Oligohalobous-indifferent (freshwater indifferent to salt)
Halophobous

As with the pollen data, diatom characteristics for each zone are tabulated and then interpreted in detail with their ecology within the site chapters. The term 'species-rich' refers to the large number of diatom taxa encountered. Although not shown on the diatom diagrams, pH régimes (Hustedt, 1939), trophic conditions (Naumaan, 1932) and lifeform classifications (Denys, 1991/2) are taken into account in the interpretation.

3.5.4 Errors in diatom analysis

In diatom analysis, it is important to recognise that two components, autochthonous and allochthonous, could make up the fossil diatom assemblage. Autochthonous diatoms would have grown and developed at the site and the allochthonous component would represent those diatoms that were brought into the area. It is difficult to assess the proportion of each of these, but several methods have been proposed by Vos and de Wolf (1993). These include diatom criteria such as fragmentation, composition of different ecological groups and positive trends in rare taxa and ecological groups within the sedimentary sequence. Additionally, some knowledge of diatom lifeform will help to assess the possibility of the diatoms being allochthonous. Plankton and marine tychoplankton forms are always allochthonous, but benthic taxa live mainly in littoral zones where it is reported that the allochthonous component is generally small (Vos and de Wolf, 1993). Another error Prince (1988) considers is the possibility of diatoms blooming under conditions of high tides and producing marine/brackish communities well above mean high water mark of spring tides.

3.6 Foraminifera, Mollusca and fish bone analyses

Foraminifera are unicellular testate organisms that live exclusively in marine environments. They can be planktonic or benthic and, therefore, range in altitude from high marsh to deep ocean (Scott and Medioli, 1986). The salient feature of Foraminifera for this project, is that they will not live in temperate freshwater environments and their presence in sediments would, therefore, indicate marine influence. Foraminifera analysis was undertaken at one site (Inver Aulavaig, borehole 36) in an area of the core that was barren of diatoms.

Identification of Mollusca was carried out by Dr. David Keen (Coventry University) on several samples from two sites, Point of Sleat and Inver Aulavaig (borehole 3a), to add palaeo-environmental information to the interpretation of the site. The information obtained from the molluscan analysis includes salinity levels, water depths and temperature of the ocean surface waters (Graham, 1971; Seaward, 1982; Peacock, 1993). Nomenclature follows Seaward (1982).

Fish bone analysis and interpretation was undertaken by Brian Irving (Carlisle) on one sample from Inver Aulavaig (borehole 3a) to establish if the assemblage of bones could give any information on the environment when the sediment was deposited. As with diatom analysis, both allochthonous and autochthonous assemblages could constitute the populations of Mollusca, Foraminifera and fish.

3.7 Radiocarbon dating and its use in sea level studies

Samples were submitted for radiocarbon dating in order to achieve some chronological control on litho- and biostratigraphical changes and, therefore, enable comparison with other areas. It was deemed to be the most appropriate technique as many of the deposits contained organic material that was dateable and the time range and precision were suitable (Smart, 1991).

The radioactive isotope of carbon, ^{14}C is produced as an end product of nuclear reactions that occur in the upper atmosphere. It is unstable and combines with oxygen to form CO_2 (Sutherland, 1987; Lowe and Walker, 1997). If the production rate of ^{14}C is constant, the amount in the atmosphere will remain constant due to its exchange with the biosphere and hydrosphere. Organisms absorb CO_2 that is in equilibrium with the atmosphere. When an organism dies, ^{14}C continues to decay following a negative exponential curve, but no replacement occurs. Knowing the rate of decay, therefore, the date of death can be established. The rate of decay is based on the Libby half-life for the ^{14}C isotope of 5568±30 years and the zero year of AD 1950 (Libby, 1955).

Two methods of radiocarbon dating have been used in this research; conventional radiocarbon and AMS dating. Conventional methods count ß emissions from ^{14}C atoms and compare the activity to a modern reference standard. AMS methods count the actual number of ^{14}C atoms as well as ^{13}C and ^{12}C atoms and separate the atoms by differences in their mass rather than their radioactivity (Pilcher, 1991). The age is calculated by comparison to a sample of known ^{14}C activity. This latter method allows very small samples to be submitted for dating.

Samples for dating were, where possible, taken from the same core on which microfossil work had been carried out reducing any errors that might occur from cross-correlating the sediments. However, four dates obtained for Talisker Bay (TKS1A5, TKS2A5, TKS3S1, TKS4S1) were extracted from a duplicate core as not enough sediment was available in the core from which samples for microfossil analysis had been extracted. The samples were stored frozen until they were sent off for dating. All the samples for radiocarbon dating were submitted to the Beta Analytic Radiocarbon Dating Laboratory, Miami. Most dates obtained were conventional bulk sample dates and involved submission of over 50 grammes of wet organic carbon-rich material. The vertical extent of the assays for analysis was kept to a minimum and usually consisted of samples of 1 or 2cm thickness with all visible fibres and wood fragments removed. One AMS date was obtained on a shell (*Buccinium* species) from Point of Sleat where there was no organic rich material available. Two AMS ages were also obtained on samples depleted in organic material from Point of Sleat. All the ages quoted in the text are uncalibrated conventional ^{14}C ages BP and have an error of $\pm 1\sigma$ unless otherwise stated (Beta Analytic Laboratory, 1996).

Errors

Several sources of error have been identified in the radiocarbon dating method. A primary assumption in radiocarbon dating is that the production of ^{14}C has not changed over time. Discrepancies, however, have been shown to exist between radiocarbon years and calendar years obtained from the dendrochronological record, from U-series dating and from varve chronology (Becker, 1992; Bard *et al.*, 1994; Kromer and Becker, 1993; Stuiver and Reimer, 1993; Stuiver *et al.*, 1993; Wohlfarth *et al.*, 1993). These variations are thought to be caused by fluctuations in the cosmic rays reaching the earth (Pilcher, 1991). Plateaux of radiocarbon years have been reported at around 12700 BP, 10000 BP and 9500 BP as a result of reduced ^{14}C concentration (Ammann and Lotter, 1989) meaning that precise ages cannot be obtained for these times. Haggart (1982) reports that in times of rapid climate change, changes in the production of ^{14}C would also have been very rapid. It is possible to calibrate the ^{14}C timescale using other chronologies and calibrated dates quoted in this research have been calculated by Beta Analytic Laboratory (Stuiver *et al.*, 1993; Talma and Vogel, 1993; Vogel *et al.*, 1993).

Another source of error results from the fact that fractionation of carbon isotopes occurs, for example in the process of photosynthesis. This results in different biochemical components for the same horizon yielding different ages (Lowe, 1991; Pilcher, 1991). Corrections have been calculated by Beta Analytic Laboratory for the effects of fractionation by comparing the ^{13}C:^{12}C ratio with standards and obtaining a value for $\partial^{13}C$%. The normal value is -25‰ and adjustments are only made if the value deviates from this (Lowe and Walker, 1997).

Radiocarbon dates which are too old can be obtained as a result of hard water errors that are often present in carbonate areas and on sediments from newly deglaciated terrain (Hedges, 1991). Where bedrock contributes carbonate to groundwater, aquatic plants will incorporate this during sub-aquatic photosynthesis and the effect of this contamination is enhanced when analysing sediments with extremely low organic content (Lowe and Gray, 1980). This older carbon component is almost impossible to isolate, although AMS dating of the humic, lipid or biochemical component could give some indication of the effect of the older carbon (Hedges, 1991). Olsson (1972) reports that 12.5% contamination could give an error of 1000 years and Peglar *et al.* (1989) reports errors of 200-1200 years in limestone areas. In lake sediments, the exchange between the lake surface and the atmosphere can be slow causing the ^{14}C:^{12}C ratio to be lower than in the atmosphere and an older date to be obtained.

Other sources of older carbon come from glacial meltwater which constantly adds older CO_2 and from coal and lignite or eroding organic material such as slopewash or break-up of soils, allochthonous components, that could be inwashed to the basin (Olsson, 1979). Marine organisms are always approximately 400 years older than the true ages due to surface upwelling and slow mixing with deep ocean water that is impoverished in ^{14}C compared to the atmosphere (Pilcher, 1991). The marine reservoir for the Lateglacial is thought to be in the order of 700-800 years (Bard *et al.*, 1994). Carbonates in marine shells can exchange with environmental carbon and bicarbonates and this can cause the date to be either younger or older (Pilcher, 1991). Dating of shells is also problematic as it is extremely hard to establish that they are in their growth position and, therefore, the same age as the stratigraphic unit in which they are found. Younger radiocarbon ages can be obtained as a result of groundwater contamination, root contamination, humic acid contamination and by submitting a sample of large vertical thickness (Lowe and Gray, 1980; Lowe and Walker, 1980; Sutherland, 1980; Pilcher, 1991).

3.8 Relative sea level index points

The calculation of relative sea level index points allows the construction of a relative sea level graph. Each index point has to be related to the same reference water level to standardise the data and allow comparison between different areas. Every feature whether physical or biological has a relationship with groundwater level, tide level or sea level. This is referred to as its indicative meaning (Shennan, 1982; 1983). All relative sea level index points need to be standardised to mean tide level to allow comparison between different areas (Shennan, 1982; 1986, van de Plaasche, 1986). Index points have a vertical and horizontal error bar to account for methodological errors.

The x-axis of a relative sea level graph plots age and these are given in radiocarbon years BP with a $\pm 2\sigma$ error box. The y-axis plots altitude and the vertical error box quantifies surveying errors, altitudinal measurements of stratigraphic horizons in the field, the altitudinal range over which the radiocarbon date was taken and altitudinal range of the reference water level. Additionally, all transgressive index points are subjected to compaction as a result of minerogenic sediments overlying the peat. It is, however, assumed that all compaction of the sediment was completed before the regressive overlap of organic sediment.

Sutherland (1981) calculated the surveying errors to be ± 0.0211m in a study of this nature which includes Bench Mark accuracy, instrumental and traverse closing errors and this value is adopted for comparability. The error in field measurements of the depth of the sediment is thought to be minimal and is estimated to be ±0.01m. Errors of this nature occur in measuring the depth to which the sampler must be lowered into the ground to retrieve the core. The vertical thickness of the radiocarbon date varied as a result of the diameter of the sampled core, density of material and weight of the sediment. The thickness was mainly 0.01m, but never exceeded 0.03m.

Two types of site have been investigated in this study and as a result, the indicative meanings of the index points are different. In isolation basin sites, the indicative meaning is related to the altitude of the rock sill. It is unclear, however, at which point of the tidal cycle marine influence to the basin ceases and this adds a vertical error to the index point. Shennan *et al.* (1995a), from their work in the Arisaig area, found significant altitudinal differences between index points from basins where glacio-isostatic, hydro-isostatic or gravitational effects were not applicable to explain them. They, therefore, concluded that tidal range, freshwater input, size and morphology of the basin and connection to the sea affected the reference water level. They suggest that small basins with little freshwater input will have a lower reference water level probably at or below mean high water of neap tides than larger basins with a freshwater input whose reference water level will probably lie at about mean high water of spring tides. The indicative range of the index points is thought to extend from the reference water level to the altitude of highest astronomical tides as a result of the macrotidal range experienced in western Scotland (Shennan *et al.*, 1995a) (Admiralty Tide Tables, 1996). The reference water level range of mean high water of spring tides (2.05mOD) to highest astronomical tides (2.25mOD), +0.2mOD (Admiralty Tide Tables, 1996), is adopted for Inver Aulavaig and Point of Sleat as it is unclear of the criteria used to distinguish between a large or small basin or what might constitute a "significant freshwater input" (Shennan *et al.*, 1995a, page 120) into the basin.

For those sites where barriers exist, if the changes recorded in the back barrier environment represent relative sea level changes, the relative sea level index points are thought to relate to a reference water level of mean high water mark of spring tides (2.05mOD) (Admiralty Tide Tables, 1996). This is equivalent to the palaeo-saltings surface where the transition between fresh and marine waters would first be recorded. Levelling of contemporary saltings surfaces at the sites indicate the altitudinal range to be 0.10m.

Compaction errors are present with transgressive index points and Cullingford *et al.* (1980) calculated that up to +68% compaction of the peat could have occurred. Compaction errors are also present as a result of the sampling equipment. With a Russian sampler, these errors are estimated to be minimal as the sediment is cut horizontally at depth and an error of ±0.01m is adopted. Gehrels *et al.* (1996) estimated that errors of up to ±0.01m occurred with a vibracorer. However, at Talisker Bay these were observed to be much larger particularly on the peat horizons. Within peat units, compaction of ±0.12m was noted and within the minerogenic horizons compaction of only ±0.01m occurred.

The table below summarises the altitudinal errors used in calculating the vertical error box of the sea level index points.

Table 3.2: Quantification of errors used in the construction of relative sea level index points

Corrections (m)	Source of altitudinal error
±0.0211	Surveying error
±0.01	Measurement of depth in field
±0.005 to ±0.015	Vertical range of radiocarbon date
+0.2	Reference water level range for isolation basins (MHWOST-highest astronomical tides)
±0.05	Reference water level range for barriers (MHWOST)
+68%	Transgressive peat contact compaction of original peat altitude
±0.01 to ±0.12	Compaction due to vibracorer (peat to minerogenic)

3.9 Loss on ignition

Low and high temperature loss on ignition were undertaken on the sediments to determine the organic carbon and calcium carbonate content of the samples and thus ascertain the true nature of the sediment. This is particularly important when analysing samples in the laboratory which may appear to be totally organic in nature and, therefore, a peat but actually may only contain a small amount of stained clastic material. Loss on ignition also contributes to the interpretation of succession from lake deposits through sedge peat to *Phragmites* peat and *Sphagnum* peat.

Samples for analysis were taken at regular intervals throughout the core and each different stratigraphic unit was sampled. At least 10g of oven-dry sediment was placed in a crucible and heated at 450°C for 12 hours in a muffle furnace. After 12 hours, the samples were reweighed and then heated at 950°C for 30 minutes. After this, the samples were weighed again and loss on ignition calculated as:

$$\% \text{ loss on ignition} = \frac{100 \times (\text{Mass of oven dry soil} - \text{Mass of ignited soil})}{\text{Mass of oven dry soil}}$$

Line graphs of percentage loss against depth have been drawn to represent the data.

3.10 Methodology employed in the study of isolation basins and its context

Preservation of marine fluctuations occurs in basins where the altitude of the relative sea level rise exceeds that of the sill of the basin (Hafsten, 1983; Kjemperud, 1981; 1986). In areas that have been glacio-isostatically uplifted, isolation basins provide a very useful way of studying relative sea level changes. This method works particularly well in areas where a suite of basins is encountered and a detailed age-altitude plot, with small scale marine oscillations can, therefore, be constructed (Shennan *et al.*, 1993; 1995a; 1996). Additionally, an area with a slow rate of land uplift would allow the identification of more transgressions than would a quicker one, although this is also dependent on glacio-eustatic changes that are occurring (Hafsten, 1983). Many workers have used isolation basins in combination with pollen, diatom analyses and radiocarbon dating to determine the history of the basin (Digerfeldt, 1975; Kjemperud, 1981; 1986; Lie *et al.*, 1983; Krzywinski and Stabell, 1984; Björck and Digerfeldt, 1986; Kristiansen *et al.*, 1988; Shennan *et al.*, 1993; 1995a; 1996). Marine waters inundate the basin and leave a signature in the sedimentary sequence. As relative sea level falls, a transition to a brackish environment is recorded as the basin becomes isolated. It is rare, however, that the transition from marine to brackish is greater than 10cm and the change from brackish to freshwater conditions is always sharp (Kjemperud, 1981). It is the boundary from brackish to freshwater conditions that marks the isolation contact from the sea at high tide and is the dateable point of negative sea level tendency (Hafsten, 1983; Lie *et al.*, 1983). The altitude at which the sea level tendency occurs is related to the altitude of the rock sill. The basin ideally should be small and relatively shallow as the response of the basin to marine fluctuations is then almost instantaneous and have relatively no freshwater input (Sutherland, 1983; Scott and Medioli, 1986).

The methodology employed in the study of isolation basins follows closely that adopted by Anundsen (1978), Hafsten (1983), Kaland *et al.* (1984), Kjemperud (1981; 1986), Björck and Digerfeldt (1986) and Anderson *et al.* (1992). Kjemperud (1986) describes four stages in determining relative sea level change from isolation basins. Firstly, the isolation contact must be established and this is most commonly achieved through diatom analysis. The second stage in isolation basin studies involves the accurate determination of the threshold of the sill of the basin (Kjemperud, 1986). The sill should consist of bedrock to minimise any altitudinal errors that could result from erosion or removal/deposition of unconsolidated sediments and closely-spaced corings should be used to determine its altitude. The third step is to date the isolation contact which is most commonly achieved by radiocarbon dating. The fourth stage is to correlate the results into a shoreline displacement diagram for the region, but this should not be applied over large areas as errors due to variations in isostatic uplift may be introduced.

Four isolation contacts have been recognised by Kjemperud (1986) that may or may not be separated by sedimentation (see Figure 3.3). The diatomological isolation contact is defined by Kjemperud (1986, page 64) as "a horizon that was the sediment-water interface at the time when the water in the photic zone of the sedimentation basin became fresh." The second isolation contact, the hydrological isolation contact, represents the time when all marine inundations to the basin ceased. This will often coincide with the diatomological contact but sometimes heavy sea water can circulate in and out of the basin at high tide beneath the photic zone. The third contact is the sedimentological isolation contact which represents the change from minerogenic allochthonous sediment, usually forming the lowest isolation contact. The final boundary is the sediment/freshwater contact related to the sediment/water interface after the hydrological isolation contact, as the last of the marine water disappeared from the basin. The diatomological contact will be referred to in this study as the isolation contact. Shennan *et al.* (1995a) have noted that the tidal range of an area may be significant in determining where the isolation contacts occur. They found that in Kjemperud's study area the Spring tidal range was only 1-2m but in western Scotland, the range is up to 4m. This has implications when determining the salinity of water in the photic zone where perhaps daily inundation of water into the basin is required to produce a polyhalobous flora.

Relative sea level index points are obtained from isolation basin studies, the altitude of each relating to the rock sill. Shennan *et al.* (1993; 1995a; 1996) from their suite of basins in western Scotland, have been able to establish many index points but because a continuous vertical sequence of sediment is not present, the data points cannot be joined together in a relative sea level graph without crude extrapolation. In areas such as western Norway, however, where much greater isostatic uplift has been experienced and basins cover a greater altitudinal extent, researchers feel that it is justified to produce a relative sea level graph (Krzywinski and Stabell, 1984). Kaland *et al.* (1984) have used isolation basin studies to establish whether time of isolation or regional differences in isolation would affect the subsequent development of the basins. They found that regional differences did not have a significant effect on basin development and nutrient status of the lake and surrounding area was the dominant factor. This is particularly relevant to the ecology of the lakes when an increase in *Fragilaria* species is often quoted as indicating the isolation of the basin. Kaland *et al.* (1984), however, found that this increase could occur before during or after isolation and was, therefore, not such a reliable indicator as maintained by previous workers (Kjemperud, 1981).

Errors

The largest source of error in this methodology could be in relating at which point of the tidal cycle marine influence ceases. It is possible that in a small basin tidal activity could occur after the sill has risen above mean sea level and conversely, in a large basin, it could stop before the basin has risen above mean sea level. This could account for errors of ±1m (Scott and Medioli, 1986). Shennan *et al.* (1995a) suggest that this error would be greatest in areas that have the largest tidal range.

Another error would result if erosion of the sill had occurred since the sediments were deposited in the basin. Sutherland (1981) demonstrated that the sill of Loch Lomond had been eroded by 4m since the time of marine transgression. Palmer and Abbott (1986) also report that the elevation of the marine deposits behind the sill could have been altered by subsequent neo-tectonic activity that would complicate the record.

Errors are common in radiocarbon dating the isolation contact, as older carbon is frequently washed into the basin (Hafsten, 1983; Sutherland, 1983; Scott and Medioli, 1986). Often only the negative sea level tendency can be dated, either because marine deposits lie directly on the bedrock or because there is not enough organic material in the sediment below the marine deposits to date. This means that only the falling limb of the relative sea level graph can be recorded.

3.11 Methodology employed in the study of barriers and tombolos and its context

Much of the coastline of Skye is wave-dominated with high energy conditions prevalent. Sediment reworking occurs before deposition and preservation of sediments is minimal, except where protection of a bay has occurred through the development of a sedimentary structure such as a barrier or tombolo. Back-barrier environments have, therefore, been sought in this research.

In recent years, work has been undertaken to investigate the mechanisms of barrier beaches in terms of many variables such as sediment supply, basement and headland geometry, wave and tidal régimes, maintenance of cross-shore drainage and relative sea level change (Carter *et al.*, 1989; Orford *et al.*, 1991). One variable will usually dominate, but sediment supply and relative sea level changes are generally considered to be the most important factors (Sloss, 1962; Curray, 1964; Allen, 1964). There are two important aspects of relative sea level change that should be considered, namely rate and magnitude (Carter *et al.*, 1989) with rate generally accepted as the more important for the evolution of coarse barriers. Relative sea level rise does not in itself cause barrier changes, but affects the different base height at which the wave action occurs (Orford *et al.*, 1995). Barriers can respond to relative sea level rise by movement horizontally or vertically, but vertical movement would be at the expense of any landward migration.

Initial accumulation of barriers occurs in the downdrift sector of a headland where sediment supply builds up at an anchor point to form a drift-aligned barrier. Gravel barriers can form rapidly if the sediment supply is adequate. Sediment source can be from offshore or onshore erosion or a combination of both and subsequent development is then controlled by the sediment supply at the point of elongation (Carter *et al.*, 1989; Orford *et al.*, 1991). Wave action allows the partitioning of heterogeneous sediments to form gravel-dominated barriers (Orford *et al.*, 1995). Equilibrium is sought with some reworking of the sediment laterally within the barrier and possible overtopping of the barrier occurs as the angle of approach of the waves becomes less oblique, causing a steep front and deposition near the crest of the barrier. The barrier then becomes swash-aligned, that is, parallel to the wave front.

Under a slow relative sea level rise, the coastline moves landward causing an increase in depth of lagoonal water or if the barrier becomes breached, a decrease in the residence time of high water in the lagoon. As the lagoon fills with terrestrial sediment, finer material is washed through the barrier (decoupling) even though the permeability is obviously decreasing (Carter *et al.*, 1989). If the sediment supply is decreased, *in situ* reworking could lead to the abandonment of solitary barriers with a long wave run up. A single crested, swash-aligned gravel barrier is associated with scarce longshore sediment supply (Orford *et al.*, 1995).

Under a rapid relative sea level rise, barriers prograde quickly and if this is coincident with a decrease in sediment supply, breaching of the barrier would occur, allowing marine influence into the lagoon again. It is possible the barrier could be destroyed as some material could become stranded onshore and some dispersed on the shelf. Carter *et al.* (1989) state that a rapid relative sea level rise in some places may prevent barrier formation. There is a need to redistribute sediment under a rapid relative sea level rise, which could lead to barrier overstepping or drowning (Carter *et al.*, 1989). By contrast, Davis and Clifton (1987) suggest the most likely preservation of facies would occur under a rapidly rising relative sea level which is in agreement with Belknap and Kraft (1981).

Boyd and Penland (1984) suggest a 6-stage model of barrier genesis under a rising relative sea level following glacial retreat in Nova Scotia (see Figure 3.4). The cyclical pattern of barrier build up, reworking and destruction is shown, but essential to the model is a source of sediment to rework. However, the barriers reach a time when they no longer penetrate to their underlying deltaic source as the shoreface retreats and the subaerial volume of the barrier decreases as sediment is lost to sinks. Studies in New South Wales (Boyd and Penland, 1984) have revealed that during rapid relative sea level rise, sediments remain on the shelf and it is only during stillstands that the barriers prograde inland.

Strief (1989) states that tidal conditions could influence the coastal geomorphology and that these régimes are then merely modified by the relative sea level. Small tidal amplitudes often result in continuous barrier systems, a mesotidal environment often results in elongated barrier islands and a macrotidal régime often results in sandy shoals. A slowly rising relative sea level could actually be recorded by a regressive overlap of peat, therefore, because of the tidal régime. In areas where relative sea level is falling, staircases of gravel ridges can form (Dawson, 1984). A series of barriers could also represent a period of storminess (Orford *et al.*, 1991).

In determining relative sea level changes from back-barrier environments, several stages are involved. Firstly, the stratigraphy of the back-barrier environment must be established. Secondly, the deepest area of the basin must be located from which to extract a sample core with the most complete stratigraphic record. All boreholes must be levelled into Ordnance Datum. Thirdly, any marine horizons must be identified and this is usually achieved through the use of diatom analysis. The altitude of these horizons can be determined directly from the levelled height of the borehole. The fourth stage is to establish the indicative meaning and age of the marine strata and to plot the index points on a relative sea level graph. It must be established whether the points directly represent relative sea level changes and can, therefore, be used as sea level index points. The geomorphology of the area and the crest height of the barrier(s) should also be established as comparison with the altitude of contemporary barriers may provide information on the altitude of relative sea level when the fossil barrier formed. It is often impossible to date the age of formation of a barrier especially if it consists of coarse sediments but closely spaced borings on the landward side of the barrier may reveal the sedimentary unit upon which the barrier has developed. Dating of this sediment would, therefore, provide a maximum age for barrier formation.

Errors

Several possible sources of error or shortcomings exist when using barrier sites to investigate relative sea level changes. It is not known how the presence of a barrier may affect the relative sea level signature in the back-barrier environment and the variables are so numerous that the outcome seems to be very site-specific (Healy, 1993). An artificially high ground water table could result from ponding behind the barrier as the interstices become plugged and, therefore, give a false relative sea level signature and it might be impossible to relate peat growth to the tidal cycle (Healy, 1993). Conversely, a barrier could become sealed and impermeable to penetration by sea water allowing only high magnitude events that overtop the barrier to be recorded (Healy, 1993). Changes in the morphology of the barrier could give artificial signatures of relative sea level changes in the back-barrier environment making interpretation of the sedimentary sequences extremely problematic. It also appears that the rate of relative sea level change is important in barrier sequences (Carter *et al.*, 1989; Orford *et al.*, 1995) and this could have implications for the preservation potential of the sediments. In every site where barriers are present, it is useful to establish the date of barrier formation to enable an assessment of which sediments may have been affected by the formation and presence of the structure.

3.12 Conclusions

Each site was investigated according to the techniques outlined in this chapter. Fieldwork was initially undertaken and representative sample cores were extracted from each site. All boreholes were levelled into Ordnance Datum (Newlyn) and all sites were geomorphologically mapped. In the laboratory, detailed pollen and diatom analyses were undertaken to establish the environmental context and salinity at the time the sediments were deposited. Additional Foraminifera, Mollusca and fish bone analyses were undertaken on some samples to complement the pollen and diatom analyses. Samples were submitted for radiocarbon dating to provide a chronological control on the pattern of deposition at the sites and loss on ignition analyses were employed to ascertain the organic and carbonate content of the sediments. Two methodologies were adopted which were dependent on whether the site under investigation contained sediments in a basin that had been intermittently connected to the sea or sediments in a back-barrier environment. The deficiencies and errors associated with all the techniques and methodologies employed have been outlined and these are considered when interpreting the data obtained from the sites.

Section B: Presentation of Results

Inver Aulavaig
Peinchorran
Talisker Bay
Point of Sleat
Ardmore Bay

Chapter 4.0 Inver Aulavaig

4.1 Introduction

Inver Aulavaig (NG 605124) lies on the west coast of the Sleat Peninsula, the most southerly peninsula of Skye. This peninsula experiences a mild climate and is the most wooded region of Skye (Birks, 1973). It occupies an ecotonal area between the *Betula*/*Corylus* woodlands of Skye and the *Quercus* woodlands of the Morar Peninsula (Williams, 1977). The woodland to the south-east of Inver Aulavaig is an ancient Druidic forest and consists of associations of *Fraxinus excelsior-Brachypodium sylvaticum* and *Corylus avellana-Oxalis acetosella* with some *Ulmus glabra*, *Prunus padus* and *Viburnum opulus* (Williams, 1977). The understorey is herb-rich and Birks (1973) reports that many pteridophytes and bryophytes reach their most northerly extent in this area. The vegetation of Inver Aulavaig consists of stands of *Betula* with *Myrica*, *Juncus* spp, Orchidaceae, *Eriophorum* and *Dryopteris*. The surface of the bog is waterlogged and remains of drainage ditches exist (Figure 4.1). A stream, Allt an Leth, flows through the peat bog. Where the stream reaches the sea a saltmarsh has formed which has a maximum altitude of 2.58mOD. In the area immediately east of the stream a small lake exists which increases in size considerably during times of heavy precipitation. Inver Aulavaig is underlain by Durness Limestone and an extensive limestone pavement exists on higher ground to the east. The study area is approximately 600m long by 475m wide.

4.2 Geomorphological mapping, borehole location and stratigraphy

The main geomorphological feature of the site is the extensive peat moss that has developed within the limestone basin. Bedrock outcrops surround the site and some outcrops are present to the south-west of the site. The lower limit of land-based vegetation in the area of the saltmarsh is 2.15mOD and the seaweed limit (*Fucus vesiculosus*) has an altitude of 3.35mOD. Six transects were cored across the peat moss (Figures 4.3-4.8) and several other boreholes were taken to complement these. The general stratigraphy of the site is described below.

In establishing the stratigraphy of Inver Aulavaig peat bog, it has been possible to determine the basal topography of the basin (Figure 4.2). The deepest area of the basin lies in the north-east, although the waterlogged area could not be investigated and may be deeper. The sides of the basin then rise steeply to the north and more gently to the south with no depressions present. To the west of the deepest area, the land rises with a very gentle gradient and a smaller depression is noted immediately to the south-east of borehole 36. To the south of borehole 36, the land rises gently and a depression is present to the north of borehole 15. The altitude of the rock threshold of the basin was determined from closely spaced borings made on the banks of the stream at the point where the stream exited the basin through the outcrops of limestone. The rock sill was found to lie at 5.10mOD and this altitude represents the minimum height the sea had to attain to enter the basin.

The deepest area of the basin, according to boreholes made, lies in the north-east of the site recorded in transect A, where the basal surface lies at an altitude of -6.2mOD (Figure 4.3). At the base, in this area (*e.g.* borehole 3a), a *limus* deposit is recorded that becomes increasingly shelly in nature up the core. Occasional wood fragments are also noted within this unit. The exception to this is borehole 4 in transect 1 that records mainly silt and clay units between -3.5 and -1.1mOD (Figure 4.4). A *Phragmites* peat unit is recorded below the surface unit in most boreholes and the top unit noted in all boreholes at the site is a *Sphagnum* peat although locally this unit contains thin lenses of minerogenic material.

In the south-east of the bog, the same general pattern of basal organic silt and silt units is noted but the shallower boreholes taken near the stream contain basal horizons of sand, clay and gravel and a smaller amount of organic silt (*e.g.* boreholes 49, 50 and 51). In the eastern area of the bog, in transect 3, the deepest sediments contain an organic sandy silt (Figure 4.5). The sand content decreases in the overlying unit and wood fragments are present. At *circa* 3.5mOD an organic silt is overlain by a *Sphagnum* peat that contains some sand at its base. In borehole 20, the stratigraphy is slightly different with silt forming the basal unit and a more organic unit, with shells and sand, overlying this. An organic silt occurs at 3.6mOD and is overlain by *Sphagnum* peat containing sand whose content decreases to the top of the borehole. In the most easterly areas, *Sphagnum* peat directly overlies the bedrock and has a maximum thickness of 2m.

In the centre of the site, transect B records a basal unit of sand and gravel at *circa* 0.2mOD in the deepest boreholes (26 and 27) (Figure 4.6). Clay overlies this in borehole 26. A *limus* is recorded in boreholes 26 and 27 which is overlaid in borehole 27 at 1.15mOD by an organic silt and in borehole 26 by a sandy, silty, clay with gravel. In boreholes 27 and 28, at an altitude of 4.2-4.3mOD some sand is present and *Phragmites australis* fibres are present in borehole 27 at this altitude. The top unit of all boreholes in this transect is a *Sphagnum* peat.

Transect C was cored in the north-west of the peat bog and a slightly different stratigraphy was recorded compared to the eastern areas (Figure 4.7). In the deepest part of this area, a clay is present that contains some sand and shells. Between 1.45-3.45mOD, in transect C, a *limus* is recorded that is approximately 1.5m thick. In two of the cores from this area (boreholes 35 and 37), the *limus* unit is overlaid by a sandy silt. In borehole 36, a thin horizon of *P. australis* fibres are recorded above the *limus*. This is in turn overlaid by minerogenic horizons containing silt, clay, sand and gravel. *Phragmites* peat is recorded at a depth of 4.68mOD and this is overlaid by a *Sphagnum* peat. To the west of the site a similar pattern of stratigraphy to transect C exists consisting of basal blue-grey clay overlain by *limus*. A sand with fine gravel in turn overlies the *limus* and a *Sphagnum* peat forms the top unit. Borehole 39, in this area, penetrated to an altitude of 2.95mOD and borehole 41 to an altitude of 5.27mOD and both record this stratigraphical sequence. In boreholes 10 and 11 of transect 1, a basal sand unit is overlain by an organic silt and the top unit is a *Sphagnum* peat.

Transect 2 was taken at the south-west of the site where the sediments are very much shallower (Figure 4.8). The deepest borehole in this sequence, borehole 15, records an organic silt with wood fragments at its base. This is overlaid by a small amount of *limus* covered by silt and gravel and then by an organic sandy silt at 6.9mOD. The top unit in all the cores in this transect is a *Sphagnum* peat, which, in the western cores of this transect, rests on bedrock. In the eastern cores of this transect, a basal silt or organic silt underlies the peat. The cores taken to the south of this transect record a maximum depth of 1m and contain only *Sphagnum* peat.

Three sampled cores were taken at Inver Aulavaig. Borehole 36 was sampled as it contained all the major stratigraphic units, was situated away from the influence of the streams and drains and appeared to have been unaffected by modern human activity. Borehole 15 was sampled as it was situated in the upper area of the basin and located far away from the rock sill and borehole 3a was sampled from the lower area and was situated closer to the rock threshold (Figure 4.1). It was thought that if marine waters had entered the basin, it may be possible to trace their lateral extent by examining several boreholes in the basin. The stratigraphy of the sampled boreholes is detailed overleaf.

Table 4.1: Stratigraphy of borehole 36 (NG 6032 1234)

Altitude (mOD)	**Depth (cm)**	**Sedimentary description**
7.98-5.75	0-223	Brown *Sphagnum* peat with some *Juncus* and *Eriophorum* fibres and wood fragments
5.75-4.70	223-328	Brown fibrous *Phragmites* peat
4.70-4.23	328-375	Brown silty sand
4.23-4.06	375-392	Brown grey silt with sand and gravel
4.06-3.81	392-417	Brown grey silty clay
3.81-3.47	417-453	Black peat with *P. australis* fibres
3.47-1.88	453-610	Brown *limus*
1.88-1.66	610-632	Grey brown clay
1.66-1.36	632-662	Brown grey organic silty sand
1.36-1.10	662-688	Dark grey silty clay
1.10-0.64	688-736	Light grey silty clay with shell fragments
0.64-0.48	736-750	Brown grey coarse sand with some clay

Table 4.2: Stratigraphy of borehole 3a (NG 6055 1238)

Altitude (mOD)	**Depth (cm)**	**Sedimentary description**
5.23-0.23	0-500	Brown *Sphagnum* peat
0.23 to -1.91	500-714	Brown black *limus* with shell and wood fragments
-1.91 to -5.08	714-1031	Brown *limus* with sand and shell fragments that increase with depth

Table 4.3: Stratigraphy of borehole 15 (NG 6039 1221)

Altitude (mOD)	**Depth (cm)**	**Sedimentary description**
8.26-6.83	0-143	Brown fibrous peat
6.83-6.62	143-164	Brown grey organic silt with sand
6.62-6.56	164-170	Green organic silt with stones and gravel
6.56-6.34	170-192	Brown *limus*
6.34-5.81	192-245	Grey green organic silt with wood

4.3 Loss on ignition

Sharp changes are noted in the percentage organic carbon content of the samples taken from borehole 36, although the carbonate content of the core remains below 3% throughout (Figure 4.9). The top four samples taken within the *Sphagnum* and *Phragmites* units record levels of over 72% organic carbon content and by Allen's (1990) definition are, therefore, considered to be peat units. At an altitude of 4.7mOD, the organic carbon content falls to below 10% coincident with the deposition of a minerogenic horizon containing silt and sand. 86% carbon content is recorded at an altitude of 4.0mOD as the stratigraphy changes to include *P. australis* fibres. The percentages of organic carbon fall over the transition to the *limus* unit, although percentages of up to 30% organic carbon content are recorded within the *limus*. Four samples were taken within the minerogenic units below the *limus* and these record a maximum of 5% organic carbon content at 1.8mOD.

4.4 Pollen analysis

The results of the pollen analysis undertaken on the three sampled cores are tabulated on the following pages and the main characteristics are outlined. The changes in the pollen assemblages are then interpreted in detail in later sections. Pollen percentage frequency diagrams are shown in Figures 4.10-4.12.

4.4.1 Borehole 36

Samples were taken at 16cm intervals from 7.98-0.48mOD (0-750cm), although pollen could not be extracted from below 0.98mOD (700cm). Six local pollen assemblage zones have been defined (Figure 4.10).

Table 4.4: Pollen zone descriptions for borehole 36

Pollen zone	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 6 IAf	7.98-5.58	0-240	***Corylus avellana*-type-*Calluna vulgaris*-Poaceae-Cyperaceae.** A generally low presence of arboreal pollen is recorded although *Betula* values increase to 18% at mid-zone and then decrease to the top of the zone. Increasing *C. avellana*-type pollen occurs to mid-zone and then declines to the upper boundary. Fluctuating frequencies of *C. vulgaris* pollen are recorded between 6-31% and some *Empetrum* and Ericaeae pollen are also noted. Poaceae frequencies fluctuate between 10-32% and Cyperaceae frequencies decline to mid-zone and then increase to 88% towards the top of the zone. The assemblage contains many herbs with noticeable *Plantago lanceolata* and *Filipendula* pollen. Peaks also occur in *Gentiana* pollen and *Plantago maritima* and *Plantago media/major*. Peaks are recorded in *Myriophyllum verticillatum/spicatum* pollen at mid-zone and *Athyrium* spores at the top of the zone. A small presence of *Equisetum* and Pteropsida spores are recorded. A pronounced peak occurs in *Lycopodium* spores and *Sphagnum* frequencies fluctuate reaching a maximum near the top of the zone.
LPAZ 5 IAe	5.58-4.30	240-368	***Alnus-C. avellana*-type-Poaceae-Cyperaceae.** *Alnus* pollen values decline through the zone and a low presence of other arboreal pollen is recorded, although there are noticeable *Betula* and *Quercus* pollen. Increasing *C. avellana*-type values are recorded in this zone. A minor presence of dwarf shrub pollen is noted. Fluctuating Poaceae and Cyperaceae values are recorded in this zone. The assemblage is herb-rich with noticeable *P. lanceolata* pollen. Decreasing Pteropsida spores are recorded and a small presence of *Polypodium* and *Sphagnum* spores are noted in this zone.
LPAZ 4 IAd	4.30-3.44	368-454	***C. avellana*-type-Cyperaceae-*Nymphaea*-Pteropsida.** Generally declining *Betula* pollen with slightly increasing *Pinus* values and a low arboreal pollen presence is recorded in this zone. *C. avellana*-type pollen is initially recorded at over 60% but declines through the zone and a low presence of *Salix* pollen is recorded throughout. Low frequencies of dwarf shrub pollen are recorded. Fluctuating frequencies of Poaceae pollen between 2-10% and increasing Cyperaceae pollen values to a maximum of 42% are noted. Initially, high frequencies of *Nymphaea* pollen are recorded, but these decline through the zone. Some *Typha angustifolia* pollen is recorded at the start of the zone with increasing Pteropsida spores and a small presence of *Equisetum*, *Athyrium*, *Osmunda regalis*, *Polypodium* and *Sphagnum* spores are noted.
LPAZ 3 IAc	3.44-2.78	454-520	**Poaceae-Cyperaceae.** There is a generally low arboreal presence, although there is noticeable *Betula* and *Pinus* pollen in this zone. There is noticeable *C. avellana*-type pollen with a low presence of *Salix* pollen. Low frequencies of dwarf shrub pollen are recorded. High frequencies of Poaceae and Cyperaceae are recorded in this zone. The assemblage is herb-rich with a noticeable presence of *P. maritima*, *Filipendula*, *P. lanceolata* and Rosaceae pollen. Low frequencies of *Myriophyllum alterniflorum* pollen are recorded and *Nymphaea* and *T. angustifolia* pollen record a low presence. There are noticeable Pteropsida and *Polypodium* spores in this zone.

LPAZ 2 IAb	2.78-2.18	520-580	**Poaceae-Cyperaceae-*M. alterniflorum*.** A low arboreal, shrub and dwarf shrub presence is recorded in this zone. High Poaceae and Cyperaceae values are recorded and the assemblage is herb-rich with noticeable *Rumex acetosa/acetosella* pollen. *M. alterniflorum* and *Myriophyllum verticillatum/spicatum* values increase to mid-zone and then decline. There are also noticeable *Nymphaea* and *T. angustifolia* pollen. *Cryptogramma crispa* values decrease through the zone and Pteropsida spores increase. There are also high values of *Athyrium* and *Polypodium* spores at the top of the zone.
LPAZ 1 IAa	2.18-0.48	580-700	**Cyperaceae-Poaceae-*Empetrum*.** Low arboreal and *C. avellana*-type pollen is recorded in this zone. *Empetrum* values increase in this zone. Increasing Poaceae values are recorded and high frequencies of Cyperaceae pollen are noted, although they decrease through the zone. An increase to 23% in *Linnaea borealis* pollen is recorded at mid-zone and there is noticeable *R. acetosa/acetosella.* A low presence of *Nymphaea* pollen and *C. crispa*, Pteropsida and *Selaginella selaginoides* spores are recorded in this zone.

4.4.2 Borehole 3a

Samples were taken at 32cm intervals from 0.23 to -5.07mOD (500-1030cm) because the primary aim was to investigate the local depositional environment of the basal 530cm of this core using diatom analysis. Pollen analysis was used to enable comparison with borehole 36 where distinct vegetational changes had been determined. The diagram is not zoned as the sequence throughout shows a fairly consistent pattern of vegetation assemblages (Figure 4.11).

Table 4.5: Pollen assemblage description for borehole 3a

Altitude (mOD)	Depth (cm)	Pollen characteristics
0.23 to -5.07	500-1030	***Alnus-C. avellana*-type-Poaceae-Cyperaceae.** Total arboreal pollen in this sequence is recorded at between 20-30% and dominated by *Alnus* and *Betula* pollen with subordinate *Pinus* and *Quercus* pollen. *C. avellana*-type pollen shows a gradual increase throughout to 35% of the assemblage and the presence of *Salix*, *Ilex* and *Hedera helix* pollen are recorded. Low values of *C. vulgaris* are recorded. Poaceae pollen fluctuates between 8-16% and Cyperaceae pollen shows a gradual decreasing trend from 50-22%. The assemblage contains many herbs including *P. lanceolata*, *P. maritima*, Ranunculaceae and *L. borealis*. *Nymphaea* pollen is recorded in the lower levels of the assemblage, Pteropsida values fluctuate between 8-22% and *Polypodium*, *Pteridium* and *Sphagnum* spores are recorded with low values throughout. *Pediastrum* spores fluctuate throughout the sequence obtaining a maximum at -2.35mOD (758cm).

4.4.3 Borehole 15

Samples were taken at 16cm intervals from 8.26-6.06mOD (0-220cm). The primary aim of investigating this core was to establish the nature of the minerogenic horizons from 6.46-6.06mOD (180-220cm) using diatom analysis. Pollen analysis was, therefore, used to establish the broad environmental context at the time the sediment was deposited. Four local pollen assemblage zones have been established for this core (Figure 4.12).

Table 4.6: Pollen zone descriptions for borehole 15

Pollen zone	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 4 I2d	8.26-8.02	0-24	**Poaceae-Cyperaceae.** Low arboreal values and low frequencies of *C. avellana*-type pollen are recorded in this zone. High Poaceae and Cyperaceae pollen values are present with few other herbs recorded. There are noticeable Pteropsida, *Isoetes lacustris*, *Pteridium*, *Sphagnum* and *Pediastrum* spores present in this zone.
LPAZ 3 I2c	8.02-7.14	24-112	***Betula-C. avellana-type-C. vulgaris*-Cyperaceae-*Sphagnum*.** Low frequencies of arboreal pollen are recorded, although initially high *Betula* values, up to 50%, occur and then decrease through the zone. Decreasing *C. avellana*-type pollen is recorded in this zone and increasing *C. vulgaris* and Ericaeae pollen is noted. Fluctuating frequencies of Poaceae pollen between 8-18% and increasing Cyperaceae values are recorded. There is a low presence of Pteropsida and *Pediastrum* spores and *Sphagnum* spores increase to the top of the zone.
LPAZ 2 I2b	7.14-6.44	112-182	***Alnus-C. avellana*-type-Poaceae-Cyperaceae.** *Alnus* pollen, in the lower levels of the zone, reaches up to 20% but decreases at the top of the zone. Other arboreal pollen records low values. Increasing *C. avellana*-type pollen to mid-zone is recorded and then it decreases. A low presence of *C. vulgaris* pollen is noted. Fluctuating Poaceae pollen between 18-30% and generally increasing Cyperaceae values to 50% occur in this zone. The assemblage is herb-rich with noticeable *P. lanceolata*, Rosaceae and *Filipendula* pollen. Pteropsida and *Sphagnum* spore values fluctuate through the zone and there are noticeable *Polypodium* and *Pediastrum* spores.
LPAZ 1 I2a	6.44-6.06	182-220	***Alnus-C. avellana*-type-Poaceae-Cyperaceae.** *Alnus* pollen increases to 53% in this zone with low values of other arboreal pollen. *C. avellana*-type pollen increases in this zone and low frequencies of *C. vulgaris* pollen are recorded. Initially high Poaceae values are noted but these decrease through the zone and fluctuating Cyperaceae values occur between 12-24%. There is noticeable *P. lanceolata*. The presence of Pteropsida, *Sphagnum* and *Pediastrum* spores are noted in this zone.

4.5 Diatom analysis

Diatom analysis was undertaken on the three sampled cores, primarily on the minerogenic horizons (Figures 4.13-4.15). It was not felt necessary to undertake diatom analysis on the overlying peat units of the cores as these were assumed to be of freshwater origin. The main features of the assemblages are tabulated below.

4.5.1 Borehole 36

Diatom analysis was undertaken from 5.48-0.48mOD (250-750cm) although no diatoms were present between 1.32-0.78mOD (666-720cm). Five local diatom assemblage zones have been identified (Figure 4.13).

Table 4.7: Diatom zone descriptions for borehole 36

Diatom zone	Altitude (mOD)	Depth (cm)	Diatom charcteristics
LDAZ 5 IAe	5.48-4.86	250-312	***Fragilaria exigua.*** Mesohalobous species, dominated by *Diploneis interrupta* and *Navicula peregrina*, constitute 14% of the assemblage at the top of the zone. This zone is dominated by oligohalobous-indifferent species, consisting primarily of *F. exigua* with subordinate *Fragiliaria construens.*
LDAZ 4 IAd	4.86-3.96	312-402	***Paralia sulcata-Fragilaria* spp.** A sharp increase occurs in polyhalobous species, dominated by *P. sulcata*, *Rhabdonema minutum* and *Amphora gigantea*, to constitute 80% of assemblage at mid-zone. Poly-mesohalobous species are present at values of up to 10% with noticeable *Cocconeis scutellum.* Values of mesohalobous species fluctuate between 3-15% and are dominated by *Achnanthes delicatula* and *Diploneis didyma.* Oligohalobous-halophilous species are recorded at less than 5% at the beginning and end of the zone. Oligohalobous-indifferent species fluctuate between 26-50% at the start of zone, become absent in mid-zone and increase to between 60-95% in the latter half of the zone. This environmental niche is dominated by *F. construens*, *F. exigua*, *Fragilaria lapponica* and *F. pinnata* with noticeable *Achnanthes minutissima* and *Fragilaria brevistriata.*
LDAZ 3 IAc	3.96-2.14	402-584	***A. minutissima-F. exigua-Tabellaria flocculosa.*** This zone is dominated by oligohalobous-indifferent species that attain values of 95% at mid-zone. The assemblage is species-rich, but is dominated by *A. minutissima*, *F. exigua*, *Achnanthes pusilla*, *Cymbella microcephela*, *Cymbella silesiaca* and *F. construens.* Halophobous species are present in this zone and are dominated by *T. flocculosa*, which attains values of over 20% at mid-zone and *Cymbella gracilis.*
LDAZ 2 IAb	2.14-1.36	584-666	***P. sulcata-Diploneis didyma-F. exigua-F. pinnata.*** Polyhalobous species, dominated by *P. sulcata*, increase towards mid-zone attaining values over 80% and then decline rapidly. A rapid increase in mesohalobous species dominated by *D. didyma* with subordinate *Achnanthes delicatula* occurs immediately prior to the peak in polyhalobous species in mid-zone. These species then decline sharply. A gradually declining presence of oligohalobous-halophilous species is recorded throughout the zone and is dominated by *Epithemia sorex.* Oligohalobous-indifferent species, dominated by *F. construens*, *F. exigua*, *F. pinnata*, *Navicula rhyncocephela* with subordinate *A. minutissima*, *Cocconeis placentula* and *Cocconeis placentula* var. *lineata* decrease at mid-zone to a presence of 8% and then increase again to the zone boundary. The freshwater assemblage is species-rich.
LDAZ 1 IAa	0.78-0.48	720-750	***Cocconeis* spp-*Fragilaria* spp.** Oligohalobous-halophilous species fluctuate between 1-12% in this zone. Oligohalobous-indifferent species account for between 64-74% of the assemblage. The assemblage is species-rich and there is a noticeable presence of *C. placentula var. lineata*, *C. placentula*, *A. minutissima*, *C. silesiaca*, *F. construens*, *F. exigua* and *F. pinnata.*

4.5.2 Borehole 3a

Diatom analysis was undertaken on samples from 0.23 to -5.01mOD (500-1024cm) to investigate the nature of the *limus* deposit and to compare the sequence with that from borehole 36. Four local diatom assemblage zones have been identified for this sequence (Figure 4.14).

Table 4.8: Diatom zone descriptions for borehole 3a

Diatom zone	Altitude (mOD)	Depth (cm)	Diatom characteristics
LDAZ 4 I3d	0.23 to -1.17	500-640	***F. construens-Fragilaria construens* var. *venter-F. exigua.*** Poly-mesohalobous species have a very low presence in this zone. The values of mesohalobous species increase to mid-zone and are dominated by *N. peregrina* and *Navicula phyllepta,* and then decline to the top of the zone. High frequencies of oligohalobous-indifferent species are recorded. *F. construens* and *F. construens* var. *venter* decrease through the zone as *F. exigua* increases and there are noticeable *A. minutissima, C. placentula* var. *lineata* and *C. silesiaca*. Halophobous species constitute 5% of the assemblage at the top of the zone.
LDAZ 3 I3c	-1.17 to -3.92	640-915	***P. sulcata-C. scutellum-F. construens-F. exigua.*** Polyhalobous species, dominated by *P. sulcata,* and *C. stauroneiformis* with noticeable *R. minutum, Thalassiosira decipiens* and *G. oceanica,* initially record frequencies of 32%, but their values then decline through the zone. Initially high poly-mesohalobous species, characterised by *C. scutellum,* are recorded, which then decline. The values of mesohalobous species fluctuate between 10-15% and slightly increasing values of oligohalobous-halophilous species are recorded at up to 5%. Increasing oligohalobous-indifferent species, dominated by *F. construens, F. exigua, F. lapponica* and *C. placentula* var. *lineata* with subordinate *F. construens* var. *venter* are present in this zone.
LDAZ 2 I3b	-3.92 to -4.60	915-983	***P. sulcata-F. construens-F. exigua-Fragilaria pinnata.*** Decreasing polyhalobous and poly-mesohalobous species are recorded in mid-zone although they begin to increase at top of the zone. The polyhalobous species are dominated by *P. sulcata* with subordinate *C. stauroneiformis* and *R. minutum* and the poly-mesohalobous species are dominated by *C. scutellum.* Mesohalobous and oligohalobous-halophilous species fluctuate between 5-10%. Increasing values of oligohalobous-indifferent species are recorded to mid-zone, although they then decrease to the upper zone boundary. This freshwater environment is dominated by *F. construens, F. exigua* and *F. pinnata* with noticeable *A. minutissima* and *C. placentula* var. *lineata.* A small peak in halophobous species occurs at mid-zone and consists of *T. flocculosa.*
LDAZ 1 I3a	-4.60 to -5.01	983-1024	***P. sulcata-G. oceanica-C. scutellum*.** Polyhalobous species, dominated by *P. sulcata* and *G. oceanica* with noticeable *R. minutum* and *Rhabdonema arcuatum,* decline from 60% through this zone. Values of poly-mesohalobous species increase through the zone and are dominated by *C. scutellum.* Mesohalobous species record low frequencies in this zone and oligohalobous-indifferent species, dominated by *F. exigua,* decline from frequencies of 15%.

4.5.3 Borehole 15

Samples were taken between 6.46-6.00mOD (180-226cm). No zones have been established for this sequence as the assemblages represented show no distinct changes (Figure 4.15).

Table 4.9: Diatom assemblage description for borehole 15

Altitude (mOD)	Depth (cm)	Diatom characteristics
6.46-6.00	180-226	***C. silesiaca-Eunotia bilunaris-Gomphonema gracile-Eunotia arcus.*** A small presence of mesohalobous species is recorded (< 5%) but this assemblage is dominated by over 55% oligohalobous-indifferent species. The dominant diatoms in this environment are *C. silesiaca, E. bilunaris, G. acuminatum, Cymbella mesiana, Gomphonema gracile, Navicula contenta* and *Navicula gallica* var. *perpusilla* with subordinate *Gomphonema subtile, Pinnularia viridis* and *Tabellaria fenestrata.* Halophobous species, dominated by *Eunotia arcus* with noticeable *Eunotia praerupta* and *Pinnularia appendiculata,* increase to 14% through this assemblage.

4.6 Mollusca analysis of borehole 3a

Mollusca analyses were undertaken on eight samples from borehole 3a by Dr David Keen. Only one sample at -3.57mOD to -3.62mOD (880-885cm) from within the *limus* deposit yielded sufficient specimens to allow an environmental reconstruction. The results of the analysis are tabulated overleaf.

Table 4.10: Frequency chart of molluscan identified

Species/genera	Frequency	Percentage frequency
Emarginula species	1	0.5
Gibbula umbilicalis (da Costa)	2	1.1
Gibbula species	2	1.1
Skenea species	1	0.5
Littorina obtusata (L.)	11	5.9
Littorina saxatalis (Olivi)	1	0.5
Hydrobia ulvae (Pennant)	22	11.8
Cingulus cingillus (Montagu)	12	6.4
Onoba semicostata (Montagu)	30	16.0
Rissoa parva (da Costa)	8	4.3
Rissoa species	39	20.9
Bittium reticulatum (da Costa)	36	19.3
Nucella lapillus (L.)	2	1.1
Hinia reticulata (L.)	1	0.5
Retusa alba	4	2.1
Chrysallida obtusata (Brown)	1	0.5
Turbonilla cf *crenata*	1	0.5
Mytillus Imodilus	1	0.5
Mysella bidentata (Montagu)	6	3.2
Parvicardium species	1	0.5
Macoma balthica (L.)	4	2.1
Scrobicularia plana (da Costa)	9	4.8
Hiatella arctica (L.)	2	1.1

4.7 Foraminifera analysis of borehole 36

Formal identification of Foraminifera was not undertaken, but in the area of borehole 36 deficient in diatoms (1.32-0.78mOD, 666-720cm), samples were prepared and the presence or absence of Foraminifera in these samples was noted. The presence of Foraminifera was taken to indicate saline conditions at the site. Below 1.06mOD (692cm), no Foraminifera or fragments were found, but at 1.06mOD (692cm) the first presence of Foraminifera, with two specimens found, was noted. At 1.08mOD (690cm), one Foraminifera was found and at 1.10mOD (688cm), 18 specimens were found. Samples were then prepared at 1.14-1.12mOD (684-686cm), 1.16-1.18mOD (680-682cm) and

1.28-1.26mOD (670-672cm) and over 300 specimens were found in each sample.

4.8 Fish bone analysis of borehole 3a

In borehole 3a, fish bones were noted at an altitude of -4.77mOD (1000cm) from within the *limus* deposit. The material was sampled in the field and sent to Brian Irving (Carlisle) for identification. The identifiable material consists almost entirely of vertebrae with some *otic bullae* although identifications were based entirely on vertebrae. All fragments are very small and eroded. The taxa identified are all small pelagic marine fish and are listed below.

Clupidae (herring family)
Clupea harengus (herring)
Sprattus sprattus (spratt)
Ammodytes tobianus (sand eel)

4.9 Radiocarbon dates

Six radiocarbon dates were obtained for borehole 36 and they are tabulated below. The two youngest dates are duplicate dates for a probable marine regression at the site, as indicated by the decrease in polyhalobous species in the diatom assemblages. The date of 3280±60 BP is an AMS date and 3140±270 is a bulk carbon date and both were obtained from within the *Phragmites* peat. The date of 3280±60 BP is considered by Beta Analytic to be most accurate and is, therefore, adopted throughout. The date of 7640±240 BP was obtained from a silty sand unit to obtain a maximum date on the increase in *Alnus* pollen. The age of 8850±170 BP was obtained where an increase in polyhalobous species of diatoms occurs and was extracted from the grey silt. 10110±140 BP dates the increase in *C. avellana*-type pollen and was obtained from within the *limus* deposit. The age of 12590±290 BP dates the start of *limus* deposition at the site and was obtained from the lower boundary of the *limus* sediment. The latter four dates are all bulk carbon dates.

Two dates have also been obtained for borehole 3a. The youngest age, 3160±40 BP, dates the decrease in polyhalobous diatoms and the oldest, 5440±50 BP, dates the increase in polyhalobous diatoms thought to represent changing marine conditions. These ages are both AMS dates and the samples were obtained from within the *limus* deposit.

Table 4.11: Radiocarbon dates for borehole 36

Conventional C14 age (BP)	C13/C12 ratio (‰)	Calibrated C14 age (BC)	Laboratory code	Altitude (mOD)	Depth (cm)
3280±60	-27.1	1685-1420	Beta-92168	4.82-4.81	316-317
3140±270	-27.1	?	Beta-92168	4.82-4.81	316-317
7640±240	-25.0	7040-5980	Beta-92166	4.13-4.12	385-386
8850±170	-25.0	8140-7525	Beta-92170	3.89-3.88	409-410
10110±140	-25.0	?-9045	Beta-92169	2.98-2.97	500-501
12590±290	-25.0	?	Beta-92167	2.30-2.28	568-570

Table 4.12: Radiocarbon dates for borehole 3a

Conventional C14 age (BP)	C13/C12 ratio (‰)	Calibrated C14 age (BC)	Laboratory code	Altitude (mOD)	Depth (cm)
3160±40	-28.8	1505-1380/1335-1330	Beta-105028	-3.95 to -3.96	918-919
5440±50	-24.5	4360-4220	Beta-105029	-4.61 to -4.62	984-985

4.10 Interpretation of pollen assemblages

At Inver Aulavaig several possible pollen source areas exist. The basin is relatively large and would, therefore, receive pollen preferentially from those producers with the best dispersal mechanisms such as *Quercus* and *Betula* (Prentice, 1988). Additionally, the basin is surrounded by slopes and runoff and slopewash into the basin could have occurred bringing pollen grains (Peck, 1973). A river flows through the site and this is another possible source of pollen. At times when water infilled the basin movement of pollen grains could have occurred vertically or horizontally and preferential preservation would have been given to those grains that were buoyant (Hoffmeister, 1954; Koreneva, 1966; Brush and Brush, 1972; West, 1980). Any marine waters entering the basin would also bias those pollen grains that are buoyant.

4.10.1 Borehole 36

LPAZ 1 IAa (2.18-0.48mOD, 580-700cm) (Figure 4.10)

Very low arboreal pollen percentages are recorded within this zone and they are characterised by *Betula* and to a lesser extent by *Pinus* and *Quercus,* suggesting that some birch, pine and oak were present in the pollen catchment area. A small peak in *L. borealis*-type pollen occurs in this zone and this is typically associated with pine woodlands up to an altitude of 730m, although it also grows in the shade of rocks (Clapham *et al.*, 1987). There are also low frequencies of *C. avellana*-type and *Salix* pollen recorded in the assemblage, suggesting that limited willow and hazel scrub developed in this area. Willow can tolerate damp environments offered by streams, rivers, marshes and fens (Clapham *et al.*, 1987). The low frequencies of the arboreal pollen, however, suggest that most of the pollen is likely to have been derived from long distance transport. The local development of trees at the site may have been restricted by the inadequate soil cover at this time as suggested by the minerogenic nature of the sediments.

This zone is dominated by high values of Cyperaceae and Poaceae indicating that open ground communities existed characterised by grasses and sedges. The high frequencies of *Empetrum* pollen, combined with the presence of pollen taxa such as *C. vulgaris, Potentilla* and *S. pratensis,* suggest that crowberry and ling heaths also developed in the environs of the site.

A suite of non-arboreal taxa and spores are also recorded in this zone. These include *R. acetosa/acetosella, Plantago* spp, Chenopodiaceae and Asteroideae and are believed to form part of a low alpine and tundra scrub (Walker *et al.,* 1994). Several of these taxa including *C. crispa* indicate the presence of bare rock and thin, unstable, minerogenic soils at the site (Moore, 1968). The presence of *Filipendula* pollen in this zone could be a result of its ability to tolerate salt spray (Hirons and Edwards, 1990), which is likely to have affected the site due to its proximity to the coast.

No basal date has been obtained for this sequence as the sediment did not contain enough organic carbon. However, a date of 12590±290 BP (Beta-92167) has been obtained for the start of *limus* deposition which is 8cm above the upper pollen zone boundary. Assuming the date to be correct, the sequence represented in this zone, therefore, occurred before 12590±290 BP and is probably of Lateglacial Interstadial age. The presence of open tundra vegetation with crowberry heath and pioneer species, such as *C. crispa* and *R. acetosa/acetosella,* would appear to agree with this date when compared to other Lateglacial pollen assemblages published for Skye (*e.g.* Birks, 1973). However, the sequence of vegetational changes for the Lateglacial Interstadial outlined by Walker *et al.* (1994) suggest that a *Betula-Juniperus* scrub was followed by scattered *Betula* woodland before *Empetrum-Erica* heaths became a dominant part of the environment. This sequence has not been identified at Inver Aulavaig, although the absence of *Juniperus* pollen and decreased amount of *Betula* pollen can be explained by their inability to establish themselves in exposed areas as in the Lateglacial assemblage at Slochd Dubh (Walker and Lowe, 1991).
It is possible that the date obtained is erroneous. Two possible mechanisms exist that are

responsible for producing a radiocarbon date that is too old. Firstly, a hard water error may have affected the date as the bedrock geology of the catchment is limestone. This would have the effect of ageing the date as older carbon residues were washed through the bedrock. Alternatively, the core may be contaminated by older inert carbon released when the soils were broken up during the latter part of the Lateglacial Interstadial. This has been noted at Loch Ashik where a basal date of 13870±190 BP is thought to be too old due to the break up of soils and inwash of inert carbon residues as the climate deteriorated during the latter part of the Lateglacial Interstadial (Walker *et al.*, 1988; Walker and Lowe, 1990). Furthermore, the preservation of the pollen was poor. *Empetrum* pollen in particular showed signs of exine damage. This could suggest some secondary derivation of the pollen, caused by the inwashing of soils as they became unstable due to climatic deterioration and has implications for taphonomic processes. The development of *Empetrum* heath is suggested during the latter part of the zone and this may equate to the *Empetrum* heaths dated to 11500-11000 BP by Walker *et al.* (1994). The dates for the development of crowberry heath, however, appear to be too young when compared to other pollen profiles in Skye (*e.g.* Walker *et al.*, 1988) and an age of between 12000 BP and 11500 BP seems more appropriate. The sparsity of the pollen was also noted and below 0.48mOD (700cm) no pollen could be extracted. This suggests little organic input to the site and limited development of vegetation since deglaciation.

LPAZ 2 IAb (2.78-2.18mOD, 520-580cm)

Low frequencies of arboreal pollen, characterised by *Betula, Fraxinus, Pinus, Quercus* and *Ulmus* are recorded in this zone, suggesting that very limited mixed woodland developed within the pollen catchment area. *C. avellana*-type and *Salix* pollen are also recorded at low frequencies and hazel and willow may have formed components of the mixed woodland or scattered stands of willow and hazel scrub may have existed. The spores of *Athyrium, Polypodium* and Pteropsida may represent ferns that formed the understorey component of these woodlands.

Empetrum pollen is recorded at only very reduced frequencies in this zone suggesting the loss of crowberry-dominated heaths. The environment was still open and dominated by grass and sedge species as indicated by the high Poaceae and Cyperaceae values in the pollen diagram. It is likely that reedswamp development was widespread and expansion of grassland had occurred. A suite of non-arboreal pollen also exists in this zone, although in very low proportions, including Rosaceae, *Filipendula* and *R. acetosa/acetosella* and would have formed components of the grass/sedge environment. *Rumex* is a ruderal species, often associated with unstable, thin soils suggesting that limited soil development had occurred in this zone and combined with the presence of Brassicaceae, Lactuceae and *Plantago* species suggests the continued presence of low alpine/tundra scrub. The presence of *C. crispa* also suggests that thin, minerogenic soils existed and areas of bare rock or montane habitat were present. Aquatic pollen including *M. alterniflorum, M. verticillatum/spicatum, Nymphaea* and *T. angustifolia* indicate that lakes, ponds or slow-moving streams were present at the site to support these populations (Clapham *et al.*, 1987; Whittington and Edwards, 1993).

This zone is constrained by the dates of 12590±290 BP, although as previously discussed this date is likely to be *circa* 600 years too old and 10110±140 BP (Beta-92169). Therefore, vegetation indicative of the Loch Lomond Stadial should be recorded within this zone. The presence of *R. acetosa/acetosella*, *C. crispa* and the high frequencies of Poaceae and Cyperaceae would suggest a tundra-type vegetation had developed at this time and *R. acetosa/acetosella* and *C. crispa* are recorded by other workers from Loch Lomond Stadial assemblages (*e.g.* Birks, 1973; Walker *et al.*, 1988; Walker and Lowe, 1990). The high frequencies of aquatic taxa in this zone are also suggestive of wet conditions that would have prevailed during the Loch Lomond Stadial. It is likely that this zone represents the Loch Lomond Stadial and the time prior to the Holocene, *i.e. circa* 11500-10000 BP. A large increase in *Myriophyllum* species is often quoted as representing the transition from the Lateglacial to the Holocene as for example, in the Loch Ashik pollen profile (Walker *et al.*, 1988, Walker and Lowe, 1990). This increase could represent the amelioration in temperature and associated wetter climates at the start of the Holocene.

LPAZ 3 IAc (3.44-2.78mOD, 454-520cm)
The arboreal component of this pollen zone, characterised by *Betula*, *Fraxinus, Pinus* and *Quercus*, increases throughout, suggesting increased local development of mixed woodland had occurred at the start of the Holocene. Alternatively, the tree pollen may represent a long-distance component to the pollen rain and may, therefore, indicate woodland development farther away within the pollen catchment area. An increase has also occurred in *C. avellana*-type pollen and this is dated at 10110±140 BP. This is interpreted as the development of hazel scrub or woodland around the site, although it is possible that the pollen is actually *Myrica* and represents development of bog myrtle at the site. Coincident with the rise in *C. avellana*-type pollen is an increase in Pteropsida spores and *Polypodium* spores are also recorded suggesting that ferns formed the understorey component of the scrub/woodland that developed in this zone.

High frequencies of Poaceae and Cyperaceae pollen continue to be recorded suggesting the continued domination of grass and sedge species at the site, although a small decrease in Cyperaceae pollen has occurred representing the loss of sedge species, possibly as a result of the expansion of woodland. A suite of non-arboreal taxa is recorded including *P.*

lanceolata, Rosaceae and *Filipendula*. *Filipendula* has also been associated with warmer conditions and a mean July temperature of over 10°C (Moore, 1968). The increase in pollen of this taxa could suggest an ameliorating climate. This is farther supported by the decline in *C. crispa* and *R. acetosa/acetosella* which can be associated with tundra climates. Towards the top of the zone an increase in *Plantago maritima* pollen occurs, which could indicate that some saltmarsh development occurred or that a population of this species developed in short grass in an area of the site closest to the sea. Barnosky (1988) however, suggests that *Plantago maritima* is sometimes recorded in the absence of other large pollen producers making its significance unclear. The presence of *Armeria/Limonium* pollen is also recorded in this zone and could represent the growth of thrift in close proximity to the coast. The frequencies of aquatics have declined in this zone suggesting that the site had become drier, although the presence of low frequencies of *M. alterniflorum*, *Nymphaea* and *T. angustifolia* pollen suggests that some open water or streams were present.

A date of 10110±140 BP has been obtained at the base of this zone and appears to correlate well with the vegetation changes observed in other pollen assemblages at Skye for this time (*e.g.* Birks, 1973; Walker *et al.*, 1988; Walker and Lowe, 1990). However, this date is situated on the radiocarbon plateau observed by Ammann and Lotter (1989) and as such, it may represent a wider age range or a different date to that suggested.

LPAZ 4 IAd (4.30-3.44mOD, 368-454cm)

Increased amounts of arboreal pollen, characterised predominantly by *Betula* and *Pinus*, occur in this zone, suggesting the development of mixed local woodland at the site. However, the pollen could be derived from long-distance transport suggesting development of woodland elsewhere within the pollen catchment area. A sharp increase in *C. avellana*-type pollen occurs in this zone and this suggests that the woodland was dominated by hazel or that stands of hazel scrub developed around the site. A small amount of *Salix* pollen is also recorded at this time and could represent the development of willow carr, possibly associated with a wetter environment. Limited *Quercus* and *Alnus* pollen are also recorded after 7640±240 BP suggesting farther development of the mixed woodland to include alder and oak. Ferns probably continued to form the understorey of the woodlands as represented by the high percentages of Pteropsida spores. The spores of *Equisetum*, *Osmunda regalis* and *Polypodium* are also likely to represent the understorey component of the woodland.

As a result of the increase in woodland at the site, the grassland appears to have diminished in extent as represented by the decline in Poaceae pollen. The local Poaceae component is likely to consist primarily of *Phragmites australis* according to the macrofossils observed in the stratigraphy. A decreased amount of herb species, characterised by Lactuceae, *Filipendula* and *P. lanceolata*, is recorded and this could result from the closure of the woodland canopy that prevented the development of a herb-rich grassland. An increase in Cyperaceae pollen occurs in this zone and this probably represents the development of reedswamp at the site in response to increased wetness. This is supported by the presence of macrofossils of *P. australis* and *Nymphaea* and *T. angustifolia* pollen recorded at the base of this zone, indicating the presence of open water or streams. Some *Sphagnum* peat development is thought to have occurred as indicated by the increase in *Sphagnum* spores. This suggests that acidification of the site began after a date of 8850±170 BP (Beta-92170), which was obtained at 3.89mOD (409cm). A change in the sediment occurs concurrent with these vegetational changes and the increase in damper conditions was possibly due to an increase in the water table rather than in surface water, as *Nymphaea* pollen declines through the zone.

LPAZ 5 IAe (5.58-4.30mOD, 240-368cm)
This zone is defined by a marked increase in *Alnus* pollen which occurs after 7640±240 BP (Beta-92166). By extrapolation, assuming sedimentation to be constant between the two dates of 7640±240 BP and 3280±60 BP (Beta-92168), the *Alnus* rise occurred at approximately 6700 BP. The development of alder carr is, therefore, suggested at the site in this zone. *Alnus* is often reported to outcompete *Pinus* and this is seen at Inver Aulavaig as *Pinus* values decrease, coincident with an increase in *Alnus* (Bennett and Birks, 1990). Hazel-dominated mixed woodland continued to be present either at the site or within the pollen catchment area as represented in the pollen profile by *C. avellana*-type, *Betula*, *Fraxinus*, *Pinus*, *Quercus* and *Ulmus*. Continued low frequencies of Pteropsida and *Polypodium* spores probably reflect the understorey component of the woodland.

High Poaceae and Cyperaceae pollen values suggest that open ground communities dominated by sedges and grasses prevailed throughout this zone. The grassland again became herb-rich as represented by the many herbs recorded in this zone but particularly *P. lanceolata*, *Filipendula* and *Potentilla*. It is sometime between 7640±240 BP and 3280±80 BP that *P. lanceolata* is recorded continuously in the pollen record and this may reflect human activity in the region of the site, although, as seen in LPAZ 1 IAa, *P. lanceolata* can form a natural component of coastal communities (Jones, 1988). If *P. lanceolata* does represent human activity at the site, it appears to have been of very low intensity. The presence of Ranunculaceae, *Plantago media/major*, Brassicaceae and Caryophyllaceae could all represent some anthropogenic activity, but, as Hirons and Edwards (1990) report, sea level fluctuations, exposure and anthropogenic activity all have the same expression in pollen assemblages (Affleck *et al.*, 1988). The acidicity of the site is suggested by the presence of *Sphagnum* spores, although these are present at low frequencies. The virtual absence of aquatics in this zone suggest that the site had become much drier and this is also reflected in the decreased frequencies of Pteropsida and *Polypodium* spores.

LPAZ 6 IAf (7.98-5.58mOD, 0-240cm)

Arboreal pollen generally decreases in this zone, although a small increase is noted in *Betula* pollen at mid-zone, probably representing a very local development of birch. The frequencies of *C. avellana*-type pollen initially increase in the zone and then decline through the zone. This evidence suggests the decline of mixed woodland and hazel scrub within the pollen catchment area. Frequencies of Pteropsida and *Polypodium* spores also decrease and this is probably associated with the decline in tree species. The development of ling- and crowberry-dominated heaths is suggested in this zone by the increased frequencies of *C. vulgaris*, *Empetrum* and Ericaceae pollen. This heathland may have been allowed to develop as the woodland canopy became more open. The presence of *Drosera rotundifolia*-type pollen is also recorded. This plant often grows in association with heathland, as it is likely to have done in this zone.

Cyperaceae pollen values decline to mid-zone but increase sharply to the top of the zone. The family is likely to have colonised the perimeters of any water bodies present at the site, but the boggy conditions present at this time probably supported many species of Cyperaceae. A herb-rich environment existed at this time and is characterised by *Filipendula*, *Potentilla*, *R. acetosa/acetosella* and *Gentiana* species that would have developed within the grassland. The continued presence of probable anthropogenic indicators such as *P. lanceolata*, Ranunculaceae and Caryophyllaceae pollen are recorded in this zone. It is possible that some pastoral activities occurred and the presence of *P. media/major* may be indicative of this.

An increase in *Sphagnum* spores and macrofossils of *Sphagnum* in the stratigraphy occur in this zone and combined with increased frequencies of dwarf shrub pollen suggest acidification and peat development at the site. Some species of *Potentilla, e.g. P. erecta*, are also commonly associated with peat bog environments (Clapham *et al.*, 1987). Increased surface wetness at the site is suggested by the presence of *M. verticillatum/spicatum* and *Athyrium, Lycopodium* and *Equisetum* spores are also recorded and represent taxa that can colonise peat bog environments (Clapham *et al.*, 1987).

4.10.2 Borehole 3a (0.23 to -5.07mOD, 500-1030cm) (Figure 4.11)

The pollen assemblage represented in borehole 3a, consists of *C. avellana*-type with *Alnus*, *Betula*, *Quercus* and decreasing *Pinus* values indicating the presence of hazel-dominated mixed woodland. The relatively high values of *Alnus* pollen are likely to indicate the development of alder carr at the site. The presence of Pteropsida, *Polypodium* and *Pteridium* spores in this assemblage are all associated with woodland environments and would possibly have formed the understorey component.

Some grassland appears to have developed at the site as represented by the consistent presence of Poaceae pollen, although this could represent *Phragmites* reeedswamp development. This appears to have been relatively herb-rich as characterised by *P. lanceolata*, *P. maritima* and Rosaceae, although the herbs recorded are in low quantities in the pollen assemblage. High Cyperaceae values are recorded in this assemblage and suggest the development of reedswamp in this area. A small amount of *Sphagnum* peat development at the site is indicated by the spores in the pollen profile and this suggests that the site is acidic in this area. The dwarf shrub component for this time is extremely low although some *C. vulgaris* pollen is recorded and some ling heath probably developed on the acidic soils at the site. Aquatic pollen, dominated by *Nymphaea*, is only recorded at the beginning of the sequence, but together with *Pediastrum* spores indicate that open pools of water were present at the site giving rise to damp conditions throughout the sequence. The frequencies of *P. lanceolata* pollen and other associated probable anthropogenic indicators, such as Brassicaceae and Caryophyllaceae pollen, are of low intensity and it is, therefore, difficult to make inferences about anthropogenic activity at the site, especially as the presence of Brassicaceae, Caryophyllaceae and *P. maritima* are all typical of coastal communities (Jones, 1988).

Two radiocarbon dates have been obtained for this sequence based on the diatom assemblages although features of the pollen assemblage were not dated. A date of 5440±50 BP (Beta-105029) has been obtained at -4.62mOD (985cm), near the base of the sequence within the *limus* deposit. A second date of 3160±40 BP (Beta-105028) has been obtained at -3.96mOD (919cm), also within the *limus*. The dates suggest that the base of the pollen sequence represents a middle Holocene vegetation assemblage which is supported by the tree taxa present.

4.10.3 Borehole 15

LPAZ 1 I2a (6.44-6.06mOD, 182-220cm) (Figure 4.12)
The arboreal pollen component in this basal zone is dominated by *Alnus* which is increasing throughout. At the beginning of the zone, it is already established at 20% suggesting the presence of alder carr at the site. *C. avellana*-type pollen is also increasing suggesting that hazel dominated woodland or scrub developed in the pollen catchment area. Pteropsida and *Polypodium* spores are recorded in this zone and are likely to be associated with the understorey component of the woodland/scrub. Other arboreal pollen, such as *Pinus*, *Quercus* and *Ulmus*, are recorded at very low frequencies, suggesting limited mixed woodland development or long-distance transport of the pollen grains.

A decline in Poaceae pollen suggests the contraction of grassland at the site probably as a result of the increase in hazel and alder development. The pollen of other herb species is recorded at low frequencies, but some *P. lanceolata*, combined with the sporadic occurrence of Brassicaceae and Ranunculaceae, is noted possibly as a result of human activity. *Sphagnum* spores are recorded in this zone suggesting some acidification of the environment and the frequencies of Cyperaceae pollen suggest some sedge or reedswamp development had occurred. The frequencies of *C. vulgaris* are very low in this zone indicating little heath development had occurred within the pollen catchment area. It is difficult to establish an age for the commencement of this zone when compared to borehole 36, but the assemblage represents a time after the *Alnus* rise and is likely to represent the middle-late Holocene.

LPAZ 2 I2b (7.14-6.44mOD, 112-182cm)
This zone records a decline in arboreal pollen, particularly *Alnus* and *C. avellana*-type also declines. Associated with the decline in woodland taxa is the decrease in Pteropsida and *Polypodium* spores which are likely to have formed the understorey component of the woodlands. Areas of open grassland and sedge communities are suggested by the high frequencies of Poaceae and Cyperaceae pollen. The presence of *Sphagnum* spores, *C. vulgaris* and *D. rotundifolia*-type pollen suggest acidic soils and peat were present at the site. The environment at this time was herb-rich and was characterised by *Filipendula*, *P. lanceolata* and *Ranunculaceae*. The pollen of *P. lanceolata,* Brassicaceae, Caryophyllaceae and Ranunculaceae recorded in this zone, could represent some anthropogenic activity, and possibly pastoral agriculture, at the site. The low frequencies of *Pediastrum* spores in the assemblage indicate that some freshwater pools were probably present on the bog surface, but were not extensive or possibly quite a fertile water body.

LPAZ 3 I2c (8.02-7.14mOD, 24-112cm)
This zone is characterised by initially high frequencies of *Betula* and *C. avellana*-type pollen suggesting that stands of birch and hazel scrub developed at the site possibly as ecological niches were provided by the decline in alder carr. The frequencies of Poaceae and Cyperaceae pollen are initially suppressed, possibly as woodland/scrub encroached onto the site. The frequencies of Cyperaceae pollen, however, increase in the latter half of the zone and indicate that a damp, marshy environment existed in this zone. Acidification of the site appears to have become more extensive, as indicated by the large increase in *Sphagnum* spores. The increase in *C. vulgaris* and Ericaceae pollen suggests the development of heathland at the site and this development is also associated with the acidic nature of the soils in this zone. *Pediastrum* spores indicate the continued presence of surface water at the site.

LPAZ 4 I2d (8.26-8.02mOD, 0-24cm)
The frequencies of *C. avellana*-type pollen have declined suggesting that hazel scrub/woodland ceased to be a major component at the site. This zone is dominated by Poaceae and Cyperaceae pollen suggesting local expansion of grass and sedge environments at the expense of all other taxa and an open environment. *C. vulgaris* values have dropped sharply probably as a result of the expansion of grass and sedge and additionally the environment may have become less acidic as suggested by the decline in *Sphagnum* spores. The presence of spores of Pteropsida and *Pteridium* in this zone, would seem to suggest the development of ferns within the damper areas of the grass and sedge environment. Some anthropogenic indicators such as *P. lanceolata*, Brassicaceae and Caryophyllaceae, are still recorded in the pollen assemblage, but in very low quantities possibly suggesting limited human activity within the pollen catchment area.

4.11 Interpretation of diatom assemblages

4.11.1 Borehole 36

LDAZ 1 IAa (1.36-0.48mOD, 666-750cm) (Figure 4.13)
This zone is characterised by a predominantly freshwater community. Most species are oligohalobous-indifferent, preferring circumneutral to alkaline waters. These species include *C. placentula* var. *lineata*, *F. construens*, *F. pinnata* and *A. minutissima* (Hustedt, 1957; van der Werff and Huls, 1974). The alkaline water for these communities would have resulted as water flowed over and through the limestone bedrock. Some species such as *F. construens* prefer water of low nutrient content (Patrick and Reimer, 1966) and the species present have a variety of lifeforms; *F. pinnata* is benthic, *F. construens* is tychoplanktonic, *A. minutissima* is epontic and *C. placentula* var. *lineata* is benthic (Denys,

1991). The entire water body is likely to have been occupied and some aquatic vegetation and substrate must have been present to support the epiphytic species. *C. placentula* inhabits alkaline, freshwater environments, but can tolerate a small amount of salt water (Patrick and Reimer, 1966). A small community of oligohalobous-halophilous species also existed at the site suggesting that perhaps salt spray enabled these communities to survive or that they developed closer to the sea, where some saline influence could be felt.

However, in this zone, little saline influence at the site is represented. Between 1.32-0.78mOD (666-720cm), no diatoms are present and this may have been caused by dissolution of the silica since deposition, rather than complete absence of diatoms at the site. The skeletal soil development, suggested by the inorganic nature of the sediments may have allowed the release of minerals and chemicals from the rocks that could have led to silica dissolution that could have destroyed the diatoms.

LDAZ 2 IAb (2.14-1.36mOD, 584-666cm)
Initially in this zone, the communities of oligohalobous-indifferent and oligohalobous-halophilous species continue in the same proportions as in the lower levels of the previous zone suggesting similar environmental conditions. However, they quickly decline as polyhalobous and mesohalobous species peak at 2.08-1.58mOD (590-640cm). The polyhalobous community almost entirely consists of *P. sulcata*. This species is considered to be planktonic in its juvenile form and benthic in its adult form (Devoy, pers. comm.; Denys, 1991). It is extremely common around the British coast (Hendey, 1976) as a littoral species. Kjemperud (1981) argues that a 45% presence of *P. sulcata* is required to indicate saline conditions and the frequencies in this zone reach up to 85%. Environmental conditions appear to have been ideal for *P. sulcata* to thrive and this has possibly resulted in the exclusion of other polyhalobous species. Both before and after the large increase in polyhalobous species, an increase occurs in mesohalobous species, dominated by *Diploneis didyma*. This is a common and widespread coastal species that is benthic and prefers euryhaline waters (Hendey, 1976; Patrick and Reimer, 1966; Denys, 1991), although Vos and de Wolf (1993) state that it is a marine-brackish epipelic form.

After the peak in polyhalobous species, an increase is noted in *A. delicatula* which is a marine-brackish epipsammic form (Vos and de Wolf, 1993) that prefers alkaline, eutrophic waters (Naumann, 1932; Hustedt, 1939). Increasing salinity is, therefore, indicated at 1.58mOD (640cm) as freshwater species decline and polyhalobous species begin to increase. The decrease in saline conditions is represented by the decline in polyhalobous species and a small increase in mesohalobous species occurs. The oligohalobous-halophilous community, dominated by *E. sorex*, also declines slightly. A similar community of oligohalobous-indifferent species, as at the start of this zone, colonised the area as the saline influence decreased suggesting similar environmental conditions returned to the site. There is a higher percentage of *Fragilaria* species, however, including *Fragilaria brevistriata, F. capucina* var. *vaucheriae, F. construens, F. exigua, F. lapponica* and *F. pinnata* and this may suggest the increased influence of streams at the site, with freshwater diatoms being brought into the area.

This zone, therefore, records an increase in saline conditions and this is likely to represent a positive marine tendency at the site. No dates were obtained for this episode as there was not sufficient organic material on which to obtain a radiocarbon age. However, by comparison with the pollen assemblage it is likely this marine phase occurred prior to *circa* 12000-11500 BP (LPAZ 1 IAa) (Figure 4.10). The intensity of the marine event appears to have overwhelmed the site, probably forcing the freshwater communities to retreat to the periphery of the basin or even to be displaced totally at this time.

LDAZ 3 IAc (3.96-2.14mOD, 402-584cm)
Polyhalobous species are recorded at the start of the zone by taxa including *Achnanthes longipes* and *Amphora gigantea* which are present at less than 5%. They may have been brought into the basin by the occasional overwash of saline waters or alternatively, the community may have survived in a small hollow in the basin where saline waters persisted for some time, after the sea had retreated from the area.

All the species that constitute the freshwater community recorded in this zone until 8850±170 BP, prefer circumneutral to alkaline waters, for example, *Navicula rhyncocephela, C. silesiaca, A. minutissima, A. pusilla* and *C. microcephela* (Patrick and Reimer, 1966). Some of these diatom species grow attached to substrate or aquatic plants, but they are present at low frequencies compared to the species present that are either epontic or benthic. The species living within the water column include *N. rhyncocephela, C. silesiaca, A. pusilla* and *A. minutissima* (Denys, 1991). Water of different mineral content would have existed at the site to support the different communities. *N. rhyncocephela* prefers water of high mineral content and *C. silesiaca* prefers eutrophic -dystrophic waters (Naumann, 1932; Patrick and Reimer, 1966). *C. microcephela* will only inhabit well-aerated habitats (Patrick and Reimer, 1966). A mosaic of different freshwater species would, therefore, have colonised water bodies within the basin.

At the top of the zone, a small increase in mesohalobous species occurs represented by taxa present at less than 5%. This small increase in mesohalobous species may suggest the possible encroachment of saline water at the site and the development of a brackish water community.

LDAZ 4 IAd (4.86-3.96mOD, 312-402cm)

At the start of this zone, a decrease in oligohalobous species occurs concurrent with an increase in mesohalobous species, which is followed by an increase in polyhalobous species. The mesohalobous community at this time is dominated by *D. didyma* although other species such as *A. delicatula*, also constitute the community. At an altitude of 4.08mOD (390cm), polyhalobous and poly-mesohalobous species increase sharply. At the start of this rise, *A. gigantea*, *G. oceanica* and *R. minutum* dominate. These are common marine species and *R. minutum* is epiphytic on larger algae or any solid substrate (Hendey, 1976). Immediately after this time, *P. sulcata* increases to constitute up to 76% of the assemblage, displacing the other communities of polyhalobous species. The poly-mesohalobous species present at this time are dominated by *C. scutellum,* which is a marine epiphyte (Vos and de Wolf, 1993) and is common on coasts all over the world (Hendey, 1976).

At an altitude of 4.50mOD (348cm), the polyhalobous community falls very sharply to a presence of less than 5% and a similar trend is seen with the poly-mesohalobous species. A small increase to 12% of mesohalobous species is recorded at the top of this zone and is dominated by *A. delicatula* and *N. peregrina*. *N. peregrina* is benthic (Denys, 1991) and prefers alkaline, eutrophic waters of high mineral content (Naumann, 1932; Hustedt, 1939; Patrick and Reimer, 1966). A large increase in oligohalobous-indifferent species occurs at this depth. This community is dominated by *Fragilaria* species, including *F. construens*, *F. exigua*, *F. lapponica* and *F. pinnata*. *F. lapponica* and *F. brevistriata* both prefer circumneutral to alkaline waters that are eutrophic to mesotrophic (Naumann, 1932, Hustedt, 1939). *F. lapponica* is often found in standing or slow-flowing waters while *F. brevistriata* is epontic and benthic (Hustedt, 1957; Denys, 1991).

This zone, therefore appears to record an increase in saline waters that began at the top of zone LDAZ 3 IAc, as represented by the increase in mesohalobous species at 4.06mOD (392cm). Polyhalobous and poly-mesohalobous species then increase sharply at 4.08mOD (390cm) representing a positive marine tendency at the site during which oligohalobous species were again displaced from the site. Polyhalobous species quickly fall at 4.50mOD (348cm), although a mesohalobous community continued to survive possibly fed by overwash into the basin or in trapped saline water at the site. The oligohalobous-indifferent species probably represent communities that tolerate standing water or slow-flowing streams that are circumneutral-alkaline or fully alkaline. Again the lifeforms of the species vary such that all ecological niches of the water bodies were occupied.

LDAZ 5 IAe (5.48-4.86mOD, 250-312cm)
This zone is dominated by oligohalobous-indifferent species, suggesting that freshwater environmental conditions were prevalent at the site. A small community of mesohalobous species persisted in the basin. The freshwater community ceases to be species-rich and consists exclusively of *F. exigua* with some *F. construens*. These two species have, therefore, flourished at the expense of all other communities. It is possible that with the development of a peat bog during this zone, the ecological niches at the site have decreased and this accounts for the decrease in diatom taxa present. A small community of mesohalobous species, dominated by *Diploneis interrupta* and *N. peregrina,* persisted in the basin possibly as a result of the influence of seaspray. *D. interrupta* is a benthic species that prefers alkaline, eutrophic waters (Naumann, 1932; Hustedt, 1939; Denys, 1991).

4.11.2 Borehole 3a

LDAZ 1 I3a (-4.60 to -5.01mOD, 983-1024cm) (Figure 4.14)
This zone is characterised by predominantly polyhalobous species probably representing saline influence at the site. Initially, a large community of *P. sulcata* occupied the area with some *G. oceanica.* The polyhalobous community is relatively species-rich and as *P. sulcata* and *G. oceanica* decline, an increase occurs in *R. minutum* at -4.77mOD (1000cm). Some *R. arcuatum,* which is epontic (Denys, 1991), is also present. As the true polyhalobous taxa fall, an increase occurs in poly-mesohalobous and mesohalobous species at -4.67mOD (990cm). A small community of oligohalobous-indifferent species, dominated by *F. exigua* also existed at the site and possibly reflects freshwater input of the streams to the site.

A mosaic of different environmental conditions, therefore, existed at the site. Saline influences were experienced in this zone and it is likely that a period of relative sea level, whose altitude was higher than the rock threshold, was underway. The true marine diatom forms would have developed in areas of the basin totally flooded by the sea, while the mesohalobous forms would have developed on the periphery of this area, where the salinity was reduced. A small freshwater area would also have existed at the basin allowing *F. exigua* to grow, although this population may have been washed into the basin by a stream.

LDAZ 2 I3b (-3.92 to -4.60mOD, 915-983cm)
This zone records a marked decline in saline conditions at the site represented by the decrease in polyhalobous and poly-mesohalobous species at -4.52mOD (975cm). This has been dated at 5440±50 BP. *P. sulcata* is still the dominant polyhalobous species and some *C. stauroneiformis*, which is epontic (Denys, 1991), dominates the poly-mesohalobous community. Some overwash into the basin allowed the continuation of reduced

communities of polyhalobous and mesohalobous diatoms, possibly in depressions within the basin that may have retained saline water. A slight increase occurs in oligohalobous-halophilous species and mesohalobous species. The mesohalobous species are dominated by *A. delicatula*. A large increase occurs at mid-zone in oligohalobous-indifferent species, although the community declines towards the top of the zone. This community is dominated by *F. construens*, *F. exigua* and *F. pinnata* with some *A. minutissima*. A peak also occurs in *T. flocculosa* at mid-zone, which represents an increase in halophobous species, indicating an absence of saline influences in the area where this species grew. *T. flocculosa* is planktonic (Denys, 1991) and Patrick and Reimer (1966) report that specimens with shorter frustules are found in acid waters of ponds and bogs and those with longer frustules are oligotrophic-mesotrophic.

LDAZ 3 I3c (-3.92 to -1.17mOD, 640-915cm)
At the start of this zone, a return to saline conditions is again recorded by the sharp increase in polyhalobous communities at the site with *P. sulcata* and *C. stauroneiformis* dominant and this has been dated at 3160±40 BP. *T. decipiens* is also recorded at the top of the zone and it is a planktonic species that is widely distributed in temperate seas, indicating that the sea surface temperature was similar to that of today. Poly-mesohalobous species continue to be dominated by *C. scutellum*. The mesohalobous species show a consistent presence throughout this zone and it is likely that they always existed at the site as the transition between the freshwater and saline communities. It is likely that they migrated across the surface of the bog as the saline influence at the site varied. Oligohalobous-indifferent species are present, although in reduced numbers possibly as their habitats were inundated by the sea. Initially, the oligohalobous-indifferent species consist of low frequencies of *Fragilaria* species. However, as the zone progresses, a change in the environment at the site occurs. Polyhalobous and poly-mesohalobous species decrease and oligohalobous -indifferent species increase to 60% of the assemblage. The freshwater community is species-rich, but is dominated by *Fragilaria* species. Salinity levels, therefore, appear to decrease at the site as the zone progresses. Freshwater communities are likely to have migrated across the bog as relative sea level fluctuated.

LDAZ 4 I3d (0.23 to -1.17mOD, 500-640cm)
The oligohalobous-indifferent community is the most dominant community at the site in this zone and consists of many species but particularly *F. construens*, *F. construens* var. *venter*, *F. exigua* and *A. minutissima*. *F. construens* var. *venter* is widely distributed in water of low nutrient content and is very common in freshwater (Hustedt, 1957, Patrick and Reimer, 1966). It is a planktonic species and grows in alkaline, eutrophic-mesotrophic waters (Naumann 1932; Hustedt, 1939; Patrick and Reimer, 1966). Mesohalobous species

are present at low frequencies in this zone and are dominated by *N. peregrina*. A negative marine tendency, therefore, appears to have been recorded at the boundary of LDAZ 4 I2d and LDAZ 3 I2c. A small increase occurs in *T. flocculosa* at the top of the zone indicating totally fresh conditions in the area it grew.

It appears that a change in relative sea level has been recorded in this borehole beginning with saline conditions that had inundated the site prior to the start of the assemblage. These marine conditions then retreated at 5440±50 BP and freshwater conditions existed. The relative sea level could have fallen to just below the rock threshold of the basin and possibly limited overwash was experienced. Relative sea level then inundated the site again at 3160±40 BP, but the saline influence appears to have retreated gradually, allowing freshwater conditions to become increasingly dominant at the site, as relative sea level regressed. As the sea receded, initially high tides would have flooded the site, then only the highest spring tides or Highest Astronomical Tides were recorded in the basin, until the sea finally withdrew.

4.11.3 Borehole 15 (6.46-6.00mOD, 180-226cm) (Figure 4.15)

The diatom assemblages record a predominantly freshwater environment. Only a small percentage of mesohalobous species are recorded at the base and top of the sequence indicating limited saline influence at borehole 15. The oligohalobous-indifferent community is relatively species-rich, but dominated by *C. silesiaca, N. contenta, C. mesiana, E. bilunaris, G. gracile* and *G. acuminatum* that are all epontic or benthic (Denys, 1991). *G. acuminatum* and *C. sinuata* both prefer alkaline and circumneutral waters. More acidic water was also present at the site to support the communities of *E. bilunaris* and *G. gracile* (Hustedt, 1939; Patrick and Reimer, 1966), possibly resulting from runoff from the surrounding peat soils.

4.12 Interpretation of the molluscan assemblage from borehole 3a (-3.57 to -3.62mOD, 880-885 cm)

All ecological information in this section has been obtained from Seaward (1982), Graham (1971) and Peacock (1993). The assemblage is dominated by marine species that today live in the sea around Skye with the exception of *L. obtusata* which will not tolerate wave exposure. There are only two species that do not require salinities of over 15‰ and *B. reticulatum,* accounting for 19% of the assemblage requires a salinity of over 25‰. This suggests that the basin in the vicinity of borehole 3a was inundated by marine waters and the species that could not tolerate this level of salinity probably developed on the periphery of the site. *H. ulvae*, which requires lower salinities, would probably have lived on wet mud or sand banks, where the influence of marine waters was limited.

The environment at the time the molluscan lived at the site appears to have consisted of many rocky outcrops, probably provided by the limestone outcrops surrounding the basin, where species could colonise the tidal pools. *C. cingillus*, *G. umbilicalis*, *R. parva*, *C. obtusa* and *L. obtusata* all inhabit rock pools. The majority of species including *G. umbilicalis*, *R. parva*, *N. lapillus* and *H. reticulata* all live on rocky shores. A saltmarsh may have formed at the extreme of the tidal limit and species such as *H. ulvae* could have colonised these areas. An offshore sandy substrate must have existed to support species such as *B. reticulatum*. Weeds would have provided a food source and acted as a sediment trap for silt among which many species such as *L. saxatalis*, *L. obtusata* and *G. umbilicalis* would have lived. A vertical zonation of molluscan would have developed at the site with littoral species present, such as *S. plana*, *M. bidentata* and *H. arctica* and some sublittoral species, for example, *H. reticulata* and *L. saxatalis*, extending to 15m depths. From the assemblage present, the minimum summer ocean surface temperature that all species could tolerate is 15.5°C, which is similar to that at present.

4.13 Interpretation of fish bone analysis from borehole 3a (-4.77mOD, 1000cm)

Interpretation of the fish bone assemblage was undertaken by Brian Irving (Carlisle). The bones identified were all vertebrae from small pelagic fish. These were Clupidae (herring family), *Clupea harengus* (herring), *Sprattus sprattus* (spratt) and *Ammodytes tobianus* (sand eel). All of the species at present live in waters around the Isle of Skye suggesting that conditions at the time the fish lived were similar to present. Irving reports that evidence from the vertebrae shows that no neural or haemal arches have survived intact on the vertebral body, which points to a consistent pattern of loss to the extremities of the vertebrae. The assemblage present reveals a classic set of attritional processes, which points to the digestion by a piscivorous animal. The most likely accumulators of this material are pelagic sea birds, most of which nest on cliffs with the exception of Laridae, Sternidae, Procelleriidae, Hydrobatidae and Phalacrocoracidae. These birds nest in large colonies and would accumulate considerable amounts of fish material during the breeding season. Fish regurgitated by piscivorous birds to feed to their chicks show the same type of attrition that is found in the assemblage. This is due to the mechanical action of the bird's crop and the digestive chemistry of the gut (Dobney *et al.*, 1996). Piscivorous birds pellet as well as defecate and both of these contain bone material with identical attritional patterns. The material is of uniform size and the most likely accumulator of fish of uniform size are nesting terns (Sternidae).

The accumulation of fish bones is unlikely to have been continuous over a large area. It is most likely that a single breeding season or a number of cumulative breeding events of a piscivorous bird has been recorded by this assemblage. The evidence strongly suggests that it is either the *Sterna paradisaea* (arctic tern) or the *Sterna hirundo* (common tern). Both of these species nest in large colonies on low-lying coasts within the palaeoarctic and a colony may have developed at Inver Aulavaig. Their diet is almost exclusively the same species and size class as the fish material identified and these fish would have been present in the waters around Skye. The evidence of the fish bones suggests the maritime location of Inver Aulavaig when accumulation of the bones occurred.

4.14 Environmental Interpretation at Inver Aulavaig

The oldest sequence at Inver Aulavaig is recorded in borehole 36 in the north-west of the basin (Figure 4.16). Initially, the basin was dominated by freshwater conditions as indicated by the oligohalobous diatoms recorded. The sediment is dominated by minerogenic material, indicating that little soil development had occurred and the diatom communities show a strong preference for alkaline waters reflecting the limestone bedrock. The loss on ignition analyses of these minerogenic sediments indicates that they contain less than 5% organic carbon content. The pollen in these sediments is very sparse and at the base of the assemblage, pollen could not be extracted. The environment was dominated by open-habitat, pioneering species characteristic of a Lateglacial Interstadial vegetation and also species that could tolerate wet conditions. It seems likely that ice had just retreated from the area when this assemblage of vegetation developed at the site. The radiocarbon date obtained at 2.30mOD (568cm) of 12590±290 BP provides a minimum age for deglaciation of this area. Meltwater could have provided the main water source for the site. Runoff is likely to have washed in sediments from the surrounding areas and this may explain a relatively fast sediment accumulation rate.

Freshwater conditions continued at the site until a depth of 1.06mOD (692cm) in borehole 36 when the first foraminiferan are noticed in the assemblage, within the basal minerogenic sediments. The foraminiferan present indicate that an increase in saline conditions has been recorded. No diatoms are present at this depth but it is likely that they did exist in the past as water would have been present at the site and have been subsequently dissolved. However, at a depth of 1.38mOD (660cm) in borehole 36, polyhalobous diatom species begin to increase confirming the onset of marine conditions at the site. Mesohalobous diatom species also increase both before and after the peak in marine species, indicating the gradual increase and decrease respectively of saline conditions. Freshwater diatom communities are displaced from the site and it is likely that as saline waters entered the basin, mesohalobous diatom species initially developed in the habitats previously occupied by oligohalobous diatom communities and that as relative sea level continued to rise, polyhalobous communities developed.

In order for the sea to penetrate this basin, it had to achieve an altitude of at least the height of the rock sill of the basin, measured at 5.10mOD. Therefore, relative sea level achieved at least an altitude currently of 5.10mOD during the Lateglacial Interstadial. After the ice retreated at the end of the Late Devensian glaciation, relative sea level fell because isostatic recovery of the land was the dominant component. However, at Inver Aulavaig, during the Lateglacial Interstadial, a transgression is recorded and two possible explanations exist for this.

It could be that the isostatic history of this basin did not follow a simple recovery curve and that uplift did not occur at a constant rate. Initially, during deglaciation, land uplift may have occurred at a faster rate than sea level rise and, therefore, relative sea level fell. Subsequently, the rate of land uplift may then have decreased or the rate of meltwater input to the oceans increased as in the Caribbean-Atlantic region (*e.g.* Blanchon and Shaw, 1995) such that relative sea level rose. As time progressed, however, the isostatic pattern was reversed and relative sea level fell as the rate of land uplift increased or as the input of meltwater to the oceans decreased.

The assemblage of pollen recorded at the time of the proposed transgression is suggestive of vegetation present during the latter part of the Lateglacial Interstadial. It is, therefore, proposed that the positive marine tendency may have occurred at *circa* 12000-11500 BP (see 4.10.1). The low percentages of carbon recorded from the loss on ignition analysis also suggests the transgression occurred during the Lateglacial Interstadial. A peak is seen at 1.78mOD above which a decrease occurs in carbon content. This is typical of the transition from the Lateglacial Interstadial to the Loch Lomond Stadial environments (Walker *et al.*, 1988) due to the break up of soils and inwash of carbon as a result of climatic deterioration.

The development of glaciers on Skye during a readvance of the ice may have caused redepression of the land that was experienced at Inver Aulavaig. This would have allowed the sea to enter the basin and marine sediments to be deposited upon deglaciation. It is possible that the transgression is a correlative of the Wester Ross Readvance recorded by Robinson and Ballantyne (1979) and Sissons and Dawson (1981) in Wester Ross and on

Coll and Tiree (Dawson, 1994). This was a readvance of glacier ice dated at between 17000-18000 BP and 13000 BP that was accompanied by a rise in relative sea level that culminated in the formation of the Wester Ross Shoreline.

The negative sea level tendency at Inver Aulavaig, when diatomological isolation of the basin occurred, coincides with the beginning of *limus* deposition, although a small peak, probably a short-lived local bloom, is seen in polyhalobous diatom species after the transgression and before 10110±140 BP. *Limus* deposition suggests that a lagoonal environment existed after the episode of high sea level and the high frequencies of aquatic pollen such as *M. alterniflorum* and *M. verticallatum/spicatum* would confirm this. The increased organic nature of the sediments, containing up to 30% organic carbon, suggests some stabilisation of the environment and increased soil depth and development at this time.

Between 10110±140 BP and 8850±170 BP, a large expansion of hazel woodland/scrub occurred and this was accompanied by a small increase in mixed woodland. Alkaline-loving oligohalobous diatom species continued to exist at the site (Figure 4.16). However, at an altitude of 3.58mOD (440cm) in borehole 36, an increase in aquatic species of plants occurs. This could indicate a rise in the groundwater table or increased surface wetness at the site. The presence of *P. maritima* pollen in LPAZ 3 IAc, suggesting the development of saltmarsh at the site, may indicate that the increase in the level of the water table was also accompanied by increasing salinity. Additionally, prior to 8850±170 BP, the presence of mesohalobous diatom species is noted and this would suggest that saline water was intermittently entering the basin allowing a small community of brackish diatoms to exist in the area of borehole 36.

At an altitude of 3.45mOD (453cm), *limus* deposition and lagoonal conditions at the site cease and an environmental change appears to have occurred as represented by the development of *Phragmites* peat. 86% organic carbon content is noted and telmatic vegetation appears to have developed at the site. In borehole 36, at an altitude of 4.08mOD (390cm) in borehole 36, a sharp increase is seen in the polyhalobous and mesohalobous diatom communities at the site. The stratigraphy at this depth consists of silt and clay and the organic content has fallen. Polyhalobous diatom species rise to over 75% of the assemblage and are dominated by *P. sulcata,* suggesting again that a littoral environment existed. This increase in polyhalobous and mesohalobous diatom species, therefore, represents a second positive marine tendency at the site that achieved an altitude of at least 5.10mOD and connection of the basin to the sea. Freshwater communities of diatoms are displaced from the site probably to the periphery of the saline water body. This increase in polyhalobous species in zone LDAZ 4 IAd (Figure 4.16) occurs shortly after a date of

8850±170 BP, although a small community of mesohalobous diatom species was present before this time. The radiocarbon age obtained for this event suggests that it is related to the Main Postglacial Transgression, which is thought to have occurred between 7000-5500 BP in western Scotland (Dawson, 1984).

The last recording of polyhalobous conditions in borehole 36, occurs at 3280±60 BP. A sharp fall in polyhalobous diatoms actually occurs before this time and the time represented between the altitudes of 4.52-4.82mOD (436-315cm) could represent overwash into the basin during, for example, periods of high tides. By 3280±60 BP, however, marine waters had fallen below the altitude of the rock sill of the basin and all saline influences in borehole 36 had ceased. This is, therefore, taken as the negative marine tendency in this borehole and diatomological isolation of the basin. In borehole 36, it is possible that the transgression lasted for approximately 5500 years although it is possible that after the Main Postglacial Transgression had ended saline water remained in the basin even though the sea had fallen below the altitude of the rock sill, *i.e.* regressed.

In borehole 3a, which is situated closer to the rock sill, saline conditions are recorded at the base of the diatom assemblage (LDAZ 1 I3a) and supported by the presence of fish bones at -4.77mOD (1000cm) and the molluscan present at between -3.57 and -3.62mOD (880-885cm) but in this area at 5440±50 BP freshwater conditions dominated (Figure 4.16). Withdrawal of the sea from the site is, therefore, recorded at this time allowing oligohalobous diatom communities to exist. The sharp decline in polyhalobous diatom species recorded in borehole 36 at 4.52mOD (436cm) could also have occurred at *circa* 5400 BP. A negative marine tendency, therefore, appears to be recorded in borehole 3a at 5440±50 BP. Occasional overwash is also suggested in borehole 3a, as in borehole 36, by the low presence of polyhalobous and mesohalobous diatom species after 5440±50 BP. Freshwater conditions are recorded in borehole 3a until 3160±40 BP when an increase in marine conditions is again recorded and connection of the basin to the sea seems to have occurred. This appears to represent a subsequent rise in relative sea level that must have attained an altitude of at least 5.10mOD. Borehole 36 has not recorded this second phase of high Holocene sea level possibly because the rise may have been of limited lateral extent. The altitude of the marine deposits representing the Main Postglacial Transgression in borehole 3a is lower than that in borehole 36 and this is likely to be due to compaction of the sediments or differences in sedimentation rates.

It is not until the middle-late Holocene, that the sequence in borehole 15, in the south of the basin begins. Fully marine conditions are not recorded in this borehole and it is thought that saline waters never penetrated this area. A small community of brackish diatoms are represented in the basal sediments of this area, but freshwater conditions always dominated. It is unlikely that the sequence of changes extends back to the time of Main Postglacial Transgression. The base of the borehole lies at 6.01mOD and it is, therefore, possible to state that the late Holocene relative sea level rise did not attain this altitude, *i.e.* is constrained by the altitudes of 5.1-6.01mOD, or that it was of limited lateral extent.

After the withdrawal of marine water from the site, conditions appear to have become drier. Hazel-dominated mixed woodland is likely to have existed on the periphery of the site but conditions at Inver Aulavaig record increasing acidification with the development of ling and crowberry heathland during the last 3000 years. The frequencies of *Sphagnum* increase and it is at this time that peat bog development occurred as indicated in the stratigraphy and the pollen assemblages.

4.15 Conclusions

The investigations at Inver Aulavaig have revealed a sequence of environmental changes that extend back to the Late Devensian. Three episodes of high relative sea level have been identified. The first occurred in the Late Devensian and probably during the Lateglacial Interstadial. It is probable that the transgression is associated with the Wester Ross Readvance which arrested the isostatic recovery of the land, caused renewed isostatic depression and upon deglaciation allowed marine waters to penetrate the site above an altitude of 5.10mOD. Alternatively, the transgression may represent the complex interplay between the land and ocean during deglaciation of the Late Devensian ice sheet. The environment during the transgression is likely to have supported a low alpine/tundra scrub with limited soil development. The Loch Lomond Stadial is represented by a small peak in carbon which then decreases and the presence of tundra-type species such as *C. crispa.*

The start of the Holocene at the site is marked by the increase in hazel scrub and the development of woodland. The second period of high relative sea level is thought to represent the Main Postglacial Transgression and is recorded from 8850±170 BP when it attained an altitude of 5.10mOD. It probably lasted until approximately 5440±50 BP, although overwash into the basin was probably experienced until 3280±60 BP. The late Holocene episode of high relative sea level began at 3160±40 BP and is only recorded in the borehole situated closest to the rock sill suggesting that it may have had limited areal and vertical extent. It is possible that the late Holocene rise in relative sea level did not attain an altitude of greater than 6.01mOD. Following the late Holocene transgression, acidification of the site occurred resulting in peat development and the spread of ling heath. Probable anthropogenic activity is sugested in this area by the presence of *P. lanceolata*, *P.*

media/major and Caryophyllaceae pollen.

Chapter 5.0 Peinchorran

5.1 Introduction

Peinchorran (NG 5280 3340) lies on the east coast of the Isle of Skye, 12km south of Portree. The study area consists of a peat bog, 400m wide by 700m long. This has formed at the centre of a tombolo as a result of the formation of cobble barriers connecting the rock outcrops of Tòrr Mór and Tòrr Beag to the mainland (Figure 5.1). These rock outcrops rise to over 41m and 27m respectively and consist of Mesozoic sedimentary rocks. The crest of the northern barrier of the tombolo has an altitude of 7.8-8.0mOD and is partially vegetated. The southern barrier is vegetated and has an altiude of 7.1-8.3mOD. A spit has formed at the south of Tòrr Beag (Rubha' an Tòrra Mhòir) and extends into Loch Sligachan. A cobble and sand beach has developed around the tombolo at low tide. The lower limit of land-based vegetation lies at 2.75-2.84mOD. The peat bog has been extensively drained and a stream drains from the surrounding slopes of Peinchorran across the site in a northerly direction breaching the northern barrier. An area at the centre of the site is waterlogged and is surrounded by stands of *Phragmites australis*. The vegetation of the peat bog consists primarily of *Sphagnum* spp, Ericaceae, *Calluna vulgaris* and *P. australis.*

5.2 Geomorphological mapping, borehole location and stratigraphy

The main geomorphological feature of the site is the tombolo with its two barriers (Figure 5.1). Three transects were cored to establish the stratigraphy. The basal unit in transects A and 1 generally consists of an organic silt with a small amount of blue grey clay present in some boreholes, *e.g.* boreholes b and c (Figures 5.2 and 5.3). In transect B, a blue grey clay forms the basal unit (Figure 5.4) and a section on the bank of the stream reveals the basal unit in this location to consist of a grey glacial diamicton, probably till. It is thought that all the boreholes bottom in glacial till. Overlying the basal sediment, in the centre of the bog, is a grey brown silty sand with *P. australis* fibres. In borehole a, a minerogenic layer between 4.0-4.2mOD overlies a *substantia humosa* and is in turn overlaindby *substantia humosa*. In the boreholes at the edges of the site (*e.g.* boreholes b and c), a brown black organic silt is recorded. Overlying the silt unit is a black *substantia humosa*, which is in turn overlaid by a sandy silt. In borehole 10, the organic silt horizon is extremely thin and is replaced by a dark blue grey sand and gravel. In transect A, the unit is more silty. The sandy silt unit has a transitional boundary with the overlying peat unit. At about 7.29mOD and 5.79mOD, black *P. australis* fibres occur in association with peat. The top stratigraphic unit in all the boreholes is a red-brown fibrous *Sphagnum* peat that is woody throughout in transects 1 and A. In boreholes to the north and south of the site, the *Sphagnum* peat unit directly overlies the till or bedrock (*e.g.* boreholes 4, 5, 11, 12 and 13).

A sample core from borehole F was recovered from the centre of the peat bog for microfossil analyses. This location was chosen because it was some distance from any present day fluvial activity, represented the longest core and contained all the main stratigraphical units identified at the site. Additionally, it did not appear to have been affected by peat cutting.

Table 5.1: Stratigraphy of borehole F (NG 5288 3320)

Altitude (mOD)	Depth (cm)	Sedimentary description
8.29-7.34	0-95	Red brown fibrous *Sphagnum* peat with wood
7.34-6.94	95-135	Brown black peat with *P. australis* fibres
6.94-5.79	135-250	Red brown black fibrous peat
5.79-5.59	250-270	Brown black peat with *Phragmites* fibres
5.59-5.14	270-315	Brown black organic silt
5.14-4.71	315-358	Grey brown organic sandy silt
4.71-4.47	358-382	Black *substantia humosa*
4.47-4.29	382-400	Grey brown sandy silt
4.29-4.25	400-404	Brown black *substantia humosa*

5.3 Loss on ignition

Samples were taken for high and low level loss on ignition analyses where visible changes were noted in the stratigraphy (Figure 5.5). The top unit of *Sphagnum* peat consists of 65-70% organic carbon and a peak of 32% occurs in the carbonate content. This is the maximum recorded carbonate content that is achieved in this stratigraphy and may suggest insufficient combustion of highly organic sediments at the lower carbonate temperature or may actually represent sulphides that were burnt off at the higher temperature. In the *Phragmites* unit below, 100% carbon content is recorded and this remains at over 95% for the lower *Sphagnum* and *Phragmites* units. As the stratigraphy becomes increasingly silty, the organic content drops to 90% and as sand forms part of the stratigraphic unit, the organic content falls to 10%. The black *substantia humosa* has an organic carbon content of 92% and the underlying minerogenic unit has an organic content of 12%.

5.4 Pollen analysis

Samples were taken at 16cm intervals for the top 340cm and at 4, 2 and 1cm intervals for the lowest 64cm. The lower minerogenic horizons were investigated at the closer sampling interval, as it was thought that if relative sea level changes were recorded they would be preserved in these sediments. Throughout the peat units, the pollen is used primarily to provide a broad environmental context of deposition and as a relative dating technique. Five local pollen assemblage zones have been identified from the pollen analysis undertaken (Table, 5.2, Figure 5.6).

Table 5.2: Pollen zone descriptions for borehole F

Pollen zone	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 5 Pe	8.29-7.33	0-96	***Corylus avellana*-type-*Calluna vulgaris*-Poaceae -Cyperaceae.** Low frequencies of *Alnus* and *Betula* pollen are recorded in this zone with decreasing *C. avellana*-type pollen. *C. vulgaris* pollen fluctuates (16-38%) in this zone. Fluctuating Poaceae pollen is noted with the presence of Poaceae diameter >40μm and Cyperaceae pollen is also recorded. In this zone, there is noticeable *Plantago lanceolata, Succisa pratensis* and *Menyanthes trifoliata* pollen. The presence of spores of *Tilletia sphagni, Diphasiastrum, Polypodium* and *Sphagnum* are also recorded in this zone.
LPAZ 4 Pd	7.33-6.81	96-148	***C. avellana*-type-Poaceae-Cyperaceae.** Low arboreal and *C. avellana*-type pollen is recorded in this zone. *C. vulgaris* values are low and pronounced Poaceae and Cyperaceae values are present at mid-zone. Ranunculaceae pollen is recorded at top of zone and there is noticeable *Circaea* and *Filipendula* pollen. Aquatics and spores are virtually absent.
LPAZ 3 Pc	6.81-5.65	148-264	***C. avellana*-type-*C.vulgaris*-Cyperaceae-Poaceae.** Fluctuating *Alnus* values are recorded with increased *Betula* through the zone and noticeable *Quercus* pollen. *C. avellana*-type pollen is present at 20%. *C. vulgaris* pollen is increasing and Ericaceae pollen shows a low presence. Poaceae values are low (10-15%) and Cyperaceae values decline in this zone. There is noticeable *P. lanceolata* and a peak in *Potentilla* pollen is noted at the start of the zone. A very small presence of aquatics and Pteropsida, *Sphagnum* and *Polypodium* spores are represented.
LPAZ 2 Pb	5.65-4.61	264-368	***Alnus*-Poaceae-Cyperaceae.** *Alnus* values increase to 85% at mid-zone and then decrease. There is noticeable *Betula* pollen in this zone. *C. avellana*-type and *Calluna vulgaris* pollen decline to mid-zone, but increase to the upper zone boundary. Fluctuating Poaceae (15-30%) is recorded and Cyperaceae values initially increase, but then decline to the top of the zone. *Plantago maritima* pollen is recorded in the lower levels and the appearance of *P. lanceolata* pollen is noted. There are noticeable *Potamogeton* values in lower levels of zone with decreased Pteropsida spores and a pronounced peak in *Sphagnum* spores.
LPAZ 1 Pa	4.61-4.25	368-404	***C. avellana*-type-*Betula*-Cyperaceae-Poaceae.** *Betula* values increase to 40% at mid-zone and then decline. The presence of *Ulmus, Pinus, Alnus* and *Quercus* pollen is recorded in this zone. *C. avellana*-type pollen decreases. An increase in *C. vulgaris* pollen occurs (20%), but falls towards the top of the zone and some Ericaceae pollen is recorded. Poaceae values fluctuate around 20%, and Cyperaceae values decrease in this zone. There is also noticeable Lamiaceae, Rosaceae and *Potentilla* pollen in this zone. *Sphagnum* spores decrease through the zone. The spores of Pteropsida are present and those of *Trichomanes speciosum* are recorded in the latter half of zone.

5.5 Diatom analysis

Diatom samples were analysed at 4, 2 and 1cm intervals to investigate the salinity of the environment in the lower minerogenic horizons. Three local diatom assemblage zones have been identified and a summary of each is tabulated and interpreted below (Table 5.3, Figure 5.7). Below 4.49mOD (380cm), no diatoms were found, although samples were prepared from 4.48-4.25mOD (381-404cm). Above 5.29mOD (300cm), the sediment was also barren of diatoms. At 4.94mOD (335cm), the diatoms were too sparse to count and in addition very badly preserved, but centres of *Navicula peregrina* and *Navicula pusilla* were observed and *Surirella linearis* was also noted. Five raphes occur at a depth of 5.15mOD (314cm) and were believed to be *Pinnularia* species.

Table 5.3: Diatom zone descriptions for borehole F

Diatom zone	Altitude (mOD)	Depth (cm)	Diatom Characteristics
LDAZ 3 Pc	4.90-4.81	339-348	***Paralia sulcata-Navicula elegans-Fragilaria lapponica.*** Increasing *P. sulcata* to 60% is recorded in this zone. Fluctuating mesohalobous species dominated by *N. elegans* and *N. peregrina* are recorded. *N. pusilla* and oligohalobous-halophilous species are recorded in the uppermost half of this zone. Oligohalobous-indifferent species peak at mid-zone and then decline. The assemblage is species-rich with noticeable *F. lapponica*, *Navicula rhyncocephela*, *Fragilaria construens* and *Fragilaria brevistriata*. An increase to 20% of diatoms with unknown ecology is also recorded in this zone.
LDAZ 2 Pb	4.81-4.60	348-369	***Fragilaria exigua.*** Rapidly declining *P. sulcata* is recorded at the start of this zone. Mesohalobous species, dominated by *Achnanthes delicatula* and *Achnanthes hauckiana*, decline through the zone. Oligohalobous species, dominated by *F. exigua*, *F. construens*, *Fragilaria construens* var. *venter* increase throughout the zone to 95%. There are also noticeable *Achnanthes distincta*, *Fragilaria pinnata* and *N. rhyncocephela* in this zone.
LDAZ 1 Pa	4.60-4.48	369-381	***Paralia sulcata.*** Very high *P. sulcata* (90-100%) and noticeable *Rhabdonema minutum* is recorded in this zone. *A. delicatula* increases at top of zone. Oligohalobous species are present at low frequencies throughout.

5.6 Radiocarbon dates

Four radiocarbon dates have been obtained for Peinchorran. Each date relates to a probable marine event as determined from the diatom assemblages but otherwise no specific features of the pollen record have been dated. Beta-83734/5 both date increases in polyhalobous species of diatoms thought to represent positive marine tendencies at the site and Beta 92170/2 both date decreases in polyhalobous species of diatoms and are thought to represent negative marine tendencies at the site. All ages obtained are bulk radiocarbon dates.

Table 5.4: Radiocarbon dates for borehole F

Conventional C14 age (BP)	C13/C12 ratio	Calibrated C14 age (BC)	Laboratory code	Altitude (mOD)	Depth (cm)
3970±140	-25.0 ‰	2845-2205	Beta-92171	4.91-4.89	338-340
4220±60	-27.8 ‰	2915-2605	Beta-83734	4.84-4.82	345-347
6600±70	-25.0 ‰	5600-5415	Beta-92172	4.62-4.59	367-370
7980±70	-27.9 ‰	7025-6570	Beta-83735	4.49-4.46	380-383

5.7 Interpretation of pollen assemblages

The pollen at Peinchorran may have been derived from several sources. Steep slopes rise to the west of the site and slopewash and runoff may have brought pollen grains onto the site (*e.g.* Peck, 1973). Additionally, a river drains these slopes and pollen may have been delivered to the site through fluvial processes. Erosion of the soils or banks of the river may have released pollen grains. Buoyant pollen grains would have been preferentially transported by the river and also a bias would have existed towards these grains in times of marine inundation of the site.

LPAZ 1 Pa (4.61-4.25mOD, 368-404cm) (Figure 5.6)
The base of the pollen assemblage is dominated by *Betula* and *C. avellana*-type. Combined with the small amount of *Pinus*, *Quercus*, *Salix* and *Ulmus* pollen, it is suggested that some mixed woodland development occurred in this zone and the presence of these taxa is characteristic of early Holocene woodland (Birks, 1973, Williams, 1977; Birks and Williams, 1983; Walker *et al.*, 1988; Walker and Lowe, 1990). Pteropsida, *Polypodium*, *Pteridium* and *S. pratensis* spores, which are all recorded in this zone, can form the understorey component in open woodlands. *C. avellana*-type pollen could also represent the development of hazel scrub at the site.

The large amount of *Sphagnum* spores, combined with Cyperaceae pollen, recorded at this time are likely to represent an acid bog environment. Acidification and peat development appear to have occurred at the site and the presence of *C. vulgaris* and Ericaceae pollen suggests the development of ling heathland. The pollen of Ranunculaceae, *Potentilla* and

Filipendula in this zone may also represent components of the heathland. The presence of Poaceae pollen suggest that open areas of grassland would have been present in this zone. A peak occurs in Lamiaceae pollen in this zone, but the ecological conditions represented are unclear, as it was only identified to family level. *T. speciosum* spores recorded in this zone, would occupy the shady, humid environments provided by rocks lying at the site (Clapham *et al.*, 1987). A decrease occurs over the upper boundary of this zone in the pollen of *C. avellana*-type, *C. vulgaris*, Rosaceae and *Potentilla* and this could represent loss of hazel scrub and heathland as the peat bog expanded.

P. maritima pollen increases over the upper boundary of the zone and sea plantain colonises saltmarshes or short turf near the sea. It is a common species and is present on most of the British Isles coastline (Clapham *et al.*, 1987). Some Chenopodiaceae pollen is also recorded and this could also indicate saltmarsh development, although many ecological conditions are represented by this family. Additionally, the presence of *Armeria/Limonium* pollen across the boundary also indicates maritime conditions and possibly some muddy saltmarsh development (Clapham *et al.*, 1987). These taxa could indicate a higher or more saline water table and it does appear that saltmarsh development may have occurred at the site in areas influenced by saline waters.

LPAZ 2 Pb (5.65-4.61mOD, 264-368cm)
The lower boundary of this zone is dated at 6600±70 BP (Beta-92172) and marks the beginning of the increase in *Alnus* pollen and the development of alder carr at the site. *Alnus* can tolerate wet conditions and is often present in the succession to fen or marsh. The longevity and competitive power of *Alnus* often means that it can expand at the expense of other species (Birks, 1989) and this could have occurred at Peinchorran, displacing the hazel scrub. The pollen of arboreal taxa such as *Betula*, *Fraxinus*, *Quercus*, *Pinus* and *Ulmus* are present, although at very low frequencies and it would seem to reflect the development of some mixed woodland in the pollen catchment area. It is likely that ferns formed an understorey component to the woodland as represented by the Pteropsida spores in this zone.

The high frequencies of Poaceae and Cyperaceae pollen suggest that an open grassland prevailed in areas of the site not occupied by hazel scrub or alder carr. The presence of *Drosera rotundifolia*-type, Ranunculaceae, *Plantago* undifferentiated, Rosaceae and *Filipendula* pollen reflect a vegetation of grassland, bog or heath. Aquatic spores are present in the lower levels of this zone and the small increase in *Potamogeton* pollen indicates that pools of water were present at the site at this time on the surface of the bog. The large peak in *Sphagnum* spores towards the top of the zone represents a short-lived expansion of damp acid conditions and development of a bog environment.

The continued presence of *P. maritima* pollen in the lower levels of the zone may indicate the presence of either a saltmarsh or proximity of the sea to the site. However, it is also present in montane grassland and beside mountain streams. It, therefore, appears that in the lower levels of this zone, a wetter environment existed that was possibly a result of increased saline influence at the site as indicated by the presence of *P. maritima*, *Armeria/Limonium* and Chenopodiaceae pollen.

The first appearance of *P. lanceolata* pollen is recorded in this zone. It occurs just below the dated horizon at 4220±60 BP (Beta-83734) and is thought to relate to anthropogenic activities at the site. It is thought that the presence of *P. lanceolata*, Chenopodiaceae, Lactuceae, Brassicaceae and Asteroideae pollen represent the start of pastoral activity at the site, although Chenopodiaceae, Brassicaceae and Asteroideae may also reflect cultivation. In the upper levels of the zone, the site becomes drier and this could in part be due to artificial drainage of the site.

LPAZ 3 Pc (6.81-5.65mOD, 148-264cm)
This zone is characterised by a marked decrease in *Alnus* pollen suggesting the decline in alder carr in the pollen catchment. An increase in *Betula* and *C. avellana*-type pollen occurs and hazel scrub and stands of birch possibly colonised the areas previously occupied by alder carr. Pteropsida and *Polypodium* spores continue to be recorded and could have formed the understorey component in the hazel-dominated woodland/scrub. A low pollen presence of other arboreal taxa is recorded, *e.g. Fraxinus, Pinus* and *Quercus* and would represent a minor presence of mixed woodland in the pollen catchment.

High frequencies of Poaceae and Cyperaceae pollen indicate the open nature of the site. An increase has occurred in ling heathland as indicated by the increase in *C. vulgaris* and Ericaceae pollen. This would suggest that the environment continued to be acid in nature with moorland/acid heath development occurring. Some other herb species, represented by Ranunculaceae, Rosaceae and *Potentilla* pollen, are present and would colonise the grassland and heath. The presence of *Sphagnum* spores in the profile confirms the wet, acid nature of the site and these factors all suggest expansion of peat in this zone.

P. lanceolata pollen increases slightly in this zone and the presence of Chenopodiaceae pollen is still noted. Combined with the presence of Ranunculaceae, *Rumex acetosa/acetosella*, and Brassicaceae pollen, this suggests the continued occurrence of anthropogenic activities in the area. It is possible that some woodland clearance has occurred in this zone as evidenced by the low frequencies of arboreal pollen.

LPAZ 4 Pd (7.33-6.81mOD, 96-148cm)
The pollen of tree species are present in extremely low quantities in this zone, suggesting little mixed woodland development in the pollen catchment area. *Alnus* pollen has declined to less than 5% of the assemblage, although an increase in *C. avellana*-type pollen has occurred. It is possible a very local change has occurred, resulting in an increase in hazel scrub that has masked more regional effects.

An increase in Poaceae and Cyperaceae pollen suggests the open nature of the environment, although the peaks of both families in the middle of the zone appear to be anomalously high at a time when the trend of both families is declining. A large component of the Poaceae pollen count could be *P. australis* as suggested by the fragments of this species noted in the core. Small increases are recorded in *Circaea* pollen and this may suggest that the grassland has become less acid (Clapham *et al.*, 1987) although *Circaea* may also be a woodland herb. This coincides with the loss of ling heathland as shown by the decline in *C. vulgaris* and Ericaceae pollen.

P. lanceolata pollen continues to be recorded in association with Chenopodiaceae pollen. Ranunculaceae pollen could be a product of arable farming methods as some species of Ranunculaceae may be associated with cornfields and other farming environments although they can also grow naturally on bogs and fens (Clapham *et al.*, 1987). Conditions at the site appear to be very dry with virtually no aquatics or spores recorded and this could be as a result of anthropogenic activities draining the land.

LPAZ 5 Pe (8.29-7.33mOD, 0-96cm)
Low arboreal pollen percentages are recorded in this zone indicating a virtually treeless environment. However, some hazel scrub development is represented by *C. avellana*-type pollen, although this decreases towards the top of the assemblage and some stands of birch are probably present suggested by the low *Betula* values. The presence of Pteropsida, *Polypodium* and *Diphasiastrum* spores could represent the understorey component in the hazel scrub.

An open environment appears to have dominated this zone. Ling heathland, as indicated by the dominance of *C. vulgaris* pollen, also forms a major component of the environment, possibly expanding at the expense of hazel scrub at the site. This species combined with the presence of *Sphagnum* spores indicate that the environment has again become more acid and peat development is indicated. An increase in *T. sphagni* spores would be associated with the presence of *Sphagnum*. It is possible open bodies of water are present at the site as indicated by the small amounts of aquatics and spores and *M. trifoliata* is a species that colonises bog environments. Poaceae and Cyperaceae values increase towards the top of the zone and *P. australis* could be an important component of the count, indicating open grassland and reedswamp development. The peak in *S. pratensis* suggests the environment may be very marshy, although it could be growing as an understorey component (Clapham *et al.*, 1987).

Anthropogenic activity is still recorded at the site by the presence of *P. lanceolata*. Additionally, an increase in Poaceae, diameter >40μm, annulus >10μm, is noted at the top of the zone, which is thought to represent cereal pollen and suggests that arable cultivation was present in this area.

5.8 Interpretation of diatom assemblages

LDAZ 1 Pa (4.60-4.48mOD, 369-381cm) (Figure 5.7)
P. sulcata totally dominates this zone (present up to 100%) and would appear to represent marine conditions at the site, although some discrepancies exist as to its ecology (see 4.11.1). Conditions appear to have been ideal during this zone to allow *P. sulcata* to thrive. It is possible that as the sea began to rise, it was accompanied by increased storm activity that forcibly removed the species from the sea bed, leading to its subsequent deposition or that an inter-tidal area developed in part of the site. It is possible that *P. sulcata* was preferentially preserved due to the amount of silica per surface area ratio and due to its centric shape. The specimens in this zone are perfectly preserved, often in chains and of very large diameters, often up to 80μm. The assemblage of *P. sulcata* could also be some function of barrier and coastal dynamics that allowed the community to thrive at the expense of other species and it is often reported that *P. sulcata* responds to some conditions well by stressing and reproducing to the detriment of other species (Devoy pers. comm.). *R. minutum* is also recorded and is a polyhalobous species, but it is epiphytic, growing attached to algae or solid substrate and thus occupying a different ecological niche to *P. sulcata*. A presence of *Cocconeis scutellum* represents a slightly less saline element to P. sulcata in this zone and is epiphytic (Patrick and Reimer, 1966).

This zone has been constrained by the dates of 7980±70 BP (Beta-83735) and 6600±70 BP and the saline conditions represented by *P. sulcata* appear to correspond to the Main Postglacial Transgression in this area (Dawson, 1984). It is unclear, however, because of the ecology of *P. sulcata* whether total inundation of the site would have occurred. This is further complicated by the coastal dynamics of the site.

LDAZ 2 Pb (4.81-4.60mOD, 348-369cm)
Initially in this zone, the removal of saline conditions is represented by the sharp fall in *P. sulcata,* which is virtually absent from the organic sandy silt unit. High levels of brackish species in the lower levels of the zone are recorded and represent the transition to less saline conditions. *A. haukiana* is a common species, but only tolerates very slightly brackish water (Patrick and Reimer, 1966) and hence it is found in the assemblage when *P. sulcata* has disappeared. *A. delicatula,* also a brackish species, prefers alkaline waters (Hustedt, 1939) that are eutrophic (Naumann, 1932). The small peak in *O. olsenii* represents a population occupying a sandy, brackish environment. The freshwater assemblage, totally dominated by *F. exigua,* increases to over 90% of the assemblage at the top of the zone and occupies a niche of eutrophic waters of low mineral content.

The bottom of this zone has been dated at 6600±70 BP and represents the transition from marine to freshwater conditions. The top of this zone is dated at 4220±60 BP and represents the rapid transition from freshwater conditions to marine. Between 6600±70 BP and 4220±60 BP, therefore, marine waters have regressed from the site and a small brackish water community first developed. This is eventually displaced as the site becomes entirely fresh, with conditions that are ideally suited to the development of *F. exigua.*

LDAZ 3 Pc (4.90-4.81mOD, 339-348cm)
This zone again records marine and brackish conditions. *P. sulcata* does not reach the frequencies achieved in the lowest zone, suggesting that a marine episode of a different magnitude or nature has occurred. It does, however, reach frequencies of over 45% towards the top of the zone and, therefore, by Kjemperud's (1981) criteria, represents saline conditions. *N. elegans* and *N. peregrina* are both benthic, brackish species that prefer alkaline, eutrophic waters and it is possible that storm activity or a high energy event brought the diatoms into the area from offshore. In the middle of this zone, *F. lapponica* reaches 58% of the assemblage and represents a short-lived local bloom that developed. *F. lapponica* lives in freshwater of low mineral content that would have developed in some areas of the site. The changes in this zone represent an increase in marine influence at the site that may be a function of the barriers or a relative sea level rise representing a later Holocene transgression in this area. The episode is constrained by the dates 4220±60 BP and 3970±140 BP (Beta-92171).

5.9 Environmental History of Peinchorran

The basal stratigraphic unit at Peinchorran consists of glacial till and is likely to have been deposited during the Loch Lomond Readvance (Figure 2.6) (Ballantyne, 1989). Loch

Lomond ice limit maps constructed by Ballantyne (1989) indicate that the limit of the Sligachan glacier was such that Peinchorran was over-run by ice, but a little further north at The Braes, the area remained ice-free during the Stadial. As a result of glacial over-riding at Peinchorran, no high, raised shorelines are found. It is upon glacial till that sedimentation began at the site. The sediments overlying the till are initially minerogenic, but become more organic with an increase to 92% carbon content at a depth of 4.61mOD (368cm). Mixed woodland, containing hazel and birch, dominated the environment with grassland and sedge species indicating more open areas of the pollen catchment (LPAZ 1 PSa) (Figure 5.8).

No date has been obtained at the base of the sequence, but it seems unlikely that a full Holocene sequence is recorded, as the frequencies of *C. avellana*-type pollen, thought to represent hazel, are too high for the early Holocene when compared to other pollen sequences for Skye (Birks, 1973; Williams, 1977; Birks and Williams, 1983; Walker and Lowe, 1990; Lowe and Walker, 1991). No diatoms are present from 4.48-4.25mOD (381 -404cm) and, therefore, the salinity of the environment at the start of the assemblage is equivocal.

At 7980±70 BP, at an altitude of 4.49mOD (380cm) (LDAZ 1 PSa), polyhalobous diatom species show a presence of greater than 95%. This is thought to reflect a relative sea level rise and marine inundation of the site, although this probably started prior to 7980±70 BP as suggested by the very abrupt increase in marine diatoms. Diatoms could not be recovered below 4.48mOD to ascertain the salinity of the environment. The increase in salinity is recorded within an organic deposit and it is possible that a saltmarsh formed in part of the site as both *P. maritima* and *Armeria/Limonium* pollen are recorded. Alternatively, an organic-rich algal mat could have formed supporting the community of *P. sulcata*. Allen (1990) states that under a rising sea level a dynamic equilibrium has to be maintained to create peat and this equilibrium is only possible when the surface of the marsh has risen to the elevation of the Highest Astronomical Tide. Peat development at the site must, therefore, have kept pace with relative sea level rise and borehole F may have been situated in a protected area of the peat moss, where terrestrial/telmatic vegetation could grow. The development of the tombolo may also have provided a protected environment that allowed peat growth to occur whilst at the same time reflecting transgression of the sea.

The tombolo at Peinchorran is classed as a double tombolo, as two barriers have formed connecting the islands to the mainland (King, 1972). The barriers could have formed in two ways dependent on the origin of the sediments. Material may have come from offshore, derived from till deposited by the Sligachan glacier (Boyd and Penland, 1984) (Figure 3.4). Swash-aligned barriers are the most common type of barrier to form from offshore material and it is possible that only one barrier formed at Peinchorran initially, connecting the rock outcrops of Tòrr Mór or Tòrr Beag to the mainland, forming a single tombolo, and that, at a later date, a second barrier formed with the development of a double tombolo.

Alternatively, as sea level rose, an erosional front may have progressed towards the rock outcrops, increasing the height of the wave base and enhancing erosion. Two point sources of sediment would then have been provided by the rock outcrops and transport of the material would have occurred in a landward direction until a point of null drift was encountered (Orford *et al.*, 1991). Reworking of the sediment would then have allowed extension of the feature and drift-aligned forms may have developed on the northern and southern flanks of the rock outcrops. In this scenario, both barriers may have formed at the same time and alternation between drift- and swash-alignment may have occurred as the wave climate and sediment supply changed.

The decrease in polyhalobous diatom species is dated at 6600±70 BP and the episode of high relative sea level between 7980±70 BP and 6600±70 BP is thought to represent the Main Postglacial Transgression in this area. Barrier formation has been associated with the Main Postglacial Transgression in western Scotland (Dawson, 1984). It is thought that, initially, the rate of relative sea level rise of the Main Postglacial Transgression was fast and that the rate then decreased (*e.g.* Smith *et al.*, 1985; Zong and Tooley, 1996). Barriers can form at different rates of relative sea level rise and are dependent on site-specific conditions (Carter *et al.*, 1989; Roy *et al.*, 1994). Carter *et al.* (1989), however, report that a rapid sea level rise drives barriers onshore, but the sediment supply can become depleted or may not keep pace with the relative sea level rise. Barriers then often become stranded onshore and excess sediment is dispersed onto the shelf. Belknap and Kraft (1981) and Davis and Clifton (1987), however, state that the greatest preservation of marine facies often occurs under a rapidly rising relative sea level and this may have occurred at Peinchorran. It is unclear when the barriers would have formed at Peinchorran, but the formation of the barrier(s) does appear necessary to allow peat growth during marine inundation of the site. Therefore, the barrier(s) needed to have formed at the beginning of the Main Postglacial Transgression, when the rate of relative sea level rise was probably fastest.

At 6600±70 BP, an increase in freshwater conditions is recorded at an altitude of 4.61mOD (368cm) (LDAZ 2 PSb) represented primarily by *F. exigua*. This date appears to represent the end of the Main Postglacial Transgression in this area. During *circa* 1400 years only 12cm of sedimentation occurred. This is an extremely slow accumulation rate especially given the fact that relative sea level was rising and associated coastal erosion might have resulted in increasing rates of sediment production and delivery. It is possible that an hiatus is recorded during the marine phase, although this is impossible to substantiate with the litho- or biostratigraphical evidence.

An increased fluvial or slopewash component to the site after 6600±70 BP may be inferred from the change in sedimentation to a more minerogenic deposit. The contact of the organic deposit with this unit is transitional and does not appear to record any erosional event. It is probable that a breach was present in the barrier(s) allowing drainage of the stream from the site, as it does today. The sedimentation rate continued to be very low with only 20cm of sediment accumulating in *circa* 2400 years, but no hiatus has been identified from the pollen assemblages.

At 4220±60 BP, a second increase in polyhalobous diatom species at this site is recorded at an altitude of 4.83mOD (346cm) (LDAZ 3 PSc) (Figure 5.8). It is thought to represent a second rise in relative sea level. A peak in aquatics, *e.g. Potamogeton,* is recorded prior to this and would appear to indicate a rising ground water table prior to marine inundation. If the barriers were still present when this episode occurred, overwashing or breaching may have taken place to deposit the sediment. Alternatively, the barriers may have been destroyed during the second marine episode with the result that the sea was able to inundate the site. Some of the diatoms that constitute the assemblage are benthic, such as *N. peregrina* and *N. elegans* and this is suggestive of increased storminess, allowing deep water forms to be deposited on the land. It is possible that a period of increased storminess occurred associated with the relative sea level rise, allowing some *Sphagnum* peat development combined with silty sedimentation. Barrier formation at the site may not have occurred until this second marine episode. A peninsula may have existed during the earliest transgression, allowing peat development in the centre and inter-tidal and marine communities to develop on the periphery. The later phase of marine influence at the site may have been recorded as material was moved from offshore to form the barriers.

Marine influence is recorded at the site until 3970±140 BP, at an altitude of 4.90mOD (339cm). It is probable that the end of the marine transgression is not represented as the diatom assemblage ends abruptly suggesting that dissolution of the diatoms has occurred. This relative sea level rise, therefore, appears to represent a later Holocene transgression. At Peinchorran, it is envisaged that the rate of input of water to the oceans during the Main Postglacial Transgression was faster than isostatic recovery of the land and, therefore, relative sea level rose. After this time, the rate of input of water to the oceans decreased and isostatic uplift of the land was the dominant effect causing freshwater conditions to be recorded. The rate of isostatic recovery of the land then decreased and sea level rise was again recorded at Peinchorran.

It is assumed that after 3970±140 BP, peat development occurred at the site in a freshwater environment (LPAZ 2 PSb) (Figure 5.8). Diatom counts were not viable above a depth of 4.91mOD (338cm) probably as a result of redigestion of silica. However, fragments of diatoms seen in the peat are believed to be of freshwater origin. Conditions at the site became drier and an acid heath environment dominated with some grassland present (LPAZ 3 PSc). The age of 4220±60 BP coincides with the first recording of *P. lanceolata* and when combined with the presence of Chenopodiaceae pollen and a slight increase in Poaceae pollen, is taken as indicating the beginning of anthropogenic activity in the area. Hazel-dominated mixed woodland with extensive *Sphagnum* and *Phragmites* peat development is recorded in the pollen record until the present day.

5.10 Conclusions

The base of the sequence at Peinchorran is thought to represent a time during the early Holocene when mixed woodland dominated the environment. The earliest transgression is believed to correspond to the Main Postglacial Transgression and was underway by 7980±70 BP when it had attained an altitude of 4.49mOD and lasted until 6600±70 BP when it had attained an altitude of 4.61mOD. It is unlikely that the start of the transgression has been recorded. The regression of the sea at 6600±70 BP coincides with an increase in alder at the site. The youngest episode of relative sea level change began at 4220±60 BP when it had attained an altitude of 4.83mOD and is recorded until 3970±140 BP when it had attained an altitude of 4.90mOD, although this is not thought to represent the end of the marine transgression. Anthropogenic activity has been recorded at the site coinciding with the start of the later relative sea level change.

It is unclear when the barriers formed at the site. They may have formed during the Main Postglacial Transgression and possibly at the start when the rate of rise was fastest. They then may have been breached or destroyed or remained in place until the second transgression occurred. However, it is possible that barrier formation did not occur until the later rise in relative sea level.

Chapter 6.0 Talisker Bay

6.1 Introduction

Talisker Bay (NG 3200 3030) lies on the west coast of the Isle of Skye. It is a high energy, headland-controlled embayment situated between the headland of Rubha Cruinn and Talisker Point (Figure 6.1). The bay consists primarily of cobbles and gravels although some sand is exposed at low tide and succeeded landward by four beach ridges. A well-developed contemporary cobble barrier with crest height 6.7mOD lies seaward of older vegetated barriers. The oldest and highest vegetated barrier crest is at 10.4-11.3mOD and consists of remnant flanks to the north and south of the bay and a second one to seaward stretches the width of the bay and has a crest altitude of 9.5-9.6mOD. The third is partially vegetated and lies between these. Behind these barriers is an extensive peat bog dominated by *Juncus* spp, *Phragmites australis, Rumex* spp and *Sphagnum* spp with stands of *Alnus* carr. The surface height of the bog increases towards the eastern end from 5.0-7.7mOD. The area has been extensively drained and two canalized streams flow through the site, namely the Sleadale Burn and River Talisker (Figure 6.1). These become confluent and flow to the sea through a breach in the barriers. The slopes to the north and south are steep and Preshal More with its steep cliffs overlooks the site from the east.

6.2 Geomorphological mapping, borehole location and stratigraphy

The main geomorphological features of the site are the barriers to seaward and the peat bog (Figure 6.1). Boreholes were made at approximately 100m intervals and two transects, transect A and transect 5, are described below (Figures 6.2 and 6.3).

All boreholes appear to end in a gravelly matrix and it is assumed that none of the boreholes reached bedrock. The basal unit in cores A3 and A4 contains some small shell fragments. Borehole A5 reveals a basal, very compressed, well-humified, organic horizon. In the central boreholes of transect A, the gravel horizon is overlaid by a brown organic silt. In core A8, the sediment overlying the basal unit at 1.2mOD, is more organic. In core A5, an organic sandy silt and in core A4 a sandy horizon at 2.5mOD, overlies the brown organic silt. These horizons are, in turn, overlaid by a brown fibrous *P. australis* peat, which is common in all the boreholes at an altitude of approximately 3mOD. This becomes more silty towards the top of the sedimentary sequences, but grades into a *Sphagnum* or *Phragmites* peat forming the surface unit. Cores 2 and 9 are very short sequences consisting only of topsoil and reaching gravel after approximately 60cm. All cores taken near the cobble barriers consist of either topsoil overlying gravel or topsoil overlying, sand which in turn rests upon gravel. Core A3 is anomalous to the rest of the transect with only the top unit being slightly organic, with clay, sand and silt constituting the underlying units. Some sand layers are also recorded in core A4.

In transect 5, boreholes B5 and C5 both record a blue-grey sand as the basal unit. Overlying this unit, the sediment becomes more silty between -2.5mOD and -0.2mOD and in C5 this unit contains organic sediment. D5 also records this unit at the same altitude and in this borehole it forms the basal unit although recovery of the sediment was impeded as the water table was very high at this location. The organic silty sand appears to taper out towards the side of the basin with A5 recording a smaller unit corresponding to this and S1 not penetrating deep enough to record it. In D5, the overlying unit is an organic silt as in A5 and a small sand and gravel layer occurs. At about 3mOD, *Phragmites* peat is again recorded in all boreholes although in S1 this sediment is not noted until an altitude of 4.6mOD probably due to its location on a gently inclined slope at the side of the valley. In borehole S1 at about 3mOD sand and gravel are recorded and these are overlaid by silt. In all cores the top unit is an organic silt.

Borehole A5 was sampled because it represented the deepest part of the basin and, therefore, hopefully the longest palaeoenvironmental sequence and contained all the major stratigraphic units. Additionally, it was situated at some distance away from any influences of the streams. Core S1 was taken to investigate in detail the minerogenic unit lying between 4.65-4.82mOD.

Table 6.1: Stratigraphy of borehole A5 (NG 3190 3012)

Altitude (mOD)	Depth (cm)	Sedimentary description
5.02-4.95	0-7	Dark brown fibrous organic silt
4.95-4.71	7-31	Brown organic silt
4.71-3.27	31-175	Dark brown very fibrous organic silt with *Phragmites australis* and *Sphagnum* fibres
3.27-2.43	175-259	Light yellow brown organic silty sand
2.43 to -0.72	259-574	Dark brown organic silt
-0.72 to -1.14	574-616	Brown organic silty sand
-1.14 to -1.92	616-694	Brown organic silt
-1.92 to -2.31	694-733	Light brown grey organic silty sand
-2.31 to -2.65	733-767	Brown *substantia humosa*
-2.65 to -3.02	767-800	Brown-grey coarse sand and gravel

Table 6.2: Stratigraphy of borehole S1 (NG 3190 3012)

Altitude (mOD)	Depth (cm)	Sedimentary description
7.29-5.09	0-220	Brown organic silt with *Phragmites* and *Sphagnum* fibres
5.09-4.82	220-247	Brown *Phragmites* peat
4.82-4.69	247-260	Dark brown organic silt with *Phragmites* fibres
4.69-3.33	260-396	Light brown silty clay
3.33-2.85	396-444	Blue-grey sand and gravel

6.3 Loss on ignition

High and low level loss on ignition analyses were undertaken on samples from borehole A5 (Figure 6.4). The top two samples record the highest carbon content from the low level loss on ignition with the *Sphagnum* and *Phragmites* peat unit recording over 80% carbon content. The carbon percentage then falls sharply in the lower sediments. Throughout the organic silt units the frequencies of carbon fluctuate between 10% and 24%, but this decreases farther when the sandy gravel units are reached. A slight increase occurs in the carbon content to 18% in the organic sandy silt unit. The high level loss on ignition analysis records between 2% and 4% carbonate content throughout the core.

6.4 Pollen analysis

Pollen analysis was undertaken on two cores, A5 and S1, from Talisker Bay and the results are tabulated below.

6.4.1 Borehole A5

Samples were taken at 8, 4, 2 and 1cm intervals throughout borehole A5 to establish if any hiatus was present in the sedimentation, to use as a relative dating technique and to reconstruct the vegetation history of the site to allow comparison with other pollen diagrams from Skye. Seven local pollen assemblage zones have been established for this diagram (Figure 6.5).

Table 6.3: Pollen zone descriptions for borehole A5

Pollen zone	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 7 Tg	5.02 to 4.27	0-75	***Corylus avellana*-type-*Calluna vulgaris*-Poaceae -Cyperaceae.** Low arboreal pollen is recorded in this zone and an increase in *C. avellana*-type pollen occurs to mid-zone and then decreases. An increase in *C. vulgaris* pollen occurs in this zone and fluctuating Poaceae values (15%-40%) with decreasing Cyperaceae values are recorded. There is noticeable *Plantago lanceolata*, *Filipendula*, *Succisa pratensis*, Apiaceae, Asteroideae and Lactuceae pollen. Decreased Pteropsida spores and low *Sphagnum* spores are noted in this zone.
LPAZ 6 Tf	4.27 to 3.52	75-150	***C. avellana*-type-Poaceae-Cyperaceae.** Low arboreal pollen is noted in this zone. A small increase in *C. avellana*-type and *Salix* pollen is recorded at mid-zone and then they decrease. There is noticeable *C. vulgaris* pollen with decreasing Poaceae values and fluctuating Cyperaceae (15-55%) pollen is recorded. Increasing *P. lanceolata* and *Filipendula* pollen are noted with *Potentilla*, Lactuceae and Apiaceae pollen and the assemblage is herb-rich. Low aquatic presence is recorded and there are noticeable *Equisetum*, Pteropsida and *Sphagnum* spores.
LPAZ 5 Te	3.52 to 2.47	150-255	**Poaceae-Cyperaceae-*Isoetes lacustris*.** Decreasing *Alnus* pollen is noted in this zone and generally low arboreal pollen. *C. avellana*-type pollen decreases with a low presence of *Salix* pollen. A slight increase in *C. vulgaris* pollen occurs. Increasing Poaceae values are recorded with initially high Cyperaceae values that decrease at the top of zone. The assemblage is herb-rich with increasing *P. lanceolata* and *Filipendula* pollen and noticeable Lactuceae, Apiaceae and *Potentilla* pollen. Very low aquatic pollen presence is noted but high *I. lacustris* spore values are recorded that decline at the top of the zone. Pteropsida spores peak at mid-zone and then decline. There is noticeable *Equisetum*, *Sphagnum* and *Polypodium* spores in this zone.

LPAZ 4 Td	2.47 to 0.77	255-425	***Alnus-C. avellana*-type-Poaceae-Cyperaceae.** *Alnus* pollen fluctuates in this zone (10-20%) and low arboreal pollen is noted. *C. avellana*-type pollen declines and low *Salix* pollen is recorded in this zone. A minor presence of *C. vulgaris* is noted with increasing Poaceae values and fluctuating Cyperaceae values (10%-25%). The presence of pollen of *P. lanceolata, Filipendula*, Apiaceae, *Potentilla* and *Rumex acetosa/acetosella* is recorded and the assemblage is herb-rich. Aquatic pollen has a very low presence and *I. lacustris* and Pteropsida spores are noted.
LPAZ 3 Tc	0.77 to -0.58	425-560	***Alnus-C. avellana*-type-Cyperaceae.** Increasing *Alnus* pollen is noted in this zone with noticeable *Quercus*, *Ulmus* and *Betula* pollen and decreasing *Pinus* pollen. Fluctuating levels of *C. avellana*-type are noted and a low presence of *Salix* pollen is recorded. A minor presence of dwarf shrub pollen is recorded. Poaceae values are low, Cyperaceae values are approximately 20% and a low presence of *Filipendula* pollen is noted. Low aquatic pollen is recorded and there are noticeable *I. lacustris*, Pteropsida and *Polypodium* spores.
LPAZ 2 Tb	-0.58 to -1.23	560-625	***C. avellana*-type-Cyperaceae.** Low arboreal pollen is recorded in this zone. High *C. avellana*-type pollen and noticeable *Salix* pollen are recorded with a low presence of dwarf shrubs. Low Poaceae values are recorded with increasing Cyperaceae values. There is a decrease in herb pollen and very low aquatic pollen presence with noticeable Pteropsida and *Polypodium* spores.
LPAZ 1 Ta	-1.23 to -2.98	625-800	***C. avellana*-type-Poaceae-Cyperaceae-*Pteropsida*.** In this zone *Betula* pollen increases to mid-zone and then decreases. An increase in *Pinus* pollen occurs and noticeable *Quercus*, *Ulmus* and some *Alnus* pollen are recorded. Fluctuating *C. avellana*-type pollen (20%-62%) is recorded and a general decline in *Salix* pollen occurs. A minor presence of dwarf shrub pollen is noted. Poaceae pollen reaches 20% and Cyperaceae values fluctuate (10%-40%). The assemblage is herb-rich with noticeable *Filipendula*, Apiaceae, Chenopodiaceae, Caryophyllaceae, *P. maritima* and Euphorbiaceae pollen. Low aquatic pollen presence is noted with an increase in *I. lacustris* and *Polypodium* spores and noticeable Pteropsida and *Sphagnum* spores.

6.4.2 Borehole S1

In borehole S1, samples were taken from 7.3-4.4mOD (0-292cm) at sampling intervals of 16, 8, 4, 2 and 1cm and four local pollen assemblage zones have been established (Figure 6.6).

Table 6.4: Pollen zone descriptions for borehole S1

Pollen zone	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 4 TBd	7.29-6.89	0-40	***C. avellana*-type-*C. vulgaris*-Poaceae-Cyperaceae.** Low arboreal pollen is recorded in this zone with decreasing *C. avellana*-type pollen. Fluctuating *C. vulgaris* values are noted (12-30%) with Poaceae and Cyperaceae pollen values generally increasing. There is noticeable *P. lanceolata*, *Filipendula*, Lactuceae and *S. pratensis* pollen. Pteropsida and *Sphagnum* spores decline in this zone.
LPAZ 3 TBc	6.89-6.09	40-120	***C. avellana*-type-Poaceae-Cyperaceae.** Low arboreal pollen is recorded with decreasing *C. avellana*-type pollen in this zone. There is noticeable *Salix* and *C. vulgaris* pollen values are increasing. Fluctuating Poaceae pollen (15-30%) is recorded with increasing Cyperaceae values to mid-zone although they decrease to the top of the zone. There is noticeable *P. lanceolata* and *Filipendula* pollen with a minor presence of Apiaceae, Lactuceae and *S. pratensis*. Very low aquatic pollen is present in this zone but noticeable Pteropsida, *Polypodium* and *Sphagnum* spores are recorded.
LPAZ 2 TBb	6.09-4.77	120-252	***C. avellana*-type-Poaceae-Cyperaceae.** Low arboreal pollen is recorded with fluctuating *C. avellana*-type pollen (8-20%). *Salix* pollen increases at mid-zone and then decreases to the zone boundary. There is noticeable *C. vulgaris* pollen with initially high Poaceae values that decrease through the zone and generally increasing Cyperaceae. The assemblage is herb rich with noticeable Apiaceae, *P. lanceolata*, *Filipendula*, Rosaceae and *Potentilla* pollen. A low aquatic spore presence is noted. There is noticeable *Equisetum*, Pteropsida and *Sphagnum* with decreasing *I. lacustris* spores in this zone.
LPAZ 1 TBa	4.77-4.29	252-300	***C. avellana*-type-Poaceae-Cyperaceae-*I. lacustris*.** A general decrease in *Alnus* pollen and low arboreal pollen is noted in this zone. *C. avellana*-type occurs at 20% and an increase occurs in *C. vulgaris* pollen. Poaceae values increase throughout the zone and Cyperaceae values fluctuate between 20-40%. The assemblage is herb-rich and an increase occurs in *P. lanceolata* and *Filipendula* pollen with noticeable *Potentilla*, Rubiaceae and Lactuceae pollen. An increase in *I. lacustris* spores occurs to mid-zone and then decreases. There is noticeable Pteropsida, *Sphagnum* and *Athyrium* spores in this zone.

6.5 Diatom analysis

Two diatom percentage assemblage diagrams are presented for Talisker Bay and the results are tabulated overleaf.

6.5.1 Borehole A5

Samples were taken from 3.02mOD (200cm) to -2.78mOD (780cm) and three local diatom assemblage zones have been identified for this assemblage (Figure 6.7).

Table 6.5: Diatom zone descriptions for borehole A5

Diatom zone	**Altitude (mOD)**	**Depth (cm)**	**Diatom characteristics**
LDAZ 3 Tc	3.02 to -1.76	200-678	***Achnanthes minutissima-Fragilaria exigua-Fragilaria brevistriata***. A peak occurs in poly-mesohalobous species at 2.02mOD (300cm) and small peaks occur in salt tolerant species at -1.08 to -1.16mOD (610-618cm) as characterised by *Achnanthes delicatula*, *Rhopalodia constricta* and *Rhopalodia brebissonii* and at 0.84mOD (418cm) by *Navicula crucicula*. Oligohalobous-halophilous species increase to 10% of the assemblage at mid-zone, but decrease at top of zone and are dominated by *Amphora veneta* and *Anomoeoneis vitraea*. Oligohalobous-indifferent species fluctuate between 45% and 90% and are dominated by *A. minutissima*, *F. brevistriata*, *F. exigua* and *Navicula subcostulata*. However, the assemblage is species-rich with noticeable *Aulacoseira lirata*, *Achnanthes pusilla*, *Cyclotella bodanica*, *Fragilaria capucina* var. *vaucheriae*, *Synedra ulna* and *Tabellaria fenestrata*.
LDAZ 2 Tb	-1.76 to -2.18	678-720	***Cocconeis scutellum-Fragilaria subsalina-F. exigua-F. brevistriata***. Poly-mesohalobous species, dominated by *C. scutellum*, fluctuate between 2% and 35% in this zone. Initially high *F. subsalina* is recorded but it is absent in the upper half of the zone. Oligohalobous-indifferent species (45-80%) dominate this zone and are characterised by *F. brevistriata* and *F. exigua* with noticeable *A. minutissima*, *Cocconeis placentula* var. *lineata*, *Fragilaria pinnata*, *F. capucina* var. *vaucheriae* and *Navicula gallica* var. *perpusilla*. Up to 15% of diatoms with unknown ecology are recorded in this zone.
LDAZ 1 Ta	-2.18 to -2.78	720-780	***F. exigua-A. minutissima***. An increase in oligohalobous-indifferent species to 95% of assemblage occurs in this zone and is dominated by *F. exigua*, *N. gallica* var. *perpusilla* and *C. placentula* var. *lineata* with noticeable *A. minutissima*. *Tabellaria flocculosa* is also recorded at low frequencies.

6.5.2 Borehole S1

For this borehole, only 20cm of minerogenic sediment at 4.85-4.57mOD (244-272cm) was examined in order to ascertain the salinity of environment at the time of deposition (Figure 6.8). It was not felt justified or necessary to zone the assemblage.

Table 6.6: Diatom assemblage description for borehole S1

Altitude (mOD)	Depth (cm)	Diatom characteristics
4.85-4.57	244-272	***F. brevistriata-F. exigua-A. minutissima*** Oligohalobous-halophilous species constitute up to 10% of the assemblage and *Synedra pulchella* dominates the mesohalobous species. The levels are dominated by oligohalobous-indifferent species characterised by *F. brevistriata, F. exigua* and *A. minutissima* with noticeable *Fragilaria capucina, Fragilaria pseudoconstruens, Fragilaria construens, Achnanthes petersenii* and *Achnanthes pusilla. F. exigua* decreases at mid-zone and then increases as *A. minutissima* decreases through the assemblage. A low presence of halophobous species is recorded.

6.6 Radiocarbon dates

Seven radiocarbon dates have been obtained for Talisker Bay, five for borehole A5 and two for borehole S1. Two of the dates obtained for borehole A5 date features of the pollen assemblage; Beta-83740 dates the base of the assemblage within the compressed basal peat and Beta-83736 dates the increase in *Alnus* pollen within the organic silt. The youngest date, Beta-83737 dates the start of peat development at the site and the other two dates, Beta-93408/Beta-93409, date the increase and decrease in marine-brackish diatoms respectively. The two dates for borehole S1 date features of the pollen assemblage with the oldest date representing the initiation of probable anthropogenic influence at the site and the youngest, the decline in tree species. All radiocarbon ages obtained are bulk radiocarbon dates.

Table 6.7: Radiocarbon dates for borehole A5

Conventional C14 age (BP)	C13/C12 ratio	Calibrated C14 age (BC)	Laboratory code	Altitude (mOD)	Depth (cm)
2350±60	-28.7 ‰	745-230	Beta-83737	3.04 to 3.01	198-201
6630±70	-29.4 ‰	5610-5430	Beta-83736	-0.57- to -0.60	559-562
7250±150	-25.0 ‰	6390-5760	Beta-93409	-1.77- to -1.79	679-681
7790±100	-25.0 ‰	6990-6415	Beta-93408	-2.16 to -2.18	718-720
8550±80	-28.6 ‰	7695-7455	Beta-83740	-2.76 to -2.79	778-781

Table 6.8: Radiocarbon dates for borehole S1

Conventional C14 age (BP)	C13/C12 ratio	Calibrated C14 age (BC)	Laboratory code	Altitude (mOD)	Depth (cm)
2140±60	-29.0 ‰	370-5	Beta-83738	4.96-4.92	233-237
3960±80	-28.8 ‰	2845-2205	Beta-83739	4.66-4.62	263-267

6.7 Interpretation of pollen assemblages

Pollen could be derived from several sources at Talisker Bay. Steep slopes surround the peat bog and it is probable that slopewash and runoff would have transported pollen to the site. Additionally, two streams flow through the area to the sea and these could have brought autochthonous sediment containing pollen grains and spores, derived from the banks of the river and further upstream. It is possible that lagoonal environments existed behind the barriers and buoyant pollen grains would have been preferentially preserved.

6.7.1 Borehole A5

LPAZ 1 Ta (-1.23 to -2.98mOD, 625-800cm) (Figure 6.5)

In this zone, the low frequencies of arboreal pollen suggest scattered areas of mixed woodland developed or small pockets of woodland may have developed within the pollen catchment area. The woodland consisted of birch, pine, oak, elm and willow as represented by the pollen of these taxa. Additionally, over 60% *C. avellana*-type pollen is recorded which is thought to represent the development of hazel woodland or scrub. The tree taxa recorded are typical of early Holocene woodland on Skye, with the dominance of hazel scrub (Williams, 1977; Birks and Williams, 1983) and the base of this zone has been dated at 8550±80 BP (Beta-83740). The peak in *Betula* pollen in this zone could be due to either a tree or small stand of trees growing in very close proximity to the sampling site. Talisker Bay is in a particularly exposed location as it lies on the west coast of Skye, open to the prevailing winds and this could have suppressed the frequencies of tree taxa present at the site. The presence of Pteropsida and *Polypodium* spores may represent an understorey component in the hazel woodland.

The vegetation appears to have been herb-rich as indicated by the range of pollen grains recorded, for example, Apiaceae, Lactuceae, *Filipendula, Plantago* species and Euphorbiaceae. An open grass/sedge environment seems to have developed in this zone as indicated by the Poaceae and Cyperaceae pollen and an increase in sedge occurs at the top of the zone possibly as conditions became wetter at the site. *Filipendula* pollen frequencies reach up to 10% in this zone and one species *F. ulmaria* grows on swamps, marshes, bogs and fens, suggesting wet conditions (Clapham *et al.*, 1987). The dwarf shrub component is represented at extremely low frequencies in this zone, indicating that heath development at the site was limited. The presence of *P. maritima* and Chenopodiaceae pollen may indicate halophytic conditions or a saltmarsh environment. *Atriplex littoralis* is also noted at the top of this zone and this is often associated with coastal locations. The peak in *Myriophyllum alterniflorum*, *Potamogeton* and *Typha angustifolium* pollen and *I. lacustris* spores indicate the presence of open water pools at this time and probably ones that were depleted in dissolved salts (Clapham *et al.,* 1987). The presence of *Sphagnum* spores in this zone probably represents some peat development at the site.

LPAZ 2 Tb (-0.58 to -1.23mOD, 560-625cm)

In this zone an increase has occurred in the total arboreal pollen to 20-30% of total land pollen and this could represent a regional component to the pollen rain. *Betula, Quercus, Pinus* and *Ulmus* pollen are all represented in this zone, suggesting the presence of mixed woodland. *C. avellana*-type pollen is present at high frequencies and it is possible that hazel formed a dominant component of the woodland or hazel scrub. The presence of Pteropsida and *Polypodium* spores would seem to represent the understorey component of these woodlands.

In other areas around the site some grassland and sedge existed as suggested by the frequencies of Poaceae and Cyperaceae pollen. The lower frequencies of pollen of these families, however, suggests that this area had decreased in extent probably due to the encroachment of hazel scrub/woodland at the site. The environment continued to be herb -rich with *Filipendula* pollen representing colonisation of marshy ground by this genus and Apiaceae, *Potentilla* and Lactuceae pollen representing components of the grass/sedge environment. Heathland has a very limited extent as represented by the low frequencies of dwarf shrub pollen in this zone. It is possible that in this zone the site had become drier as represented by the lower frequencies of *I. lacustris* and Pteropsida spores although the frequencies increase at the top of the zone suggesting that some open areas of water still persisted within the environment.

LPAZ 3 Tc (0.77 to -0.58mOD, 425-560)

In this zone an increase in *Alnus* pollen occurs and this has been dated at 6630±70 BP (Beta-83736). Birks and Williams (1983) state that *Alnus* often expands at the expense of *Salix* and *Corylus* and this appears to have occurred at Talisker Bay. The increase in *Alnus* is also often associated with a decline in *Pinus* (Bennett, 1984) and a fall in *Pinus* pollen occurs concurrent with the rise in *Alnus* pollen at Talisker Bay. The development of alder carr at the site appears to be represented in this zone. Limited mixed woodland consisting of birch, pine, oak, elm and willow is still represented by the low frequencies of arboreal pollen taxa at the site and the dominance of hazel scrub/woodland is represented by the high frequencies of *C. avellana*-type pollen. The hazel scrub/woodland, however, appears to have declined in its extent, possibly as a result of competition from alder. *Betula* pollen shows a decline from the previous zone, indicating that stands of birch have also been out-competed. It would seem likely that Pteropsida and *Polypodium* continued to form the understorey components to the woodlands as represented by the spores in the assemblage.

Despite the dominance of alder carr and hazel scrub at the site some grass and sedge still existed as represented by the pollen of these taxa. The presence of pollen of *Filipendula*, Rosaceae, *R. acetosa/acetosella* and *S. pratensis* all suggest colonisation of a grassland environment that was possibly marshy in places, although *S. pratensis* may have formed an understorey component of the woodlands. Heathland is still of limited extent as represented by the low frequencies of dwarf shrub pollen. An increase has occurred in *I. lacustris* spores, indicating perhaps a higher groundwater table that would give rise to more surface water that supported *M. alterniflorum* as represented by the pollen in the assemblage.

LPAZ 4 Td (2.47-0.77mOD, 255-425)
The boundary between this zone and LPAZ 3 Tc marks the beginning of the decline in woodland as represented by the pollen of *Quercus*, *Pinus* and *Ulmus*. High frequencies of *Alnus* and *C. avellana*-type pollen are still recorded, however, suggesting the continued presence of stands of hazel scrub and alder carr, although the frequencies of *C. avellana*-type pollen start to decline in the upper half of the zone. A slight decline in *Polypodium* and Pteropsida spores has occurred and this could be related to the decline in arboreal taxa if they were forming the understorey component.

An increase in Poaceae pollen in this zone may indicate expansion of grassland into areas previously occupied by woodland. Concurrent with the increase in Poaceae pollen is the development of a herb-rich vegetation. *Filipendula, Potentilla, R. acetosa/acetosella, S. pratensis* and Apiaceae pollen are all recorded and these taxa would have formed part of the grass and sedge environment. The presence of some aquatic species such as *M. alterniflorum* and spores of *I. lacustris* would indicate some surface wetness at the site.

The persistence of *P. lanceolata* is recorded in the pollen record from 0.52mOD (450cm) to the top of the sequence. This species is often associated with anthropogenic activity, although a natural presence at the site is thought to occur and probably developed as the woodland declined. The first recording of a Poaceae grain with diameter >40μm and annulus >10μm is also noted in this zone. This could be a cereal pollen grain and, therefore, represent arable agricultural practices in the pollen catchment area. Additionally, Apiaceae, *R. acetosa/acetosella* and Lactuceae can also be associated with human activities. These lines of evidence may, therefore, indicate some anthropogenic activity had begun at the site. This may have involved some clearance of woodland as suggested by the initial decline in some woodland species at the beginning of the zone and the commencement of agricultural practices at the site.

LPAZ 5 Te (3.52-2.47mOD, 150-255cm)

This zone represents an end to the dominance in the pollen record of tree and shrub taxa at Talisker Bay, suggesting the loss of alder carr and hazel scrub. *Alnus* declines to a very low presence by 2350± 60 BP (Beta-83737) and it is envisaged that only isolated trees of this genus remained at the site. *C. avellana*-type would have formed small stands possibly within a scrub environment, but all other arboreal components of the pollen record are recorded at very low frequencies. A decline in *Ulmus* is also noted in at the lower boundary of this zone and this may be correlated with the middle Holocene elm decline (Peglar, 1993; Peglar and Birks, 1993).

High frequencies of Poaceae and Cyperaceae pollen suggest the continuation of grass and sedge environments at the site. Coincident with the decline in tree taxa is an increase in *I. lacustris*, Pteropsida and *Equisetum* spores. It is no longer plausible that Pteropsida formed an understorey component and it is possible that surface wetness had increased at this time and this order may be associated with increasing acidity and peat growth. Pteropsida may, therefore, have developed in areas of the grass/sedge environment. The increase in Cyperaceae pollen could also suggest increased surface wetness at the site. A peak in *C. vulgaris* pollen and a small increase in *Sphagnum* spores are associated with an increase in acidification of the area and peat development. At Talisker Bay the increase in *C. vulgaris* occurs prior to 2350±60 BP. The environmental change recorded at Talisker Bay corresponds to a change in the stratigraphy from an organic to minerogenic sedimentation (3.12-2.27mOD, 190-275cm) and this would appear to suggest that the surface wetness was caused by fluvial activity, either by flooding or the changing course of the stream, or by sediment brought in from a seaward direction.

Probable anthropogenic influences continue to be recorded at the site by the increase in *P. lanceolata* pollen and the presence of Lactuceae, Apiaceae, Asteroideae and *Potentilla* pollen that can all be related to agricultural activities (Jones, 1988). The environment is herb-rich and this is associated with the expansion of grassland at this time. There is good evidence to suggest that anthropogenic activities at the site involved removal of trees at this time.

LPAZ 6 Tf (4.27-3.52mOD, 75-150cm)

The presence of tree pollen is less than 10% of total land pollen in this zone and could represent either isolated trees growing at the site or a long distance pollen component. A small increase in *C. avellana*-type pollen is recorded and it is possible that some stands of hazel continued to grow at the site. Increased frequencies of *Salix* pollen are recorded and these species could have become established on the edges of the stream as they are today.

This zone records very much drier conditions at the site as seen from the decline in wet-loving plants. *I. lacustris* spores are absent from the assemblage and the values of Pteropsida and *Equisetum* spores have declined. The frequencies of aquatic pollen are also present in extremely low quantities. Open-habitat species dominate the pollen assemblage and an initial increase in Poaceae pollen, combined with the presence of *Filipendula* pollen, represents further expansion of grassland at the site. This family could be dominated by *P. australis,* as suggested by fragments of this species in the stratigraphy. The frequencies of Poaceae pollen decrease through the zone as Cyperaceae pollen increases, suggesting the development of sedges occurred later in the zone at the expense of grassland. Continued peat formation and acidification of the site is suggested by the increasing frequencies of *C. vulgaris* pollen and a large increase occurs in *Sphagnum* spores in this zone, although this is short-lived and probably represents a local area of peat close to the sampling site. The presence of other dwarf shrub pollen is also noted in this zone, suggesting development of mixed heathland.

Evidence for probable anthropogenic activity is still recorded in the pollen assemblage. Frequencies of *P. lanceolata* pollen have increased. The grassland continues to be herb-rich and families such as Apiaceae, Lactuceae and Asteroideae are present and can be associated with human activities (Jones, 1988). Human activities at Talisker Bay could have involved draining of the land to provide the drier environment recorded in this zone and additionally pastoral farming.

LPAZ 7 Tg (5.02-4.27mOD, 0-75cm)

In this zone, a small increase has occurred in *C. avellana*-type pollen and suggests the continued presence and possible expansion of stands of hazel scrub/woodland at the site. The presence of Pteropsida and *Polypodium* spores possibly represent the understorey component of this scrub. *C. vulgaris* frequencies have increased, indicating ling heathland development and combined with the presence of *Sphagnum* spores, suggests that acidic conditions and peat development prevailed in this zone. The high Poaceae and Cyperaceae frequencies represent the development of grass and sedges at the site and a mosaic of different vegetation patternsis likely to have existed. A peak in *S. pratensis* and the presence of *Filipendula* pollen are noted in this zone representing areas of marsh, fen, meadow or pasture (Clapham *et al.*, 1987). The grassland supports a herb-rich environment and probable anthropogenic indicators such as *P. lanceolata, R. acetosa/acetosella*, Lactuceae, Asteroideae and Apiaceae are still recorded in the pollen assemblage. It is suggested that these taxa represent grazing at the site.

6.7.2 Borehole S1

LPAZ 1 TBa (4.77-4.29mOD, 252-300cm) (Figure 6.6)

This zone is characterised by low arboreal pollen suggesting that little mixed woodland occurred within the pollen catchment area. However, some alder carr and hazel scrub/woodland is likely to have existed at the site, as represented by the relatively high frequencies of *Alnus* and *C. avellana*-type pollen. The presence of Pteropsida, *Athyrium Sphagnum* and *Polypodium* spores in this could represent an understorey component for the woodland or damp boggy conditions at the site.

The vegetation is dominated by grass and sedge as represented by the high frequencies of Poaceae and Cyperaceae pollen. The grass species could consist primarily of *P. australis*, as indicated in the stratigraphy and a date of 3960±80 BP (Beta-83739) has been obtained at an altitude of 4.66mOD (263cm) for *Phragmites* deposition. The pollen of Rubiaceae and *Filipendula* represent taxa that would also colonise the grassland. The high frequencies of *I. lacustris* at mid-zone, indicate that pools of water, probably depleted in dissolved salts, were present (Clapham *et al.*, 1987). At the top of this zone an increase in *C. vulgaris* pollen is recorded and a slight increase in *Sphagnum* spores suggests that acidification of the site and peat development had begun in this zone. The initiation of ling heath development is also represented by the increase in *C. vulgaris* pollen. It is not until after 3960±60 BP that an increase in *P. lanceolata* pollen is recorded and this, combined with the pollen of Apiaceae and Lactuceae would suggest that human activity at the site had commenced. The sequence of predominantly herb vegetation with alder carr and hazel scrub/woodland present appears to correlate with zone LPAZ 5 Te.

LPAZ 2 TBb (6.09-4.77mOD, 120-252cm)

All tree taxa have declined in this zone represented by low arboreal pollen frequencies although some *C. avellana*-type pollen is still recorded and suggests that isolated trees or small stands of hazel scrub persisted. An increase in *Salix* pollen occurs in this zone and as in LPAZ 6 Tf could relate to colonisation of the wetter areas of the site, such as the banks of the stream. Poaceae pollen initially increases in this zone with increasing Cyperaceae pollen throughout the zone, indicating an open grass and sedge vegetation existed. Decreased frequencies of *I. lacustris* spores are recorded and the spore frequencies in general have decreased, although a slight increase in *Equisetum* is recorded and possibly indicates a local expansion of the species near the sampling site. These changes recorded in the pollen assemblage suggest that the site had become drier. The increased presence of *C. vulgaris* pollen would represent the development of acid heathland at the site. The presence of *Sphagnum* spores confirms the acidic nature of the environment and would represent some development of *Sphagnum* moss at the site. *P. lanceolata* has an increased presence in this zone and other species associated with human activities are also noted. These include the pollen of Apiaceae, Lactuceae, *R. acetosa/acetosella* and *Potentilla*. The pollen assemblage in this zone represents a sequence similar to LPAZ 6 Tf.

LPAZ 3 TBc (6.89-6.09mOD, 40-120cm)

C. avellana-type pollen decreases in this zone and the extent of woodland development is still very restricted, as suggested by the low frequencies of arboreal pollen that could represent a long distance component to the pollen rain. The vegetation at this time is dominated by grass and sedge species, as represented in the pollen assemblage by high frequencies of Poaceae and Cyperaceae pollen. The grassland is herb-rich with a noticeable increase in *Filipendula* pollen and the peak in *S. pratensis* appears to correspond to that seen in LPAZ 7 Tg and represents a local short-lived increase of the species. Few aquatic species are recorded and conditions at the site, therefore, seem to have become drier. Spore frequencies have also fallen, although the frequencies of Pteropsida spores increase in the upper half of the zone, but decline to the zone boundary. *C. vulgaris* frequencies are still maintained and some *Sphagnum* spores are present suggesting that peat growth and heathland development persisted at the site. Human activity at the site is suggested by the pollen of *P. lanceolata*, Apiaceae, Lactuceae and *Potentilla* and probably represented grazing activity.

LPAZ 4 TBd (7.29-6.89mOD, 0-40cm)

Some hazel scrub/woodland development is suggested at the site in this zone by the increased presence of *C. avellana*-type pollen. The low presence of other arboreal pollen would suggest limited mixed woodland development within the pollen catchment area. The low frequencies of Pteropsida spores in this zone could represent an understorey component of the woodland or they could be growing within the open vegetation at the site. A predominantly herb-rich grass and sedge landscape appears to have developed as represented by the frequencies of Poaceae and Cyperaceae pollen and the presence of, for example, *S. pratensis* and *Filipendula* pollen. Acidification of the area is represented by *C. vulgaris* pollen and *Sphagnum* spores. It is suggested that heathland development occurred in this zone as represented by the presence of *C. vulgaris* pollen. Human presence is suggested by the frequencies of *P. lanceolata* combined with the presence of Apiaceae, Asteroideae and Lactuceae and one grain of Poaceae with diameter > 40m that possibly represents cereal pollen.

6.8 Interpretation of diatom assemblages

6.8.1 Borehole A5

LDAZ 1 Ta (-2.18 to -2.78mOD, 720-780cm) (Figure 6.7)

This zone represents entirely freshwater conditions at the site. *C. placentula* var. *lineata* is epiphytic on aquatic plants and other objects (Patrick and Reimer, 1966) and *A. minutissima* also grows attached to substrata (Denys, 1991) indicating that pools of water were present at the site with aquatic plants growing on the periphery. The presence of these epiphytic species indicates low-energy, quiet water conditions existed during this zone. The presence of *N. gallica* var. *perpusilla*, *A. minutissima, C. placentula* var. *lineata* and *F. exigua* all indicate that circumneutral to alkaline waters were present at the site, reflecting dissolved minerals in water from runoff and the groundwater component. The high peak in *F. exigua* at the top of the zone could indicate a local bloom of the species in close proximity to the sampling site, possibly to the exclusion of *N. gallica* var. *perpusilla* and *C. placentula* var. *lineata*. The presence of *T. flocculosa,* a species that tolerates no salt, confirms the freshwater nature of this environment.

LDAZ 2 Tb (-1.76 to -2.18mOD, 678-720cm)

This zone demonstrates a slight increase in saline influence at the site as represented by an initial peak in oligohalobous-halophilous species and then mesohalobous and poly -mesohalobous species. *C. scutellum* is a marine-brackish epiphyte (Vos and de Wolf, 1993), which is common on coasts all over the world (Hendey, 1976) and is recorded at levels up to 35% in the lower levels of the zone. *F. subsalina* initially attains values of up to 20% in this zone and suggests the increase in salinity at the site. However, freshwater species fluctuate between 45-85% of the assemblage and would appear to suggest that only part of the site was affected by the increase in salinity. The freshwater species recorded such as *F. exigua, F. brevistriata, A. miutissima, Fragilaria pinnata, C. placentula* var. *lineata* and *N. gallica* var. *perpusilla* all prefer water of low nutrient content (Hustedt, 1939). Halophobous species have virtually been displaced from this zone, probably as a result of the increase in saline influence.

LDAZ 3 Tc (3.02 to -1.76mOD, 200-678cm)

This zone indicates freshwater conditions. The assemblage of oligohalobous-indifferent diatoms, which tolerate virtually no salt content in the water, contains over 100 species, but the species with over 5% presence indicated in Figure 6.7, *e.g. Fragilaria* species, *A. minutissima, A. lirata, N. subcostulata* and *Synedra ulna* suggest the dominance of nutrient poor and alkaline water at the site. However, there is some indication of a slight saline influence at the site as suggested by peaks in the taxa of *C. scutellum, R. brebisonii, A.*

veneta, N. cincta and *Rhopalodia constricta.* It is envisaged that this influence was of limited extent allowing the continued dominance of freshwater species and is possibly related to periodic overwash of the barriers and/or storm events. An increase in *A. vitraea* diatoms that prefer alkaline conditions (Patrick and Reimer, 1966) are recorded from 2.26-0.24mOD (276-478cm) and represent the establishment of a slightly saline demanding community, that may have developed as a result of sea spray.

6.8.2 Borehole S1 (4.85-4.57mOD, 244-272cm) (Figure 6.8)

The levels investigated for borehole S1 indicate freshwater conditions dominated during the accumulation of this sediment. Species such as *A. minutissima* and *A. pusilla* would occupy circumneutral to alkaline waters and species such as *F. brevistriata* would occupy the acidic waters of the site. The decrease in *A. minutissima* and increase in *F. exigua* and *F. brevistriata* through the zone indicates that increasingly acidic conditions prevailed at the site. *A. vitraea* and *S. pulchella* represent an environmental niche of low salinity at the site, possibly due to the influence of sea spray.

6.9 Environmental history of Talisker Bay

The basal date of 8550±80 BP obtained on *substantia humosa* from borehole A5 represents a time when freshwater conditions prevailed at the site. Streams entering the site from runoff and flowing through the site, possibly meandering and cutting new channels, would have provided the freshwater element and may account for the sandy horizons recorded in boreholes from the centre of the site. The freshwater diatom species recorded in LDAZ 1 Ta (Figure 6.9) are epiphytic and would have colonised waterlogged areas of the environment attached to aquatic plant species. A hazel-dominated mixed woodland is likely to have existed at this time with extensive hazel scrub or woodland. Ferns would have formed the understorey component and a grass and sedge environment would have existed in other areas of the site.

At an altitude of -2.17 to -1.78mOD (719-680cm), increased salinity is represented in the diatom assemblages by *C. scutellum, R. brebisonii* and *F. subsalina* and constrained by the dates of 7790±100 BP (Beta-93408) and 7250±150 BP (Beta-93409) (LDAZ 2 Tb). It is possible that this increased salinity represents partial marine inundation of the site. Coincident with this is a decline in organic sedimentation and the presence in the pollen assemblage of *P. maritima, A. littoralis* and Chenopodiaceae that indicate halophytic conditions or a saltmarsh environment. However, the diatom analysis reveals that a dominant freshwater community continued to grow at the same time suggesting that two sources of water were present and that the site was not overwhelmed by the sea. It is possible that towards the back of the bog marine influence was not felt and freshwater communities continued to exist. The increased salinity may represent a relative sea level rise or alternatively, the presence of these two diatom communities could be a function of barrier dynamics and coastal geomorphology.

Sediment for barrier formation at Talisker Bay has two possible origins: either from erosion of the headlands or from the offshore zone. In the first scenario, an erosional front would progress towards the shoreface, attacking the headlands of Rubha Cruinn and Talisker Point and transporting the sediment along the headland flanks towards Talisker Bay, until a point of null-drift was encountered (Orford *et al.*, 1991). This erosion would have been accentuated in times of relative sea level rise by increasing the base height of wave attack. Sediment would begin to build up in a spit-type cell and growth would occur on the updrift side. If the wave period dropped, the longshore drift component would have dominated and the barrier would have become extended forming a drift-aligned barrier across the bay (Orford *et al.*, 1991).

In the second scenario, the source of the sediment is from offshore and cobbles would have slowly built up on the shoreline and pronounced ridges would have developed. The fact that multiple barriers exist at Talisker Bay indicates that the sediment availability was high and was more likely to have been derived from offshore. The model proposed by Boyd and Penland (1984) has applicability to Talisker Bay under a marine transgression (Figure 3.4). Sediments deposited by Late Devensian ice could have been reworked by wave processes and when the energy régime increased, as it would in times of storms or relative sea level rise, the sediment would be driven upon the shore as a barrier system. In time, small ridges would have coalesced and a longshore sediment transport pathway would have been established. In western Ireland, most gravel barriers are of this form with shoreface reworking and erosion providing sediment to be moved onshore (Orford *et al.*, 1991). Orford *et al.* (1991) feel that this mechanism may have been important in the Holocene when the rate of relative sea level rise decreased. The barriers are made of cobbles and when first formed, filtration of water and fine sediment could have occurred in both directions through the barrier. This would have continued until a time when the interstices became plugged with sediments.

It is possible that the increase in saline conditions in LDAZ 2 TB is related to the start of the Main Postglacial Transgression in this area. Dawson (1982) maintains that many of the Western Isles were subjected to shingle ridge formation during this episode and it is possible that barrier formation was initiated at Talisker Bay at this time. The Main

Postglacial Transgression as recorded in Scotland appears to have been very rapid initially and then over time its rate decreased until regression occurred (*e.g.* Smith *et al.*, 1985; Zong and Tooley, 1996). Carter *et al.* (1989) state that a rapid relative sea level rise may in places prevent barrier formation and this would suggest that barriers were formed during the latter part of the Main Postglacial Transgression, when the rate of relative sea level decreased, although this is in contrast with the conclusions of Belknap and Kraft (1981) and Davis and Clifton (1987). It is possible that the initial rapid relative sea level rise of the Main Postglacial Transgression allowed increased erosion of the headlands and possibly remobilised sediment, but that barrier initiation and accumulation of sediment did not begin until later during the transgression.

It is possible that the dates of 7790±100 BP and 7250±150 BP constrain barrier formation at the site. The oldest date represents the increase in saline conditions at the site and possibly the movement of sediment onshore to form the barriers. The youngest date may represents the closing of the site to further marine influences when barrier formation was complete. If the barrier formation occurred when the rate of relative sea level rise was greatest then the dates of 7790±100 BP to 7250±150 BP also represent this phase of the rise.

Four barriers are present at Talisker Bay and it is unclear whether they would all have formed during this episode of increased salinity. It is possible that the barriers could have formed as the sea regressed, exposing sediment that could have been deposited as barriers at a progressively lower altitudes after the culmination of the Main Postglacial Transgression (Dawson, 1982). Evidence for this mode of formation may exist at Talisker Bay as only the extreme sides of the highest barrier are present indicating that some reworking of the middle of the feature has occurred. Each of the barriers is breached by the stream at present and it is probable that the breaches always existed.

As saline influences ceased at the site after 7250±150 BP, an organic silt was deposited. A mixed woodland still existed in the pollen catchment area and was dominated by hazel woodland/scrub (Figure 6.9). Ferns continued to form the understorey and some grass and sedge environment existed. Freshwater conditions dominated the environment from 3.02 to -1.78mOD (200-680cm) as represented by the diatom assemblages in LDAZ 3 Tc. Within this zone, however, small peaks are seen in saline tolerant species. These occur at -1.08 to -1.16mOD (610-618cm) in *A. delicatula*, *R. constricta*, *R. brebisonii* and *A. veneta*, at 0.84mOD (418cm) in *N. crucicula* and at 2.02mOD (300cm) in *C. scutellum*. These are short-lived blooms of the species and it is possible that periodic overwash allowed some saline water into the site enabling a community of these species to develop. Each of the peaks in these diatoms could be related to storm activity at the site during which waves overtopped the barriers. Saline water could also have entered the site through a breach in the barriers which would have existed to allow freshwater drainage of the site. If storm activity affected this site, which is likely given its location on the exposed west coast, it is possible that barrier formation is connected with these events. The oldest and highest barrier may have formed, as proposed during the Main Postglacial Transgression and subsequently, during episodes of storminess, the three other barriers may have formed.

In borehole S1, the species of saline tolerant taxa record less than 10% presence throughout. This suggests that the sediment in this borehole has not been affected by any relative sea level rise, presumably due to its altitude. If the Main Postglacial Transgression is represented by the increase in saline conditions in borehole A5, it attained a maximum altitude of -1.78mOD at 7250±150 BP. The small percentages of saline tolerant taxa recorded in borehole S1, probably reflect the influence of sea spray in this area.

Probable anthropogenic activities at the site are first recorded in LPAZ 4 Td by the persistence of *P. lanceolata,* Apiaceae, *R. acetosa/acetosella* and Lactuceae in the pollen assemblage (Figure 6.9). Clearance of woodland seems to have occurred during LPAZ 5 Te and is dated at 2140±60 BP and arable farming became established. *F. pinnata* peaks at this time and is an eutrophic species, indicating an increase in organic production and its presence could be attributed to the inwash of sediment caused by human clearance or artificial drainage at this time. *Phragmites* and *Sphagnum* peat development and acidification of the site is then recorded until the present day.

6.10 Conclusions

At the base of the sequence in borehole A5, a hazel-dominated mixed woodland is recorded and grass and sedge species existed at the site. At 7790±100 BP, it is possible that the start of the Main Postglacial Transgression has been recorded by the increase in poly-mesohalobous and oligohalobous-halophilous diatoms at an altitude of -2.17mOD. The increase in saline conditions lasted until 7250±150 BP at an altitude of -1.78mOD. If this increase in salinity does represent the Main Postglacial Transgression, it is unlikely to represent the entire duration by comparison with other areas (*e.g.* Peinchorran). This may have been as a result of barrier formation that prevented further penetration of marine waters at the site.

Following the decrease in salinity at the site, an increase in *Alnus* pollen is recorded at 6630±70 BP and represents the development of alder carr at the site. Anthropogenic indicators are recorded in the pollen assemblages beginning at 3980±80 BP and increased acidification and clearance of woodland is recorded subsequently.

Chapter 7.0 Point of Sleat

7.1 Introduction

Point of Sleat (NG 5640 0030) lies at the south-west tip of the Sleat Peninsula. The coastal basin investigated in this study is approximately 250m long by 200m wide and is largely infilled by peat, with vegetation cover comprising Ericaceae, *Vaccinium* spp, *Juncus* spp, *Sphagnum* spp and *Pteridium* spp (Figure 7.1). The site is approximately circular in outline and is surrounded by bedrock, rising on all sides to form a basin. To the south and east the Moine schist rise steeply to over 280m forming hills. The site is drained by a small burn flowing to the south-west where it meets the sea. The peat moss has been drained artificially and is partly used for grazing. Some bedrock outcrops occur within the peat moss forming small and low-lying vegetated rock knolls. The elevation of the surface of the basin varies between 4.3-5.3mOD and this site is open to the influence of westerly and south-westerly winds and storms.

7.2 Geomorphological mapping, borehole location and stratigraphy

Geomorphological mapping of the area revealed a basin separated from the sea by two barriers to the north-east. A saltings surface has formed seaward of the basin and the highest point measured on the surface is 3.9mOD. The lower limit of land based vegetation is at 1.9mOD. Along the shore, to the north of the site, is a rock platform that occurs at between 2.4-2.7mOD. At the north-west of the site, two vegetated barriers occur of which the higher crest height lies between 10.8-11.1mOD and the lower at between 7.5-7.8mOD.

Three transects were cored at the site (Figures 7.2 and 7.3). At the base of the deepest boreholes, in the centre of the bog, is a pink sandy clay. Some sand bands occur within this unit, which is extremely stiff and hard to penetrate, but it is believed that at least in boreholes 3 and 4, bedrock was reached. Overlying the pink clay is a blue clay unit that contains some sand horizons. At a depth of between *circa* 1.0-1.5mOD most boreholes record shells within a sandy matrix (*e.g.* in transect 1 and the two central cores in transect A). Overlying this unit, either a silty sand is recorded or in some cores (*e.g.* boreholes 4 and 24) the sediment becomes more organic with some *Phragmites australis* fibres and some *Sphagnum* recorded. In other cores (*e.g.* boreholes 1 and 6), a sand unit overlies the shelly sand. Organic-rich sediment forms the top units in all cores with a *Phragmites*-rich area overlaid by *Sphagnum* peat.

From the cores taken, the broad shape of the basin was established (Figure 7.4). A deep central area is recorded to over 8m in depth that gradually becomes shallower in a south-east north-west direction. In a north-east south-west direction, however, the sides of the basin rise steeply. The cores taken from the periphery of the basin in transect A record a sandy horizon overlaid by *Sphagnum* in the north-east and to the south-west, silt and sand are overlain by *Sphagnum* peat (*e.g.* boreholes 15, 16, 18 and 19). In some of the peripheral cores, *Sphagnum* peat directly overlies bedrock (*e.g.* boreholes 11 and 17).

Transect 2 was cored to establish the lowest altitude of bedrock in this area. If the sea had inundated this basin, it would have done so through the area with the lowest elevation. As the ground surrounding the site rises in all directions, apart from where the stream flows into the sea, this should represent the point of marine penetration to the basin. The cores in transect 2 extend to a maximum depth of 23cm. The stratigraphy consists of a sandy gravel horizon, of maximum depth 10cm, overlaid by *Sphagnum* peat. The altitude of the lowest point reached in these boreholes, therefore, represents the minimum altitude that the sea had to attain in order to penetrate the basin. This was recorded in borehole 5 with a basal altitude of 4.13mOD. The altitude of the rock sill of the basin is, therefore, considered to lie at 4.13mOD.

Borehole 3 was chosen to sample as it contained a long sequence of sediment from the centre of the basin. It did not appear to have been affected by modern human disturbance and contained all the main stratigraphic units recorded at the site. Additionally, it was situated at some distance from any fluvial influence.

Table 7.1: Stratigraphy of borehole 3 (NG 5645 0030)

Altitude (mOD)	Depth (cm)	Sedimentary description
4.63-3.88	0-75	Brown *Sphagnum* peat
3.88-3.68	75-95	Brown organic sediment with *Phragmites* fibres
3.68-2.95	95-168	Grey brown organic sandy silt
2.95-1.43	168-320	Grey brown silty sand with shell fragments
1.43 to -0.71	320-392	Grey clay with occasional shell layers
-0.71 to -1.88	392-651	Pink dense clay with occasional sand layers
-1.88 to -2.69	651-732	Pink clay with fine sand
-2.69 to -3.26	732-789	Pink grey clay with sand

7.3 Loss on ignition

Samples were taken at 50cm intervals from 3.83mOD to the base of borehole 3. The highest recorded carbon content of 37% is from the top sample in the organic *Phragmites* unit (Figure 7.5). This indicates that a large percentage of minerogenic material is present in this sample and by Allen's (1990) definition would not be classified as a peat. In the underlying samples, the carbon content falls and fluctuates between 1% and 4%. The carbonate fraction of the samples, as indicated by the high level loss on ignition also fluctuates between 1% and 4%.

7.4 Pollen analysis

Pollen samples were analysed at 16cm intervals to provide a skeletal pollen diagram that would establish the broad environmental context in which the sediments were deposited and would allow comparison with the radiocarbon dates. It was not, however, used to reconstruct a detailed vegetational history at the site. Samples were prepared for the core from 3.65 to -3.12mOD (98-775cm), but the samples taken from within the clay units were barren of pollen. Pollen analysis was, therefore, only undertaken on samples from 3.65-1.53mOD (98-310cm). Three pollen zones have been identified (Figure 7.6).

Table 7.2: Pollen zone descriptions for borehole 3

Pollen zone	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 3 PSc	3.73-2.89	90-174	**Cyperaceae-Poaceae-*Corylus avellana*-type-*Alnus*.** The arboreal pollen is characterised by *Alnus* with low *Betula*, *Pinus* and *Quercus* values. Low frequencies of *Calluna vulgaris* pollen are recorded. High Cyperaceae and fluctuating frequencies of Poaceae pollen are noted (10-20%) and a low presence of other herb pollen is recorded. Fluctuating Pteropsida and low frequencies of *Pteridium* and *Sphagnum* are recorded. Initially, high frequencies of *Pediastrum* are noted that decline to mid-zone but increase at the top of the zone.
LPAZ 2 PSb	2.89-2.13	174-250	**Cyperaceae-Poaceae.** Low arboreal and shrub pollen with increased numbers of dwarf shrub pollen are recorded at the top of the zone. High Cyperaceae (55-80%) pollen and frequencies of Poaceae pollen at *circa* 20% are noted. An increased number of other herb pollen are recorded in low numbers, including Brassicaceae, Caryophyllaceae and *Plantago lanceolata.* Low frequencies of aquatic spores are recorded and some Pteropsida, *Selaginella selaginoides* and *Sphagnum* spores are present. Low *Pediastrum* frequencies are recorded in this zone.
LPAZ 1 PSa	2.13-1.53	250-310	**Cyperaceae-Poaceae-*C. avellana*-type.** Low arboreal pollen with increasing *C. avellana*-type pollen and low frequencies of dwarf shrub pollen is recorded in this zone. Low Poaceae pollen (10-15%) with high Cyperaceae (> 75%) pollen are recorded, although the latter decreases through the zone. A low presence of other herb pollen is noted. Aquatics and spores are present in very low numbers although there is noticeable *Nymphaea* pollen. Increasing *Pediastrum* values are noted through the zone.

7.5 Diatom analysis

Diatom samples were taken throughout the core from 3.73mOD to -3.12mOD (90-775cm). It was found that below 1.03mOD (360cm), within the clay units, no diatoms occur with the exception of one level at -1.47mOD (610cm). From 2.05-1.03mOD (258-566cm), the levels were still depleted in diatoms and the high clay content of the sediment affected the preparation of the slides. Samples in this area of the core were, therefore, taken at larger intervals. Above 2.05mOD (258cm) samples were generally taken at 5cm intervals although closer spaced sampling of 1cm was undertaken to accurately identify the change from polyhalobous to oligohalobous conditions. Four diatom zones have been identified (Figure 7.7).

Table 7.3: Diatom zone descriptions for borehole 3

Diatom zone	**Altitude (mOD)**	**Depth (cm)**	**Diatom characteristics**
LDAZ 4 PSd	3.73-3.56	90-108	***Fragilaria construens-Fragilaria exigua-Fragilaria lapponica.*** Polyhalobous and mesohalobous species have a very low presence in this zone. Oligohalobous-indifferent species are present at over 80% and are dominated by *F. construens*, *F. exigua* and *F. lapponica.*.
LDAZ 3 PSc	3.56-2.99	108-164	***Paralia sulcata.*** Polyhalobous species, dominated by *P. sulcata* increase in this zone. Mesohalobous species, dominated by *Diploneis minor*, increase at mid-zone (12%) and then decline. Oligohalobous-indifferent species decrease in the lower levels of zone and are then absent during mid-zone. Low frequencies of *F. exigua* are recorded at the top of zone.
LPAZ 2 PSb	2.99-2.65	164-198	***F. exigua-F. construens.*** Polyhalobous, poly-mesohalobous and mesohalobous species are recorded at low values in this zone. Oligohalobous-indifferent species fluctuate between 75-90% and are dominated by *F. construens* and *F. exigua.*
LDAZ 1 PSa	2.65 to -1.47	198-610	***P. sulcata-F. construens-F. exigua.*** Fluctuating frequencies (8-20%) of polyhalobous species, dominated by *P. sulcata*, are recorded through the zone but an increase to 75% occurs at the top of the zone. Low frequencies of poly-mesohalobous species are noted with increasing mesohalobous species at the top of zone. Oligohalobous-indifferent species, characterised by *F. construens,* have a high presence through the zone but show a general decline to top of zone where they are absent in top sample.

7.6 Mollusca analysis

Mollusca analysis was undertaken on five samples from Point of Sleat. However, only one sample (1.61-1.56mOD, 302-307cm) yielded sufficient molluscan to provide a viable count.

Table 7.4: Results of molluscan analysis

Species /genera	Frequency	Percentage
Acmaea virginea (Muller)	1	0.2
Gibbula species	1	0.2
Lacuna vincta (Montagu)	243	46.4
Littorina obtusata (L.)	4	0.8
Hydrobia ulvae (Pennant)	249	47.5
Onoba semicostata (Montagu)	4	0.8
Rissoa species	4	0.8
Omalogyra atomus (Philippi)	1	0.2
Skeneopsis planorbis (Fabricus)	7	1.3
Arca species	1	0.2
Mytilus/Modilus	9	1.7

7.7 Radiocarbon dates

Four radiocarbon dates have been obtained at this site based on the changes in polyhalobous species of diatoms that may be related to relative sea level changes. The youngest age (Beta-93813) dates a decrease in polyhalobous species and is a bulk carbon date. The oldest age (Beta-93990) has been obtained from a marine shell, *Buccinium* species, and dates a gradual increase in polyhalobous species. The two other dates are AMS dates obtained from the grey brown sand unit. The older of these (Beta-098613) dates a decrease in polyhalobous species and the younger (Beta-098612) dates an increase in polyhalobous species.

Table 7.5: Radiocarbon dates obtained for borehole 3

Conventional C14 age (BP)	C13/C12 ratio (‰)	Calibrated C14 age (BC)	Laboratory code	Altitude (mOD)	Depth (cm)
2850±100	-25.0	1295-810	Beta-93813	3.58-3.56	105-107
3830±60	-21.9	2885-2035	Beta-098612	2.91-2.90	172-173
10460±50	-21.0	?	Beta-098613	2.68-2.67	195-196
12570±70	0.0	?	Beta-93990	1.44	319

The AMS date obtained on the shell may have been affected by the marine reservoir effect.

This is in the order of 700-800 years for the Loch Lomond Stadial (Bard *et al.*, 1994). An average of 750 years could, therefore, be deducted from 12570±70 BP to achieve a date of 11820±70 BP.

7.8 Interpretation of pollen assemblages

At Point of Sleat, the pollen source areas include the slopes surrounding the basin which could bring grains and spores into the basin by slopewash and runoff and the river flowing to the south-west of the site. Buoyant pollen grains may have been preferentially preserved at this site if the basin became full of water, either in times of higher relative sea level or as a freshwater lagoon. If the basin did contain water, movement of pollen grains could have occurred vertically and horizontally affecting the depositional sequence.

LPAZ 1 PSa (2.15-1.53mOD, 250-310cm) (Figure 7.6)
Below 1.53mOD (310cm) pollen could not be extracted from the samples. In this zone, the pollen was sparse and corroded. This has been recorded at other sites on Skye (*e.g.* Birks, 1973; Walker *et al.,* 1988; Lowe and Walker, 1990) and is associated with the reworking of pollen and break up of interstadial soils just prior to the Loch Lomond Stadial. Walker *et al.* (1988) and Lowe and Walker (1990) noted that at Loch Ashik up to 75% of the assemblage consisted of deteriorated pollen during the Loch Lomond Stadial. The date of 11820±70 BP (Beta-93990) (corrected for the Lateglacial marine reservoir) at 1.44mOD (319cm) suggests that the poor state of the pollen is a result of deteriorating conditions prior to the Loch Lomond Stadial and this has taphonomic implications.

In this zone, very low arboreal pollen is recorded. It is likely that the tree taxa recorded represent a regional component of the pollen rain and that woodland was unlikely to have become established at the site. This is especially true of *Pinus,* which has a winged pollen grain making it particularly susceptible to wind transportation. *C. avellana*-type values increase in this zone and could suggest development of hazel scrub at the site, although the pollen could be reworked. The pollen assemblage is dominated by Cyperaceae with subordinate Poaceae pollen. An open sedge environment appears to have developed with some grassland development, possibly in the drier areas of the site. Few other herb species are recorded and some ling and crowberry heath development, characterised by *C. vulgaris* and *Empetrum* pollen is suggested. It is possible that a Lateglacial tundra-type vegetation existed that inhibited the growth of more thermophilous taxa. The species recorded would have initially colonised the very thin soils that existed shortly after deglaciation and pioneer species such as *Rumex acetosa/acetosella* are recorded in the pollen profile. The increase of *Pediastrum* spores during this zone indicate that a freshwater lake may have existed

(Chapman, 1964; Fritsch, 1965) and a sedge environment could, therefore, have developed on the periphery of this. Some open water pools, of pH 5-8, are also indicated by the presence of *Nymphaea* pollen (Clapham *et al.*, 1987). The presence of some *Sphagnum* and *Pteridium* spores suggest that acidification had begun at the site and this is reinforced by the presence of *C. vulgaris* and *Empetrum* pollen in the assemblage.

The pollen assemblage recorded in this zone appears to represent a Lateglacial environment and probably one during the Loch Lomond Stadial. However, an anomaly to this is the early presence of *C. avellana*-type pollen. On Skye, pollen assemblages from other sites have revealed that *C. avellana*-type pollen is not recorded until *circa* 9600 BP. For example, at Loch Ashik, an increase in *C. avellana*-type pollen occurs after 9540±70 BP (Williams, 1977), at Loch Cleat after 9000±100 BP (Williams, 1977; Birks and Williams, 1983), at Loch Meodal after 9610±150 BP (Birks, 1973; Williams, 1977) and at Loch Cill Chroisd, the *Corylus* rise has been dated at 9655±150 BP. There are several possible explanations for the early appearance of *C. avellana*-type pollen at Point of Sleat. Firstly, the pollen may actually represent *Myrica* which could have had a local occurrence at this site. A second explanation is that the presence of *C. avellana*-type pollen at this time is due to its location near a refugium (Deacon, 1974; Huntley, 1993). Several areas have been identified in north-west Europe where *Corylus* retreated and survived during the Loch Lomond Stadial. This allowed early colonisation from these refugia into the surrounding areas after the stadial. The nearest refugium to Skye, however, exists in the border region of Scotland, which would suggest that colonisation by hazel would also be recorded earlier on the border of Scotland and England. This, however, has not been recorded by Boyd and Dickson (1986) for south-west Scotland and this explanation is, therefore, unlikely to apply for Skye. Huntley (1993) also considers the possibility of Lateglacial expansion of *Corylus* northwards due to its increased climatic tolerance.

An alternative hypothesis is that the corrected date of 11820±70 BP is in fact too old, as a result of hard water errors that have been introduced due to reworking of sediments during the Loch Lomond Stadial. During the Late Devensian, soils were very thin as a result of much inwashing of sediments and the relatively short time that had elapsed since deglaciation to allow soil development to occur. Inert carbon residues from bedrock or from older carbon residues could have been washed into the basin and deposited with the sediment and this would affect the radiocarbon dates obtained. Walker *et al.* (1988) and Walker and Lowe (1990) report that, at Loch Ashik, the three dates obtained before 11590±160 BP are probably in error for these reasons. At Point of Sleat, the carbon content of the sediments was so low that bulk carbon samples could not be used. An AMS date, therefore, had to be obtained on a shell, *Buccinium* species. Errors could have occurred with this method due to the possible allochthonous provenance of the shell. It is impossible to assess which of the hypotheses for the early of appearance of *C. avellana*-type is correct.

LPAZ 2 PSb (2.89-2.13mOD, 174-250cm)

This zone records low frequencies of arboreal pollen suggesting that virtually no woodland development occurred in the pollen catchment area. The frequencies of *C. avellana*-type pollen have declined suggesting that hazel scrub is present in very reduced numbers at the site or again that the pollen has been reworked. A small increase in *Salix* pollen is recorded at 2.69mOD (194cm) and could suggest a wet area existed allowing the development of stands of willow. An increase in the presence of dwarf shrub pollen, characterised by *C. vulgaris*, *Empetrum* and Ericaceae, suggests continued acidification of the site and expansion of ling and crowberry heathland.

High levels of non-arboreal taxa are recorded in the profile and Cyperaceae pollen is dominant. Reedswamp is thought to have prevailed at the site with some grassland also present. A suite of other non-arboreal taxa, for example, Brassicaceae, *Potentilla*, *Aster*, Apiaceae and Lactuceae, is also recorded, particularly after 2.69mOD (194cm) and these may have been members of a herb-rich grassland. A small percentage of aquatic species and spores is recorded. *Sphagnum* spores are present in the lower levels of the zone and combined with the dwarf shrub pollen would also indicate acidification of the environment. Other spores such as *S. selaginoides*, Pteropsida and *Pteridium* are present above 2.69mOD (194cm) and would additionally suggest the presence of an acidic, bog environment. Very low frequencies of aquatic pollen, such as *Nymphaea* and *M. alterniflorum,* combined with the low presence of *Pediastrum* spores would suggest that limited surface water was present in this zone and that the lake had probably decreased in surface area.

A date of 10460±50 BP (Beta-098613) has been obtained at 2.68mOD (195cm), towards the top of the zone and the pollen assemblage agrees with this suggesting the continuation of a Lateglacial open vegetation. The date, however, suggests that the first appearance of *P. lanceolata* associated with Brassicaceae and Caryophyllaceae pollen was a part of the coastal vegetation community and not associated with anthropogenic influences. At a depth of 2.91mOD (172cm), the boundary of this pollen zone with LPAZ 3 Psb, a date of 3630±60 BP (Beta-098612) has been obtained. This implies that 23cm of sedimentation occurred in *circa* 7000 years or an unconformity is present possibly due to anthropogenic activities. Between the dates, no commonly used chronological indicators are present in the pollen diagram to validate the dates, due to the suppressed amount of arboreal taxa at the site. The stratigraphy does not show there to be an unconformity present as there is a transitional contact between the shelly sandy silt and the sandy silt. This apparently extremely slow sedimentation rate makes the interpretation of the assemblage very problematic.

LPAZ 3 PSc (3.73-2.89mOD, 90-174cm)
An increase in all arboreal taxa is noted in this zone, characterised by *Alnus*, *Quercus* and *Pinus* with minor *Ulmus*, *Salix* and *Betula* pollen and would appear to represent the development of a mixed woodland within the pollen catchment area. The appearance of *Alnus* pollen is noted at 2.69mOD (194cm) and it subsequently increases through this zone, possibly representing development of alder carr at the site. It is a species that can tolerate wet and brackish conditions (Clapham *et al.*, 1987). *C. avellana*-type pollen increases throughout this zone and would suggest the development of hazel scrub. Some *Salix* pollen is also present, possibly suggesting continued damp conditions with stands of willow present. An increase in spores between 2.91-3.45mOD (172-118cm) is also likely to be related to the development of woodland at the site. Pteropsida, *Polypodium* and *Pteridium* spores are recorded and are likely to have formed the understorey of the woodland or hazel scrub. The vegetation, therefore, appears to have become more closed in this zone, although above 3.12mOD (118cm) the frequencies of all the tree taxa decline possibly suggesting some clearance of the site. Ling and crowberry heath development appears to have continued at the site, as suggested by the presence of *C. vulgaris* and *Empetrum* pollen.

It is also at this time that an increase in the species of herbs, for example, *R. acetosa/acetosella* and Rosaceae, is recorded and this is accompanied by a gradual decline in Cyperaceae pollen. The decline in Cyperaceae pollen at the site may be related to the encroachment of the site by arboreal species or to the onset of drier conditions. Grassland increases at the site as represented by the Poaceae pollen and the sample at 3.67mOD (96cm) is likely to represent *P. australis* as indicated by macrofossils in the stratigraphy. This could represent telmatic succession of vegetation around the periphery of a lake. Acid conditions still existed in this zone as recorded by the presence of *Sphagnum* spores. *S. selaginoides* is present coincident with the *Alnus* pollen and grows on damp mossy ground (Clapham *et al.*, 1987). Small amounts of aquatic species, such as *Nymphaea*, are recorded and these could also indicate that some open water or slow-flowing streams were present. Increasing frequencies of *Pediastrum* spores in this zone would suggest the presence of freshwater at the site and possibly a lake environment.

The base of this assemblage is dated at 3630±60 BP. It is possible that this zone represents a post-clearance vegetation assemblage, although an increase in *Alnus* pollen appears to occur at this time. The *Alnus* rise is commonly dated at *circa* 6600 BP on Skye (Williams, 1977; Birks and Williams, 1983): for example, at Loch Cleat, the *Alnus* rise has been dated at 6590±80 BP, at Loch Meodal at 6590±110 BP and at Loch Ashik at 6360±80 BP (Williams, 1977; Birks and Williams, 1983). It is possible that the date of 3630±60 BP is, therefore, in error. Alternatively, it is possible that some erosional event or unconformity has removed the beginning of the increase in *Alnus* pollen at this site or some factor has delayed its establishment.

Low frequencies of *P. lanceolata* pollen are recorded and the presence of *R. acetosa/acetosella* would appear to represent the natural succession of a coastal community and not anthropogenic activity (Jones, 1988). At 3.58mOD (105cm) an age of 2850±100 BP (Beta-93813) has been obtained and at this time, in other sequences from Skye, the anthropogenic component is usually quite marked (Williams, 1977; Birks and Williams, 1983).

7.9 Interpretation of diatom assemblages

LDAZ 1 PSa (2.65 to -1.47mOD, 198-610cm) (Figure 7.7)
This zone appears to contain several communities of diatoms. The sample at -1.47mOD (610cm) supports a small population of *P. sulcata*. The small presence of *Mastogloia smithii* represents a niche of brackish, alkaline waters (Patrick and Reimer, 1966). Denys (1991) states that it is epontic and benthic and Hendey (1976) states that it is common on all British coasts. The ecology of these species could, therefore, suggest that an inter-tidal area with open water pools existed.

The dominant community at this time, however, is freshwater. *F. construens* and *F. exigua* are both planktonic (Denys, 1991; Vos and de Wolf, 1993) with *F. construens* preferring alkaline waters (Hustedt, 1939). Above the mean tide level, therefore, a freshwater community developed at the site. This environment appears to have existed during the Late Devensian with an age of 11820±70 BP obtained towards the top of the zone.

At an altitude greater than 2.43mOD (220cm) a change is noted in the diatom assemblages. Polyhalobous and mesohalobous species increase in value to an altitude of 2.65mOD (198cm) and the sediment at this level has been dated at 10460±50 BP. *D. minor* is a marine-brackish epipsammon (Vos and de Wolf, 1993) and combined with *Opephora olsenii* would colonise sandy beaches in the littoral zone (Hendey, 1976). *Diploneis didyma* and *Diploneis smithii* are marine-brackish epipelons (Vos and de Wolf, 1993) that are common species in British waters (Hendey, 1976). The encroachment of saline conditions, therefore, appears to be recorded at this time and the oligohalobous-indifferent species decline rapidly until they are absent in the top level of this zone. It appears that either increased storm activity is recorded at this time and that the site has been regularly inundated with saline waters allowing the community of *P. sulcata* to thrive. Alternatively, a relative sea level rise occurred at this time that excluded all freshwater communities from the site. A sandy area would have developed allowing the epipsammic species to grow.

LDAZ 2 PSb (2.99-2.65mOD, 164-198cm)

The boundary of this zone marks a very rapid change to freshwater conditions, characterised by the presence of *F. construens* and *F. exigua* in particular. Polyhalobous and mesohalobous species are virtually absent and would, therefore, suggest that storm activity had decreased or that the sea had regressed from the site. Alkaline conditions are still present as represented by the assemblage of diatoms present (*e.g. F. construens*). The small amount of *P. sulcata* could indicate some inter-tidal area continued to exist on the periphery of the basin or that occasional inwash of saline waters to the site occurred.

LDAZ 3 PSc (3.56-2.99mOD, 108-164cm)

A date of 3830±50 BP has been obtained at the start of this zone. Oligohalobous-indifferent species decline rapidly in this zone as *P. sulcata* increases to form 95% of the assemblage. This again would indicate either increased storm activity or a relative sea level rise. The increase in polyhalobous species appears to have occurred over a relatively long time and is more likely to represent a relative sea level change. At mid-zone, a peak occurs in *D. minor* and this would again suggest development of a sandy beach (Hendey, 1976) with the presence of sand in the stratigraphy confirming this. At the top of the zone, a peak in *Cocconeis disculus* is recorded and this suggests that some area of alkaline (Hustedt, 1939), eutrophic-mesotrophic water is present (Naumann, 1932). Its ecology is epontic and benthic (Denys, 1991) and Vos and de Wolf (1993) suggest that it can tolerate some brackish component. It appears that an inundation of marine waters occurred in this zone and the development of a beach and/or inter-tidal area occurred.

LDAZ 4 PSd (3.73-3.56mOD, 90-108cm)

The lower boundary of this zone has an age of 2850±100 BP and marks the rapid change from polyhalobous species to domination by oligohalobous-indifferent species. Polyhalobous and mesohalobous species are minimal and it appears that marine influence has decreased to such an extent that no inter-tidal conditions are recorded. A peak in *F. lapponica* is initially noted and this is a planktonic species (Denys, 1991) that prefers alkaline-circumneutral waters of low mineral content (Patrick and Reimer, 1966). It also prefers eutrophic-mesotrophic waters (Naumann, 1932) as do the other oligohalobous species present, for example, *F. construens*. Saline conditions, therefore, appear to have ceased at the site and a freshwater, alkaline environment existed. The alkaline environment is probably a function of the bedrock and is dominant throughout the sequence.

7.10 Interpretation of the molluscan assemblage

All ecological information obtained on the species present in this assemblage has been derived from Seaward (1982), Graham (1971) and Peacock (1993). The assemblage is dominated by two species, *L. vincta* and *H. ulvae*. *L. vincta* lives sublittorally between 0-40m depths, but often migrates upshore to breed. It occurs commonly at LWMOST where fucoids are abundant and can tolerate a minimum summer temperature of 16°C and a maximum winter temperature of 8°C. *H. ulvae* prefers estuarine conditions although it can be found on open coasts. It extends from sublittoral levels but is common on the uppermost third of the coast and can also occur on saltmarshes or on weeds. The other species present account for 6% of the assemblage and live amongst weeds or in rock pools.

It is possible a saltmarsh existed that supported *H. ulvae* and much aquatic vegetation in general seems to have been present to support the species present in this assemblage. All species presently live around Skye with the exception of *L. obtusata* which will not withstand wave exposure (Seaward, 1982).

7.11 Environmental history of Point of Sleat

It is likely that the basin at Point of Sleat, which has a deep central area, was formed as a result of glacial scouring. In the centre of the site, the basal sediment consists of clay and sand that has a 1% carbon content and 3% carbonate fraction. No microfossils are present in this sediment and it would seem to represent a deposit that accumulated rapidly after deglaciation of the area. No soil development had occurred at this time and no pollen appears to be present. The absence of diatoms is probably due to dissolution of the silica. The sandy clay deposit seems most likely to represent fluvial activity or intensive slopewash as the basin began to infill with water and sediment.

It is above the boundary of the pink clay at -1.88mOD (651cm) that the first diatom count, at -1.47mOD (610cm), could be made. The sediment consists of 2% organic carbon and 3% carbonate content. The diatom assemblage is predominantly freshwater but a small population of *P. sulcata* existed at the site (LPAZ 1 PSa) (Figure 7.9). The clay deposit would seem to represent deposition in a lake environment and it is envisaged that the deepest area of the basin contained a lake that was rapidly infilled (Figure 7.8). The occasional input of saline waters is likely to have occurred with the result that *P. sulcata* is recorded. This suggests that at this time relative sea level was higher than 4.13mOD, the altitude of the rock sill and it is likely that an inter-tidal area developed close to the site.

The environmental conditions that existed at the site as sediments accumulated between -1.47mOD (610cm) and 1.08mOD (355cm) are unknown as the deposits in these layers are barren of pollen and diatoms. At 1.08mOD (355cm), still within the clay unit, diatom communities are again found and are virtually identical to the lowest sample investigated at -1.47mOD (610cm). The lfrequencies of organic carbon and carbonate content are unchanged throughout the clay unit and it seems that no hiatus in sedimentation is evident. It would seem logical to assume that a similar environment persisted at the site with the overwash of saline waters into a predominantly freshwater lake (Figure 7.8).

At 1.32mOD, a peak is seen in the percentage carbon curve followed by a decline. This is typical of the sequence observed during the transition from Lateglacial Interstadial to Loch Lomond Stadial (Walker *et al.*, 1988). The date of 11820±70 BP obtained at 1.44mOD (319cm) broadly agrees with the loss on ignition data and marks the first recorded vegetation development at the site. A very open sedge/grass environment developed represented by Cyperaceae pollen (LPAZ 1 PSa) (Figure 7.9). This would suggest that some soil development had occurred and that telmatic vegetation was growing on the periphery of the lake. The diatom assemblages at this time still record predominantly freshwater conditions, although some saline communities are recorded at between 5-15% (LDAZ 1 PSa). At 1.43mOD (320cm), a change in the stratigraphy is noted, although the carbon and carbonate fractions are still the same as in the lower levels. A sandy silt is present with Mollucsa (Figure 7.9). Two species of molluscan, *L. vincta* and *H. ulvae*, are recorded that indicate salinities of between 5-40‰ (Peacock, 1993). An inter-tidal and/or saltmarsh environment seems to have developed that would have supported these species. It appears that after 11820±70 BP, but before 10460±50 BP, fucoids and aquatic plants were present to support the species of molluscan, but also some rock pools with pebbles, silt, mussels and coralines that may have formed in bedrock surrounding the basin (Graham, 1971).

The inundation of saline waters either through storm activity or a higher relative sea level at this time brought Mollusca, *P. sulcata* and other polyhalobous and poly-mesohalobous diatom species into the basin. However, only small amounts of aquatics are recorded at this time and so if fucoids and weeds grew, they are likely to have developed at some distance from the sampling site. The high frequencies of Cyperaceae pollen at this time could indicate some reedswamp development around the periphery of the lake and the high frequencies of *Pediastrum* spores at this time confirm a lake environment to have existed (LPAZ 1 PSa). Some acidification at the site had occurred as indicated by the presence of *Sphagnum* spores and dwarf shrub pollen, *e.g. C. vulgaris.*

At 2.38mOD (225cm), an increase in *P. sulcata* is noted within the shelly sandy silt unit concurrent with an increase of mesohalobous diatom species. Oligohalobous-indifferent diatom species decrease and are absent above 2.63mOD (200cm). If a relative sea level rise had occurred it had to be of at least magnitude 4.13mOD. The lake at this time had infilled with 5.9m of sediment and any saline influence would be felt to a much larger degree than when the lake was developing and contained a large volume of freshwater with little sediment. Once saline water had entered the basin it remained long enough to displace all freshwater communities. Brackish diatom communities would have developed on the periphery of the lake in the inter-tidal areas and families typical of coastal communities are noted such as Brassicaceae, Caryophyllaceae and Chenopodiaceae (Jones, 1988).

Marine regression occurred and is recorded in the stratigraphy at 2.73mOD (190cm) and at an age of 10460±50 BP. This relates to a time when the relative sea level fell below 4.13mOD and diatomological isolation of the basin occurred. It appears that high relative sea level has been recorded prior to 11820±70 BP, although the low frequencies of saline-demanding diatoms suggest that perhaps only overwash of marine waters into the basin was experienced. The increase in marine influence after 11820±70 BP is thought to be related to a readvance of ice during the Loch Lomond Stadial that reversed isostatic recovery of the land and upon deglaciation allowed marine waters to invade the area.

Freshwater conditions prevailed at the site after 10460±50 BP, as indicated by the presence of *F. construens* and *F. exigua,* with less than 10% polyhalobous and mesohalobous diatom species present (LDAZ 2 PSb) (Figure 7.9). The regression of the sea from the site enabled the development of some hazel scrub with ferns forming the understorey component (LPAZ 2 PSb). Acidification or surface wetness at the site seems less pronounced at this time with decreased *Sphagnum* spores and dwarf shrub pollen noted. The environment appears to be quite herb-rich with, for example, Caryophyllaceae and *P. lanceolata* noted. Some aquatics, represented by *Nymphaea* and *Myriophyllum alterniflorum* pollen, are recorded at this time but in low quantities and an increase in *Pediastrum* spores are recorded suggesting that the lake has become fresh again. These freshwater conditions are recorded until 3830±60 BP when there is an increase in saline influence at the site.

After 3830±60 BP, the majority of the basin would have been inundated by the sea and on the periphery of this area, reedswamp, represented by Cyperaceae pollen, would have developed. On the surrounding hills some peat development and heathland, represented by *Sphagnum* spores and *C. vulgaris* pollen, possibly existed. Anthropogenic activity at the site seems minimal and no pronounced increase is seen in the non-arboreal pollen taxa which commonly indicate human activity.

As the later marine transgression developed, the freshwater diatom communities at the site declined rapidly and the polyhalobous diatom species increased (LDAZ 3 PSc). Complete inundation of the basin probably occurred although it is unclear to what altitude the transgression would have attained, although it was greater than 4.13mOD, the altitude of the rock sill (Figure 7.8). Marine waters would have entered via the stream and flooded the basin bringing *P. sulcata* and displacing all freshwater diatom species. An inter-tidal area could have developed on the periphery of the embayment that would have supported *P. sulcata* and some mesohalobous species.

The marine invasion of the site appears to be related to a relative sea level rise that occurred during the Late Holocene. This is suggested by the pattern of vegetation assemblages present when compared to other profiles established for skye (e.g. Williams, 1977; Birks and williams, 1983). The Main Postglacial Transgression does, therefore, not appear to have been recorded at the site. There are three possible reasons for this. Firstly the relative sea level rise in this area of Skye was not of sufficient altitude, *i.e.* less than 4.13mOD, to penetrate the basin. A second explanation is that some hiatus has been recorded at this time and evidence of the Main Postglacial Transgression has been eroded. It is possible that sediment deposited by the Main Postglacial Transgression lay very close to the altitude of the threshold of the basin and that subsequently erosion by streams removed these deposits. It is also possible that some erosion by the later rise in relative sea level occurred and younger marine sediments were deposited at or just below the altitude of the rock sill. A third explanation is that the Main Postglacial Transgression was actually erosive in nature and removed sediment. The stratigraphy, however, does not appear to record a break in sedimentation from 3.68-1.43mOD (95-320cm), although it is likely that the start of the *Alnus* rise is not recorded.

Marine conditions continued at the site until 2850±100 BP, when marine regression is recorded and the basin again became isolated. The polyhalobous and mesohalobous diatom species decline rapidly and are replaced by freshwater communities and the sediment becomes more organic at 3.68mOD (95cm). As saline influence at the site gradually decreased from complete inundation to penetration during high tide and to only spring tides levels, freshwater communites of diatoms developed and telmatic vegetation such as *P. australis* would have migrated from the edges of the lake and colonised the newly deposited sediment, thus allowing the development of *Sphagnum* peat.

It is difficult to establish the age of the barriers and how they relate to the evolution of the basin, although they may be associated with the relative sea level changes recorded. The higher lies at 10.8-11.1mOD and the lower at 7.5-7.8mOD. Both are vegetated and are unaffected by any present day storm activity. It is possible that they formed under a higher relative sea level and Dawson (1984) reports that many shingle ridges on the west coast of Scotland formed during the Main Postglacial Transgression. No visible sediments of the barrier were seen and so it is unclear of the particle size constituting the ridges. It is also unknown whether the barriers would date from the same episode of relative sea level change or whether as one is 3m higher than the other, they could possibly relate to different episodes. It is also possible that the barriers are very much older and possibly of Late Devensian age.

A rock platform in this area lies between 2.4-2.7mOD and could be related to Main Rock Platform on the west coast (Main Lateglacial Shoreline) (Dawson, 1988). In other areas of Skye, a low rock platform has been described occurring at between 2-7mOD (Richards, 1969; 1971). A quadratic trend-surface isobase map for the Main Lateglacial Shoreline, predicts this shoreline that to lie at *circa* 6mOD at Point of Sleat (Firth *et al.*, 1993). It is possible that either the platform is not a correlative of the Main Lateglacial Shoreline or that the isobase map requires modification.

7.12 Conclusions

Two episodes of relative sea levels higher than present have been recorded at Point of Sleat. The maximum altitude of these is unknown although each attained at least 4.13mOD. The oldest episode of high relative sea level appears to have occurred within the Late Devensian. It is possible that this is related to isostatic loading by Loch Lomond glaciers which are thought to have halted isostatic recovery of the land, caused renewed isostatic depression and upon deglaciation allowed marine waters to penetrate the area. The pollen assemblage at the time of the Late Devensian transgression records a low alpine/tundra scrub.

Regression of the sea occurred at 10460±50 BP when the basin became isolated from the sea and if no hiatus exists in the stratigraphy it can be stated that freshwater conditions dominated until 3830±60 BP. Little arboreal development occurred and the environment was dominated by grass and sedge species. At 3830±60 BP, a later marine phase is recorded when the basin became connected to the sea once more. This lasted until 2850±100 BP when isolation of the basin is recorded. The Main Postglacial Transgression does not appear to have been recorded at the site and this may be as it did not attain an altitude of 4.13mOD or because an hiatus exists in the sequence representing erosion of sediments relating to this transgression.

Chapter 8.0 Ardmore Bay

8.1 Introduction

Ardmore Bay (NG 2200 6100) lies on the west coast of the Waternish Peninsula (Figure 8.1). The site consists of a raised fossil tombolo, with barriers to the north and the south. In the south, a largely gravel, vegetated barrier lies at 3.0-3.1mOD and in the north, a cobble barrier lies at 3.5-3.9mOD. A large arcuate bay has formed at the south of the tombolo and the beach consists predominantly of basalt cobbles. At the centre of the tombolo, between the barriers, an area of peat has developed, colonised by *Sphagnum* spp, *Calluna vulgaris*, Ericaceae and *Juncus* spp. The area of peat is approximately 300m long by 150m wide and the surface increases in elevation from south to north. A small loch lies at the south-east margin of the peat area. The peninsula consists of two rock outcrops, Ard Mòr and Ard Beag, composed of Tertiary plateau lavas and these rise to over 36m. At the north of the tombolo, the land descends steeply to the sea. A small beach composed largely of cobbles stretches between the rock outcrops. A stream drains across the site and the area is artificially drained.

Richards (1971) undertook levelling and geomorphological work on the Ardmore Peninsula and reported that raised beaches are present which are eroded in till and are overlaid by shingle. He suggested that the shingle had been derived from erosion of the old tombolo surface. Richards believed that the low-lying area between Ard Beag and Ard Mòr was a Postglacial raised beach.

8.2 Geomorphological mapping, borehole location and stratigraphy

The tombolo curves 180° from the mainland enclosing Ardmore Bay (Figure 8.1). A transect was cored from north to south with boreholes located at 20m intervals (Figure 8.2). Boreholes 1, 2 and 3 end in a blue grey slightly organic gravelly sand and no sediment was penetrated below an altitude of 3.2mOD. In two cores from the centre of the transect, a brown green grey silt overlies a brown organic silt containing *Phragmites australis* fibres between 3.5-3.6mOD and this is in turn overlaid by a brown black fibrous peat. Borehole 4 records an organic unit overlying impenetrable basal deposits and borehole 1 records an organic unit above basal sand and gravels, which are overlaid by a mottled blue grey silty clay at 3.8mOD. A reddish organic silt forms the top unit in borehole 1.

An additional transect was cored from west to east across the site to verify the general stratigraphy, but these boreholes were not levelled into Ordnance Datum (Figure 8.3). The pattern of stratigraphy across this transect is consistent, with the basal unit consisting of a blue-grey organic silt and sand overlaid by a mottled brown grey organic silt unit that is in turn overlain by a *Sphagnum* and *Phragmites* peat. Borehole 3 was sampled for farther analyses.

Table 8.1: Stratigraphy of borehole 3 (NG 2195 6100)

Altitude (mOD)	Depth (cm)	Sedimentary description
4.63-4.17	0-47	Brown black fibrous peat
4.17-3.63	47-100	Brown black peat with *Phragmites australis* fibres
3.63-3.45	100-118	Brown organic silt with decreased *Phragmites* fibres
3.45-3.38	118-125	Brown green silt
3.38-3.35	125-128	Brown green silty sand
3.35-3.28	128-135	Brown grey gravelly sand

8.3 Loss on ignition

High and low level loss on ignition were undertaken on four samples from borehole 3 (Figure 8.4). The top two samples record the highest carbon content and are taken from the brown black fibrous peat. The carbon content decreases in the second sample, from 92% to 77%, although still within the peat unit. In the third sample within the organic silt, the organic content drops to 18% and in the deepest sample only 8% carbon content is recorded. The carbonate content of the samples is less than 2% throughout.

8.4 Pollen analysis

Pollen analysis was undertaken on samples at 8 and 16cm intervals from borehole 3 to establish the broad environmental context in which the deposit accumulated (Figure 8.5).

Table 8.2: Pollen zone descriptions for borehole 3

Pollen zones	Altitude (mOD)	Depth (cm)	Pollen characteristics
LPAZ 5 ABe	4.63-4.57	0-8	**Poaceae-Cyperaceae**. Poaceae pollen values of 58% dominate this zone with subordinate Cyperaceae pollen. A low presence of other herb pollen, particularly *Filipendula* is recorded.
LPAZ 4 ABd	4.57-4.29	8-34	**Cyperaceae-*Calluna vulgaris***. Low frequencies of arboreal and shrub pollen are recorded. The dwarf shrub component is dominated by *C. vulgaris* which increases to mid-zone and then declines. Poaceae pollen values decrease in this zone coincident with increasing Cyperaceae pollen. A low presence of other herb pollen is recorded. A peak in *Typha latifolia* pollen is recorded at the top of the zone and Pteropsida and *Sphagnum* spores are also recorded.
LPAZ 3 ABc	4.29-4.15	34-48	**Cyperaceae-*Sphagnum***. Low frequencies of arboreal, shrub, *C. vulgaris* and Poaceae pollen are recorded in this zone. High frequencies of Cyperaceae pollen (70%) are recorded, but little other herb pollen is noted. Spores are dominated by increasing *Sphagnum* with subordinate Pteropsida.
LPAZ 2 ABb	4.15-3.49	48-114	**Cyperaceae-Poaceae-*Corylus avellana*-type**. Low frequencies of arboreal pollen are recorded in this zone. Frequencies of *C. avellana*-type pollen increase to mid-zone and then decline. Increasing Poaceae and decreasing Cyperaceae pollen are recorded and the low presence of other herb pollen is noted. In the lower levels of this zone, the presence of aquatic species, particularly *Selaginella selaginoides,* are noted. Pteropsida spores are recorded throughout the zone and *Sphagnum* spores show a declining trend.
LPAZ 1 ABa	3.49-3.29	114-134	**Cyperaceae-Poaceae**. A low presence of arboreal and shrub pollen is recorded. The zone is dominated by high frequencies of Cyperaceae pollen with subordinate Poaceae pollen. The low presence of other herb pollen is recorded with *Rumex acetosa/acetosella,* particularly noted at the top of the zone.

8.5 Diatom analysis

Samples were taken at 5cm intervals from 3.68-3.29mOD (95-134cm), in the lower minerogenic horizons of the core, to investigate the salinity of the environment at the time the sediment was deposited (Figure 8.6).

Table 8.3: Diatom zone descriptions for borehole 3

Diatom zones	Altitude (mOD)	Depth (cm)	Diatom characteristics
LDAZ 3 ABc	3.68-3.66	95-97	***Pinnularia rupestris***. Mesohalobous species are recorded at 6% and oligohalobous-indifferent species are present at 70% and dominated by *P. rupestris*.
LDAZ 2 ABb	3.66-3.43	97-120	***Fragilaria exigua-Caloneis bacillum-Diploneis ovalis.*** Poly-mesohalobous species, dominated by *Diploneis bombus*, show a low presence in the lower levels of the zone. Mesohalobous species increase throughout and are dominated by *Caloneis westii, Navicula digitoradiata* and *Navicula peregrina*. Oligohalobous-halophilous species record a presence of between 15 and 25% with a consistent presence of *D. ovalis*. Oligohalobous-indifferent species decline and are dominated by *F. F. exigua* with subordinate *Fragilaria construens*. Halophobous species are recorded at the 5% level at mid-zone.
LPAZ 1 ABa	3.43-3.29	120-134	***C. bacillum-F. construens-F. exigua.*** Frequencies of oligohalobous-halophilous species decline through the zone coincident with increasing oligohalobous-indifferent species to over 50%. This group is dominated by *C. bacillum* that increases as *F. construens* and *F. exigua* decline. Declining frequencies of halophobous species are recorded.

8.6 Radiocarbon Date

One conventional bulk radiocarbon date was obtained for Ardmore Bay to establish the length of time represented by the sequence. It was obtained from the brown green silty sand unit.

Table 8.4: Radiocarbon date for borehole 3a

Conventional C14 age (BP)	C13:C12 ratio	Calibrated C14 age (BC)	Laboratory Code	Altitude (mOD)	Depth (cm)
9980±110	-25.0 ‰	?	Beta-93813	3.35-3.34	128-129

8.7 Interpretation of pollen assemblages

At Ardmore Bay, the pollen grains could have derived from several sources. It is possible that slopewash and runoff from the steep slopes to the east may have brought sediment onto the peat bog. If marine inundation of the site occurred then buoyant pollen grains may have been preferentially preserved.

LPAZ 1 ABa (3.49-3.29mOD, 114-134cm) (Figure 8.5)

The tree and shrub pollen total is minimal throughout the pollen sequence and could represent a regional component. It is likely the restricted presence of trees throughout the sequence is a reflection of the exposure of the site as Ardmore Bay lies on the west coast of the Waternish Peninsula and is exposed to Atlantic storms. Birks (1973) reports that exposure is the main factor preventing tree growth on Skye.

The sequence, in this zone, is dominated by Poaceae and Cyperaceae pollen suggesting a grass and sedge environment developed. The open nature of the environment could be a legacy from the Lateglacial, with tundra-type vegetation dominating. Pollen such as *R. acetosa/acetosella,* Brassicaceae, Caryophyllaceae, Lactuceae and Asteroideae are recorded representing species that colonise open landscapes and *R. acetosa/acetosella* is additionally associated with Lateglacial and early Holocene environments (Walker *et al.*, 1988; Lowe and Walker, 1991).

LPAZ 2 ABb (4.15-3.49mOD, 48-114cm)

The lower levels from 3.49-4.15mOD (114-48cm) record an open environment. Low frequencies of *Pinus*, *C. avellana*-type and *Salix* pollen are recorded in this zone suggesting that a minimum amount of woodland existed, although some hazel scrub or stands of willow may have been present in the pollen catchment area.

The domination by Poaceae and Cyperaceae pollen suggest open grassland and sedgeland were widespread. Herb species typical of grasslands such as Lactuceae and *R. acetosa/acetosella* are represented in the pollen profile and *Filipendula* pollen represents a genus that can tolerate damp conditions (Clapham *et al.,* 1987). Between 3.69-3.59mOD (94-104cm) wetter conditions are recorded at the site by the pollen of *Nymphaea* and *Potamogeton* which indicate the possible existence of lakes, ponds and slow-moving streams and *S. selaginoides, Lycopodium* spores and *Sphagnum* spores that indicate the presence of damp, mossy ground (Clapham *et al.*, 1987). In addition, Pteropsida spores, identified in the lower levels, represent a species that can survive well in damp environments.

LPAZ 3 ABc (4.29-4.15mOD, 34-48cm)

The presence of *Pinus* and *C. avellana*-type pollen are recorded in this zone and may suggest some local wood/scrub development at the site, although this component could also be regional. Above 4.15mOD (48cm), conditions at the site become drier with no aquatic species recorded. *Sphagnum* and Pteropsida spores are still identified, however, indicating that some damp areas were still present, although the ferns may have formed an understorey component in the woodland. An environmental change appears to occur in this zone with the initiation of peat development and associated acidification. This is indicated by the large increase in *Sphagnum* spores. Ling- and crowberry-dominated acidic heath is represented by *C. vulgaris, Empetrum* and Ericaceae pollen.

LPAZ 4 ABd (4.57-4.29mOD, 8-34cm)
It is possible that hazel scrub was still present at the site as a low, but consistent, presence of *C. avellana*-type pollen is recorded. However, the very low frequencies of arboreal pollen at this time indicate that virtually no trees were present at the site or even within the pollen catchment area. The frequencies of Poaceae and Cyperaceae pollen fluctuate in this zone and an increase in *C. vulgaris* pollen is recorded, suggesting that an expansion of ling-dominated heath occurred in this zone. The presence of other herb pollen such as *Filipendula, Potentilla,* Lactuceae and Caryophyllaceae indicate the continued open nature of the environment and development within a grass and sege environment. The peak in *T. latifolia* pollen, combined with the presence of *Potamogeton* spores at 4.54mOD (9cm) and *Sphagnum* spores, represents either reedswamp development or growth of the species around a lake or pond where there was siltation and rapid decay of organic matter (Clapham *et al.*, 1987).

LPAZ 5 ABe (4.63-4.57mOD, 0-8cm)
This top level suggests an open environment dominated by grasses with some sedge development existed as represented by the high frequencies of Poaceae and Cyperaceae pollen. The development of the grassland seems to have displaced some of the dwarf shrubs and it is possible that the site had become less acid at this time as indicated by the decline in *Sphagnum* spores. A slight increase in *Filipendula* pollen at this time would indicate damp, marshy conditions at the site (Clapham *et al.*, 1987).

8.8 Interpretation of diatom assemblages

LDAZ 1 ABa (3.43-3.29mOD, 120-134cm) (Figure 8.6)
The freshwater conditions present before and after 9980±110 BP supported two communities of diatoms: halophilous species and species indifferent to salt. *Pinnularia lundii* is the dominant oligohalobous-halophilous species and prefers alkaline waters that must have been locally present at the site (Hustedt, 1939). The other community of freshwater diatoms consists predominantly of *Pinnularia* species with some *Fragilaria brevistriata* and these may have colonised areas further away from saline influence. The *Pinnularia* species present are benthic and live in acidic waters (Patrick and Reimer, 1966). *F. brevistriata* also lives in acidic environments (Hustedt, 1939; Denys, 1991). The

dominant halophobous species is *Navicula cocconeiformis,* which is benthic and prefers acidic, oligotrophic waters (Naauman, 1932; Hustedt, 1939; Denys, 1991). Water bodies of different pH and trophic status, therefore, existed at the site throughout this time, although acidic waters dominated.

LDAZ 2 ABb (3.66-3.43mOD, 97-120cm)
All the mesohalobous species present in this zone are benthic. *Diploneis interrupta, N. peregrina* and *C. westii* are all eutrophic and prefer alkaline waters. The two peaks of *D. bombus* represent a benthic community living in brackish waters of a higher salinity. It is possible that sea spray provided the brackish element at the site or increased storm activity brought these benthic diatoms onshore from the inter-tidal zone. The species present could not have survived in marine conditions, however, indicating that the sea at this time did not flood the area and the freshwater component continued to dominate these levels.

LPAZ 3 ABc (3.68-3.66mOD, 95-97cm)
This top level is dominated by freshwater conditions and in particular a peak is seen in *P. rupestris,* which represents an ecological niche of cool water of low mineral content (Patrick and Reimer, 1966).

8.9 Environmental history of Ardmore Bay

It is thought that all boreholes at the site are underlaid by glacial deposits and Richards (1971) reported that glacial till underlies the entire tombolo feature. It is upon the till or gravels that organic sedimentation began at 9980±110 BP. Freshwater conditions existed at this time with very little brackish component (LDAZ 1 ABa) and the site was dominated by sedge vegetation (LPAZ 1 ABa) (Figure 8.7). A change in sedimentation occurs at 3.38mOD (125cm) and silt is recorded in the stratigraphy but this does not seem to represent any significant environmental change. The diatoms at this level continue to record freshwater conditions and a grassland vegetation developed at the site. It appears, therefore, that no hiatus is represented by this change in stratigraphy. The silt unit has a terrestrial origin and could be derived from slopewash, or possibly from a stream that drained the slopes of Ard Beag and flowed across the area, or from a small loch that was present in this vicinity.

On top of the silt unit, an organic silt at 3.45mOD (118cm), with an increased carbon content contains brackish diatoms. At 3.57mOD (106cm), it appears that an environmental change is recorded with mesohalobous, benthic species of diatoms reaching 20% of the assemblage (LDAZ 2 ABb) (Figure 8.7). Also recorded at this time is an increase in aquatic species (LPAZ 2 ABb). It is likely that an increase in the groundwater table occurred and that it had become more saline. It is possible that this is related to either a relative sea level rise in this area or increased storm activity that occurred at this time. If a relative sea level rise was responsible, it does not appear to have been of a large enough magnitude to inundate the site, as polyhalobous diatom species are not recorded and freshwater taxa still dominate the diatom assemblage. Additionally, if the site was flooded, it would be expected that some change in stratigraphy would be noted as sediment was moved inland from the offshore environment.

It is possible that this environmental change was linked to the formation of the double tombolo *i.e.* barrier formation to the north and south of the site enclosing sediment within. Tombolos can take many forms dependent on their orientation to wave direction and sediment supply (King, 1972). Material can be moved along the coast in either direction by longshore drift and deposited where a point of null drift occurs. Alternatively, the meeting of refracted waves behind an island can lead to the formation of tombolos, as the waves meet at right angles to the swell waves and deposit material. Curvature of the feature is often indicative of wave refraction (King, 1972). The source of material for the tombolo can, therefore, be derived from offshore or from movement along the coast.

At Ardmore Bay, the tombolo has a curved form indicating formation by refracted waves with the dominant wave component from the south. It is likely that the tombolo, therefore, formed as waves became refracted around Ard Beag and Ard Mòr. This would have resulted in the two rock outcrops initially joining and then the entire feature becoming linked to the mainland. As refraction occurred and the waves lost energy, material from the offshore zone would have been deposited. It seems probable that only the southern edges of the feature were inundated by the sea and that the sampling location was protected from marine influence possibly by the formation of the barriers. It is unlikely that waves overtopped the cliffs of the northern shore and the shallow offshore area to the south of the tombolo appears to have been a focus for deposition. The formation of the tombolo is likely to have been associated with a change in coastal energy régimes that could have occurred with either a relative sea level rise or increased storminess. The benthic lifeform of the diatoms recorded in LDAZ 2 ABb (Figure 8.7) could indicate that storms were responsible for their deposition.

It is possible that the environmental change recorded is related to the Main Postglacial Transgression and it is reported that barrier formation was widespread during this period in western Scotland (Dawson, 1984). If the Main Postglacial Transgression is represented, it was not of a magnitude to flood the site and this is important in terms of isostatic uplift patterns. It is possible that in borehole 3, peat growth was sufficient to keep pace with relative sea level rise or that barrier formation prevented penetration of the area by the sea. It is possible that marine deposits associated with the Main Postglacial Transgression are not present in this area due to the effects of isostatic tilting and differential uplift, but are merely represented in a saline groundwater table.

After this brackish phase, freshwater conditions are recorded at the site (LDAZ 3 ABc) (Figure 8.7). Peat development, with associated acidification as shown by the diatom taxa present, the high frequencies of *Sphagnum* spores and dwarf shrub development, appear to have occurred. The presence of *Sphagnum* spores and aquatic species indicate damp conditions and open pools of water existed. Some reedswamp development is indicated by the presence of *T. latifolia* pollen and this is likely to have occurred on the periphery of the water bodies. It is hard to identify any anthropogenic activity at the site and it is possible that human influence was always of limited extent due to the exposure of the site. In comparison with other pollen assemblages for northern Skye, the vegetation is very species poor and virtually no tree development occurred.

Another feature of the sequence obtained from Ardmore Bay is the extremely low sedimentation rate. In 10000 years only 129cm of material has been deposited. The low accumulation rate may indicate that extensive peat cutting has occurred at the site and this has reduced the depth of sediment present or that an hiatus is present. Settlement of the area occurred in the sixteenth century and in A.D. 1570 at Millegearraidh, a battle occurred between the Macleods and MacDonalds. Some small cairns, possibly grave mounds, are present at the site and possibly date from this battle and some disturbance of the top sediments could, therefore, have occurred.

8.10 Conclusions

The base of the pollen sequence represents an open environment dominated by grass and sedge species. The woodland component is minimal, as it is throughout the pollen sequence, probably as a result of exposure at the site. An increase in salinity is recorded at 3.45mOD and may reflect barrier formation at the site or the indirect effects of a relative sea level rise. This may be a local expression of the Main Postglacial Transgression. However, total marine inundation of the site does not appear to have occurred and it is, therefore probable that the Main Postglacial Transgression did not attain an altitude of 3.34mOD at this location. No anthropogenic influences are recorded at the site and throughout the sequence an open landscape dominated.

Section C: Conclusions of Research

Late Devensian and Holocene relative sea level and coastal changes on the Isle of Skye
Late Devensian and Holocene vegetational changes on the Isle of Skye
Conclusions
References

Chapter 9.0 Relative sea level changes on the Isle of Skye

9.1 Introduction

The research undertaken in this study has revealed several episodes of Late Devensian and Holocene relative sea level change on the Isle of Skye. The changes at each site are summarised and the relative sea level index points obtained are presented. Four age-altitude plots are constructed against both uncalibrated and calibrated radiocarbon timescales (Figures 9.1-9.4). A chronological approach is then adopted to discuss the relative sea level changes and comparisons are made between sites on Skye and with other areas of Scotland, particularly on the west coast. The implications of these findings for the empirical and rheological isobase models (*e.g.* Lambeck, 1991; 1993a; 1993b; Firth *et al.*, 1993) are considered. A discussion of the influence of geomorphology on the preservation of the relative sea level record and the implications of using isolation basins and back-barrier environments completes the chapter.

9.2 Inver Aulavaig

The earliest record of relative sea levels, higher than present, at Inver Aulavaig is believed to have occurred in the latter part of the Lateglacial Interstadial because of the low alpine, tundra-type vegetation recorded in the pollen assemblage (Figure 4.10). High frequencies of *Empetrum* pollen, combined with *C. vulgaris*, are recorded suggesting the development of heathland and the environment is very open and dominated by grass and sedge species. The presence of *R. acetosa/acetosella* and *C. crispa* suggest the presence of thin, unstable soils that would have been present following deglaciation. Additional evidence for the age of this marine phase is provided from the percentage carbon loss on ignition profile. A peak is recorded at 1.78mOD prior to decreased values that remain low until 2.58mOD (Figure 4.9). The peak in the profile is thought to represent the break up of interstadial soils and the inwash of carbon to the basin as the climate deteriorated during the Loch Lomond Stadial and the low percentage carbon values reflect the restricted soil development during the stadial (Walker *et al.*, 1988). The transgression during the Lateglacial Interstadial attained an altitude of greater than 5.10mOD, the altitude of the rock threshold. The date of 12590±290 BP obtained after the trangression seems to have been affected by a hard water or other older carbon error and, therefore, appears to be too old.

The second episode of high relative sea level is recorded at 8850±170 BP (borehole 36 in the north-west of the basin) and represents the first relative sea level index point at the site when connection of the basin to the sea occurred above a threshold level of 5.10mOD. This episode lasted until 3280±60 BP in borehole 36 and represents the second relative sea level index point, when regression of the sea fell below an altitude of 5.10mOD and isolation of the basin occurred, although a decrease in marine influence is recorded throughout this episode (Figure 4.16). It is thought that this episode correlates with the Main Postglacial Transgression. A freshwater episode has been recorded within the later rise in relative sea level in borehole 3a dated between 5440±50 BP and 3160±40 BP. This borehole is situated close to the stream and the rock sill in the north of the basin and was probably more sensitive to fluctuations of relative sea level than borehole 36. Additionally, the distance of borehole 36 from the stream, may have meant that marine waters were registered for longer at this location. It is thought that the date of 5440±50 BP represents the diatomological isolation of the basin from the sea when relative sea level fell below 5.10mOD and represents the third relative sea level index point at the site. At 3160±40 BP, saline influences increase in borehole 3a and this date represents connection of the basin to the sea once more at an altitude of 5.10mOD and provides the fourth relative sea level index point at the site. The altitude of the transgression that began at 3160±40 BP is probably constrained by the altitudes of 5.10-6.01mOD as a core investigated in the south-west of the basin, with a basal altitude of 6.01mOD, did not register any marine influences. The maximum altitudes of these three transgressions have not been established.

9.3 Peinchorran

Two periods of high Holocene relative sea level have been identified at Peinchorran. The older of these was underway by 7980±70 BP when it had attained an altitude of 4.49mOD and had ceased by 6600±70 BP at an altitude of 4.61mOD. This episode is thought to relate to the Main Postglacial Transgression. The younger rise in relative sea level dates from 4220±60 BP when relative sea level attained an altitude of 4.83mOD and probably continued after 3970±140 BP by which time it had attained an altitude of 4.90mOD. Barriers probably formed during one or both of the marine phases recorded at the site.

9.4 Talisker Bay

A small increase in marine and brackish diatom species occurs in the assemblage at Talisker Bay and is dated at between 7790±100 BP at an altitude of -2.18mOD and 7250±150 BP at an altitude of -1.79mOD. At their maximum, only 35% of diatom species are marine and, therefore, total marine inundation of the site does not appear to have occurred. It is possible that the earliest date of 7790±100 BP represents the start of the Main Postglacial Trangression and that barrier formation may have occurred during this period and closed the site off to farther marine influences. It is unclear whether the increase in saline influence at the site is related to a relative sea level change or whether it is a function of barrier morphodynamics and merely represents the proximity of the sea to the site.

9.5 Point of Sleat

Two marine episodes are recorded at Point of Sleat. The older phase shows limited marine presence from the base of the diatom assemblage (LDAZ 1 PSa) (Figure 7.7) prior to a sharp increase which ends at 10460±50 BP. Several lines of evidence suggest that this marine phase occurred within the Loch Lomond Stadial although limited overwash into the basin may have been recorded earlier than this by the low frequencies of marine diatoms at the base of LDAZ 1 PSa (Figure 7.7). The pollen assemblage is dominated by reedswamp and grass species with some heathland development and combined with the presence of *R. acetosa/acetosella* is suggestive of tundra-type vegetation (Figure 7.6). All the pollen showed signs of corrosion probably as a result of the break up of soils because the climate deteriorated. The percentage carbon curve shows a small peak at 1.32mOD prior to the start of the pollen assemblage and then a decline until *circa* 2.2mOD which is typical of the carbon profile for the time prior to and during the Loch Lomond Stadial (Figure 7.5) (Walker *et al.*, 1988). The earliest radiocarbon date, with a correction for the Lateglacial marine reservoir, is 11820±70 BP obtained at 1.44mOD and appears to agree well with the proposed age for the transgression.

The second marine episode occurs between 3830±60 BP and 2850±100 BP and is thought to represent a late Holocene rise in relative sea level. The relative sea level rise in both cases attained an altitude of at least 4.13mOD, the altitude of the rock threshold of the basin, although the maximum altitude of the transgression has not established. Three relative sea level index points have been obtained for this site. The first represents a negative marine tendency at 10460±50 BP when the basin became isolated from the sea, the second, a positive marine tendency at 3830±60 BP when connection of the basin to the sea occurred and the third, a negative marine tendency at 2850±100 BP, when again the basin became isolated from the sea.

9.6 Ardmore Bay

It does not appear that marine inundation of the site of Ardmore Bay occurred during the Holocene. A date of 9980±110 BP has been obtained at 3.34mOD and, therefore, it seems likely that Holocene relative sea level did not attain this altitude in this area. A small increase in brackish diatoms to *circa* 20% is recorded beginning at 3.57mOD, that may be related to the formation of the tombolo and may reflect the indirect effects of the Main Postglacial

Transgression. The formation of the tombolo may have prevented inundation of the area by the sea.

9.7 Relative sea level index points and age-altitude plots

Relative sea level index points have been calculated from the sites (Table 9.1) and have been used to construct four age-altitude plots (Figure 9.1-9.4). The relative sea level changes recorded during the Late Devensian have not been dated directly and do not appear on the plots with the exception of the negative sea level tendency recorded at Point of Sleat at 10460±50 BP. Figures 9.1 and 9.2 plot all relative sea level data recorded at the sites against uncalibrated and calibrated timescales respectively. Figures 9.3 and 9.4 plot only the relative sea level index points obtained from the isolation basins and two index points from Peinchorran that are thought to be true marine signals. They are plotted against uncalibrated and calibrated radiocarbon years and are based on mean tide level of 0.4m (Admiralty Tide Tables, 1996). The indicative range of the relative sea level index points obtained from isolation basins is thought to relate to between mean high water of spring tides and highest astronomical tides. At the barrier sites, it is assumed that a palaeo-saltings surface is represented by the marine sediments and this equates to the mean high water mark of spring tides. Both sites, therefore, have reference water levels related to the mean high water of spring tides and are, therefore directly comparable, although the indicative range of isolation basins is greater. Relative sea level index points obtained from isolation basins are considered to be true signals of relative sea level changes. However, at a site where barriers exist, it is often unclear how barrier formation may have affected the relative sea level record.

Age-altitude plots have been selected as the most appropriate method of displaying the data. It was considered to be inaccurate to join the relative sea level index points together in a graph for two reasons. Firstly, the sites are situated at some distance from one another and variation in the glacio-isostatic history of the sites is expected. It is, therefore, inappropriate to consider that a similar pattern of relative sea level changes may have affected all the areas studied. Secondly, the record of relative sea level changes obtained from isolation basins is not continuous, as only discrete changes in the altitude of relative sea level above or below that of the rock threshold are recorded.

9.8 Late Devensian relative sea level changes

At Inver Aulavaig and Point of Sleat, evidence for marine transgressions within the Late Devensian have been recorded. It seems unlikely that both periods of high relative sea level

Table 9.1: Radiocarbon dates, altitudes and indicative meaning of relative sea level index points

Site	Laboratory code	Radiocarbon age ±2σ BP	Calibrated age BC	Altitude (m OD)	Indicative range (m)	Type of contact	Number of index point
Inver Aulavaig	Beta-92167	3280 ± 120	1685-1420	+5.10	+0.28 to -0.08	Diatomological and hydrological isolation contact	11
Inver Aulavaig	Beta-92170	8850 ± 340	8140-7525	+5.10	+0.28 to -0.08	Diatomological connection contact	2
Inver Aulavaig	Beta-105028	3160 ± 80	1505-1380 1335-1330	+5.10	+0.28 to -0.08	Diatomological connection contact	12
Inver Aulavaig	Beta-105029	5440 ± 100	4360-4220	+5.10	+0.28 to -0.08	Diatomological isolation contact	7
Point of Sleat	Beta-93813	2850 ± 200	1295-810	+ 4.13	+0.28 to -0.08	Diatomological and hydrological isolation contact	13
Point of Sleat	Beta-098612	3830 ± 120	2460-2120 2080-2050	+ 4.13	+0.28 to -0.08	Diatomological connection contact	10
Point of Sleat	Beta-098613	10460 ± 100	——	+ 4.13	+0.28 to -0.08	Diatomological isolation contact	1
Peinchorran	Beta-92171	3970 ± 280	2885-2035	+4.90	±0.10	Discrete point of relative sea level	9
Peinchorran	Beta-83734	4220 ± 120	2915-2605	+4.84	+0.11 to -0.10	Possible positive marine tendency	8
Peinchorran	Beta-92172	6600 ± 140	5600-5415	+4.44	±0.11	Possible negative marine tendency	6
Peinchorran	Beta-83735	7980 ± 140	7025-6570	+4.40	+0.26 to -0.11	Discrete point of relative sea level	3
Talisker Bay	Beta-93408	7250 ± 300	6390-5760	-1.78	±0.21	Possible negative marine tendency	5
Talisker Bay	Beta-93409	7790 ± 200	6990-6415	-2.17	±0.21	Possible positive marine tendency	4

represent the same episode. The evidence of pollen and the radiocarbon date at Point of Sleat suggest that the marine period may have started and ended later at Point of Sleat (relative sea level index point 1) than at Inver Aulavaig.

After deglaciation, it is probable that relative sea level fell due to the rapid isostatic rebound of the land. This was despite a rising glacio-eustatic sea level resulting from the input of meltwater to the oceans. This fall in relative sea level has been recorded by many workers on both the east and west coasts of Scotland, *e.g.* in the Arisaig area (Shennan *et al.*, 1995a; 1996) and in the Moray Firth where Firth (1984) identified 10 Lateglacial shorelines representing a continuous fall in sea level. Dominant freshwater conditions at the base of the diatom assemblages for Point of Sleat (Figure 7.7) and Inver Aulavaig (Figure 4.13) suggest that sea level was below the altitudes of the rock thresholds in these areas during the initial phases of deglaciation. In some areas, however, readvances of ice during the Late Devensian are reported to have been associated with a relative sea level rise caused by a halt in isostatic rebound and renewed isostatic depression of the land. In Wester Ross, for example, a readvance is thought to have occurred at *circa* 17000-18000 BP to 13000 BP (Robinson and Ballantyne, 1979). This has been associated with a transgression, at the culmination of which, the Main Wester Ross Shoreline formed. As well as being recorded in the Wester Ross region (Robinson and Ballantyne, 1979; Sissons and Dawson, 1981), a correlative of the Main Wester Ross Shoreline is thought to occur on the islands of Coll and Tiree (Dawson, 1994). A pronounced beach ridge in Jura, the Colonsay Ridge, whose crest height lies at 19-20mOD, may also have represent a halt in deglaciation or a relative marine transgession, but it is unclear whether these changes took place during the Wester Ross Readvance (Dawson, 1982; Dawson *et al.*, 1997).

It is possible that the Wester Ross Readvance may have been responsible for the transgression recorded at Inver Aulavaig by arresting the isostatic rebound of the land, causing renewed isostatic depression and upon deglaciation, allowing marine waters to penetrate the sites. The date of 10460±50 BP for the negative marine tendency at Point of Sleat, however, makes it unlikely that the unloading effects of the Wester Ross Readvance are recorded here as it is too young to be related to high relative sea levels associated with this. At Inver Aulavaig, however, where based on the evidence of pollen, it is possible that the transgression may be older than at Point of Sleat, it is possible that the transgression may relate to this ice readvance.

The transgressive episode recorded at Point of Sleat may be associated with the Loch Lomond Readvance, as the pollen assemblages suggest tundra-type conditions to have existed during this phase. The readvance may have caused a reversal of isostatic uplift and renewed isostatic depression of the land during the build up of Loch Lomond Stadial ice (Sutherland, 1984; Firth, 1986; Firth *et al.*, 1993). The isostatic depression may have been emphasised on Skye during the Loch Lomond Stadial as a result of the independent ice centre that developed in the Cuillin mountains. At Loch Gruinart in Islay, a high relative sea level is implied prior to 9950±70 BP that may also be correlated to a transgression during the Loch Lomond Stadial. The timing of the transgressive period at Point of Sleat may closely correspond to that at Loch Gruinart (Dawson and Dawson, 1997).

The transgressive periods recorded at Point of Sleat and Inver Aulavaig are in contrast to the pattern of falling relative sea level that has been recorded in many areas during the Late Devensian and may reflect a different isostatic history on Skye. Peacock *et al.* (1978) produced a relative sea level graph for the Ardyne area which implies a continuous fall from *circa* 38mOD at *circa* 13000 BP to *circa* 8mOD at *circa* 11000 BP. This trend, however, results from extrapolation between radiocarbon dated sites of fossil marine fauna and a transgression(s) may have occurred between the index points. Detailed isolation basin studies from the Arisaig area have revealed a fall in relative sea level from 20.6mOD at 12040±110 BP to 16.32mOD at 11940±105 BP and a further fall to 16.26mOD at 11895±95 BP (Shennan *et al.*, 1993; 1994; 1995a; 1995b; 1996). Further studies also revealed a fall from 17.8mOD at 11820±145 BP to 9.3mOD at 10755±90 BP and at Loch nan Eala, relative sea level is reported to have fallen from 6.3mOD at 10500±90 BP to *circa* 5.2m at 10060±86 BP. These studies recorded no transgressive episodes during the Late Devensian although this could be a function of the isolation basin methodology which does not provide a continuous record of relative sea level changes. It is also possible that a trangression occurred before 12040±110 BP and is possibly recorded at an altitude of between *circa* 38mOD (Peacock *et al.*, 1978) and 20.6mOD (Shennan *et al.*, 1993; 1994; 1995a; 1995b; 1996).

9.9 Implications for the Late Devensian isobase map and rheological model

At Point of Sleat, a rock platform occurs at 2.4-2.7mOD that may be related to the Main Rock Platform. The quadratic trend-surface isobases for this shoreline lie at *circa* 6mOD for the west coast of southern Skye (Firth *et al.*, 1993), although extrapolation of the isobases for the Main Lateglacial Shoreline constructed by Dawson (1988) suggest a lower altitude for this shoreline. Richards (1969; 1971) also found that a low rock platform, a possible correlative of the Main Rock Platform, occurs at between 2-7mOD between Portree and Staffin and this data combined with that at Point of Sleat may suggest the isobase map of Dawson (1988) to be more accurate than that of Firth *et al.* (1993). The first relative sea level index point at Point of Sleat, occurring at an altitude of 4.13mOD at 10460±50 BP

(Figures 9.1 and 9.3), broadly fits in age and altitude with the isobase map of Firth *et al.* (1993) for the Main Lateglacial Shoreline.

The three-layer earth model of Lambeck (1993b) for 10500 BP, using an increase in the ice load of *circa* 17% for northern Scotland, suggests that mean sea level around Skye attained an altitude of -15mOD during the latter part of the Loch Lomond Stadial. This is in contrast to the field data obtained in this study which suggests that relative sea level attained an altitude of 2.48mOD (based on mean sea level) at 10460±50 BP at Point of Sleat (Figure 9.3). This discrepancy may be due to renewed isostatic depression of the earth's crust experienced as a result of the build up of ice during the Loch Lomond Stadial, which had a greater effect than the rheological model predicts. It appears, therefore, that modification of this model is needed. Shennan (1995a), however, suggests that the model provides a good fit for the data obtained from the Arisaig area where mean sea levels are predicted to lie at 3.5mOD. This may imply that Skye experienced a different isostatic history to that of mainland Scotland possibly as a result of the build up of independent ice centres on Skye, for example, during the Loch Lomond Stadial.

9.10 Early-middle Holocene relative sea level changes on Skye

At the sites studied, no high relative sea levels equivalent to those recorded on the east coast as in, for example, the Forth valley at *circa* 9600 BP by the Main Buried Beach, have been identified (*e.g.* Sissons, 1966; Sissons and Brooks, 1971). The early Holocene minimum of relative sea level, as isostatic rebound of the land again became the dominant component, is recorded at Point of Sleat and Inver Aulavaig between 10460±50 BP and 8850±70 BP and is in close agreement with the dates obtained by Shennan *et al.* (1993; 1994; 1995a; 1995b; 1996) in Arisaig for this period.

The earliest record of relative sea level changes on Skye within the Holocene occurs at Inver Aulavaig. A transgression is recorded at 8850±70 BP (relative sea level index point 2) and represents a relative sea level rise that attained an altitude of at least 5.10mOD. This positive marine tendency is thought to represent the Main Postglacial Transgression at the site, when the glacio-eustatic sea level rise outpaced isostatic recovery of the land in this area (Figures 9.1-9.4). At Peinchorran, a transgression is believed to have been underway by 7930±70 BP (index point 3), when it had achieved an altitude of 4.49mOD (index point 5) and is also thought to be related to the Main Postglacial Transgression (Figures 9.1 and 9.2). The maximum altitude of 4.61mOD obtained for the transgression at Peinchorran is lower than at Inver Aulavaig where it attained an altitude of greater than 5.10mOD and it may be that increased isostatic depression was experienced at the latter site due either to its proximity to the centre of isostatic uplift in Scotland or due to the build up of ice in the Cuillins during the Loch Lomond Stadial. It is possible that the Main Postglacial Transgression has been recorded at Talisker Bay (relative sea level index point 4) reaching an altitude of -2.18mOD at 7790±100 BP, although the evidence is equivocal (Figures 9.1 and 9.2). If this transgression is represented at Talisker Bay, the low altitude and the later date for the start of the transgression suggest that considerably less isostatic depression was experienced at this site compared to at Peinchorran or Inver Aulavaig.

At the two other sites studied, Point of Sleat and Ardmore Bay, it does not appear that the Main Postglacial Trangression has been recorded, although at Point of Sleat the barriers identified to the north-west of the site may be related to this transgression. At Point of Sleat it is possible that a hiatus exists in the isolation basin record and evidence of the trangression has been eroded. If the Main Postglacial Transgression caused the basin to completely fill with sediment, erosion by streams that drained the surrounding hills and flowed across the site, may have removed the deposits. Some erosion of the sediments of the Main Postglacial Trangression may also have occurred as a result of a late Holocene rise in relative sea level that attained an altitude of greater than 4.13mOD or due to the erosive nature of the Main Postglacial Transgression itself. At Ardmore Bay, no marked increase in marine influence has been identified, although it is proposed that the indirect effects of the Main Postglacial Transgression may have been recorded by a small increase in brackish conditions at the site. However, the transgression in this area is unlikely to have attained an altitude of 3.34mOD, probably as a result of the limited isostatic depression experienced due to its location some distance away from the centre of uplift.

Studies on the west coast of Scotland record similar dates to Skye for the Main Postglacial Transgression. At Loch Gruinart, the transgression is thought to have been underway by *circa* 9100 BP at an altitude of *circa* 0.4mOD. At Loch nan Eala in Arisaig, dates of *circa* 8700 BP at an altitude of 6.3mOD and *circa* 8300 BP at an altitude of 5.2mOD have been obtained for the transgression, although in the Arisaig area, as at Inver Aulaviag, the transgression would have begun earlier than the dates suggest, as in isolation basin studies, relative sea level has to attain the altitude of the rock sill before it can be registered. The dates obtained for the transgression on Skye appear to fit with those obtained for other areas on the central west coast of Scotland. The Main Postglacial Transgression was underway at most sites on the east coast of Scotland by *circa* 8500 BP (Smith *et al.*, 1983).

The maximum altitude obtained by the Main Postglacial Transgression has not been established for the sites on Skye and the timing of the culmination is also unknown. Regression of the sea occurred at Peinchorran at 6600±70 BP having attained an altitude of

4.61mOD (relative sea level index point 6), when isostatic recovery of the land once more became the dominant component (Figures 9.1-9.4). This is likely to represent the end of the Main Postglacial Transgression in this area. At Inver Aulavaig, it is possible that regression of the sea, to below 5.10mOD, occurred at 5440±50 BP (relative sea level index point 7) (Figures 9.1-9.4). At Talisker Bay the complete duration of the Main Postglacial Transgression may not have been recorded possibly as a result of barrier formation which occurred within the early stages of the Main Postglacial Transgression and prevented relative sea level from subsequently entering the site. Thus, the end of marine influence here is recorded at 7250±150 BP (relative sea level index point 5) (Figures 9.1 and 9.2).

9.11 Implications for the isobase map and rheological model for the middle Holocene

According to the quadratic trend-surface isobase map, the Main Postglacial Shoreline at Peinchorran is predicted to lie at *circa* 8mOD (Firth *et al.*, 1993) which appears to lie *circa* 4m too high when compared to the field evidence at Peinchorran. At Talisker Bay, the Main Postglacial shoreline is predicted to lie at 6-7mOD, *circa* 8m too high for the field evidence, although it is likely that the formation of the barrier at the site has confused the pattern of isostatic uplift. At Ardmore Bay, the Main Postglacial Shoreline is predicted to lie at 4mOD which also appears to be in error as no marine signal was found above an altitude of 3.34mOD. Shennan *et al.* (1995a) also found that the isobase maps for Main Postglacial Shoreline predicted it to lie approximately 2m higher than field data revealed and when the indicative meanings of the features are taken into account, Shennan *et al.* (1995a) report that the discrepancy increases. The isobase map for the Main Postglacial Shoreline, therefore, appears to be in error for this area of Scotland, although the trend of the isobases appears to be correct. This is partly due to the paucity of data points available when the maps where constructed but primarily because the altitudes of a range of features with different indicative meanings, including gravel terraces and carse deposits, were used to construct the maps (Firth *et al.*, 1993). As the trend of the isobases appears to be correct for Skye, it is likely that erosion of the deposits representing the Main Postglacial Transgression at Point of Sleat has occurred.

It is difficult to assess the validity of the model of Lambeck (1991) for 6000 BP as no dated index points have been directly established for this time. Lambeck's (1991) model predicts mean sea levels around Skye at 6000 BP to have been at approximately 1mOD around Skye. When related to a reference level of mean high water mark of spring tides, *i.e.* adding +1.65m (Admiralty Tide Tables, 1996), the sea surface is predicted to lie at an altitude that is too low for Inver Aulavaig, where relative sea level is recorded at an altitude of greater than 5.10mOD until 5440±50 BP.

9.12 Middle-late Holocene relative sea level changes

From 5440±50 BP until 4220±60 BP, no relative sea level changes are recorded from the five sites studied on Skye, although in both boreholes 36 and 3a at Inver Aulavaig, a small amount of saline influence is recorded until 3280±60 BP (relative sea level index point 11). This is thought to represent overwash into the basin. This implies that the altitude of relative sea level here remained near to 5.10mOD from 5440±50 BP until 3280±60 BP or that some saline waters remained trapped in the basin in the vicinity of the boreholes. Alternatively, increased storminess during this time may have allowed saline waters to be intermittently washed into the basin, allowing the limited growth of marine diatoms. However, isostatic rebound of the land again became the dominant component after *circa* 5400 BP.

At 4220±60 BP, a positive marine tendency is recorded at Peinchorran (relative sea level index point 8) (Figures 9.1-9.4). Relative sea level attained an altitude of 4.83mOD as sea level rise, once more, outpaced that of isostatic rebound of the land. At Peinchorran, this transgression reached an altitude of 4.90mOD (index point 9) by 3970±140 BP (Figures 9.1 and 9.2). A late Holocene rise in relative sea level is also recorded at Point of Sleat beginning at 3830±60 BP when the basin became connected to the sea (relative sea level index point 10) and regressing at 2850±100 BP below an altitude of 4.13mOD (relative sea level index point 13) when the basin became isolated (Figures 9.1-9.4). At Inver Aulavaig, a late Holocene rise in relative sea level is also implied at 3160±40 BP (relative sea level index point 12) when relative sea level attained an altitude greater than 5.10mOD (Figures 9.1-9.4).

The late Holocene transgression attained an altitude of at least 4.13mOD at Point of Sleat, probably between 5.10-6.01mOD at Inver Aulavaig and 4.90mOD at Peinchorran. It is possible that the transgression recorded at the three sites relates to the same marine episode and that the diachroneity, of this episode is represented. Alternatively, the periods of high relative sea level in the late Holocene may relate to different fluctuations of relative sea level. This has been recorded in other areas of Scotland, particularly in peripheral areas where the isostatic recovery of the land was less than that of sea level rise (*e.g.* Dawson and Smith, 1997). These are dated at 4760±60 BP in the Philorth valley (Smith *et al.*, 1982), at *circa* 4400 BP and *circa* 1200 BP in the Wick River valley (Dawson and Smith, 1997) and at *circa* 5300 BP, *circa* 4700 BP and *circa* 3400 BP in Morecambe Bay (Zong and Tooley, 1996). It appears that an increased number of transgressions are recorded with distance away from the uplift centre, hence in the Wick River valley and Morecambe Bay, peripheral locations, two and three transgressions are recorded, respectively. At Inver Aulavaig, the recording of saline influences in borehole 36 from 8850±170 BP until 3280±60 BP may be as a result of the recording of several fluctuations that all attained an altitude of 5.10mOD and are, therefore, recorded in one sequence.

Late Holocene transgressions have not been recorded in this area of Scotland previously. In none of the work in the Arisaig area has a late Holocene transgression been identified (Shennan *et al.*, 1993; 1994; 1995a; 1995b). Shennan *et al.* (1995b) record a continuous fall in relative sea level from 6.65 mOD at 3940±45 BP at Kentra Moss and 6.27mOD at 4010±50 BP at Loch nan Eala to 3.87mOD at 1080±40 BP at Kentra Moss. Twelve relative sea level index points in between these dates each represent a negative marine tendency at a progressively lower altitude. This continuous fall in relative sea level could be as a result of its situation closer to the centre of isostatic uplift relative to Skye. Relative sea levels higher than present are implied at Point of Sleat and Inver Aulavaig until *circa* 3000 BP. This has implications for the settlement of man in these areas and the preservation of the archaeological record and also for the rate of geomorphological processes.

9.13 Implications for the late Holocene isobase map

A quadratic trend surface isobase map for a late Holocene shoreline has been constructed by Firth *et al.* (1993) but the altitudes predicted for the shoreline appear to be greatly in error. An altitude of *circa* 11mOD is predicted for the shoreline at Peinchorran and *circa* 10mOD at Inver Aulavaig and Point of Sleat. The inaccuracies of the isobase map for the late Holocene shoreline are probably almost entirely due to the lack of data for this shoreline on the west coast of Scotland which would introduce errors in altitude and age for this shoreline.

9.14 Barrier formation

At four of the sites studied, the presence of barriers is recorded. It seems probable that their formation is linked to relative sea level changes that would have either moved sediment onshore or increased the base height of wave attack causing increased erosion and, therefore, supplying sediment in that way. There is no evidence at Point of Sleat for the time of barrier formation. At Talisker Bay, Peinchorran and Ardmore Bay, it is possible that the formation of the barriers is related to the Main Postglacial Transgression. At Talisker Bay, at least one of the barriers, probably the higher is thought to have formed during the first part of the Main Postglacial Transgression when the rate of relative sea level rise is considered to have been fastest (*e.g.* Smith *et al.*, 1985; Zong and Tooley, 1996). Several workers report that the most likely preservation of marine facies occurs under a rapidly rising relative sea level (Belknap and Kraft, 1981; Davis and Clifton, 1987). If barrier formation at Talisker Bay did occur during the Main Postglacial Transgression, it is possible that the dates of 7790±100 BP and 7250±150 BP constrain its formation. The earliest date would represent the onshore movement of sediment when some saline influence was recorded and the later date would represent the stabilisation of the barrier and the closing of the site to farther marine penetration. Additionally, if the dates do constrain the barrier formation, it is likely that they also represent the time of fastest rate of relative sea level rise associated with the Main Postglacial Trangression.

The formation of this barrier at Talisker Bay is believed to have prevented farther penetration of the area by marine influences with the sediment probably derived from the offshore zone (*e.g.* Boyd and Penland, 1984) (Figure 3.4). The other barriers at Talisker Bay may subsequently have formed as relative sea level fell causing reworking of the middle of the barrier(s) or they may have formed during times of increased storminess as suggested by the short-lived peaks of marine diatoms in the assemblages (LDAZ 3 Tc) (Figure 6.6).

At Peinchorran and Ardmore Bay, two barriers have formed that in each case have formed a double tombolo. At Peinchorran, it is unclear when the barriers formed but three possibilities exist. They may have formed during the Main Postglacial Transgression but allowed the penetration of marine waters at the site. In this case it is probable that the barriers at this site also formed during the early part of the transgression when the rate of sea level rise was greatest. This may have occurred prior to 7980±70 BP when it is thought that the Main Postglacial Transgression had begun in this area. Alternatively, the barriers at Peinchorran may have formed during the late Holocene rise in relative sea level as sediment was again brought onshore. The third possibility is that the barriers formed during the Main Postglacial Transgression, were subsequently destroyed and were reformed again during the later rise in relative sea level.

9.15 Comparison of isolation basin and barrier sites for the recording of relative sea level changes

Contrasts in the preservation of the relative sea level record in isolation and back-barrier environments have been identified from the present investigation. Each methodology has disadvantages which make interpretations of relative sea level changes problematic. Ideally these deficiencies should be recognised and quantified to assess the comparability of the relative sea level index points, although this is often impossible. The marine deposits behind a barrier are thought to relate to a palaeo-saltings surface which lies at approximately mean high water mark of spring tides, although this may not always be accurate and could represent lagoonal conditions. Factors such as tidal range would influence the environment. In an isolation basin environment, isolation is thought to occur at between mean high water mark of spring tides and highest astronomical tides, although with a large freshwater input to the basin the indicative range is thought to increase to between high water mark of neap tides and highest astronomical tides. Additionally, in isolation basin studies it is unclear at which point during isolation marine influence decreases to a level not capable of supporting marine diatom taxa. Shennan *et al.* (1995a) suggest that possibly daily inundation of marine waters is required. Tidal range will also have an effect on this, with those areas with smaller tidal ranges registering isolation and connection of the basin faster than in those areas with meso-tidal or greater tidal ranges.

If a continuous sequence of sediment is obtained from behind a barrier and the relationship of the barrier to the sediments is known, it is possible to construct a relative sea level graph. This relationship, however, is extremely difficult to establish as shown in the present study. However, in an isolation basin, a relative sea level graph cannot be constructed unless a suite of basins is obtained with their rock thresholds lying at very closely spaced altitudes. This is because isolation basins only record discrete changes in relative sea level as relative sea level either transgresses or regresses above the height of the rock sill.

The greatest problem with barrier environments is that they are very site-specific making it difficult to generalise about changes that may have occurred. It is difficult to establish how the presence of the barrier or changes in its morphology have affected patterns of sedimentation. It is possible, as suggested in the sequence at Talisker Bay, that the formation of the barrier prevents farther inundation of the sea and, therefore, provides only a local, site-specific regressive signature in the relative sea level record. In contrast at Peinchorran, it is proposed that barrier formation had only minimal effect on the sedimentation behind the barrier and subsequent penetration of the area by the sea was not affected. The rate of relative sea level change seems to be important in the establishment of barriers and may account for the differences in the preservation of the relative sea level record at the sites. Dating of barrier formation would obviously aid the interpretation of the back-barrier sediments at the sites considerably and would allow an assessment of which sediments may have been affected by the barrier. This is often extremely difficult to establish especially where the calibre of the sediment in the barrier is large. Boreholes cannot be taken through the barrier to establish the underlying sediment and, therefore, provide a maximum age for barrier formation. The size of the sediment in the barrier is also important in determining whether percolation of marine waters may have affected the back-barrier sediments.

Other difficulties involved with barriers sites include the variation in the crest height of the barrier which is important in determining whether overwash may have affected the back-barrier environment either in times of storms or during relative sea level rises. This must be considered when interpreting marine signals in the back-barrier environment, although it is extremely difficult to establish how high the crest of the barrier was above relative sea level when it formed. Breaches in barriers are common allowing the drainage of freshwater from the site and possibly decreasing the altitude at which marine penetration of the back-barrier environment can occur. This does not, however, appear to have occurred at Talisker Bay. Artificially high groundwater tables can form behind barriers and cause organic-rich sedimentation to occur above or keep pace with relative sea level rise, as suggested at the site of Peinchorran during the Main Postglacial.

It appears, from the results of this study, that greater preservation of marine sediments occurred in isolation basin sites because protection from erosion was provided. Thus, the Lateglacial marine sediments are only preserved at Inver Aulavaig and Point of Sleat where isolation basins exist. However, an exception to this is thought to occur when the basin becomes full of sediment. Subsequent episodes of relative sea level change may not be registered at all or, as suggested at Point of Sleat, erosion of the previously deposited sediment may need to occur to allow marine sediments of any later transgression to be deposited. At barrier sites, even if Lateglacial deposits were deposited, they are likely to have been eroded by subsequent events.

In the central western area of Scotland, the topography of the landscape seems ideally suited to the preservation of sediments within bedrock hollows and this is especially useful in an area deficient in extensive estuarine sediments. Shennan *et al.*, (1993; 1994; 1995a; 1996) have used the isolation basin methodology very successfully and its use has also been demonstrated in this research. The use of diatom analysis very clearly identifies the diatomological isolation and connection contacts of the basin. The transition from an increase in aquatics and spores (LPAZ 4 IAd) (Figure 4.10), representing an increase in the groundwater table, followed by an increase in mesohalobous diatom species (LDAZ 2 IAb) (Figure 4.13) as the water table becomes more saline and overwash into the basin is recorded and finally to marine conditions in the basin is often identified and is clearly seen in the sequence at Inver Aulavaig (borehole 36). The transition from marine conditions to brackish and finally to fresh as isolation occurs can also be identified accurately.

Some deficiencies in the method, however, are also present. Erosion of the rock sill may have occurred since the changes in relative sea level took place and, therefore, the altitude at which the changes occurred would be inaccurate. The size of the basin, its depth and the freshwater input are important to the record of relative sea level changes preserved. This is demonstrated at Inver Aulavaig where the borehole (borehole 3a) taken from a deeper area situated closer to the rock sill and near the stream recorded more sensitive fluctuations in relative sea level than borehole 36 which was situated some distance from the rock sill and the stream and was from a shallower area of the basin. A major drawback with this method is that the maximum altitude obtained by the transgression cannot be established unless a suite of basins, with the altitudes of the rock sills at closely spaced intervals, can be used. Additionally, the age of the start of a transgression can never be accuarately established as relative sea level has to attain the altitude of the rock sill before it can be registered in the basin. This means that relative sea level changes are always recorded of shorter duration than they actually occur.

9.2 Summary of the advantages and disadvantages of using isolation basins and back-barrier environments for the investigation of relative sea level changes

Isolation basins	**Barrier sites**
and the relative sea level record	
It is unclear how the size of and freshwater input to a basin affects the reference water level increasing its range from MHWOST-Highest Astronomical Tides to MHWONT-Highest Astronomical Tides.	It is unclear whether the reference water level of marine sediments behind barriers always relates to a palaeo-saltings surface, *i.e.* MHWOST or whether it is dependent on tidal range.
A suite of basins is required to produce a relative sea level graph as only discrete changes are recorded. The maximum altitude of the transgression cannot be determined accurately.	A relative sea level graph may be produced as continuous changes are recorded, providing the relationship of the barrier to the sediments behind it, is established.
It is unclear how tidal range may affect the level at which isolation and connection of the basin to the sea occurs.	The calibre of the sediments in the barrier is important in determining the amount of percolation of marine waters to the back-barrier environment.
Slower rates of isostatic recovery record smaller scale transgressions but the rate of relative sea level change does not affect the preservation of the sediments.	The rate of relative sea level changes is important in the lifecycle of barriers and, therefore, the preservation of the relative sea level record.
Erosion of the rock sill may have occurred.	The formation of a barrier or changes in its morphology may cause marine penetration of the site to cease and, therefore, give a false relative sea level signature.
Preservation of the sediments is enhanced as protection is provided against erosion	All barriers are very site-specific making any record obtained from back-barrier sediments relevant only to the local area.
A clear, easy to interpret sequence of freshwater-brackish-marine-brackish-freshwater assemblages develop.	An artificially high groundwater table may occur behind a barrier giving a false signature of relative sea level changes and making it hard to relate peat growth to the tidal cycle.
If the basin is full of sediment, it cannot register farther changes in relative sea level.	Establishing the date of barrier formation is extremely difficult.
The size of the basin and its depth are important to the accuracy of the marine record.	
The change in relative sea level is always recorded of shorter duration than it occurred.	

9.16 Conclusions

Several episodes of relative sea levels higher than present, have been identified on the Isle of Skye. The earliest is recorded from the isolation basin at Inver Aulavaig and is thought to be as a result of the renewed isostatic depression experienced during the Wester Ross Readvance. The second Late Devensian trangression is recorded at Point of Sleat and may have occurred as a result of the renewed isostatic depression of the land that accompanied the Loch Lomond Readvance. The second period of relative sea level change is recorded from *circa* 8900 BP until *circa* 5400 BP and represents the Main Postglacial Transgression on Skye. It is possible that barrier formation at four of the sites occurred during this transgression, probably during the early stages when the rate of relative sea level rise was fastest. Following regression of the sea, a period of low relative sea level is recorded until *circa* 4200 BP when a late Holocene rise in relative sea level took place at the three most southerly sites between *circa* 4220 BP and *circa* 2900 BP. It is possible that the transgressions represent several fluctuations due to the peripherality of the sites in relation to the centre of isostatic uplift.

The quadratic trend-surface isobase map of Firth *et al.* (1993) for the Main Lateglacial Shoreline appears to fit broadly in age and altitude with the data obtained for Skye but the model of Lambeck (1993b) for 10500 BP, from the field data, would appear to need modification. This is possibly as a result of ice build up on Skye associated with the Loch Lomond Readvance and renewed isostatic depression that accompanied it. The isobase map for the Main Postglacial Shoreline appears to need modification as the predicted contours lie approximately 4m higher than the altitude of the marine deposits representing this shoreline were recorded. It is difficult to fully test the model of Lambeck (1991) for 6000 BP. The late Holocene shoreline isobase map of Firth *et al.* (1993) appears to need a major readjustment.

The use of isolation basins in this research has been particularly recognised and combined with diatom analysis appears to accurately identify changes in relative sea level. The protected environment of a basin allowed the preservation of Lateglacial marine sediments which was very useful. The barrier sites appeared more problematic to interpret and this is primarily due to their site-specific nature which makes the relative sea level record only of local relevance.

Chapter 10.0 Late Devensian and Holocene vegetation changes on the Isle of Skye

10.1 Introduction

This chapter summarises vegetational changes that have been reconstructed in the present study, from the Late Devensian to the present day. A chronological approach is adopted and comparisons are made between sites and also with other published pollen data from Skye.

10.2 Late Devensian vegetational changes

Lateglacial vegetation assemblages have been recorded from two sites in this study, namely Inver Aulavaig (borehole 36) and Point of Sleat (Figures 4.10 and 7.6). At the base of both of these profiles (LPAZ 1 IAa and LPAZ 1 PSa), pollen could not be extracted suggesting very limited vegetation development following deglaciation. The minerogenic nature of the sediments and the fast sedimentation rates may also have contributed to the sparsity of the pollen. At other Lateglacial sites in Skye, very sparse pollen amounts have also been recorded. Thus, Birks (1973) noted that before *circa* 12500 BP at Loch Cill Chroisd (see Figure 10.1 for location of all pollen sites mentioned in the text), pollen could not be counted and Fossitt (1994) reports that pioneer communities are generally pollen-poor as the vegetation cover is sparse. At Lochan Doilead, on the Morar Peninsula, polleniferous sedimentation did not begin until *circa* 12200 BP (Williams, 1977).

Low arboreal pollen frequencies suggest that limited woodland development occurred at both sites in the basal horizons and it is possible that this component of the pollen spectra was derived from long-distance transport, reflecting a more regional component. Inadequate soil cover has been suggested as a contributory factor to the tree record during the Lateglacial (Fossitt, 1994). *Betula* pollen, recorded at Inver Aulavaig, may indicate some birch scrub development at the site, but *Pinus* pollen, with its winged pollen grain, is particularly considered to be of long-distance provenance (Walker and Lowe, 1990) and the low frequencies at both sites suggest that it never really became established (Bennett, 1984).

At Point of Sleat, an increase in *Corylus avellana*-type pollen occurs within the Lateglacial and at Inver Aulavaig, low frequencies of this pollen grain are recorded. This is thought to represent hazel woodland or scrub development at the site. The occurrence of *C. avellana* -type pollen is considerably earlier than predicted by Birks' (1989) isochrone maps for the rational rise of *C. avellena.* It is also earlier than it has been observed at most other sites on Skye, although at Slochd Dubh the presence of *Corylus* is recorded from early in the Late Devensian (Walther, 1984). It is possible that the sites in the south of Skye were in close proximity to a refugium and this allowed early colonisation of the species (Deacon, 1974; Huntley, 1993) or that the pollen actually represents *Myrica* pollen and bog myrtle grew locally at these three sites. Huntley (1993) considers the possibility of expansion of *Corylus* northwards during the Lateglacial Interstadial unlikely as it is a thermophilous species, even though it has a greater climatic tolerance than other tree taxa, *e.g.* oak and elm. Furthermore, no *Corylus* macrofossils have been recorded in Lateglacial sediments in northern Europe, although there is a possibility that hazel stands survived in Atlantic regions of north-west Europe during the Lateglacial Interstadial. In addition, hazel development may have benefitted from lack of competition from other trees at the site. *Salix* pollen is also noted at low frequencies at Inver Aulaviag and Point of Sleat and Fossitt (1994) noted that *Salix* was a primary coloniser in western Donegal on unstable mineral soils, such as those which are likely to have existed at both sites during the Lateglacial. The *Salix* pollen recorded may represent *Salix herbacea* and, therefore, an arctic-alpine environment, suggesting that cold climatic conditions existed when the basal sediments at Inver Aulavaig and Point of Sleat were deposited.

The sequences at Loch Ashik and Slochd Dubh also show limited arboreal development during the Lateglacial with some *Betula*, increasing *Juniperus* and decreasing *Salix* pollen recorded (Walther, 1984; Walker and Lowe, 1987; Walker *et al.*, 1988; Walker and Lowe, 1990). At Loch Cill Chroisd and Lochan Coir' a' Ghobhainn, restricted *Betula* pollen is recorded and a peak is recorded in *Juniperus* pollen, indicating limited birch and juniper scrub development (Birks, 1973; Walther, 1984; Walker and Lowe, 1990). No *Juniperus* pollen is recorded at either Inver Aulavaig or Point of Sleat and this could be due to a combination of exposure and wet soils, which are not favoured by juniper (Birks, 1973). Differences emerge between the sites due to exposure to onshore winds and aspect and these are reflected in the degree to which juniper growth and tree development occurred at a site. Sites with protection provided by the Cuillins tend to record increased juniper scrub development during the Lateglacial. Walker *et al.* (1988) report that sites to the north-east and south-west of the Cuillins record stronger development of woody vegetation and a richer aquatic flora, as a result of the increased shelter from storms. The *Betula* pollen recorded in all profiles at this time is likely to have grown as birch scrub rather than woodland, although it is thought that at Loch Meodal birch woodland became established (Williams, 1977). It is possible that the *Betula* pollen represents *Betula nana* and indicates dwarf shrub development at the sites.

At Inver Aulavaig and Point of Sleat, an open vegetation is initially recorded at the base of the assemblages (LPAZ 1 IAa and LPAZ 1 PSa). It is dominated by Cyperaceae with some Poaceae pollen, indicating that open ground communities existed, characterised by grasses and sedges and suggesting a tundra-type vegetation. Development of crowberry and ling heath is suggested at both sites by the pollen of *Empetrum* and to a lesser extent *Calluna vulgaris* and Ericaceae. *Empetrum* was a common species during the Lateglacial Interstadial and has been recorded at Loch Cill Chroisd, Slochd Dubh, Loch Ashik and Lochan Coir' a' Ghobhainn as well as on Mull (Birks, 1973; Walther, 1984; Lowe and Walker, 1986; Walker *et al.*, 1988; Walker and Lowe, 1990). Fossitt (1994) comments that the role of *Empetrum* in successional sequences varies in the Lateglacial. At Inver Aulavaig, the *Empetrum* grains showed signs of exine damage, suggesting secondary derivation possibly due to the inwashing of soils as they became unstable due to the climatic deterioration at the end of the Lateglacial and during the Loch Lomond Stadial. Fossitt (1994) reports that sites in western Donegal record no reworking of *Empetrum* pollen grains and sites in Skye generally record much higher frequencies as shown at Loch Ashik and Loch Cill Chroisd (Birks, 1973; Walker *et al.*, 1988; Walker and Lowe, 1990). *Empetrum nigrum* is considered to be a northern-montane pioneer species (Birks, 1973) and the higher frequencies at Inver Aulavaig compared to at Point of Sleat, may be due to its development on the surrounding slopes.

The increase in *Cryptogramma crispa* spores at Inver Aulavaig and the presence of these spores at Point of Sleat suggests that a boulder scree landscape was present at these sites and possibly that there were partially snow-covered areas locally. *C. crispa* represents an arctic-alpine element in the flora (Birks, 1973) and at Loch Cill Chroisd, Birks (1973) identified this species before 12500 BP. The presence of Chenopodiaceae, Asteroideae, *Plantago* species and *Rumex acetosa/acetosella* pollen at Inver Aulavaig is thought to be indicative of disturbed ground and probably formed part of a low alpine and tundra scrub (Walker *et al.*, 1994). The soils during the Lateglacial Interstadial are likely to have been extremely thin and possessed a high mineral content (Moore, 1968; Birks, 1973) and the species recorded reflect this. *R. acetosa/acetosella* pollen is also noted at Point of Sleat and *Rumex*, a pioneering, tall herb, is a common component of the pollen spectra of Lateglacial age, being recorded at high frequencies at Loch Ashik (Walker *et al.*, 1988; Walker and Lowe, 1990) and at Loch Cill Chroisd, Sloch Dubh and Lochan Coir' a' Ghobhainn (Birks, 1973; Walther, 1984; Walker and Lowe, 1990).

The Lateglacial period in other published pollen diagrams from Skye shows similar patterns to that at Inver Aulavaig and Point of Sleat and records changes from open-habitat vegetation to dwarf shrub heath and grassland (Birks, 1973; Williams, 1977; Birks and

Williams, 1983; Walther, 1984; Walker *et al.*, 1988; Walker and Lowe, 1990). Common to all sites are increasing *Empetrum* values, *Salix* pollen, often declining, low *Betula* frequencies, domination by Poaceae and Cyperaceae pollen and the presence of *Rumex* pollen at high frequencies. However, at Slochd Dubh, Loch Cill Chroisd and Lochan Coir' a' Ghobhainn, *Huperzia selago* forms a component of the assemblage (Birks, 1973; Walther, 1984; Walker and Lowe, 1990). This montane heath component favours solifluction-affected soils (Williams, 1977) which were unlikely to have existed at Inver Aulavaig or Point of Sleat. Also at Slochd Dubh, *Artemisia* pollen is present and this is often quoted as a pioneering genus of Lateglacial environments (Walker and Lowe, 1990; Walker *et al.*, 1994). However, *Artemisia* has not been recorded at either Inver Aulavaig or Point of Sleat and this may be due to intermittent or prolonged snow cover in this area. This is supported by the presence of *C. crispa* spores and the relatively suppressed frequencies of *Rumex* when compared to other profiles (Walker and Lowe, 1991). It is probable that the pollen profile for Inver Aulavaig (borehole 36) extends farther back into the Lateglacial than the Point of Sleat sequence. The tundra-type conditions associated with the transition from the Lateglacial Interstadial to the Loch Lomond Stadial and through the stadial, however, are common to both sequences.

10.3 Early Holocene vegetational changes (10000-7000 BP)

The transition from the Lateglacial to the Holocene is shown most clearly in the Inver Aulavaig profile (LPAZ 2 IAb). It is marked by an increase in tree taxa characterised by *Betula* and *Pinus* pollen and also by an increase in *C. avellana*-type pollen. The large increase in *Myriophyllum alterniflorum* and *Myriophyllum verticillatum/spicatum* recorded at Inver Aulavaig, is a characteristic often quoted as marking the transition from the Lateglacial to the Holocene as, for example, in the Loch Ashik profile (Walker *et al.*, 1988; Walker and Lowe, 1990) and could be associated with wetter conditions as the climate improved and the temperature became warmer. Lowe (1993) suggests the decline in *Myriophyllum* species, seen in LPAZ 3 IAc, reflects reduced water levels in the lakes of Skye and Mull possibly responding to warmer, drier conditions in the early Holocene.

At Inver Aulavaig, a date of 10110±140 BP records the increase in *C. avellana*-type pollen, suggesting development of hazel scrub or woodland at the site (LPAZ 3 IAc). At Loch Ashik, a date of 10090±90 BP has been obtained for the increase in *Corylus* (Walker *et al.*, 1988; Walker and Lowe, 1990). At Loch Meodal, the *Corylus* rise occurs at 9610±150 BP (Birks, 1973; Williams, 1977), at Loch Cleat at 9760±150 BP (Williams, 1977; Birks and Williams, 1983) and at Loch Cill Chroisd at 9655±155 BP (Birks, 1973). It is thought that *C. avellana* colonised from the Irish Sea and became established in the south of Ireland and on the west coast of Wales and Scotland prior to 9500 BP (Birks, 1989). The areas south and east of the Cuillin mountain range on Skye were, therefore, colonised considerably earlier than the rest of the island. At Ardmore Bay, an increase in *C. avellana*-type pollen is recorded and, although, this has not been dated directly, it is known to have occurred after 9980±110 BP (LPAZ 1 ABa) (Figure 8.5). Birks and Williams (1983) noted that by 9700 BP, at Loch Ashik, hazel was established. Huntley (1993) suggests that the early establishment of hazel during the early Holocene resulted from suitable climatic conditions. Climate during the early Holocene was characterised by warm summer conditions, the occurrence of summer water deficits and continued cold winters (Huntley, 1993). These conditions would have excluded other thermophilous taxa when compared to hazel. Smith (1970) suggests that fires could also aid the establishment of *Corylus* as it is considered to be fire-tolerant being able to resprout from the rootstock. Rackham (1980), however, has questioned this premise. Huntley (1993) suggested that the climate of the early Holocene, combined with the increase in solar radiation, may have been conducive to the increase in natural fires and they could have excluded other species to the advantage of hazel at Inver Aulavaig.

Betula values also increase at Inver Aulavaig after 10110±140 BP representing the development of birch scrub and woodland. Birks' (1989) isochrone map for *Betula* predicts that between 9950 BP and 9750 BP, the presence of birch increased rapidly on Skye. At Inver Aulavaig, birch appears to have been present prior to 10110±140 BP, but did not increase until after this date. This agrees well with Birks' (1989) rational rise. At Peinchorran and Talisker Bay, *C. avellana*-type and *Betula* pollen dominate the base of the assemblages, indicating that some hazel and birch woodland or scrub development occurred at these sites during the early Holocene (LPAZ 1 Ta and LPAZ 1 Pa) (Figures 6.5 and 5.6). The frequencies, however, were not of the magnitude of those at Loch Ashik, where high frequencies were maintained until *circa* 6300 BP (Williams, 1977). At all sites studied, the values of *Betula* pollen are suppressed compared to other pollen diagrams possibly reflecting the base-rich nature of the sites (Williams, 1977). At Loch Meodal, *Betula* pollen accounts for over 40% of total land pollen during the early Holocene and at Loch Cleat and Loch Ashik, between 25% and 30% of total land pollen (Williams, 1977; Birks and Williams, 1983). Local conditions or competition from other tree taxa, therefore, did not allow birch dominance and this could be related to the exposure of coastal locations compared to those inland.

Low frequencies of *Fraxinus*, *Pinus* and *Quercus* pollen are recorded at Inver Aulavaig suggesting increased development of mixed woodland during the early Holocene (LPAZ 4 IAd). At Point of Sleat and Ardmore Bay, during this period, the frequencies of tree taxa are very suppressed possibly as a result of exposure and aspect, suggesting perhaps regional, but not local development, of hazel-dominated mixed woodland (LPAZ 2 PSb and LPAZ 2 ABa). Low frequencies of *Pinus*, *Quercus* and *Ulmus* pollen recorded at Peinchorran (LPAZ 1 Pa), indicate that some mixed woodland development occurred and their presence is characteristic of early Holocene woodland (Birks, 1973, Williams, 1977; Birks and Williams, 1983; Walker *et al.*, 1988; Walker and Lowe, 1990). At Talisker Bay, the basal zone (LPAZ 1 Ta) records low frequencies of *Alnus*, *Pinus*, *Quercus* and *Ulmus* pollen representing the development of mixed woodland at the site. Birks (1973) claims that woodland development was virtually absent from Skye, although Edwards and Berridge (1994) suggest that woodland occurred in sheltered locations in the west of Scotland. From this study, it appears that the Isle of Skye provided protected locations for the development of woodland, although it may not have been extensive. This is also suggested at Loch Ashik, Loch Meodal and Loch Cleat, where mixed woodland developed during the early Holocene (Williams, 1977, Birks and Williams, 1983). At Loch Doilead, Loch Ashik, Loch Mealt, Loch Cill Chroisd and at 9990±130 BP at Loch Cleat, a peak in *Juniperus* pollen is recorded, suggesting development of juniper scrub (Birks, 1973; Williams, 1977; Birks and Williams, 1983). This is not recorded at any site in this study and may suggest a preference by juniper for sheltered inland sites.

Birks' (1989) Holocene isochrone maps suggest that Skye became colonised by *Ulmus* at between 8500 BP and 8000 BP. *Ulmus* never formed a major arboreal component at the sites studied, although from 8550±80 BP there is a continuous record in the pollen profile at Talisker Bay, suggesting good agreement with the isochrone map. *Quercus* is estimated to have arrived at between 6500 BP and 6000 BP which appears to be later than recorded at Talisker Bay, where it occurred between 8550±80 BP and 7790±100 BP. At Loch Ashik, Williams (1977) noted that *Ulmus* and *Quercus* pollen were present at low frequencies after 9000 BP, also suggesting the rational limits may be too late for Skye. At Talisker Bay, *Pinus* pollen is present in the profile from 8550±80 BP, although the rational limit determined by Birks (1989) does not occur until after 5000 BP for this area of Skye. At Talisker Bay, Inver Aulavaig and Peinchorran, Pteropsida spores are recorded, suggesting ferns formed the understorey component of the woodlands during the early-middle Holocene and at Inver Aulavaig and Talisker Bay, *Polypodium* spores are also recorded. These spores have also been recorded at Loch Cleat and Loch Ashik, where they are also thought to have formed the understorey (Williams, 1977; Birks and Williams, 1983).

It does not appear that the woodland canopy was completely closed, at any of the sites studied, in contrast with Loch Meodal where the development of extensive birch woodland is reported (Williams, 1977). Maguire (1985) suggests that arboreal pollen values of less than 20% indicate an open woodland and values of greater than 45% indicate a forest. At each site a large percentage of Cyperaceae pollen is recorded with subordinate Poaceae pollen. This suggests that most of the landscape at the site was open and dominated by sedge and grass species. The exception to this is Peinchorran where hazel colonisation appears to have been considerably more extensive during the early Holocene. At Talisker Bay, the environment was extremely herb-rich while at Ardmore Bay and Point of Sleat, the vegetation was restricted in species, probably reflecting a variety of factors including geology, soil, aspect and exposure. At each site, limited dwarf shrub heath development is suggested by the low frequencies of *C. vulgaris* pollen.

10.4 Middle Holocene vegetational changes (7000-4000 BP)

A marked increase in *Alnus* pollen has been recorded at three of the sites studied. At Talisker Bay, *Alnus* expansion has been dated at 6630±70 BP (LPAZ 3Tc) and at Peinchorran at 6600±70 BP (LPAZ 2 Pb). At Inver Aulavaig, the *Alnus* rise was not dated directly, but by extrapolating between the dates obtained at the site and assuming constant sedimentation rate, the *Alnus* expansion is thought to have occurred at *circa* 6700 BP (LPAZ 5 IAe). Birks' (1989) isochrone map for *Alnus glutinosa* predicts that arrival on Skye occurred between 6500 BP and 6000 BP. *A. glutinosa* is thought to be a pioneer species capable of colonising a wide range of successional habitats and seems to have a preference for establishment at coastal locations, which could account for its early presence at the sites studied (Birks, 1989; Hirons and Edwards, 1990; Lowe, 1993). It also has an ability to withstand wet environments, often being associated with the Main Postglacial Transgression and is often present in the succession to acid fen or marsh (Bennett, 1990). *Alnus* would have colonised from the mainland (Birks, 1989) and sites in the north appear to have been colonised by *Alnus* approximately 200 years later. At Loch Ashik, the *Alnus* rise occurred at 6360±80 BP (Walker *et al.*, 1988; Walker and Lowe, 1990) at Loch Cleat at 6590±80 BP and at Loch Meodal at 6590±100 BP (Williams, 1977; Birks and Williams, 1983). The dates obtained in this study, therefore, agree well with those previously obtained for Skye. The *Alnus* rise is complicated because there is great intra-regional diversity in the establishment of alder in British pollen diagrams (Lowe, 1993). Birks and Williams (1983) state that *Alnus* often expands at the expense of *Salix* and *C. avellana*-type and this appears to have occurred at Peinchorran, Talisker Bay and Inver Aulavaig due to its longevity and competitive power (Birks, 1977). No *Salix* rise has been noted at any site prior to the *Alnus* rise as reported by Hirons and Edwards (1990) on the Isle of Rhum. *Alnus* is also reported to outcompete *Pinus* (Bennett, 1984) and this is noted at Talisker Bay and Inver Aulavaig although the frequencies of *Pinus* are low throughout these sequences.

During the middle Holocene, other vegetation consisted of hazel-dominated mixed woodland at Inver Aulavaig and Peinchorran with open ground communities dominated by grass and sedge species (LPAZ 5 IAe and LPAZ 2 Pb). At Talisker Bay (LPAZ 3 Tc), the presence of birch decreases as *Alnus* pollen increases and at Peinchorran, the frequencies of hazel decline which could be due to competition if they were growing locally. Pteropsida spores continued to form the understorey components to the woodlands.

At Inver Aulavaig, woodland represented by the pollen of *C. avellana*-type and *Betula*, but also with *Fraxinus*, *Pinus*, *Quercus* and *Ulmus* continued to be either present at the site or record the regional pollen component (LPAZ 5 IAe). Frequencies of Poaceae and Cyperaceae pollen are high in LPAZ 5 IAe representing an open grass/sedge landscape. A similar pattern is seen at Peinchorran (LPAZ 3 Pe). Some scrub development is represented by *C. avellana*-type pollen, but this decreases towards the top of the assemblage and arboreal percentages are recorded at low frequencies. It is possible that a middle Holocene *Ulmus* decline has been identified at Talisker Bay (LPAZ 5 Te), although this has not been recorded at any of the other sites, possibly due to the suppressed frequencies of this genus throughout the assemblages (*e.g.* Peglar, 1993; Peglar and Birks, 1993). The decline in elm is usually attributed to either disease or to human activites (Peglar, 1993). At Loch Meodal, the decline in elm and spread of grassland and heath has been dated at 5160±100 BP (Williams, 1977). At Loch Ashik, the decline in elm occurs at *circa* 4530 BP and at Loch Cleat, a distinct woodland clearance occurs at 5200 BP (Williams, 1977).

The vegetation pattern for Point of Sleat is broadly similar to other sites in Skye in the middle Holocene with some *Alnus* pollen present, but low arboreal taxa generally and decreasing amounts of Pteropsida, *Pteridium* and *Polypodium* spores, representing a decline in woodland and its associated understorey component (LPAZ 2 PsB). Cyperaceae pollen dominates indicating extensive reedswamp development. At Ardmore Bay conditions at the site became drier with no aquatics recorded (LPAZ 2ABb). An open environment dominated by grasses and sedges appears to have developed with virtually no trees present at the site.

At this time in northern Skye, grassland dominated with the occasional development of birch/hazel scrub and willow carr (Williams, 1977). At Loch Cleat, pine/birch woodlands were present with bog, heath and grassland (Williams, 1977; Birks and Williams, 1983) and birch/hazel/alder woodlands dominated at Loch Meodal with some grassland, heath and bog development (Birks and Williams, 1983). Williams (1977) found a peak in *Pinus* pollen at Loch Ashik and dated it to between 4150±70 BP and 3950±70 BP. Birks and Williams (1983) at the same site dated this to between 4600 BP and 3900 BP, but at no sites studied could an increase in *Pinus* be identified. It is possible that local conditions, such as wetness or salinity, may have prevented extensive growth of pine at these sites.

10.5 Late Holocene vegetational changes (4000 BP to present)

At Inver Aulavaig, Peinchorran, Talisker Bay and Ardmore Bay, an increase in *Sphagnum* spores and *C. vulgaris* pollen in the late Holocene suggests the development of ling heath representing acidification of the sites. This occurs at Inver Aulavaig after a date of 3280±60 BP (LPAZ 6 IAf), at Peinchorran, after 3970±140 BP (LPAZ 3 Pc) and at Talisker Bay after 3960±90 BP (LPAZ 1 TBa) (Figure 6.6). At Point of Sleat, *C. vulgaris* pollen and *Sphagnum* spores are recorded throughout suggesting that limited heath and peat development occurred throughout the Holocene, but it is impossible to identify an increase in acidic conditions during the late Holocene. A trend of acidification is also recorded at other sites around Skye and associated with the development of heathland at all sites studied is the presence of *Potentilla* and *Succisa pratensis,* which are common on acid heaths. At Loch Cleat, *Calluna* frequencies increase after 3100±60 BP (Birks and Williams, 1983), at Loch Ashik after 2700±60 BP, although frequencies before this time are high and fluctuating (Walker *et al.*, 1988; Walker and Lowe, 1990) and at Loch Meodal at 1930±50 BP (Williams, 1977; Birks and Williams, 1983). Acidification at *circa* 3000 BP, therefore, appears to have been a regional event.

At Talisker Bay, an end to the dominance in the pollen record of tree taxa is recorded in LPAZ 6 TBf. *Alnus* declines to a very low presence and it is envisaged that only isolated trees of this species remained at the site. *Corylus* would have formed small stands possibly within a scrub environment, but all other arboreal components of the pollen record are present at very low frequencies. In some Holocene pollen assemblages, for example at Loch Meodal (Williams, 1977), the persistence of tree taxa such as birch and alder are noted until the present day. At Loch Ashik, the decline in *Betula* and *A. glutinosa* pollen are noted after 2700±60 BP, but *C. avellana*-type pollen is recorded until the present day (Williams, 1977). An age of 2350±60 BP has been obtained for the decline in *Alnus* at Talisker Bay and it is shortly before this that the decline in other arboreal taxa are noted.

The decline of woodland during the latter half of the Holocene is extensively recorded from Scottish pollen sites (*e.g.* on Rhum (Hirons and Edwards, 1990); on South Uist (Bennett *et al.*, 1990); in south-west Scotland (Boyd and Dickson, 1986) and also in Ireland (Fossitt, 1994). In some diagrams, a decline in *Pinus* pollen after 4000 BP can be identified (Bennett, 1984), but this was not found at the sites studied. This is probably due to the low frequencies of pine recorded throughout the pollen assemblages, which may indicate that it was outcompeted at the sites studied or that they were too low-lying for this predominantly upland species to colonise (Bennett, 1984).

10.6 Anthropogenic effects on the vegetation

The influence of man on the vegetation is thought to be recorded at Inver Aulavaig, Peinchorran and Talisker Bay. At Inver Aulavaig, sometime between 7640±240 BP and 3280±80 BP (LPAZ 5 1Af), *Plantago lanceolata* is recorded continuously in the pollen record. This species combined with the presence of Ranunculaceae, *Plantago media/major*, Brassicaceae and Caryophyllaceae pollen could represent some anthropogenic activity at the site and possibly pastoral activities. The first appearance of *P. lanceolata* pollen at Peinchorran is recorded just before an age of 4220±60 BP and combined with the presence of Chenopodiaceae pollen is thought to relate to anthropogenic and agricultural activities at the site (LPAZ 2 Pb). At Talisker Bay, the persistence of *P. lanceolata* is recorded in the pollen record from LPAZ 4 Td until the top of the sequence. Coincident with this at Talisker Bay is a rising Poaceae curve indicating the expansion of grassland into areas previously occupied by woodland. The first recording of a possible cereal pollen grain with diameter >40μm and annulus >10μm is noted here and also at Peinchorran (LPAZ 5 Pa) probably represented arable agricultural practices at the sites.

Additionally, at Talisker Bay (LPAZ 4 Td) and Peinchorran (LPAZ 2 Pb) a decline in tree pollen, representing the loss of woodland, occurs, coincident with anthropogenic indicators in the pollen profile. A decline in *Quercus*, *Pinus* and *Ulmus* pollen is noted at Talisker Bay and a decline particularly in *Alnus* pollen is noted at Peinchorran. This suggests that some clearance of the landscape occurred at this time, as a result of human occupation of the area. At Peinchorran, conditions at the site appear to become drier with virtually no aquatics or spores recorded after the appearance of anthropogenic indicators in the pollen assemblages. This could be as a result of artificial drainage of the land. It is possible that the peak in Ranunculaceae pollen recorded in LPAZ 4 Pd could be a product of arable farming practices as some species of Ranunculaceae are particularly associated with cornfields and other farming environments, although they can also grow naturally on bogs and fens (Clapham *et al.*, 1987).

It is generally accepted that the first human impact on Skye occurred at *circa* 5000 BP (Birks, 1973; Williams, 1977; Birks and Williams, 1983; Lowe and Walker, 1991). At Loch Cleat, anthropogenic influences are noted after 4840±90 BP and at Loch Meodal at 5160±100 BP (Williams, 1977; Birks and Williams, 1983). The persistence of grassland communities are represented in the pollen assemblage of Loch Meodal and man would favour these areas for grazing animals rather than heathland. Regional differences appear at this time to have been accentuated due to anthropogenic activities. The fertile soils of the Trotternish Peninsula were heavily farmed, while in the east of Skye, bogs and heaths developed and in the south, grass and heathland were more common (Birks and Williams, 1983). At Point of Sleat and Ardmore Bay, it is possible that anthropogenic activity was never extensive due to their exposed locations which were inhospitable to human settlement. At Loch Ashik a virtual absence of occupation is implied by the very low frequencies obtained for *P. lanceolata*, grass and other herb pollen (Williams, 1977). This is thought to be as a result of poor soils and the development of heath and peat at the site which may also account for the lack of anthropogenic activity at Point of Sleat and Ardmore Bay.

10.7 Conclusions

The general patterns of vegetation change from the Late Devensian to the present day are broadly similar for all sites in Skye. During the Lateglacial, differences appear to have resulted between sites in the lee of the Cuillins, where more woodland and scrub could develop and those without protection from exposure, where tree frequencies were suppressed. Additionally, in some areas, snow cover may have remained for longer and this may have prevented the growth of certain genus, such as *Artemisia*, recorded at other sites. However, the development of crowberry-dominated heath is recorded at all sites during the Lateglacial. Signs of exine damage on the pollen grains of *Empetrum* are widespread, suggesting secondary derivation of this species, prior to the Loch Lomond Stadial.

Exposure is likely to have been greatest in coastal locations throughout the Holocene and this could explain the apparently limited extent of woodland development in the locations studied. Point of Sleat and Ardmore Bay appear to have been particularly affected by this. *Juniperus* pollen was not identified at any site studied. In the early Holocene the development of mixed woodland was dominated by hazel and birch although hazel may have formed scrub at some sites. The woodland canopy does not appear to have been closed and extensive areas of grass and sedge developed. Alder expansion is recorded at Inver Aulavaig, Talisker Bay and Point of Sleat during the middle Holocene and the dates obtained for this agree well with those previously obtained for Skye. The maximum extent of woodland at the sites studied was achieved during the middle Holocene. During the late Holocene, evidence of acidification of all sites is recorded with the expansion of heathland and *Sphagnum* peat development. Evidence for human activity is also present, although exposure may have restricted human occupation at Point of Sleat and Ardmore Bay.

Chapter 11.0 Conclusions

This chapter summarises the conclusions of the research. It has been divided into those findings related to the patterns of Late Devensian and Holocene relative sea level changes and those which concern the methodologies and techniques employed. Recommendations for future work in the light of these conclusions are outlined and an overview of the research concludes the chapter.

11.1 Relative sea level changes on the Isle of Skye

Three phases of relative sea level change have been identified on the Isle of Skye. The earliest phase of relative sea level higher than that of present day, has been identified within the Late Devensian at Point of Sleat and Inver Aulavaig. Both transgressions are thought to relate to readvances of ice that arrested isostatic recovery of the land, caused renewed isostatic depression and upon deglaciation allowed marine waters to penetrate the areas. At Inver Aulavaig, the transgression is thought to have occurred earlier and be correlated to the Wester Ross Readvance (Robinson and Ballantyne, 1979; Sissons and Dawson, 1981) and at Point of Sleat the transgression is thought to have been caused as a result of the Loch Lomond Readvance (Sutherland, 1984; Firth, 1986). The altitude of these transgressions is unknown although it attained an altitude of at least 4.13mOD at Point of Sleat and at least 5.10mOD at Inver Aulavaig. It is probable that high relative sea levels occurred until 10460±50 BP at Point of Sleat when regression of the sea is recorded.

The second episode of relative sea level higher than present is recorded in the Main Postglacial Transgression at three of the sites studied. It was recorded earliest at Inver Aulavaig at 8850±170 BP where it attained an altitude of at least 5.10mOD. The transgression began at Peinchorran prior to 7980±70 BP when relative sea level was recorded at an altitude of 4.49mOD and at Talisker Bay at 7790±100 BP, relative sea level had attained an altitude of -2.18mOD. At Point of Sleat, the Main Postglacial Transgression may be represented by barrier formation at the site, but it is likely that if any sediments were deposited in the basin they were subsequently eroded.

It is possible that the Main Postglacial Transgression was associated with barrier formation at three of the other sites studied; Peinchorran, Talisker Bay and Ardmore Bay. This probably occurred during the early stages of the transgression when the rate of relative sea level rise was fastest and at Talisker Bay, it is thought that barrier formation occurred between 7790±100 BP and 7250±150 BP. At Peinchorran, where a later rise in relative sea level is recorded, it is possible that barrier formation could also have occurred during the late Holocene. The effect of barrier formation on the relative sea level record at the areas studied appears to be very site-specific. At Talisker Bay, barrier formation is thought to have prevented farther inundation of the site by the sea while at Peinchorran, if the barriers formed during the Main Postglacial Transgression, the relative sea level record seems only to have been affected when the barriers were forming. The value of index points from barrier sites, however, is unclear and it is possible that only local changes in relative sea level are recorded.

The third episode of relative sea levels higher than present has been recorded at three of the sites studied. At Peinchorran this began at 4220±60 BP when it attained an altitude of 4.83mOD, at Inver Aulavaig it began at 3160±40 BP and attained a maximum altitude of between 5.1-6.01mOD and at Point of Sleat, a transgression has been dated at between 3830±60 BP and 2850±100 BP when it attained an altitude of greater than 4.13mOD. It is unclear whether these transgressions relate to one diachronous episode of high relative sea level or whether several fluctuations of relative sea level were experienced. This episode of late Holocene high relative sea levels has not been recorded from the central west coast of Scotland prior to this research. Shennan *et al.* (1995a; 1995b) record a continuously falling relative sea level from the maximum of the Main Postglacial Transgression to *circa* 1100 BP in the Arisaig area. The implications of high relative sea levels at *circa* 4000 BP to *circa* 2800 BP on human settlement and geomorphological processes in these areas should be emphasised.

This research has allowed an assessment to be made of the empirical and rheological models. The quadratic trend-surface isobase map of Firth *et al.* (1993) for the Main Lateglacial Shoreline appears to fit broadly with the field evidence obtained from the sites studied on Skye. However, the model of Lambeck (1993b) for 10500 BP appears to require modification. The isobase map for the Main Postglacial Shoreline (Firth *et al.*, 1993) appears to lie approximately 4m higher than field evidence suggests and the isobase map for a late Holocene Shoreline appears to be greatly in error (Firth *et al.*, 1993).

11.2 Methodological conclusions

The value of isolation basins in this study should be emphasised. The relatively protected environment of a basin allows sediments to accumulate undisturbed until a critical point is reached when the basin is full and can no longer register changes. The topography of southern Skye makes it particularly conducive to the preservation of sediments within bedrock hollows and this has proved especially useful in an area devoid of estuarine locations. It is only in the locations comprising isolation basins that Lateglacial marine sediments have been found on Skye in this research. By contrast, the value of back-barrier environments for recording relative sea level changes appears to be limited. The site -specific nature of barrier sites makes assumptions about the broad scale fluctuations of relative sea level changes very tentative.

The use of pollen analysis in this research has been recognised, particularly for verifying the radiocarbon dates of Late Devensian age. This proved particularly useful at Inver Aulavaig, where the radiocarbon dates may have been affected by a hard water error as a result of the limestone basin. The use of pollen in monitoring relative sea level changes has been found to be extremely limited, probably as vegetation reacts relatively slowly, compared to diatoms, to environmental changes. The use of diatom analysis in this research has been found to be extremely valuable in identifying changes in relative sea level. Their use particularly in isolation basin environments where transitions are identified prior to and after a trangression, is recognised and recommended.

11.3 Recommendations for future work

This research has revealed that contemporary studies into the morphodynamics of barriers is needed especially in relation to relative sea level changes. These studies should occur in different geomorphological settings, under different energy régimes and in sites with varying sediment availability. It is important to understand how the rate of relative sea level changes affects barrier formation and assessment of the value of index points from these sites is required. This is particularly important for studies on the west coast of Scotland where coastal barriers are common. Contemporary studies of isolation basins are also needed to identify at which point in the tidal cycle isolation occurs and which variables affect this. An assessment of how much input of saline water to an isolation basin is needed to sustain a marine flora is also required. Further investigations should be undertaken to establish the indicative meaning of the relative sea level index points obtained from these environments and how the input of freshwater to a basin may affect them.

This research has revealed discrepancies between the isobase maps of Firth *et al.* (1993) and field evidence on Skye. More data on relative sea level changes from the west coast of Scotland is, therefore, required to make the models more accurate. Standardisation of all the data, probably to mean tide level, should also occur to make the data points directly comparable.

A final recommendation for future research involves diatoms. One deficiency in using diatoms in research of this nature is the large number of species identified whose ecology is unknown. Contemporary studies into the ecology of diatom species, would greatly benefit, the interpretation of the assemblages. Detailed studies of the diatom flora of modern day saltmarshes, mudflats and other coastal environments may also benefit the interpretation of transitions that represent relative sea level changes.

11.4 Overview of the research

It is hoped that this research has contributed to our knowledge of patterns of Late Devensian and Holocene relative sea level changes on Skye and on the west coast of Scotland in general. The identification of three, or possibly more, periods of high relative sea level change on the Isle of Skye has questioned some previous assumptions made about patterns of relative sea level change on the Scottish west coast and indicated that the empirical and rheological models need modification. The value of using isolation basins in studies of relative sea level change has been clearly demonstrated and the development of this method in Scottish sea level studies should be investigated farther.

References

Admiraal, W. (1984) The ecology of estuarine sediment-inhabiting diatoms.
Progress in Phycological Research, **3**, 269-322.

Admiralty Tide Tables (1996) Volume 1 European waters including Mediterranean Sea.
Hydrographer of the Navy.

Affleck, T.L., Edwards, K. and **Clarke, A.** (1988) Archaeological and palynological studies at Mesolithic pitchstone and flint site of Auchareoch, Isle of Arran.
Proceedings of the Society of Antiquities of Scotland, **118**, 37-59.

Allen, J.R.L. (1990) The formation of coastal peat marshes under an upward tendency of relative sea level.
Journal of the Geological Society, **147**, 743-745.

Allen, P. (1964) Sedimentological models.
Journal of Sedimentology and Petrology, **34**, 289-293.

Ammann, B. and **Lotter, A.F.** (1989) Late-Glacial radiocarbon- and palynostratigraphy on the Swiss Plateau.
Boreas, **18**, 109-126.

Andersen, B.G. (1981) Late Weichselian ice sheets in Eurasia and Greenland.
In, **Denton, G.H.** and **Hughes, T.J.** (eds) *The Last Great Ice Sheets.*
John Wiley, New York, 1-65.

Anderson, F.W. and **Dunham, K.W.** (1966) The geology of northern Skye.
Memoir of the Geological Survey of the United Kingdom.

Anderson, R.C., Jacobson, G.L. Jr., Davis, R.B. and **Stuckenrath, R.** (1992) Gould Pond, Maine: late-glacial transitions from marine to upland environments.
Boreas, **21**, 359-371.

Andrew, R. (1984) *A practical pollen guide to the British flora.*
Quaternary Research Association, Cambridge. pp139.

Anundsen, K. (1978) Marine transgression in Younger Dryas in Norway.
Boreas, **7**, 49-60.

Atkinson, T.C, Briffa, K.R. and **Coope, G.R.** (1987) Seasonal temperatures in Britain during the last 22000 years, reconstructed using beetle remains.
Nature, 325, 587-593.

Ballantyne, C.K. (1988) Ice sheet moraines in Southern Skye.
Scottish Journal Of Geology, **24**, 301-304.

Ballantyne, C.K. (1989) The Loch Lomond Readvance on the Isle of Skye: glacier reconstruction and palaeoclimatic implications.
Journal of Quaternary Science, **4(2)**, 95-108.

Ballantyne, C.K. (1990) The Late Quaternary glacial history of the Trotternish Escarpment , Isle of Skye, Scotland and its implications for ice-sheet reconstruction.
Proceedings of the Geological Association, **101**, 171-186.

Ballantyne, C.K. (1994) Gibbsitic soils on former nunataks: implications for ice sheet reconstruction.
Journal of Quaternary Science, **9(4)**, 73-80.

Ballantyne, C.K. and **Sutherland, D.G.** (1987) (eds) *Wester Ross Field Guide.* Quaternary Research Association, Cambridge.

Ballantyne, C.K. and **Benn, D.I.** (1991a) Introduction. In, **Ballantyne, C.K., Benn, D.I., Lowe, J.J.** and **Walker, M.J.C.** (eds) *The Quaternary of the Isle of Skye.* Quaternary Research Association, Cambridge, Chapter 1, 1-10, pp 172.

Ballantyne, C.K. and **Benn, D.I.** (1991b) The glacial history of the Isle of Skye. In, **Ballantyne, C.K., Benn, D.I., Lowe, J.J.** and **Walker, M.J.C.** (eds) *The Quaternary of the Isle of Skye.* Quaternary Research Association, Cambridge, Chapter 2, 11-34, pp 172.

Ballantyne, C.K. and **McCarroll, D.** (1995) The vertical dimensions of Late Devensian glaciation on the mountains of Harris and southeast Lewis, Outer Hebrides, Scotland. *Journal of Quaternary Science,* **10(3)**, 211-223.

Barber, K.E. (1976) History of Vegetation. In, **Chapman, S.B.** (ed) *Methods in Plant Ecology.* Blackwell Scientific Publications, Oxford, 5-83.

Bard, E., Arnold, M., Mangerud, J., Paterne, M., Labeyrie, L., Duprat, J., Mélières, M-A, Sønstegaard, E. and **Duplessy, J-C.** (1994) The North Atlantic atmosphere-sea-surface ^{14}C gradient during the Younger Dryas climatic event. *Earth and Planetary Science Letters,* **126**, 275-287.

Barnosky, C.W. (1988) A Late-glacial and Post-glacial Pollen Record from The Dingle Peninsula, County Kerry. *Proceedings of the Royal Irish Academy, Dublin.* Section *B-Biological, Geological and Chemical Science,* **88B(2)**, 23-37.

Battarbee, R.W. (1986) Diatom analysis. In, **Berglund, B.E.** (ed) *Handbook of Holocene Palaeoecology and Palaeohydrology.* John Wiley & Sons Ltd, Chichester. Chapter 26, 527-570, pp869.

Becker, B. (1992) The history of dendrochronology and radiocarbon calibration. In, **Taylor, R.E., Long, A.** and **Kra, R.S.** (1992) *Radiocarbon After Four Decades.* Springer-Verlag, London, 34-49, pp596.

Belknap, D.F. and **Kraft, J.C.** (1981) Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic shelf. *Marine Geology,* **42**, 429-442.

Bengtsson, L. and Enell, M. (1986) Chemical analysis. In, **Berglund, B.E.** (ed) *Handbook of Holocene Palaeoecology and Palaeohydrology.* John Wiley and Sons Ltd, Chichester. 423-454, pp 869.

Benn, D.I., Lowe, J.J. and **Walker, M.J.C.** (1992) Glacier response to climatic change during the Loch Lomond Stadial and early Flandrian: geomorphological and palynological evidence from the Isle of Skye, Scotland. *Journal of Quaternary Science,* **7(2)**, 125-144.

Bennett, K.D. (1984) The Post-glacial history of *Pinus sylvestris* in the British Isles. *Quaternary Science Reviews,* **3**, 133-155.

Bennett, K.D. and **Birks, H.J.B.** (1990) Postglacial history of alder (*Alnus glutinosa* (L.) Gaertn.) in the British Isles.
Journal of Quaternary Science, **5(2)**, 123-133.

Bennett, K.D., Fossitt, J.A., Sharp, M.J. and **Switsur, V.R.** (1990) Holocene vegetational and environmental history at Loch Lang, South Uist, Western Isles, Scotland.
New Phytologist, **114**, 281-298.

Bennett, K.D., Whittington, G. and **Edwards, K.J.** (1994) Recent plant nomenclatural changes and pollen morphology in the British Isles.
Quaternary Newsletter, **73**, 1-6.

Birks, H.J.B. (1973) *Past and present vegetation of the Isle of Skye. A palaeoecological study.*
Cambridge University Press, Cambridge. pp 415.

Birks, H.J.B. (1989) Holocene isochrone maps and patterns of tree-spreading in the British Isles.
Journal of Biogeography, **16**, 503-540.

Birks, H.J.B. and **Birks, H.H.** (1980) *Quaternary Palaeoecology.*
Edward Arnold, London. pp 289.

Birks, H.J.B. and **Williams, W.** (1983) Late-Quaternary vegetational history of the Inner Hebrides.
Proceedings of the Royal Society of Edinburgh, **83B**, 269-292.

Birnie, J., Gordon, J., Bennett, K. and **Hall, A.** (1993) *The Quaternary of Shetland. Field Guide.*
Quaternary Research Association, London, pp140.

Bishop, P. and **Jones, E.J.W.** (1979) Patterns of glacial and postglacial sedimentation in the Minches, North West Scotland.
In, **Banner, F.T., Collins, M.B.** and **Massie, K.S.** (eds) *The North-West European shelf seas: the sea bed and the sea in motion-1. Geology and sedimentology.*
Amsterdam: Elsevier, 89-194.

Bishop, W.W. and **Coope, G.R.** (1977) Stratigraphical and faunal evidence for Lateglacial and early Flandrian environments in south-west Scotland.
In, **Gray, J.M.** and **Lowe, J.J.** (eds) *Studies in the Scottish Lateglacial Environment.*
Pergamon Press, Oxford, 61-88.

Bishop, W.W. and **Dickson, J.H.** (1970) Radiocarbon dates related to the Scottish Late-glacial sea in the Firth of Clyde.
Nature, **227**, 480-482.

Björck, S. and **Digerfeldt, G.** (1986) Late Weichselian-Early Holocene shore displacement west of Mt. Billingen, within the middle Swedish end-moraine zone.
Boreas, **15**, 1-18.

Blanchon, P. and **Shaw, J.** (1995) Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse.
Geology, **23(1)**, 4-8.

Bonney, T.G. (1871) On a cirque in the syenite hills of Skye.
Geological Magazine, **8**, 535-540.

Boulton, G.S., Jones, A.S., Clayton, K.M. and **Kenning, M.J.** (1977) A British ice-sheet model and patterns of glacial erosion and deposition in Britain.
In, **Shotton, F.M.** (ed) *British Quaternary Studies*
Clarendon Press, Oxford, 231-246.

Boulton, G.S., Smith, G.D., Jones, A.S. and **Newsome, J.** (1985) Glacial geology and glaciology of the last mid-latitude ice sheets.
Journal of the Geological Society of London, **142**, 447-474.

Boulton, G.S, Peacock, J.D. and **Sutherland, D.G.** (1991) Quaternary.
In, **Craig, G.Y.** (ed) *Geology of Scotland.*
The Geological Society, London, 504-543.

Bowen, D.Q., Rose, J., McCabe, A.M. and **Sutherland, D.G.** (1986) Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales.
Quaternary Science Reviews, **5**, 299-340.

Boyd, R. and **Penland, S.** (1984) Shoreface translation and the Holocene stratigraphic record: Examples from Nova Scotia, the Mississippi Delta and eastern Australia.
Marine Geology, **60**, 391-412.

Boyd, W.E. and **Dickson, J.H.** (1986) Patterns in the Geographical Distribution of the early Flandrian *Corylus* rise in southwest Scotland.
New Phytologist, **102**, 615-623.

Brookes, D. and **Thomas, K.W.** (1967) The distribution of pollen grains on microscope slides. Part 1. The non-randomness of the distribution.
Pollen et Spores, **IX(3)**, 621-629.

Browne, M.A.E., Harkness, D.D., Peacock, J.D. and **Ward, R.G.** (1977) The date of deglaciation of the Paisley-Renfrew area.
Scottish Journal of Geology, **13**, 301-303.

Browne, M.A.E., McMillan, A.A. and **Graham, D.K.** (1983) A late-Devensian marine and non-marine sequence near Dumbarton, Strathclyde.
Scottish Journal of Geology, **19**, 229-234.

Browne, M.A.E. and **McMillan, A.A.** (1984) Shoreline inheritance and coastal history in the Firth of Clyde.
Scottish Journal of Geology, **20**, 119-120.

Brush, G.S. and **Brush, L.M.** (1972) Transport of pollen in a sediment laden channel: a laboratory study.
American Journal of Science, **272**, 359-381.

Carter, R.W.G., Forbes, D.L., Jennings, S.C., Orford, J.D., Shaw, J. and **Taylor, R.B.** (1989) Barrier and Lagoon Coast Evolution under differing Relative Sea-Level Regimes: Examples from Ireland and Nova Scotia.
Marine Geology, **88**, 221-242.

Chapman, V.J. (1964) *The Algae.*
McMillan Publishers Limited, London.

Charlesworth, J.K. (1956) The Lateglacial history of the Highlands and Islands of Scotland.
Transactions of the Royal Society of Edinburgh, **62**, 769-928.

Chesher, J.A, Smythe, D.K. and **Bishop, P.** (1983) The geology of the Minches, Inner Sound and Sound of Raasay.
Report of the Institute of Geological Sciences **No.83/6.**

Clapham, A.R., Tutin, T.G. and **Moore, D.M.** (1987) *Flora of the British Isles.*
Cambridge University Press, Cambridge. pp 688.

Clough, C.T. and **Harker, A.** (1904) *The geology of west-central Skye, with Soay.*
Memoir of the Geological Survey of the United Kingdom.

Cornish, R. (1982) Glacier flow at a former ice-divide in SW Scotland.
Transactions of the Royal Society of Edinburgh. Earth Sciences, **73**, 31-41.

Cox, E.J. (1996) *Identification of freshwater diatoms from live material.*
Chapman and Hall, London, pp156.

Cullingford, R.A. (1977) Lateglacial raised shorelines and deglaciation in the Earn-Tay area.
In, **Gray, J.M.** and **Lowe, J.J.** (eds) *Studies in the Scottish Lateglacial Environment.*
Pergamon Press, Oxford, 15-32.

Cullingford, R.A. and **Smith, D.E.** (1966) Lateglacial shorelines in Eastern Fife.
Transactions of the Institute of British Geographers, **39**, 31-51.

Cullingford, R.A. and **Smith, D.E.** (1980) Late Devensian Shorelines in Angus and Kincardineshire, Scotland.
Boreas, **9**, 21-38.

Cullingford, R.A., Caseldine, C.J. and **Gotts, P.E.** (1980) Early Flandrain land and sea level changes in lower Strathearn.
Nature, **284**, 159-161.

Cullingford, R.A., Caseldine, C.J. and **Gotts, P.E.** (1989) Evidence of early Flandrian tidal surges in lower Strathearn, Scotland.
Journal of Quaternary Science, **4(1)**, 51-60.

Cullingford, R.A., Smith, D.E. and **Firth, C.R.** (1991) The altitude and age of the Main Postglacial Shoreline in eastern Scotland.
Quaternary International, **9**, 39-52.

Cundill, P.R. (1979) Contemporary pollen spectra on the North York Moors.
Journal of Biogeography, **6**, 127-131.

Curray, J.R. (1964) Transgressions and regressions.
In, **Miller, R.L.** (ed) *Papers in Marine geology (Shepard Commemorative Volume)*
McMillan, New York, N.Y., 175-203.

Cwynar, L.C., Burden, E. and **McAndrews, J.H.** (1979) An inexpensive method for concentrating pollen and spores from fine-grained sediments.
Canadian Journal of Earth Science, **16(5)**, 1115-1120.

Dahl, S-O., Ballantyne, C.K., McCarroll, D. and **Nesje, A.** (1996) Maximum altitude of Devensian glaciation on the Isle of Skye.
Scottish Journal of Geology, **32(2)**, 107-115.

Davis, R.A. Jr. and **Clifton, H.E.** (1987) Sea-level change and the preservation potential of wave-dominated and tide-dominated coastal sequences.
In, **Nummedal, D., Pilkey, O.H.** and **Howard, J.D.** (eds) *Sea-level fluctuations and Coastal Evolution.*
Society of Economic Palaeontologists and Mineralogists Special Publication, **41**, 167-178.

Dawson, A.G. (1979) Former sea-level changes in the Scottish Hebrides.
Hebridean Naturalist, **3**, 16-22.

Dawson, A.G. (1980a) The Low Rock Platform in western Scotland.
Proceedings of the Geologists' Association, **91**, 339-344.

Dawson, A.G. (1980b) Shore erosion by frost: an example from the Scottish Lateglacial.
In, **Lowe, J.J.**, **Gray, J.M.** and **Robinson, J.** (eds) *The Lateglacial of North-West Europe.*
Pergamon Press, Oxford, 45-54.

Dawson, A.G. (1982) Lateglacial sea-level changes and ice-limits in Islay, Jura and Scarba, Scottish Inner Hebrides.
Scottish Journal of Geology, **18(4)**, 253-265.

Dawson, A.G. (1984) Quaternary sea-level changes in Western Scotland.
Quaternary Science Reviews , **3(3)**, 345-368.

Dawson, A.G. (1988) The Main Rock Platform (Main Lateglacial Shoreline) in Ardnamurchan and Moidart, western Scotland
Scottish Journal of Geology, **24**, 163-74.

Dawson, A.G. (1991) Scottish landform examples-3. The raised shorelines of northern Islay and western Jura.
Scottish Geographical Magazine, **107**, 207-12.

Dawson, A.G. (1994) Strandflat development and Quaternary shorelines on Tiree and Coll, Scottish Hebrides.
Journal of Quaternary Science, **9(4)**, 349-356.

Dawson, A.G, **Long, D.** and **Smith, D.E.** (1988) The Storegga Slides: evidence from eastern Scotland of a possible tsunami.
Marine Geology, **82**, 271-6.

Dawson, A.G, **Dawson, S.**, **Foster, I.**, **Tooley, M.**, **Brookes, C.** and **Smith, D.E.** (1997) Lateglacial relative sea level changes, Ruantallain-Shian Bay, western Jura.
In, **Dawson, A.G.** and **Dawson, S.** (eds) *The Quaternary of Islay and Jura.*
Quaternary Research Association Field Guide, Cambridge. Chapter 3.1, 17-40, pp123.

Dawson, S. and **Dawson, A.G.** (1997) Holocene relative sea level changes Gruinart, Isle of Islay.
In, **Dawson, A.G.** and **Dawson, S.** (eds) *The Quaternary of Islay and Jura.*
Quaternary Research Association Field Guide, Cambridge. Chapter 7.1, 78-98, pp123.

Dawson, S. and **Smith, D.E.** (1997) Holocene relative sea-level changes on the margin of a glacio-isostatically uplifted area: an example from northern Caithness, Scotland.
The Holocene, **7(1)**, 59-79.

Deacon, J. (1974) The location of refugia of *Corylus avellana* L. during the Weichselian glaciation.
New Phytologist, **73**, 1055-1063.

Denys, L. (1991/2) *A check-list of the diatoms in the Holocene coastal deposits of the Western Belgian Coastal Plain with a survey of their apparent ecological requirements. 1. Introduction, ecological code and complete list.*
Professional Paper No. 246. Ministere des Affaires Economiques. Service Geologique de Belgique. pp 41.

Denys, L. (1991/3) *A check-list of the diatoms in the Holocene coastal deposits of the Western Belgian Coastal Plain with a survey of their apparent ecological requirements. II Centrales.*
Professional Paper No. 247. Ministere des Affaires Economiques. Service Geologique de Belgique. pp 91.

Devoy, R.J.N. (1977) *Flandrain sea-level changes and vegetational history of the Lower Thames estuary.* Unpublished PhD Thesis, Churchill College, Cambridge.

Dickson, J.H., Stewart, D.A., Thompson, R., Turner, G., Baxter, M.S., Drndarsky, N.D. and **Rose, J.** (1978) Palynology, Palaeomagnetism and radiometric dating of Flandrian marine and freshwater sediments of Loch Lomond.
Nature, **274**, 548-53.

Digerfeldt, G. (1975) A standard profile for Littorina transgressions in western Skåne, south Sweden.
Boreas, **4**, 125-142.

Dobney, K., Jacques, D. and **Irving, B.** (1996) *Of Butchers and Breeds: Report on Vertebrate Remains from various Sites in the City of Lincoln.*
Lincoln Archaeological Studies: 5. Lincoln, pp215.

Edwards, K.J. (1981) The separation of *Corylus* and *Myrica* pollen in modern fossil samples.
Pollen et Spores, **XXIII (2)**, 205-218.

Edwards, K. J. and **Berridge, J.M.A.** (1994) The Late-Quaternary vegetational history of Loch a' Bhogaidh, Rinns of Islay.
New Phytologist, **128**, 749-769.

Erdtman, G. (1960) The acetolysis method.
Svensk Botanisk Tidskrift, **54**, 561-564.

Fægri, K., Kaland, P.E. and **Krzywinski, K.** (1989) *Textbook of Pollen Analysis. IV Edition.*
John Wiley and Sons Ltd, Chichester. pp328.

Firth, C.R. (1984) *Raised shorelines and ice limits in the inner Moray Firth and Loch Ness areas, Scotland.* Unpublished PhD thesis, Coventry Polytechnic.

Firth, C.R. (1986) Isostatic depression during the Loch Lomond Stadial: preliminary evidence from the Great Glen, northern Scotland.
Quaternary Newsletter, **48**, 1-9.

Firth, C.R. and **Haggart, B.A.** (1989) Loch Lomond Stadial and Flandrian shorelines in the Inner Moray Firth area, Scotland.
Journal of Quaternary Science, **4**, 37-50.

Firth, C.R. and **Haggart, B.A.** (1991) *Late Quaternary coastal evolution in the inner Moray Firth: Field Guide.*
West London Institute, London.

Firth, C.R., Smith, D.E. and **Cullingford, R.A.** (1993) Late Devensian and Holocene Glacio-isostatic Uplift patterns in Scotland.
Quaternary Proceedings, **3**, 1-14.

Flinn, D. (1978) The most recent glaciation of the Orkney-Shetland Channel and adjacent areas.
Scottish Journal of Geology, **14**, 109-123.

Forbes, A.R. (1923) *Place-names of Skye and adjacent islands.*
Alexander Gardner Ltd, Paisley. pp495.

Forbes, J.D. (1846) Notes on the topography and geology of the Cuchullin Hills in Skye, and on the traces of ancient glaciers which they present.
Edinburgh New Philosophical Journal, **40**, 76-99.

Fossitt, J.A. (1994) Late-glacial and Holocene vegetational history of Western Donegal, Ireland.
Biology and the Environment, Proceedings of the Royal Irish Academy, **94(B)**, 1-31.

Fritsch, F.E. (1965) *The structure of the algae and reproduction.*
Cambridge University Press, Cambridge.

Fyfe, J.A., Long, D. and **Evans, D.** (1993) The geology of the Malin-Hebrides sea area.
British Geological Survey. United Kingdom Regional Report, pp91.

Gehrels, W.R., Belkanp, D.F. and **Kelley, J.T.** (1996) Integrated high-precision analyses of Holocene relative sea-level changes: Lessons from the coast of Maine.
Geological Society of America Bulletin, **108(9)**, 1073-1088.

Graham, A. (1971) *British Prosobranchs. Synopses of the British Fauna (New series) No. 2.*
Academic Press, London. pp 662.

Gray, J.M. (1972) Trend Surface Analysis: trends through clusters.
Area, **4**, 275-279.

Gray, J.M. (1974a) The Main Rock Platform of the Firth of Lorn, Western Scotland.
Transactions of the Institute of British Geographers, **61**, 81-99.

Gray, J.M. (1974b) Lateglacial and Postglacial Shorelines in western Scotland.
Boreas, 3, 129-138.

Gray, J.M. (1975) The Loch Lomond Readvance and contemporaneous sea-levels in Loch Etive and neighbouring areas of Western Scotland.
Proceedings of the Geologists' Association, **86**, 227-38.

Gray, J.M. (1978) Low level shore platforms in the south-west Scottish Highlands.
Transactions of the Institute of British Geographers, **3**, 151-164.

Gray, J.M. (1983) The measurement of shoreline altitudes in areas affected by glacio-isostasy, with particular reference to Scotland.
In, **Smith, D.E.** and **Dawson, A.G.** (eds) *Shorelines and Isostasy.*
Academic Press, London, 97-128.

Gray, J.M. and **Ivanovich, M.** (1988) Age of the Main Rock Platform, western Scotland.
Palaeogeography, Palaeoclimatology, Palaeoecology, **68**, 337-345.

Greensmith, J.T. and **Tucker, E,V.** (1986) Compaction and consolidation.
In, **van de Plaasche, O.** (ed) *Sea-level research: a manual for the collection and evaluation of data.*
Geo Books, Norwich. Chapter 22, 591-603, pp618.

Grimm, E.C. (1991) Tilia version 1.08 and Tilia*graph 1.17. Program for the analysis and display of microfossil data. Illonois State Museum, Springfield, Illonois.

Hafsten, U. (1983) Biostratigraphical evidence for Late Weichselian and Holocene sea-level changes in southern Norway.
In, **Smith, D.E.** and **Dawson, A.G.** (eds) *Shorelines and Isostasy. Institute of British Geographers, Special Publication, No. 16.*
Academic Press, London. Chapter 7, 161-181, pp387.

Haggart, B.A. (1982) *Flandrian Sea Level Changes in the Moray Firth Area.* Unpublished PhD Thesis, University of Edinburgh.

Haggart, B.A. (1986) Relative sea-level change in the Beauly Firth, Scotland.
Boreas, **15**, 191-207.

Haggart, B.A. (1987) Relative sea-level changes at a site in the Beauly Firth area, Scotland. In, **Tooley, M.J.** and **Shennan, I.** (eds) Sea-level Changes. Blackwell, Cambridge, Chapter 3, 67-108. pp397.

Haggart, B.A. (1989) Variations in the pattern and rate of isostatic uplift indicated by a comparison of Holocene sea-level curves from Scotland. *Journal of Quaternary Science*, **4**, 67-76.

Hall, A.M. and **Bent, A.J.A.** (1990) The limits of the last British Ice Sheet in northern Scotland and the adjacent shelf. *Quaternary Newsletter*, **61**, 2-12.

Harker, A. (1901) Ice erosion in the Cuillin Hills, Skye. *Transactions of the Royal Society of Edinburgh*, **40**, 221-252.

Healy, M. G. (1993) *Holocene coastal evolution and relative sea-level change in West Cornwall, United Kingdom.* Unpublished Phd thesis, University of Cork.

Hedges, R.E.M. (1991) AMS Dating: Present Status and Potential Applications. Quaternary Proceedings No. 1. In, **Lowe, J.J.** (ed) *Radiocarbon Dating: Recent Applications and Future Potential.* Quaternary Research Association, Cambridge. 5-10, pp89.

Hendey, N.I. (1976) *An Introductory Account of the Smaller Algae of British Coastal Waters. Part V: Bacillariophyceae (Diatoms).* Ministry of Agriculture, Fisheries and Food. Fishery Investigations *Series IV.* Otto Koeltz Science Publications, West Germany. pp 317.

Hirons, K.R. and **Edwards, K.J.** (1990) Pollen and related studies at Kinloch, Isle of Rhum, Scotland, with particular reference to possible early human impacts on vegetation. *New Phytologist*, **116**, 715-727.

Hoffmeister, W.S. (1954) *Microfossil prospecting for petroleum.* U.S. Patent 2686108, Washington D.C. pp4.

Huntley, B. (1993) Rapid early-Holocene migration and high abundance of hazel (*Corylus avellana* L.): alternative hypotheses. In, **Chambers, F.M.** (ed) *Climate change and human impact on the landscape.* Chapman and Hall, London, Chapter 17, 205-215.

Hustedt, F. (1930-1966) *Die Kieselalgen. Deutschlands, Österreichs und der Schweiz. 1 Teil* (1930) pp 920, *2 Teil* (1959) pp 845, *3 Teil* (1961-6) pp 816. Koeltz Scientific Books, USA.

Hustedt, F. (1939) Systematische und ökolische Untersuchungen über die Diatomeen-flora von Java, Bali und Sumatra III. Die ökologische Faktoren und ihr Einfluss auf die Diatomeenflora. *Archiv für Hydrobiologie Aus Supplement,* **16**, 274-344.

Hustedt, F. (1957) Die diatomeenflora des Flusssystems der Weser im Gebiet der Hansestadt Bremen. *Abhandlungen hrsg. vom Naturwissenschaftlichen Verein zu Bremen*, **34**, 181-440.

Jacobson, G.L. Jr. and **Bradshaw, R.H.W.** (1981) The selection of sites for palaeovegetational studies. *Quaternary Research*, **16**, 80-96.

Jamieson, T.F. (1865) On the history of the last geological changes in Scotland. *Quarterly Journal of the Geological Society of London*, **21**, 161-203.

Jardine, W.G. (1964) Post-glacial sea-levels in south-west Scotland.
Scottish Geographical Magazine, **80**, 5-11.

Jardine, W.G. (1971) Form and age of Late-Quaternary shore-lines and coastal deposits of south-west Scotland: critical data.
Quaternaria, **14**, 103-114.

Jardine, W.G. (1975) Chronology of Holocene marine transgression and regression in south-western Scotland.
Boreas, **4**, 173-196.

Jardine, W.G. (1980) Holocene raised coastal sediments and former shorelines of Dumfriesshire and eastern Galloway.
Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society, 3rd Series, **55**, 1-59.

Jardine, W.G. (1981) Status and relationships of the Loch Lomond Readvance and its stratigraphical correlatives.
In, **Neale, J.** and **Flenley, J.** (eds) *The Quaternary in Britain.*
Pergamon Press, Oxford, 168-73.

Jones, R.L. (1988) The Impact of early Man on Coastal Plant Communities in the British Isles.
In, **Jones, M.** (ed) *Archaeology and the Flora of the British Isles. Human influence on the evolution of plant communities.*
Oxford University Committee for Archaeology Monograph Number 14. Botanical Society of the British Isles Conference report Number 19.

Kaland, P.E., Krzywinski, K. and **Stabell, B.** (1984) Radiocarbon dating of transitions between marine and lacustrine sediments and their relation to the development of lakes.
Boreas, **13**, 243-258.

King, C.A.M. (1972) *Beaches and Coasts*
Edward Arnold, London. pp570.

Kjemperud, A. (1981) Diatom changes in sediments of basins possessing marine/lacustrine transitions in Frosta, Nord-Trøndelag, Norway.
Boreas, **10**, 27-38.

Kjemperud, A. (1986) Late Weichselian and Holocene shoreline displacement in the Trondheimsfjord area, central Norway.
Boreas, **15**, 61-82.

Koreneva, E.V. (1966) Marine palynological researches in the U.S.S.R.
Marine Geology, **28(4)**, 565-574.

Krammer, K. and **Lange-Bertalot, H.** (1986-1991) *Süßwasser von Mitteleuropa: 1 Teil: Naviculacece* (1986) pp 876
2 Teil: bacillariacec, Epithemiaceae, Surireellaceae (1988) pp 596
3 Teil: Centrales, Fragilariaceae, Eunotiaceae (1991) pp 576
4 Teil: Achnanthaceae, Kritische Ergänzungen zu Navicula (lineolatae) und Gomphonema Gesamtliteraturver zeichnis. Teil 1-4. (1991) pp 437
VEB Gustav Fischer Verlag, Stuttgart.

Kristiansen, I.L., Mangerud, J. and **Lømo, L.** (1988) Late Weichselian/Early Holocene pollen- and lithostratigraphy in lakes in the Ålesund area, western Norway.
Review of palaeobotany and Palynology, **53**, 185-231.

Kromer, B. and **Becker, B.** (1993) German oak and pine ^{14}C calibration 7200-9400 BC.
Radiocarbon, **35**, 125-137.

Krzywinski, K. and **Stabell, B.** (1984) Late Weichselian sea level changes at Sotra, Hordaland, western Norway.
Boreas, **13**, 159-202.

Lambeck, K. (1990) Glacial rebound, sea-level change and mantle viscosity.
Quarterly Journal of the Royal Astronomical Society, **31**, 1-30.

Lambeck, K. (1991) Glacial rebound and sea-level change in the British Isles.
Terra Nova, **3**, 379-389.

Lambeck, K. (1993a) Glacial rebound of the British Isles-I. Preliminary model results.
Geophysical Journal International, **115**, 941-959.

Lambeck, K. (1993b) Glacial rebound of the British Isles-II. A high-resolution, high precision model.
Geophysical Journal International, **115**, 960-990.

Le Coeur, C. (1994) *Évolution Géomorphologique et Échelles d'Analyse: l'Exemple des Hebrides Internes (Écosse).* Unpublished Thèse du Doctorat d'État, Université Paris 1, Panthéon-Sorbonne.

Libby, W.F. (1955) *Radiocarbon Dating.*
University of Chicago Press, Chicago.

Lie, S.E., **Stabell, B.** and **Mangerud, J.** (1983) Diatom stratigraphy related to Late Weichselian sea level changes in Sunnmøre, western Norway.
Norges Geologiske Undersoekelse, **380**, 203-219.

Long, D., **Bent, A.J.A.**, **Harland, R.**, **Gregory, D.M.**, **Graham, D.K.** and **Morton, A.C.** (1986) Late Quaternary palaeontology, sedimentology and geochemistry of a vibrocore from the Witch Ground Basin, Central North Sea.
Marine Geology, **73**, 109-123.

Long, D., **Smith, D.E.** and **Dawson, A.G.** (1989) Holocene tsunami deposit in eastern Scotland.
Journal of Quaternary Science, **4**, 61-6.

Longfellow, H.W. The secret of the sea
In, *Longfellow Poems* (1970)
Everyman's Library, London, 340-341, pp491.

Lowe, J.J. (1991) Stratigraphic Resolution and Radiocarbon dating of Devensian Lateglacial Sediments. Quaternary Proceedings No. 1.
In, **Lowe, J.J.** (ed) *Radiocarbon Dating: Recent Applications and Future Potential.*
Quaternary Research Association, Cambridge. 19-25, pp89.

Lowe, J.J. (1993) Isolating the climatic factors in early- and mid-Holocene palaeobotanical records from Scotland.
In, **Chambers, F.M.** (ed) *Climate change and human impact on the landscape.*
Chapman and Hall, London, Chapter 7, 67-82.

Lowe, J.J. and **Gray, J.M.** (1980) The Stratigraphic Subdivision of the Lateglacial of NW Europe: A Discussion.
In, **Lowe, J.J.**, **Gray, J.M.** and **Robinson, J.** (eds) *Studies in the Lateglacial of North-West Europe.*
Pergamon Press, Oxford. 157-175, pp205.

Lowe, J.J. and **Walker, M.J.C.** (1977) The reconstruction of the Lateglacial environment in the southern and eastern Grampian Highlands.
In, **Gray, J.M.** and **Lowe, J.J.** (eds) *Studies in the Scottish Lateglacial Environment.*
Pergamon Press, Oxford, 101-118.

Lowe, J.J. and **Walker, M.J.C.** (1980) Problems Associated with Radiocarbon Dating the close of the Lateglacial Period in the Rannoch Moor Area, Scotland.
In, **Lowe, J.J., Gray, J.M.** and **Robinson, J.** (eds) *Studies in the Lateglacial of North-West Europe.*
Pergamon Press, Oxford. 123-137, pp205.

Lowe, J.J. and **Walker, M.J.C.** (1986) Lateglacial and early Flandrian history of the Isle of Mull, Inner Hebrides, Scotland.
Transactions of the Royal Society of Edinburgh: Earth Science, **77**, 1-20.

Lowe, J.J. and **Walker, M.J.C.** (1991) Vegetational history of the Isle of Skye II. The Flandrian.
In, **Ballantyne, C.K., Benn, D.I., Lowe, J.J.** and **Walker, M.J.C.** (eds) *The Quaternary of the Isle of Skye.*
Quaternary Research Association, Cambridge, Chapter 8, 119-142, pp 172.

Lowe, J.J. and **Walker, M.J.C.** (1997) *Reconstructing Quaternary Environments*
Longman, Essex, 2nd Edition, 237-273.

McCann, S.B. (1966) The limits of the Lateglacial Highland, or Loch Lomond Readvance along the West Highland seaboard from Oban to Mallaig.
Scottish Journal of Geology, **2**, 84-95.

McCann, S.B. (1968) Raised shore platforms in the Western Isles of Scotland.
In, **Bowen, E.G., Carter, H.** and **Taylor, J.A.** (eds) *Geography at Aberystwyth.* London, 22-34.

McCarroll, D., Ballantyne, C.K., Nesje, A. and **Dahl, S-O.** (1995) Nunataks of the last ice sheet in northwest Scotland.
Boreas, **24**, 305-323.

McVean, D.N and **Ratcliffe, D.A.** (1962) *Plant communities of the Scottish Highlands.*
HMSO, London. pp 445.

Maguire, D.J. (1985) The former distribution of forest and moorland on northern Dartmoor.
Area, **17(3)**, 193-203.

Moore, P.D. (1968) Human influence upon Vegetational History in North Cardiganshire.
Nature, **217**, 1006-1009.

Moore, P.D., Webb, J.A. and **Collinson, M.E.** (1991) *Pollen Analysis.*
Blackwell Scientific Publications, London. Second edition. pp 216.

Mörner, N-A, (1971) Eustatic changes during the last 20,000 years and a method of separating the isostatic and eustatic factors in an uplifted area.
Palaeogeography, palaeoclimatology and palaeoecology, **9**, 153-181.

Movius, H. (1942) The Irish Stone Age.
Cambridge University Press, Cambridge.

Naumaan, E. (1932) Grundzüge der regionalen Limnologie.
In, **Thienemann, A.** (ed) *Die Binnengewässer. Band II. E.*
Schweizerbart'sche Verlagsbuchhandlung, Stuggart.

Olsson, I.U. (1972) The pretreatment of samples and the interpretation of the results of C14 determinations.
Acta Universitatis Ouluensis A 3 Geology, **1**, 9-37.

Olsson, I.U. (1979) A warning against radiocarbon dating of samples containing little carbon.
Boreas, **8**, 203-207.

Orford, J.D., Carter, R.W.G., and **Jennings, S.C.** (1991) Coarse Clastic Environments: Evolution and Implications for Quaternary Sea Level Interpretation.
Quaternary International, **9**, 87-104.

Orford, J.D., Carter, R.W.G., McKenna, J. and **Jennings, S.C.** (1995) The relationship between the rate of mesoscale sea-level rise and the rate of retreat of swash-aligned gravel dominated barriers.
Marine Geology, **124**, 177-186.

Palmer, A.J.M. and **Abbott, W.H.** (1986) Diatoms as indicators of sea-level change.
In, **van de Plaasche, O.** (ed) *Sea-level research: a manual for the collection and evaluation of data.*
Geo Books, Norwich. Chapter 16, 457-487, pp618.

Patrick, R. and **Reimer, C.W.** (1966) *The Diatoms of the United States. Exclusive of Alaska and Hawaii. Volumes1* (pp 688) *and 2* (pp 213).
Monographic series of Academy of Natural Sciences of Philadelphia # 13, Pennsylvannia.

Peacock, J.D. (1971) Marine shell radiocarbon dates and the chronology of deglaciation in western Scotland.
Nature, Physical Sciences, **230**, 43-45.

Peacock, J.D. (1975) Scottish late and post-glacial marine deposits.
In, **Gemmell, A.M.D.** (ed) *Quaternary studies in North East Scotland*, 45-48.
Aberdeen University, Aberdeen.

Peacock, J.D. (1993) Late Quaternary marine molluscs as palaeoenvironmental proxies: A compilation and assessment of basic numerical data for NE Atlantic species found in shallow water.
Quaternary Science Reviews, **12**, 263-275.

Peacock, J.D. (1997) Was there a readvance of the British ice sheet into the North Sea between 15ka and 14ka BP?
Quaternary Newsletter, **81**, 1-8.

Peacock, J.D., Graham, D.K., Robinson, J.E. and **Williamson, I.P.** (1977) Evolution and chronology of late-Glacial marine environments at Lochgilphead, Scotland.
In, **Gray, J.M.** and **Lowe, J.J.** (eds) *Studies in the Scottish Lateglacial Environment.*
Pergamon Press, Oxford. 89-100.

Peacock, J.D., Graham, D.K., and **Wikinson, I.P.** (1978) Late-glacial and Post-glacial marine environments at Ardyne, Scotland, and their significance in the interpretation of the history of the Clyde sea area.
Report of the Institute of Geological Sciences, **78/17**, pp25.

Peacock, J.D., Graham, D.K. and **Wilkinson, I.P.** (1980) Late and Post-glacial marine environments in part of the Inner Cromarty Firth, Scotland.
Institute of Geological Sciences Report, **80**, 1-11.

Peacock, J.D. and **Harkness, D.D.** (1990) Radiocarbon ages and the full-glacial to Holocene transition in seas adjacent to Scotland and southern Scandinavia: a review.
Transactions of the Royal Society of Edinburgh: Earth Sciences, **81**, 385-396.

Peach, B.N., Horne, J., Woodward, H.B., Clough, C.T., Harker, A. and **Wedd, C.B.** (1910) *The Geology of Glenelg, Lochalsh and south-east part of Skye.*
Memoir of the Geological Survey of the United Kingdom.

Peck, R.M. (1973) Pollen budget studies in a small Yorkshire catchment.
In, **Birks, H.J.B.** and **West, R.G.** (eds) *Quaternary Plant Ecology*
Blackwell Scientific Publishers, Oxford, 43-60.

Peglar, S.M. (1993) The mid-Holocene decline at Diss Mere, Norfolk, UK: a year-by-year pollen stratigraphy from annual laminations.
The Holocene, **3(1)**, 1-13.

Peglar, S.M., Fritz, S.C. and **Birks, H.J.B.** (1989) Vegetation and land use at Diss, Norfolk, U.K..
Journal of Ecology, **77**, 203-222.

Peglar, S.M. and **Birks, H.J.B.** (1993) The mid-Holocene *Ulmus* fall at Diss Mere, South-East England-disease and human impact?
Vegetation History and Archaeobotany, **2**, 61-68.

Pilcher, J.R. (1991) Radiocarbon Dating.
In, **Smart, P.L.** and **Frances, P.D.** (eds) *Quaternary Dating Methods- A user's guide.*
Quaternary Research Association technical Guide no. 4, Cambridge. Chapter 2. pp 233. 16-36.

Prentice, I.C. (1988) Records of vegetation in time and space: the principles of pollen analysis.
In, **Huntley, B.** and **Webb, T.** (eds) *Vegetation History*
Kluwer Academic Publishers, Dordrecht, 18-42.

Prince, H.E. (1988) *Lateglacial and Post-glacial sea-level movements in North Wales with particular reference to techniques for the analysis and interpretation of unconsolidated estuarine sediments.*
Unpublished PhD thesis, University of Wales.

Rackham, O. (1980) *Ancient Woodland: its History, Vegetation and Uses in England.*
Edward Arnold, London.

Richards, A. (1969) Some aspects of the evolution of North-East Skye.
Scottish Geographical, **85**, 122-131.

Richards, A. (1971) *The evolution of marine cliffs and related landforms in the Inner Hebrides.*
Unpublished PhD Thesis. University of Wales.

Ritchie, W. (1966) The post-glacial rise in sea level and coastal changes in the Uists.
Transactions of the Institute of British Geographers, **39**, 79-86.

Ritchie, W. (1979) Machair development and chronology of the Uists and adjacent islands.
Proceedings of the Royal Society of Edinburgh, **B77**, 107-122.

Ritchie, W. (1985) Inter-tidal and sub-tidal organic deposits and sea-level changes in the Uists, Outer Hebrides.
Scottish Journal of Geology, **21**, 161-76.

Robinson, M. (1982) Diatom analysis of early Flandrian lagoon sediments from East Lothian, Scotland.
Journal of Biogeography, **9**, 207-22.

Robinson, M. (1993) Microfossil analysis and radiocarbon dating of depositional sequences related to Holocene sea-level change in the Forth Valley, Scotland.
Transactions of the Royal Society of Edinburgh: Earth Sciences, **84**, 1-60.

Robinson, M. and **Ballantyne, C.K.** (1979) Evidence for a glacial readvance pre-dating the Loch Lomond Advance in Wester Ross.
Scottish Journal of Geology, **15**, 271-277.

Roy, P.S., Cowell, P.J., Ferland, M.A. and **Thom, B.G.** (1994) Wave-dominated coasts. In, **Carter, R.W.G.** and **Woodroffe, C.D.** (eds) *Coastal Evolution. Late Quaternary shoreline morphodynamics.*
Cambridge University Press, Cambridge. Chapter 4, 121-186, pp517.

Scott, D.B. and **Medioli, F.S.** (1986) Foraminifera as sea level indicators.
In, **van de Plaasche, O.** (ed) *Sea-level research: a manual for the collection and evaluation of data.*
Geo Books, Norwich. Chapter 15, 435-456, pp618.

Scottish Natural Heritage and **British Geological Survey** (1993) *Skye: a landscape fashioned by geology.*
Scottish Natural Heritage, Battleby, pp23.

Seaward, D.R. (1982) (ed) *Sea Area Atlas of the Marine Molluscs of Britain and Ireland.*
Nature Conservancy Council, Shrewsbury.

Sejrup, H.J., Haflidason, H., Aarseth, I., King, E., Forsbeg, C.F., Long, D. and **Rokoengen, K.** (1994) Late Weichselian glaciation history of the northern North Sea.
Boreas, **23**, 1-13.

Shennan, I. (1982) Interpretation of Flandrian sea-level data from the Fenland, England.
Proceedings of the Geologists Association, **83(1)**, 53-63.

Shennan, I. (1983) A problem of definition in sea-level research methods.
Quaternary Newsletter, 17-19.

Shennan, I. (1986) Flandrian sea-level changes in the Fenland. II: Tendencies of sea-level movement, altitudinal changes, and local regional factors.
Journal of Quaternary Science, **1(2)**, 155-179.

Shennan, I., Innes, J.B., Long, A.J. and **Zong, Y.** (1993) Late Devensian and Holocene relative sea level changes at Rumach, near Arisaig, northwest Scotland.
Norsk Geologisk Tidsskrift, **73**, 161-174.

Shennan, I., Innes, J.B., Long, A.J. and **Zong, Y.** (1994) Late Devensian and Holocene relative sea level changes at Loch nan Eala, near Arisaig, northwest, Scotland.
Journal of Quaternary Science, **9**, 261-81.

Shennan, I., Innes, J.B., Long, A.J. and **Zong, Y.** (1995a) Late Devensian and Holocene relative sea-level changes in northwestern Scotland: New data to test existing models.
Quaternary International, **26**, 97-123.

Shennan, I., Innes, J.B., Long, A.J. and **Zong, Y.** (1995b) Holocene relative sea level changes and coastal vegetation history at Kentra Moss, Argyll, northwest Scotland.
Marine Geology, **124**, 43-59.

Shennan, I., Rutherford, M.M., Innes, J.B. and **Walker, K.J.** (1996) Lateglacial and ocean margin environmental changes interpreted from biostratigraphic and lithostratigraphic studies of isolation basins in northwest Scotland.
In, **Andrews, J.T., Austin, W.E.N., Bergsten. H.** and **Jennings, A.E.** (eds) Late *Quaternary Palaeoceanography of the North Atlantic margins.*
Geological Society Special Publication **No. 111**, 229-244.

Sissons, J.B. (1966) Relative sea level changes between 10300-8300 B.P. in part of the Carse of Stirling.
Transactions of the Institute of British Geographers, **39**, 19-29.

Sissons, J.B. (1967) *The evolution of Scotland's Scenery.*
Oliver and Boyd, London.

Sissons, J.B. (1969) Drift stratigraphy and buried morphological features in the Grangemouth-Falkirk-Airth area, central Scotland.
Transactions of the Institute of British Geographers, **48**, 19-50.

Sissons, J.B. (1972) Dislocation and non-uniform uplift of raised shorelines in the western part of the Forth Valley.
Transactions of the Institute of British Geographers, **55**, 145-159.

Sissons, J.B. (1974) Lateglacial marine erosion in Scotland.
Boreas, **3**, 41-8.

Sissons, J.B. (1976) Lateglacial marine erosion in south-east Scotland.
Scottish Geographical Magazine, **92**, 17-29.

Sissons, J.B. (1977) The Loch Lomond Readvance in southern Skye and some palaeoclimatic implications.
Scottish Journal of Geology, **13**, 23-36.

Sissons, J.B. (1979) Palaeoclimatic inferences from former glaciers in Scotland and the Lake District.
Nature, **278**, 518-521.

Sissons, J.B. (1980) Palaeoclimatic inferences from former Loch Lomond Advance glaciers.
In, **Lowe, J.J.**, **Gray, J.M.** and **Robinson, J.E.** (eds) *Studies in the Lateglacial of North-west Europe.*
Pergamon Press, Oxford, 31-43.

Sissons, J.B. (1981) Lateglacial marine erosion and a jökulhlaup deposit in the Beauly Firth.
Scottish Journal of Geology, **15**, 7-19.

Sissons, J.B. (1982) The so called high "interglacial" rock platform of western Scotland.
Transactions of the Institute of British Geographers, NS, **7**, 205-16.

Sissons, J.B. (1983a) The Quaternary geomorphology of the Inner Hebrides: a review and reassessment.
Proceedings of the Geological Association, **94**, 165-175.

Sissons, J.B. (1983b) Shorelines and Isostasy in Scotland.
In, **Smith, D.E.** and **Dawson, A.G.** (eds) (1983) *Shorelines and Isostasy. Institute of British Geographers Special Publication, No.16.*
Academic Press, London. Chapter 9, 209-225. pp387.

Sissons, J.B. and **Smith, D.E.** (1965) Peat bogs in a postglacial sea and a buried raised beach in the western part of the Carse of Stirling.
Scottish Journal of Geology, **1**, 247-55.

Sissons, J.B., **Smith, D.E.** and **Cullingford, R.A.** (1966) Late-glacial and post-glacial shorelines in south-east Scotland.
Transactions of the Institute of British Geographers, **39**, 9-18.

Sissons, J.B. and **Brooks, C.I.** (1971) Dating of early postglacial land and sea level changes in the western Forth Valley.
Nature Physical Science, **234**, 124-7.

Sissons, J.B. and **Dawson, A.G.** (1981) Former sea-levels and ice limits in part of Wester Ross, northwest Scotland.
Proceedings of the Geologists' Association, **92(2)**, 115-124.

Sissons, J.B. and **Cornish, R.** (1982) Differential glacio-isostatic uplift of crustal blocks at Glen Roy, Scotland.
Quaternary Research, **18**, 268-288.

Sloss, L.L. (1962) Stratigraphic models in exploration.
Journal of Sedimentology and Petrology, **32**, 415-422.

Smart, P.L. (1991) General Principles.
In, **Smart, P.L.** and **Frances, P.D.** (eds) *Quaternary Dating Methods- A user's guide.*
Quaternary Research Association technical Guide no. 4, Cambridge. Chapter 1, 1-16, pp233.

Smith, A.G. (1970) Late and Post-Glacial vegetational and climatic history of Ireland: a review.
In, **Stephens, N.** and **Glasscock, R.E.** (eds) *Irish Geographical Studies in Honour of E. Estyn Evans.*
Department of Geography, The Queen's University Belfast, Belfast, 65-88.

Smith, D.E. (1968) Post-glacial displaced shorelines in the surface of the carse clay on the north bank of the River Forth, in Scotland.
Zeitschift für Geomorphologie, NF, **12**, 388-408.

Smith, D.E., Sissons, J.B. and **Cullingford, R.A.** (1969) Isobases for the Main Perth Raised Shorelines in south-east Scotland as determined by trend-surface analysis.
Transactions of the Institute of British Geographers, **46**, 46-52.

Smith, D.E., Thompson, K.S.R. and **Kemp, D.D.** (1978) The Late Devensian and Flandrian history of the Teith Valley, Scotland.
Boreas, **7**, 97-107.

Smith, D.E, Cullingford, R.A. and **Seymour, W.P.** (1982) Flandrian relative sea level changes in the Philorth Valley, north-east Scotland.
Transactions of the Institute of British Geographers, NS, **7**, 321-6.

Smith, D.E, Cullingford, R.A. and **Brooks, C.L.** (1983) Flandrian relative sea level changes in the Ythan Valley, Northeast Scotland.
Earth Surface Processes and Landforms, **8**, 423-438.

Smith, D.E. and **Cullingford, R.A.** (1985) Flandrian relative sea level changes in the Montrose Basin area.
Scottish Geographical Magazine, **101**, 92-104.

Smith, D.E., Dawson, A.G., Cullingford, R.A. and **Harkness, D.D.** (1985) The stratigraphy of Flandrian relative sea level changes at a site in Tayside, Scotland.
Earth Surface Processes and Landforms, **10**, 17-25.

Smith, D.E., Turbayne, S.C., Dawson, A.G. and **Hickey, K.R.** (1991) *The temporal and spatial variability of major floods around European coasts.*
Final report of work undertaken by Coventry Polytechnic for the Commission of the European Communities under contract EV4C 0047 UK (H), pp512.

Smith, D.E., Firth, C.R., Turbayne, S.C. and **Brooks, C.L.** (1992) Holocene relative sea level changes and shoreline displacement in the Dornoch Firth area, Scotland.
Proceedings of the Geologists' Association , **103**, 237-257.

Stace, C. (1991) *New flora of the British Isles.*
Cambridge University Press, Cambridge. pp1178.

Strief, H. (1989) Barrier islands, tidal flats and coastal marshes resulting from a relative rise of sea level in East Frisia on the German North Sea Coast.
Proceedings KNGMG Symposium "Coastal lowlands, Geology and Geotechnology" 1987 213-223.

Stuiver, M. and **Reimer, P.J.** (1993) Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program.
Radiocarbon, **35**, 215-230.

Stuiver, M., Long, A., Kra, R.S. and **Devine, J.M.** (1993) Calibration-1993.
Radiocarbon, **35(1)**.

Sutherland, D.G. (1980) Problems of Radiocarbon Dating Deposits from Newly Deglaciated Terrain: Examples from the Scottish Lateglacial.
In, **Lowe, J.J., Gray, J.M.** and **Robinson, J.** (eds) *Studies in the Lateglacial of North-West Europe.* Pergamon Press. 139-149, pp205.

Sutherland, D.G. (1981) *The raised shorelines and deglaciation of the Loch Long/Loch Fyne area, Western Scotland.* Unpublished PhD thesis, University of Edinburgh.

Sutherland, D.G. (1983) The dating of former shorelines.
In, **Smith, D.E.** and **Dawson, A.G.** (eds) *Shorelines and Isostasy. Institute of British Geographers, Special Publication, No. 16.*
Academic Press, London. Chapter 6, 129-157, pp387.

Sutherland, D.G. (1984) The Quaternary deposits and landforms of Scotland and the neighbouring shelves: A review.
Quaternary Science Reviews, **3**, 157-254.

Sutherland, D.G. (1987) Dating and Associated Methodological Problems in the Study of Quaternary Sea-Level Changes.
In, **Devoy, R.J.N.** (ed) *Sea Surface Studies. A Global View.*
Croom Helm, London. Chapter 6. 165-197.

Sutherland, D.G. (1991) Late Devensian glacial deposits and glaciation in Scotland and the adjacent offshore region.
In, **Ehlers, J., Gibbard, P.L.** and **Rose, J.** (eds) *Glacial deposits in Great Britain and Ireland.*
A.A. Balkema, Rotterdam, 121-127.

Synge, F.M. (1977) Records of sea levels during the Late Devensian.
Philosophical Transcations of the Royal Society of London, **B280**, 211-228.

Synge, F.M. and **Smith, J.S.** (1980) *A Field Guide to the Inverness area.*
Quaternary Research Association, Aberdeen.

Talma, A.S. and **Vogel, J.C.** (1993) A simplified approach to calibrating C14 dates.
Radiocarbon, **35(2)**, 317-322.

The Little Minch Sheet 1795 (1994)
International Chart Series, Taunton.

Tinsley, H.M. and **Smith, R.T.** (1974) Surface pollen studies across a woodland/heath transition and their application to the interpretation of pollen diagrams.
New Phytologist, **73**, 547-565.

Tooley, M.J. (1978) *Sea-level changes. North-West England during the Flandrian Stage.*
Clarendon Press, Oxford.

Traverse, A. (1988) *Paleopalynology.*
Allen and Unwin Inc., Winchester, 375-430.

Troels-Smith, J. (1955) *Characterization of Unconsolidated Sediments.*
Danmarks Geologiske Undersøgeise, **IV(3)**, 10.

Turner, J. (1964) Surface sample analyses from Ayrshire, Scotland.
Pollen et Spores, **VI (2)**, 583-592.

van de Plaasche, O. (1982) *Compaction and other sources of error in Obtaining Sea-Level Data: Some results and Consequences.*
Eiszeitalter u. Gegenwart, **30**, 171-181.

van de Plaasche, O. (1986) (ed) *Sea-level research: a manual for the collection and evaluation of data.*
Geo Books, Norwich. pp618.

van den Hoek, C., Admiraal, W., Clijn, F. and **de Jonge, V.N.** (1979) The role of algae and seagrasses in the ecosystem of the Wadden Sea: A review.
In, **Wolff, W.J.** (ed) *Flora and vegetation of the Wadden Sea. Report 3.*
Stichting Veth tot Steun aan Waddenonderzoek, Leiden. pp 118.

van der Werff, A. and **Huls, H.** (1957-1974) *Diatomeeënflora van Nederland.*
Otto Koeltz Science Publishers, West Germany (reprinted, 1976).

Vasari, Y. (1977) Radiocarbon dating of the Lateglacial and Early Flandrian Vegetational Succession in the Scottish Highlands and the Isle of Skye.
In, **Gray, J.M.** and **Lowe, J.J.** (eds) *Studies in the Scottish Lateglacial Environment.*
Pergamon Press, Oxford, 143-162.

Vasari, Y. and **Vasari, A.** (1968) Late and Postglacial macrophytic vegetation in the lochs of Northern Scotland.
Acta Botanica Fennica, **80**, 1-20.

Vogel, J.C., Fuls, A., Visser, E. and **Becker, B.** (1993) Pretoria Calibration curve for short lived samples.
Radiocarbon, **35(1)**, 73-86.

Vos, P.C. and **de Wolf, H.** (1988) Methodological aspects of palaeoecological diatom research in coastal areas of the Netherlands.
Geologie en Mijnbouw, **67**, 31-40.

Vos, P.C. and **de Wolf, H.** (1993) Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects.
Hydrobiologia, **269/270**: 285-296.

Walker, M.J.C. and **Lowe, J.J.** (1987) Flandrian environmental history of the Isle of Mull, Scotland III. A high-resolution pollen profile from Gribun, western Mull.
New Phytologist, **106**, 333-347.

Walker, M.J.C. and **Lowe, J.J.** (1990) Reconstructing the Environmental History of the Last Glacial-Interglacial Transition: Evidence from the Isle of Skye.
Quaternary Science Reviews, **9**, 15-49.

Walker, M.J.C. and **Lowe, J.J.** (1991) Vegetational history of the Isle of Skye I. The Late Devensian Lateglacial Period (13-10ka BP)
In, **Ballantyne, C.K., Benn, D.I., Lowe, J.J.** and **Walker, M.J.C.** (eds) *The Quaternary of the Isle of Skye.* QRA, Cambridge, Chapter 7, 98-118, pp 172.

Walker, M.J.C., Ballantyne, C.K., Lowe, J.J. and **Sutherland, D.G.** (1988) A reinterpretation of the Lateglacial environmental history of the Isle of Skye, Inner Hebrides, Scotland. *Journal of Quaternary Science*, **3**, 135-146.

Walker, M.J.C., Bohncke, S.J.P., Coope, G.R., O'Connell, M., Usinger, H. and **Verbruggen, C.** (1994) The Devensian/Weichselian Late-glacial in northwest Europe (Ireland, Britain, north Belgium, The Netherlands, northwest Germany). *Journal of Quaternary Science*, **9(2)**, 109-118.

Walther, M. (1984) *Geomorphologische Untersuchungen zum Spätglazial und Früholozän in den Cuillin Hills (Insel Skye, Schottland).* Unpublished PhD thesis, Free University of Berlin.

West, R.G. (1970) Pollen zones in the Pleistocene of Great Britain and their correlation. *New Phytologist*, **69**, 1179-1183.

West, R.G. (1980) *The pre-glacial Pleistocene of the Norfolk and suffolk coasts.* University Press, Cambridge, 1-11.

Whittington, G. and **Edwards, K.J.** (1993) Vegetation change on Papa Stour, Shetland, Scotland: a response to coastal evolution and human interference? *The Holocene*, **3(1)**, 54-62.

Williams, W. (1977) *The Flandrian Vegetational History of the Isle of Skye and the Morar Peninsula.* Unpublished PhD thesis, University of Cambridge.

Wohlfarth, B., Björck, S., Possnert, G., Lemdahl, G., Brunnberg, L., Ising, J., Olsson, S. and **Svensson, N.O.** (1993) AMS dating Swedish varved clays of the last interglacial/glacial transition and the potential/difficulties of calibrating Late Weichselian 'absolute' chronologies. *Boreas*, **22**, 113-128.

Wright, W.B. (1911) On a preglacial shoreline in the western Isles of Scotland. *Geological Magazine, Decade 5*, **8**, 97-109.

Zong, Y. and **Tooley, M.J.** (1996) Holocene sea-level changes and crustal movements in Morecambe Bay, northwest England. *Journal of Quaternary Science*, **11(1)**, 43-58.