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Foraminiferal Ecology of Contemporary Isolation Basins in Northwest Scotland

Volume One:

Main Text, Tables, and References

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Philip Damien Laidler

Thesis submitted for the degree of Doctor of Philosophy.

*Department of Geography,
University of Durham*

January 2002



14 JUN 2002

For my Mum, Sister, and Alison Scott.

In memory of my Father.

Declaration

This thesis is the result of my own work. Data from other authors contained herein are acknowledged at the appropriate point in the text.

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Damien Laidler

Durham, January 2002

Abstract

Foraminiferal Ecology of Contemporary Isolation Basins in Northwest Scotland

Damien Laidler, University of Durham, January 2002

Isolation basins contain high-resolution records of environmental change relating to RSL and climate since the last glacial maximum, and provide valuable data in constraining regional and global ice sheet and earth rheology models. A key weakness in current research is a lack of information regarding the identification of the reference tide level of different stages of basin isolation, and the role of factors such as freshwater input in controlling palaeosalinity. To address these issues, this thesis reports data collected from modern isolation basins from twenty sites in northwest Scotland.

The basins range in size and elevation of their sill within the tidal cycle. Surface sediment samples were analysed for their foraminiferal composition, and other analyses of water chemistry and sedimentology were completed. Statistical analyses show a poor correlation between sill altitude and fauna. A transfer function was therefore produced based on average salinity, but calibration of this using fossil data was unsuccessful. This research demonstrates that the modern training set lacks adequate analogues for many of the fossil foraminiferal assemblages recorded in previous work. Likely causes for this include differences in the relative abundance of foraminiferal species between the modern and fossil data-sets, and the fact that no modern basin was found which has the water depth and salinity required for reconstruction of the fully marine stage.

Because of these factors, foraminiferal data should be used with care in the definition of the indicative meaning of isolation basin sea-level index points. The statistical methods do, however, yield the first detailed understanding of the distributions of foraminifera in contemporary shallow water isolation basins, particularly with reference to their optimum and tolerance values for environmental variables. Variable salinity species such as *Miliammina fusca* are dominant in the training set, displaying their broad tolerance of environmental conditions.

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Introduction

1.1 BACKGROUND

Isolation basins have been used extensively in the reconstruction of former sea-levels through detailed lithostratigraphic, biostratigraphic and chronostratigraphic analyses (e.g. Kjemperud, 1981a; Retelle *et al.*, 1989; Long *et al.*, 1999; Shennan *et al.*, 2000a). These studies have been carried out in formerly-glaciated areas such as Scandinavia, Greenland, Russia, Canada and the west coast of Scotland, where examination of the lithostratigraphy and microfossils provide evidence of changes from a marine to freshwater environment within the basin (isolation), or *vice versa* (connection).

Generally, isolation basins provide a high-resolution record of sea-level index points. This record has been interpreted using pollen, diatoms and, more recently, foraminifera and thecamoebians (testate amoebae). The data obtained have then been used in the testing and fine-tuning of models. These include relative sea-level age-altitude curves and isobase models (e.g. Shennan *et al.*, 1995; Long *et al.*, 1999), and models of ice sheet extent and isostatic rebound such as those of Lambeck (e.g. 1993b; Shennan *et al.*, 2000a).

The methodology of isolation basin studies has evolved substantially from the earliest work in Scandinavia (believed to be Sundelin in 1919). This has transpired through the development of microfossil studies, the use of absolute dating methods (including the increased accuracy introduced by AMS dating), and in the higher resolution of results which are now sought from the records in isolation basins. This development has occurred particularly through the work on the northwest coast of Scotland by Shennan *et al.* (1993, 1994, 1995, 1996a, 1996b, 1999, 2000a).



It was essential that such developments were implemented in order to improve the interpretation of the high-resolution record contained within the fossil basins, especially considering the low amount of uplift and large tidal range around Scotland in comparison to that of Scandinavia and many other areas with isolation basins. One of the aims within this advance was to attempt to identify the indicative meaning at which the isolation of basins occurs; the indicative meaning being the vertical relationship between the local environment in which a sea-level indicator accumulated and a contemporaneous reference tide level (e.g. Shennan, 1982; van de Plassche, 1986). This would begin to take account of the often prolonged isolation process in Scotland caused by the low rate of uplift and significant tidal range (e.g. Shennan *et al.*, 1999; Lloyd, 2000) by identifying at precisely what point in the tidal cycle a basin becomes isolated.

The main difference between isolation basins and other coastal environments in considering the indicative meaning of a sea-level indicator is that it is not the elevation of a sample relative to sea-level which controls the indicative meaning of that sample. Instead, it is the elevation of the basin sill to which the indicative meaning of a sample must be related, as it is this which controls the marine input.

The process of determining the indicative meaning of basin isolation is complicated by the fact that it is not uniform between basins. Shennan *et al.* (1995; 2000a) and Lloyd (2000) identify freshwater input as one of the factors which will control salinity within the basin. They believe that a basin with a significant freshwater input will isolate when its sill is lower in the tidal cycle than one which has little or no freshwater input. How much lower in the tidal cycle a basin will isolate when it receives a given freshwater input has not yet been quantified, however, as there is no existing published work investigating the range of processes and environments which occur within modern isolation basins (i.e. those basins which currently have varying degrees of restricted exchange with a marine environment).

In this thesis a number of modern basins are investigated in terms of the diversity and variability of the processes occurring within them, and the foraminifera which they contain. The work is necessarily founded upon a detailed, consistent methodology to ensure that the full range of environments is covered, and that

statistical analyses may be accurate. From this, it is hoped to achieve a more detailed understanding of the isolation basin environment at different stages in the tidal cycle, in order that more precise results can be obtained from the high-resolution RSL record contained in fossil isolation basins in Scotland. As this is a CASE (Co-operative Awards in the Science of the Environment) studentship, in collaboration with Scottish Natural Heritage, those sites or types of sites which are valuable in the interpretation of the RSL record will also be identified, along with any apparent threats to their continued existence. This will assist in making conservation management recommendations for isolation basins on the grounds of importance to research and their educational value in improving public awareness and understanding.

1.2 RESEARCH CONTEXT

1.2.1 Research Aims

This thesis has the following research aims:

- i. Identify and quantify the importance of the variables that control patterns of isolation basin sedimentation, including the presence and distribution of their biota, in order that the precision of sea-level and environmental reconstructions may be improved.
- ii. Evaluate the applicability of presently used methods of statistical environmental reconstruction methods to isolation basin environments, and assess the importance of sill elevation in determining the indicative meaning of a basin.
- iii. Identify those isolation basin sites with the best regional, national and international records of RSL changes, and develop recommendations for their conservation management.

1.2.2 Research Objectives

The research aims will be addressed using the following objectives:

- i. Develop a methodological approach which considers the inputs, process and outputs associated with the isolation basin environment, and allows an accurate, systematic study of that environment, and the foraminifera which it contains.
- ii. Identify the environmental variable(s) which control the foraminiferal assemblages within modern isolation basins.
- iii. Identify the effects of seasonality and intra- and inter-basin variability upon the isolation basin environment and any general or site-specific trends which occur in the environmental and / or biological data.
- iv. Develop a transfer function for foraminifera in isolation basins, based upon the environmental variable of interest, and test its applicability to fossil isolation basins using a number of statistical techniques on a range of fossil data.
- v. Apply the resulting transfer function to fossil sites, in order to reconstruct aspects of the former environment. If the transfer function is unsuccessful, investigate the probable reasons behind this, and discuss how the methods of sampling could be improved in future research, and the implications of this result for the use of isolation basins in reconstructing RSL.
- vi. Review the distribution of isolation basins and assess the significance of this type of record in RSL reconstruction.
- vii. Provide an interpretation of isolation basins and their use in the reconstruction of RSL, at both site-specific and broader levels, for the purpose of education.

1.3 THESIS STRUCTURE

This thesis is split into two volumes:

VOLUME ONE – Text and Tables

Chapter Two considers the use of data from fossil isolation basins, in terms of their importance in the reconstruction of former RSL, their potential applications, and the levels of accuracy inherent within them, and also begins to consider the processes in operation in modern isolation basins or saline lagoons.

Chapter Three outlines in detail the methods used in selecting appropriate sites, and the methodology employed in collecting the data from modern isolation basins for this research. It also considers the use of foraminifera in this study, and the associated implications of this.

Chapter Four summarises the three field areas used in the research, and provides a detailed introduction to each individual basin. It also introduces the Marine Nature Conservation Review (MNCR) survey of saline lagoons, which was carried out following their listing as a priority habitat in the 1992 EC Habitats Directive.

Chapter Five describes the contemporary foraminiferal distribution and environments within the study sites, focusing on three examples in particular. The combined modern training set which will be used in the statistical analyses is introduced. The basic relationships between the foraminiferal species and their environment within the combined modern training set are investigated, and the foraminiferal ecology within each of the groups identified by cluster analysis is identified.

Chapter Six tests the foraminiferal assemblages identified by cluster analysis in *Chapter Five*, and determines the relationship between a screened foraminiferal training set and the pre-selected environmental variables. From this a transfer function is developed, based on the average salinity of each sample. The performance of the transfer function is tested using foraminiferal data from three fossil isolation basin cores.

Chapter Seven discusses the implications of the findings of *Chapter Six* for RSL reconstruction using isolation basins, and assesses the applicability of commonly

used statistical environmental reconstruction techniques to isolation basin environments. Potential improvements to the sampling strategy for modern isolation basins are suggested for future research, and developments in the understanding of isolation basin environments and the ecology of individual foraminiferal species gained through this research are outlined.

Chapter Eight considers the conservation management of modern and fossil isolation basins, and the potential changes which can occur in this environment, both naturally and through anthropogenic activity. The focus is largely on the fossil basins, as these are currently unprotected from human activity, with implications for the accuracy of reconstructions if modifications are made, particularly to the sill. Named sites are recommended for inclusion in the Geological Conservation Review (GCR) and / or for protection through conservation designations.

Chapter Nine presents the conclusions of this thesis, assesses the success of the research in meeting the aims and objectives, evaluates the methodology employed, and summarises recommendations for future research.

VOLUME TWO – Figures and Appendices

The figures and plates for the thesis are grouped in order, according to the chapter number.

Appendix One outlines the methods employed in levelling the sill altitudes, and the preparation of samples and cross-checking of results in the laboratory.

Appendix Two provides a list of all foraminiferal species in the modern training set.

Appendix Three gives a graphical presentation of the foraminiferal and environmental data from the seventeen individual sites not discussed in detail in *Chapter Five*, but included in the combined modern training set.

Appendix Four presents the formulation of the Standardised Water Level Index, which was used to standardise the elevation of each basin sill relative to its local tidal range.

Appendix Five presents tabulated results from the calibration and testing of the transfer function using fossil data.

Saline Lagoons, Isolation Basins and their Application to Sea-Level Studies

2.1 INTRODUCTION

Isolation basins are natural coastal rock depressions which may have been isolated from or connected to the sea by changes in relative sea-level (RSL) or, more recently, by anthropogenic activity. Their use in investigations of RSL change has been stressed by research undertaken in areas such as Scandinavia, Greenland and Scotland, providing well-constrained age and altitude information for RSL (sea-level index points) in areas, such as the north and west coasts of Scotland, where the comparative dearth of morphological, stratigraphical and biogenic material has severely impeded previous research (Gray, 1983; Shennan, 1989, 1992). The data obtained from them have also been employed in the testing of hypotheses often derived from morphological work (Shennan *et al.*, 1993, 1994, 1995, 1996a, 1996b). The features do not, however, always provide the desired levels of accuracy on a regional and/or local basis, owing to restrictions in their spatial distribution and difficulties in accounting for sources of error, respectively.

This chapter considers the following issues:

- The processes operating within modern isolation basins.
- The effectiveness of fossil isolation basins in reconstructions of RSL.
- The research methodologies developed for the interpretation of fossil basins.
- The contribution of fossil isolation basins to the present understanding of sea level - ice sheet - land movement interactions.
- The current constraints upon the interpretation of sea-level index point data determined from fossil isolation basins.

2.2 CONTEMPORARY PROCESSES IN MODERN ISOLATION BASINS

Modern isolation basins (i.e. those with an intertidal sill) may also be termed saline lagoons, and further classified as silled, isolated, sluiced, or inlet (with a sill) types, under the Joint Nature Conservation Committee (1996) classification, with the definition depending upon the degree of isolation from the open sea (Barnes, 1980). Saline lagoons are listed as a priority habitat requiring protection in the European Community Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (the 'Habitats Directive'; Council of the European Communities, 1992).

Lagoons in this sense are interpreted as "expanses of shallow coastal water, of varying salinity and water volume, separated or partially-separated from the sea by sand banks or shingle, or, less frequently, by rocks" (European Commission, 1996). Only those lagoons which are rock-bound would be classed as isolation basins, *sensu stricto*, although one basin used in this study is held behind a thick (*ca.* 10m) shingle barrier, as there is no evidence of marine water seepage.

Any modern isolation basin has a number of inputs and outputs, which vary on a diurnal, seasonal, annual and longer-term basis. An example of the latter is inter-annual climate variability such as that caused by the North Atlantic Oscillation. The marine input is controlled by the elevation of the sill within the tidal cycle, the width of the sill, and the orientation of the basin relative to the coast. Thus, a narrow sill will restrict water exchange more than a wider sill, whilst a long, thin basin, with a sill along its whole length and the longest axis running parallel to the shore, will receive a greater marine input than a similar basin with the longest axis orientated perpendicular to the coast (e.g. Davies and Haslett, 2000). The balance of all inputs and outputs, together with issues such as basin surface area and depth, will determine the environmental conditions within the basin.

Figures 2.1 – 2.3 collectively provide a conceptual model of the changes in a basin through time, based upon changes in inputs and outputs during the isolation process, from marine to freshwater conditions. Figure 2.1 represents a basin with its sill at five different stages of the tidal cycle during a fall in RSL, with the environment changing from fully marine to freshwater conditions. Figure 2.2 is related to this, in

showing the typical changes in the microfossil salinity groups through the five stages, and the basic sediment types which would accompany these changes. Finally, Figure 2.3 shows two conceptual model of perceived changes in the environmental conditions which would occur during the isolation process. Both figures assume constant climatic conditions, but Figure 2.3a assumes a constant linear change in environmental conditions during the isolation process, whilst Figure 2.3b assumes a curvi-linear response. In practice, it is not yet known which model the isolation process follows more accurately.

2.3 RELATIVE SEA-LEVEL

Mean sea-level (MSL) for the UK is taken from the Newlyn tide gauge (1915 – 1921). The altitude of any point in the tidal cycle, at any location, can be calculated using Newlyn as a reference. Mean tide level (MTL) is the mid-point of the tidal range at a given point. Most tides around the world are, however, asymmetrical, causing mean sea-level (MSL) to occur above or below MTL. Sea-level curves based upon MSL are, therefore, actually based upon MTL (Jardine, 1986). The various stages of the tidal cycle, together with the acronyms used for each throughout this thesis, are detailed in Table 2.1.

Stage of Tide	Acronym	Tidal Zone
SUPRATIDAL ZONE		
Highest Astronomical Tide	HAT	
Mean High Water Spring Tide	MHWST	
Mean High Water Neap Tide	MHWNT	
Mean Sea-level*	MSL	
Mean Tide Level	MTL	INTERTIDAL ZONE
Mean Low Water Neap Tide	MLWNT	
Mean Low Water Spring Tide	MLWST	
Lowest Astronomical Tide	LAT	
SUBTIDAL ZONE		

Table 2.1: Tide levels in the inter-tidal zone. *MSL may be above or below MTL.

The general pattern of changes in RSL is produced through the interaction of eustatic and isostatic factors. This signal is, however, then confused by processes operating at the local scale (Shennan *et al.*, 2000b). The change in RSL ($\Delta\xi_{\text{rsl}}$) for each sample or site, at time τ , and location φ , can be expressed schematically as

$$\Delta\xi_{\text{rsl}}(\tau, \varphi) = \Delta\xi_{\text{eus}}(\tau) + \Delta\xi_{>\text{iso}}(\tau, \varphi) + \Delta\xi_{\text{local}}(\tau, \varphi) \quad (1)$$

where $\Delta\xi_{\text{eus}}(\tau)$ is the time-dependent eustatic factor; $\Delta\xi_{>\text{iso}}(\tau, \varphi)$ is the total isostatic effect of glacial rebound, including the contributions from both ice (glacio-isostatic) and water (hydro-isostatic); and $\Delta\xi_{\text{local}}(\tau, \varphi)$ is the total effect of local processes. These local processes can also be expressed schematically as

$$\Delta\xi_{\text{local}}(\tau, \varphi) = \Delta\xi_{\text{tide}}(\tau, \varphi) + \Delta\xi_{\text{sed}}(\tau, \varphi) \quad (2)$$

Where $\Delta\xi_{\text{tide}}(\tau, \varphi)$ is the total effect of changes in the tidal regime, and the elevation of the sediment with reference to tide levels at the time of deposition, and $\Delta\xi_{\text{sed}}(\tau, \varphi)$ is the total effect of sediment consolidation since the time of deposition (Shennan *et al.*, 2000b). It should be noted, however, that in the case of isolation basin processes, $\Delta\xi_{\text{sed}}$ is not likely to be directly relevant.

2.4 FOSSIL ISOLATION BASINS AND THE INTERPRETATION OF FORMER SEA-LEVELS

Sundelin, in 1919, first recognised isolation basins to be depositories of records of RSL change (Svante Bjorck, pers. comm., 1999). They have since been investigated to varying degrees, by numerous researchers, in Scandinavia (e.g. Fægri, 1940; Hafsten and Tallantire, 1978; Kjemperud, 1981a, 1981b, 1986; Svendsen and Mangerud, 1987; Corner and Haugane, 1993; Bondevik *et al.*, 1997a, 1997b, 1998; Eronen *et al.*, 2001), Canada (Retelle *et al.*, 1989), Russia (Snyder *et al.*, 1997; Corner *et al.*, 1999), Greenland (e.g. Foged, 1972, 1973, 1977; Bennike, 1995; Long *et al.*, 1999) and Scotland (e.g. Dickson *et al.*, 1978; Thompson and Wain-Hobson, 1979; Shennan *et al.*, 1993, 1994, 1995, 1996a, 1996b, 2000a; Lloyd, 2000), with Seppä *et al.* (2000) and Eronen *et al.* (2001) believing lake isolation studies to be the most reliable method for reconstructing shore displacement history in areas affected by postglacial uplift.

Studies of isolation basins represent part of a general advance in work on RSL change in the UK. This reflects a shift in emphasis from the largely fragmentary morphological evidence provided by elevated shorelines and glaciofluvial terraces, for which age constraints are usually inferred, to a more detailed lithostratigraphic, biostratigraphic and chronostratigraphic procedure, in which absolute dating techniques are used (cf. Shennan *et al.*, 1993, 1994, 1995, 1996a, 1996b). All isolation basin investigations have, to a degree, sought to obtain similar information (high-resolution RSL data), seeking to elucidate the local, and ultimately the regional, patterns of deglaciation and concomitant RSL change.

Typically, the isolation history of basins can be broken down into three phases, as represented by the sedimentological and biological evidence. Holtedahl (1953) and Hafsten (1983) identified the transitions in depositional conditions of basins throughout the isolation process (Figure 2.4, A, B & C). Kjemperud (1986) developed this further to identify up to four isolation contacts that may occur at the marine – brackish transition in a basin isolated by RSL fall. They are the sediment transition contact, the diatomological (phytological) contact, the hydrological contact, and the sediment / freshwater contact (Figure 2.5). One noticeable difference between the sedimentary units of basins in Scandinavia (e.g. Bondevik *et al.*, 1997b) and Greenland (Long *et al.*, 1999), and those in Scotland is the general lack of a laminated transitional unit, although similar transitions are seen in the biostratigraphy of all basins. Such a unit was observed during a field visit to the upper basin to Loch nan Eala in September 2001, but has only been identified in one core. Possible reasons for this are that a difference in the speed of isolation, climate, lake bottom oxygenation conditions, or water currents largely prevented the formation or preservation of such a unit in the Scottish basins.

The methodological approach to the research, and applications of the data achieved, have developed through the some of the earlier Scandinavian studies (e.g. Kjemperud, 1981a, 1981b, 1986) and, more recently, through research in Scotland by Shennan *et al.* (1993, 1994, 1995, 1996a, 1999). These developments are evident in the latest work on fossil basins in Scotland by Shennan *et al.* (1995, 1996a, 1999, 2000a) and in the work at Disko Bugt, Greenland, by Long *et al.* (1999), primarily with respect to the relation of sea-level index points to a reference water level (e.g. Shennan, 1982, 1992; Shennan *et al.*, 1995) and, in the case of Long *et al.* (1999), attempts to identify the three of the

four isolation/connection contacts of Kjemperud (1986; the sediment / freshwater contact is ignored).

In the morphological work undertaken in Scotland from the mid-nineteenth century (e.g. Chambers, 1848), the inductive approach to the study of raised beaches led Jamieson (1865) to propose the theory of what has been subsequently termed 'glacio-isostasy'. It was not until the pioneering work of Sissons and his students, from 1962 onwards, however, that a more consistent empirical approach (geomorphological mapping and accurate instrumental levelling of all identifiable terraces) was firmly introduced, creating a benchmark for Scottish studies of former RSL (e.g. Sissons, 1962a, 1963; Cullingford and Smith, 1966; Smith *et al.*, 1969).

If the elevated shorelines formed by the process of isostasy were everywhere continuous and horizontal (cf. Sissons, 1962a, 1962b; Earp *et al.*, 1962), the resolution of past sea-levels would be a relatively simple task. However, palaeo-shorelines possess gradients which, on the whole, reflect variations in the rate of uplift, as a consequence of the interplay between a plethora of rheological components and ice mass distribution. Partly as a result of this, preservation of late Quaternary shorelines has been far from perfect, with till deposits and aeolian sand covering many of the remaining features (Sissons, 1962a, 1963). This has led to the rather disjointed morphological evidence of former RSL change, which make inferences of age based upon the correlation of features from one area to another particularly conjectural (e.g. Lambeck, 1993b).

In contrast, in areas such as Scandinavia, Greenland, and North America/Canada, the Weichselian ice sheets were considerably thicker than that which occupied Scotland, resulting in a comparatively higher rate, and greater overall amount of isostatic readjustment, producing well-defined morphological evidence. The identification and dating of isolation contacts in these regions of rapid uplift is also reasonably straightforward, especially when coincident with a micro- or meso-tidal environment, as the transitional (brackish) unit tends to be thin, representing an abrupt isolation process (e.g. Kjemperud, 1986; Long *et al.*, 1999; Shennan *et al.*, 1994, 1995).

However, whilst isolation basins in Scandinavia and Greenland may record RSL changes of 50-100m or more, and experience a present micro- or meso-tidal range of spring tides of 1-2m or less, Scotland, in contrast, has experienced RSL change of a maximum of 30 – 40m near the centre of the ice (but considerably less further from the centre), since the start of the Lateglacial (Windermere) Interstadial, with the present mean spring tidal range being *ca.* 4m around much of the western coast (Shennan *et al.*, 1994). This produces a much longer transitional phase (Zong, 1997; cf. Long *et al.*, 1999) of perhaps 500 - 1000 years or more (Shennan *et al.*, 1996a), to the more extreme 6500 cal years taken for the isolation of Loch nan Corr (Lloyd, 2000), providing a high-resolution record of the isolation process and allowing investigation of the more subtle changes in RSL over several millenia.

As a result of the small amount of uplift and relatively large tidal range, variations in tidal range are often significant when compared to actual differences in RSL change between sites in northwest Scotland (Shennan *et al.*, 1994). It was, therefore, essential that the methodology of Scottish isolation basin studies should focus upon accurate levelling of the basin sill and precise estimation of the indicative meaning (Shennan, 1982; van de Plassche, 1986), using relevant stratigraphical data, such as the isolation contacts identified by Kjemperud (1986). The diatomological contact normally represents a lower reference tide level than the hydrological contact, but a higher tide level than the sedimentological contact (Shennan *et al.*, 1994; Long *et al.*, 1999; Figure 2.5). Without such precision, inter-site differences in the reference tide level may form an appreciable component of what appears to be variation in RSL between locations (Shennan *et al.*, 1994).

Unlike the sea-level research in, for example, Scandinavia, there had been only limited focus on isolation basins in Scotland until the series of papers produced by Shennan *et al.* from the mid-1990s. These latter studies concentrate exclusively on the west coast of the country, where sheltered depositional environments are severely restricted, which, in part, explains the lack of stratigraphic studies in the area (Shennan *et al.*, 1993, 1994, 1995). Isolation basins were investigated as one of three sets of depositional environments (raised tidal flats, isolation basins, and dune/beach systems), reflecting the fact that there is no dominant palaeoenvironment in the area, and in order

to provide a measure of intercalibration of Late Devensian and Holocene RSL changes (Shennan *et al.*, 1993, 1995). Isolation basins and tidal marshes were determined as the providers of the most reliable, precise sea-level data (Shennan *et al.*, 2000a), using a combination of the lithostratigraphical and biostratigraphical records (Shennan *et al.*, 1994).

2.4.1 Sea-level indicators

It was Kjemperud (e.g. 1981b) who began to introduce modifications to the traditional hypothesis-testing methodology employed in isolation basin studies, where radiocarbon dates were obtained for above and below the isolation contact and pollen and macrofossil analyses conducted. Lithostratigraphy was not described to any great extent, or according to a consistent convention, in the published work of the Scandinavian studies, although Kjemperud (1981b) does refer to lithological boundaries in the basins, and the radical transition from the “sediment milieu” controlled by the fjord, to local (basin) control. Kjemperud (1986) progressed to identify the four isolation contacts which may be recognised in basins isolated by RSL fall, as well as employing local diatom assemblage zones as indicators of temporal changes in the water environment (1981b). Kjemperud (1981a) also distinguishes the role of time-bound and time-transgressive factors in the development of microfossil communities in isolation basins.

Shennan *et al.* (1996c) identify the following lithostratigraphical and biostratigraphical techniques as being commonly employed as sea-level indicators.

2.4.1.1 Pollen analysis

Pollen analyses, like diatom analyses, have been widely used during the Scottish isolation basin studies of Shennan *et al.* (1993, 1994, 1995, 1996a, 1996b) in the determination of sea-level tendencies and reference water levels. Pollen was also the microfossil evidence used in the earliest works on isolation basins in Scandinavia (e.g. Sundelin (Svante Bjorck, pers. comm. 1999); Fægri, 1940). As sea-level rises, the transition from terrestrial, to saltmarsh, to marine environments will be recorded in the pollen record.

2.4.1.2 Diatom analysis

Diatoms are widespread microscopic unicellular plants, which normally live in wet, naturally illuminated (photosynthetic) environments (Palmer and Abbott, 1986). The species composition of diatoms is controlled by particular ecological sensitivities, with the primary factors in most cases being salinity, nutrient supply, competition, and, in some environments, pH (Hendey, 1964; Palmer and Abbott, 1986; Shennan *et al.*, 1993).

The resulting diatom assemblage can be used to reconstruct the environmental history (Palmer and Abbott, 1986), and they have been particularly well used in investigations of fossil isolation basins.

A common diatom genus in most isolation basins is *Fragilaria* spp. (a salt-tolerant freshwater type; Zong, 1997), characterising the diatom flora during isolation from the sea, regardless of the time of isolation. The species is thought to reflect nutrient supply during the process (Stabell, 1985). In the Scottish studies, and in some of the lower basins of Arveprinsen Ejland, Disko Bugt (Long *et al.*, 1999), *Paralia sulcata* dominates the ingression and isolation contacts, and is commonly replaced by *Fragilaria* spp., indicating a gradual reduction in marine influence with fluctuating salinities (i.e. a slow isolation process, and/or a relatively large tidal range) (Zong, 1997).

2.4.1.3 Foraminiferal analysis

Foraminiferal assemblages often occur in well-defined altitudinal zones in saltmarsh environments (Scott and Medioli, 1978). In isolation basins, the elevation is, to an extent, standardised by the sill, rendering such vertical zonation more unlikely within basins until one moves towards their intertidal areas. Other environmental factors, such as salinity, are therefore deemed to control the foraminiferal assemblages present in isolation basins. It follows that it is important that the controlling environmental variables on the contemporary foraminiferal distribution are determined before relating the modern data to fossil assemblages for the interpretation of former RSL. Further consideration of this is given in section 3.4.1.

2.4.1.4 Stratigraphical analysis

Kjemperud (1986) lists the sediment transition as one of the four isolation contacts because it typically characterises the visible change from a clastic marine horizon to a transitional lacustrine clay gyttja, before a freshwater gyttja is deposited following isolation (e.g. Retelle *et al.*, 1989). Although this contact is usually the first to occur (and will occur lower down a core than, say, the phytological contact), as the tidal energy entering the basin reduces, lowering the capacity to carry coarser sediments, it provides a useful indicator in the field, prior to the return of the core to the laboratory for detailed analysis. Basic stratigraphical descriptions, together with levelling data, can also allow preliminary comparison between sites.

In terms of sediment description in the field, the semi-objective method of sediment description devised by Troels-Smith (1955) has been employed and reported throughout the Scottish studies of Shennan *et al.* (and that of Long *et al.* (1999) in Greenland), through which “the descriptions of the layers then serve as a solid foundation for interpretation and correlation” (Tooley, 1981).

2.4.2 Sea-level index points

A sea-level index point is a datum which can be employed to show vertical movements of RSL, once information about the geographical position, environment, indicative meaning, altitude and age of a sample are established (Shennan, 1982). They can be produced from a wide range of palaeoenvironments.

Each sea-level index point should consist of:

- A geographical position;
- An indicative meaning;
- An age;
- A tendency of sea-level movement.

The tendency of sea-level movement describes whether the point records an increase or decrease in marine influence (Shennan, 1980, 1982), and should not be used to infer an absolute vertical movement of sea-level; rather, only the movement of the

sea relative to the land surface should be considered, in terms of a positive (rise in RSL) or negative (fall in RSL) tendency (Shennan, 1980; Tooley 1982).

A single sea-level index point is unlikely to define a change in RSL on a regional scale, owing to the complex interaction of local factors (Shennan, 1992). Through the correlation of numerous tendencies in a region, by radiocarbon dating of index points, the dominant tendency during particular time periods can be established. Where the index points are constrained in terms of their age and altitude, an evaluation of the dominant regional tendency may also identify regional oscillations of RSL (Shennan *et al.*, 1983).

2.5 INDICATIVE MEANING

To compare samples for age/altitude analysis, a sea-level index point must have an indicative meaning (Shennan, 1982). The indicative meaning of a sample describes the vertical relationship between the local environment in which a sea-level indicator accumulated and a contemporaneous reference tide level (Shennan, 1982, 1986; van de Plassche, 1986; Horton *et al.*, 1999b). This assessment for each sample is especially important in macrotidal areas (Shennan, 1986).

Each sample is firstly related to its reference tide level (reference water level), such as mean high water springs tide (MHWST), before also being defined in terms of its indicative range, or modern vertical range (an estimate of how accurately the tide level can be estimated from the available evidence; Shennan *et al.*, 1995; Horton *et al.*, 1999b).

In determining the indicative meaning and indicative range of a sample, Shennan (1986) stresses:

- The indicative meaning is dependent upon the type of stratigraphic overlap under consideration.
- The reference water level for each type of indicator should be given only as a mathematical expression of the tidal level (e.g. the mid-point between MHWST and HAT), rather than a single tidal level \pm a constant factor (e.g. MHWST \pm 80 cm), as

the constant factor could indicate very different tidal inundation characteristics between sites, depending upon the tidal range.

- The indicative range can be reduced through the dating of the level where the biostratigraphic and lithostratigraphic evidence reveal a change in the environment.
- The accuracy of reference tide levels must be assessed.

The methods and techniques employed in recent Scottish isolation basin studies follow the common flexible methodology proposed by Tooley (1978) and Shennan (e.g. 1982, 1986, 1992) for Holocene sea-level studies in Great Britain as a whole. This involves accurate levelling, lithostratigraphic and biostratigraphic interpretation, and absolute dating, to produce sea-level index points, for which the indicative meaning is then established.

In the case of isolation basins, the altitudinal component of the indicative meaning is not based on the sample itself, but rather on the elevation of the sill, thus standardising the indicative meaning for the whole site at any given point in time. In the Scottish studies by Shennan *et al.*, basins are assigned a reference tide level in the range MLWST to MHWST (1993, 1994, 1995, 1996a, 1996b, 2000a), depending upon the sample dated and / or the freshwater input into the basin (Shennan *et al.*, 1995).

The level of marine influence entering the basin may also have an effect upon the reference tide level, if the basins are stacked as a 'staircase' sequence, where one basin controls the input to the next (e.g. the Rumach sequence of basins). This would be of particular importance if the marine water is mixed with freshwater (i.e. experiences a reduction in salinity) in one basin, before being passed into the basin behind during high tide, or into the basin in front during low tide. The effect would be further enhanced in poorly-mixed basins, where a halocline exists (e.g. Loch Roe lagoon (section 4.4.13)); if only the top section of water (freshwater) from one basin is transferred into another, the initial supply of water is likely to be of reduced salinity, until the energy from the incoming tide ensures more uniform mixing of the water input.

2.6 APPLICATION OF DATA FROM SEA-LEVEL RECONSTRUCTIONS

Through the acquisition of accurate sea-level index points in isolation basin studies, a common approach (e.g. Shennan *et al.*, 1993, 1994, 1995, 1996a, 1996b; Long *et al.*, 1999) has been to examine the validity and levels of precision of RSL curves (age-altitude empirical) and isobase models, such as those of Sissons (1963, 1966, 1969, 1972, 1983), Weidick (1993, 1996) and Rasch and Nielsen (1995), and the models of ice-sheet extent/isostatic rebound proposed by Boulton *et al.* (1977, 1985) and Lambeck (1991, 1993a, 1993b, 1995) for Great Britain.

Although the isobase maps produced by Sissons (1966, 1969, 1983) and Firth *et al.* (1993) were provisional, they, together with the associated Forth Valley chronology, have become widely adopted by subsequent authors as a means of correlation with their study areas. The most frequently used were the Main Lateglacial Shoreline (+5 to +8m OD) and the Main Postglacial Shoreline (+10 to +12m OD) (e.g. Sissons, 1983). Owing to the poor development of palaeo-shoreline forms in northwest Scotland, these maps were weakly constrained in this area, and no detailed chronology of RSL changes existed for the Late Devensian and Holocene until the work of Shennan *et al.* (1993, 1994).

As in other locations, isolation basin studies in Scotland have tended to collect a record of RSL change which covers the Holocene, and often parts of the Late Devensian, at a precision not encountered in previous studies, including radiocarbon dates which frequently produce the first RSL chronology for the local area (Shennan *et al.*, 1993, 1994, 1995). Through the collection of the high-resolution data, Shennan *et al.* (1993, 1994, 1995, 1996a) were able to examine the applicability of Sissons' (1966, 1969, 1983) morphologically-derived Forth Valley isobase models and RSL curve to areas of northwest Scotland such as Ardtoe and Arisaig.

The age-altitude model based upon the Sissons' (1983) isobases from the Forth Valley predicts a fall in RSL to a minimum at c.11,000 years BP, then a relative rise until the beginning of the Holocene, before a further relative fall. Many favour formation of the Main Lateglacial Shoreline (or 'Main Rock Platform'; Sissons, 1969, 1983), during the latter part of the Lateglacial Interstadial and through the Loch Lomond Stadial (e.g.

Stone *et al.*, 1996), implying that RSL either fell very slowly or was approximately stable, to allow time for shoreline formation (Figure 2.6). The data from isolation basins, including those at Loch nan Eala, Rumach, and Ardtoe, however, show a fall of *ca.* 9 mm / yr until 10 kyr ¹⁴C BP (Shennan *et al.*, 2000a). They do not, therefore, support a Younger Dryas oscillation in RSL or appear to provide the relatively stable RSL conditions postulated as being necessary for formation of the rock platforms during the Lateglacial (Shennan *et al.*, 1993, 1994, 1995, 1996a).

The new data for Scotland display general patterns which are similar to curves suggested by Lambeck (1991, 1993a, 1993b) in his high-resolution mathematical rebound models, although there is spatial and temporal variation in the detail of the curves. Isolation basins were used in testing his models for Scotland, given the availability of well-constrained age and altitude parameters (Shennan *et al.*, 1995), which can be used to test and improve both the isostatic (mantle rheology and ice model parameters) and eustatic components (Shennan *et al.*, 2000a). A closer fit exists with curves predicted for areas covered by a greater thickness of ice than that adopted in Lambeck's numerical model for the glacial maximum (Shennan *et al.*, 1993, 1994, 1995).

Lambeck (1993b) suggested that an increased ice load of *c.*17%, over northern Scotland, was required to give a closer regional fit between predictions and published observations. Further modelling by Shennan *et al.* (2000a) found a balance for the whole of Scotland to be difficult to achieve, where 4 different ice models were experimented with against a fixed set of earth rheological parameters. One of the main reported reasons was a lack of accuracy in the determination of the northern limit of the ice sheet. Shennan *et al.* (2000a) concluded that the inter-dependencies between ice model, earth model, and eustasy model can only be resolved if analyses are extended to larger areas, using a large database of accurate sea-level observations and new ice sheet parameters for the entire area, such as those proposed by Ballantyne *et al.* (1998). As part of this, improved evidence for past sea-level change, particularly for the Late Devensian period, for localities in northern Scotland is required, if further constraints are to be placed upon the northern extent of the ice sheet (Shennan *et al.*, 2000a).

2.7 LEVEL OF ACCURACY

It is evident that, through the relatively short time period in which isolation basins have been utilised in Scottish RSL reconstructions, the methodology has evolved from that employed in the early Scandinavian studies, involving relatively limited amounts of stratigraphic interpretation and levelling, through developments introduced by Kjemperud (e.g. 1981b, 1986), to that of the Scottish and Greenland studies of Shennan *et al.* (1993, 1994, 1995) and Long *et al.* (1999) respectively. It is well exemplified in the work of Shennan *et al.* (1996a), where pollen, diatom, foraminiferal, and dinoflagellate cyst data were combined to form composite biozones which record the gradual marine-freshwater transition at Ardtoe and the concomitant regional changes in environment.

Developments in the methods employed have increased the resolution of the data, through reductions in its margins of error, partly (though not entirely) as a necessity, in response to the differing relationship of tidal range and relative uplift in Scotland. For example, foraminifera and diatoms can provide supporting evidence for each other; pollen and dinoflagellate cysts can provide correlations between marine and terrestrial sequences and palaeoenvironments (Shennan *et al.*, 1996a). Palynological data can “corroborate the indicative meaning and tendency of sea-level index points” (Shennan, 1992; p.165), as well as providing a general picture of the predominant environment and a relative age with which to check the radiocarbon date of an horizon (put to good use by Kaland *et al.*, 1984).

The improvements in the methods have led to clarification of most age and altitude information obtained in respect of RSL changes, so that the records can be used not only as input data for isobase, age-altitude and numerical rebound models but, alternatively, as independent checks for these types of models (Shennan *et al.*, 1995; cf. Shennan *et al.*, 2000a). Perhaps the most important development in the common methodology formulated by Shennan is the recording of lithostratigraphy, biostratigraphy and elevation data, and their publication in research papers in a form which allows re-interpretation and testing with independent data sets by other authors (e.g. Shennan *et al.*, 1995). This process would be much more difficult to undertake

with some of the earlier Scottish sea-level work, and the earlier isolation basin research in Scandinavia and Greenland.

However, despite the increase in resolution which these data provide in the reconstruction of former relative sea-levels, isolation basins are not a panacea for sea-level studies. On the western coast of Scotland, the occurrence of quiet-water depositional environments is severely limited (e.g. Shennan *et al.*, 1993, 1994, 1995), so that on many of the islands, the sites with complete, undisturbed sequences, are only likely to be found on more easterly coasts. On the mainland, sites are spatially restricted, so that, in some areas, localised data will be sparse. Even when isolation basins do occur, and form a staircase within an area, RSL changes or limits may not be elucidated at the preferred level of accuracy if the indicative meaning of a sample can not be accurately quantified or basin sills are not present around critical altitudes, such as to constrain the mid-Holocene maximum (e.g. Shennan *et al.*, 1994, 1995). In considering this, it is, therefore, important that the value of samples as indicators of RSL change only be assessed once the errors have been considered, and that the margins of error are then stated during the reporting of results.

2.7.1 Indicative Meaning

Some RSL indicators do not have a consistent reference tide level. Godwin (1940) stated that fenwood peat will begin to form at MHWST in coastal fens, whilst in backswamp areas, groundwater effects can be the controlling factor, approximating to MTL. The most probable source of this error in defining the indicative meaning from isolation basins research comes from the amount of freshwater entering a basin, and the size of that basin. Uncertainties have been displayed in the indicative meaning ascribed to the diatomological and hydrological isolation contacts of the upper and main basins at Loch nan Eala, owing to the “significant freshwater input into the system” (Shennan *et al.*, 1994, 1995; p.120). Whilst the two contacts are, respectively, usually related to MHWST and HAT, in order to produce the dominance of polyhalobous diatom taxa as observed in both basins at Loch nan Eala, regular penetration by marine water is a likely requirement.

If the marine influx has to overcome the effects of freshwater coming into the system, particularly in large basins such as those at Loch nan Eala where there is greater inertia behind the salinity conditions to overcome, it is likely that the salinity of the photic zone will be much reduced. Shennan *et al.* (1995) believe, in this case, that the diatomological isolation contact occurred at or below MHWNT, lowering the reference water level from the more typical HAT by 1.7m. This resulted in a more comparable fit between this and other sea-level index points from the area. There is, however, no reason given as to why MHWNT was chosen as the appropriate level in the tidal regime. A similar exercise has been undertaken for other isolation basins in Scotland, with corrections to the indicative meaning for each basin provided by Shennan *et al.* (2000a).

Although, in the above case, changing the reference tide level did lead to a more significant overall fit for the Loch nan Eala and Rumach data in the RSL curve produced (Shennan *et al.*, 1995), the situation stresses the need for studies using modern analogue basins. This should include the use of Scottish isolation basins situated in macrotidal environments, and involve hydrological modelling, quantification of the variables controlling salinity, and the identification of appropriate reference water levels during the isolation and connection processes, depending upon what are believed to be the main controlling factors on each basin, such as the freshwater input and basin area (Shennan *et al.*, 1999).

2.7.2 Tidal Range

The approach of interpreting past or fossil sea-level indicators based upon modern tide levels may be inaccurate. This is caused not only by changes in the tidal range through time and inter-site space, but also local tidal variations within some sites, or between adjacent sites. Local-scale changes present more of a problem in salt-marsh environments (for example, in terms of within estuary changes in tide level), but they are still applicable to isolation basin research. The tidal record for a site is extrapolated from the nearest primary or secondary port and, as such, disregards any variation which is likely to be present between the port and the site.

As the indicative meaning of a site or sample is based upon its reference water level in the tidal cycle, a constant relative tidal regime (i.e. between sites/areas) through time is assumed in the calculation of the indicative meaning. The regime itself, in absolute terms for each site, is also assumed to relate to present tidal conditions (Shennan, 1980). Shennan (1980) acknowledged that, through making this assumption, the value of the indicative meaning is decreased, but it is necessary whenever sea-level index points with different indicative meanings are being considered. Clearly, this is an important consideration in the reconstruction of isolation basin environments.

Previous studies which identify changes in tidal range through time have involved a sedimentary analysis method, or a more complex modelling approach. Roep (1986) and Roep and Beets (1988) estimated palaeotidal range by comparing the thickness of fossil sediment units with those formed under present day tidal conditions using pits along the barrier shoreline of the western Netherlands. Scott and Greenberg (1983), and Austin (1991) used numerical tidal modelling to illustrate significant changes in the tidal range in the Bay of Fundy and the northwestern European continental shelf respectively. Shennan *et al.* (2000c) combined the use of sedimentary evidence from cores with modelling to reproduce palaeogeographies (coastline positions and bathymetries) and tidal changes for the western North Sea, as part of the extensive Land-Ocean Interaction Study (LOIS). They concluded that the western North Sea had experienced an increase in tidal range during the Holocene. The periods of most rapid change coincide with major changes in palaeogeography. They also concluded that greater account needs to be taken of sediment transport and accumulation.

A similar, in-depth approach is required for the western coast of the UK, in order to ascertain any temporal and relative spatial changes in the tidal regime along the western coast of Scotland. Until such a time, the assumption of a constant tidal regime must remain in place within the methodology of the indicative meaning.

2.7.3 Modern Samples

Contemporary species and environment data has been used in the reconstruction of the past, following Hutton's principle of Uniformitarianism where the 'past is the key to the present' or, in this case, the present is the key to the past. Initially, such reconstructions were based upon matching similar patterns by eye. More recently, however, statistical methods have introduced a more objective approach and a greater degree of accuracy to these reconstructions.

The use of modern samples as an analogue for former environments involves a number of basic requirements and assumptions, some of which are related purely to ecological controls, and some which are concerned with statistical significance. These are outlined in full in section 3.5.1, from Birks (1995) but, as a summary, the ecological requirements and assumptions include the following:

- The modern and fossil data-sets should be of consistent taxonomy.
- The taxa in the modern environment are related to the environment in which they live.
- The taxa in the modern data-set are the same biological entities as those in the fossil data, and their response(s) to the environmental variables have not changed significantly over time.

There is also an assumption that what is being collected at the surface is actually a modern sample, and not the product of a disturbed sequence. The simplest way to satisfy this requirement is to avoid areas of exposed coastline and basins with strong tidal currents. Limited disturbance will still occur through biological activity, but this should be restricted largely to the upper surface of the sediment. As 1 cm depth of material is collected as a modern sample, the effect of this should be negligible.

The avoidance of disturbed sequences, and the accurate measurement of variables across the entire range of the environment in terms of space and time, are the main requirement to reduce errors in modern samples. These procedures are outlined in full in chapter 3 and Appendix One.

Within the modern isolation basins, there is also likely to be an as yet unquantified change in the natural conditions brought about through anthropogenic activity. This can be brought about by changes in the vegetation cover of catchments, with resulting impacts on water chemistry and the hydrology of basins through inputs from their catchment. As these human impacts have increased through time, there is likely to be some lowering in the precision of reconstructions for fossil sites available from modern isolation basins.

2.7.4 Basin Infilling

Problems with sediments are introduced in isolation basins through the natural infilling of basins by peat following isolation. Such infilling is believed to have prevented a mid-Holocene incursion signature in the Arisaig area (Shennan *et al.*, 1995). Evidence for the age and altitude of the Holocene maximum, which led to the formation of the Main Postglacial Shoreline, is not accurately constrained in the staircase composed of the Loch nan Eala and Rumach (Iochdar and Meadhonach) isolation basins, with only one sea-level index point covering approximately 4000 years of the early- and mid-Holocene (Shennan *et al.*, 1993, 1994, 1995). Whilst the upper basin at Loch nan Eala (+6.6m OD) records a positive tendency of RSL, no such Holocene 'connection' is evident in the deposits of Rumach Iochdar (the next highest basin in the area, at +9.3m OD). This limits the Holocene maximum only to within a 2.7m altitude variation (OD) and a 2600 year time-frame (the difference in elevation and age of the sea-level index points at Loch nan Eala upper basin and Rumach Iochdar).

Shennan *et al.* (1995) postulate that peat growth may have filled the Rumach Iochdar basin with sediment, preventing the incursion of seawater. Evidence given in support of this includes a regressive contact at Glenacross (*ca.* 7km north, with an elevation just 0.04m lower than that of Rumach Iochdar), and palynological data from Loch nan Eala, which show peat formation before the *Alnus*-rise (Shennan *et al.*, 1993), dated at 6600 ¹⁴C years BP (i.e. earlier than the suggested dates for the Holocene maximum in the area) (Shennan *et al.*, 1995). Presumably any hiatus caused by such a marine incursion would since have been destroyed by subaerial erosion, although this is not discussed by Shennan *et al.* (1995).

2.7.5 Dating

There are numerous sources of error associated with radiocarbon (^{14}C) dating methods, with the major areas being temporal variations in ^{14}C production, fractionation of ^{12}C and ^{14}C , marine reservoir effect, hard-water errors in areas of carbonate rocks, and contamination from organic infiltration. Lowe and Walker (1997) provide a comprehensive review of the subject.

In the case of the marine reservoir effect, Shennan *et al.* (2000a) gained identical dates (2σ age range) from 678 cm depth for the bulk limnic sediment (7942 – 8178 cal BP) and calcareous foraminiferal tests (7976 – 8108 cal BP) from the same isolation basin. This could indicate that either the mixing of sea-water in shallow marginal marine environments is such that the marine reservoir effect is negligible or, alternatively, that the reservoir effect is offset by old carbon in the limnic mud (Shennan *et al.*, 2000a). Retelle *et al.* (1989), faced a similar problem. Their radiocarbon dates from isolation basins, based on Total Organic Content (TOC), were consistent within a core (i.e. they aged down-core), but there was conflicting evidence when several cores from the same site were dated. This led Retelle *et al.* (1989) to investigate the possible causes of the discrepancies. They concluded that the variability was caused by old (isotopically dead) carbon within the lake sediments, such as that from local calcareous bedrock (hard-water effect) or redeposited organic matter, particularly in basins containing sediments of low organic content (high organic content reduces the influence of contamination; Kaland *et al.*, 1984). Bjorck *et al.* (1998) conducted a similar study in a soft-water lake in Sweden, and found the same problem with bulk sediments. By avoiding the hard-water scenario, the study of Bjorck *et al.* (1998) supports the suggestion of the inwashing of older organic material causing a reservoir effect in isolation basin environments.

The age control for large sections of sea-level research, including isolation basin research in Scotland during the early 1990s, has been obtained through the use of the conventional ^{14}C dating method. This requires comparatively large volumes of organic material (≥ 90 gm), and for the isolation basins required a 3 cm slice of sediment from directly above the isolation contact (Shennan *et al.*, 1996a). The more

recently developed AMS technique, however, requires only 1 cm (< 1 gm) of material from the isolation contact. Its development has also allowed the reduction of errors and the range of environments from which dated material can be taken to be expanded. For the Ardtoe isolation basin (Shennan *et al.*, 1996a), the AMS method provided an isolation date 700 years older than that provided by the conventional method (Shennan *et al.*, 2000a). The process of re-dating Scottish isolation basins using the AMS method is ongoing, with Shennan *et al.* (2000a) reporting the results obtained so far.

2.7.6 Levelling

There are seldom sufficient basins within a local area which cover the whole range of RSL changes, from the earliest marine limit to present sea-level (Hafsten, 1983). Because of this, data from basins in several areas within a region may be used for interpretation. An assumption within this is that the different areas have not experienced different rates of uplift. However, differential uplift does occur (e.g. Hafsten, 1983; Shennan *et al.*, 1996a), with the general situation that the further back in the stratigraphic record that is researched, the greater the difference is likely to be between areas. There is no consideration of this within the indicative meaning methodology, although it clearly has implications in the pursuit of high-resolution records, and should be borne in mind when interpreting results from different areas.

Altitudinal errors are also apparent within sites, when levelling the altitude of stratigraphic boundaries, and the upper boundary of the bedrock sill. Shennan (1980, 1982, 1986) identified three different main sources of errors:

- Measurement of depth of a borehole.
- Levelling of the site to an Ordnance Survey benchmark (or, as Global Positioning System (GPS) equipment is becoming more accurate, tying the elevation of a site into the Ordnance Survey National Grid system).
- Accuracy of benchmarks to the second Ordnance Datum (OD) at Newlyn.

Shennan (1982) developed the broad areas of error in the original and measured altitude of stratigraphic boundaries, based on data collected in the Fenland. Some of these errors, such as the angle of the borehole and the measurement of stratigraphic

boundaries can be applied to fossil isolation basins, but it is only those relating to levelling, and the accuracy of the Ordnance Datum benchmark system which can be realistically applied to research on modern isolation basins. Shennan (1982) gives an estimate of ± 0.15 m for the accuracy of a benchmark to OD in the Fenland. This is a somewhat conservative estimate for NW Scotland, however, especially as the benchmark system is now unmaintained, following its succession by the much more accurate primary GPS network.

An additional advantage of the GPS approach is that the data from the primary GPS network is freely available for download from the internet. Results from personal GPS systems can then be linked into this in order to fit the levelling into the National Grid system. If benchmarks have to be used, some in Britain have recently been re-levelled by GPS to form part of a secondary network, and their elevation and location, together with primary GPS network data are available from an Ordnance Survey website (<http://www.gps.gov.uk>), free of charge.

Levelling error may also have been introduced for some fossil isolation basins by human modification. Examples of this are Ardtoe (Shennan *et al.*, 1996a) and Loch nan Eala (Shennan *et al.*, 1994; Shennan *et al.*, 2000a), where engineering works have led to the partial removal or burial of the basin sill, making the altitude difficult to determine accurately. This has obvious implications in the construction of age-altitude plots, where the elevation of these basins may be artificially lowered.

2.8 SUMMARY

- There are numerous types of sea-level indicator, which can be collected from a wide range of palaeoenvironments (Section 2.4.1).
- The data from each sample should be collated as a sea-level index point (Section 2.4.2), comprising of an age, altitude, indicative meaning (Section 2.5) and tendency of RSL movement.
- In western Scotland, isolation basins are one of the most suitable environments, in terms of age and altitude, from which data can be collected or constrained, using lithostratigraphical and biostratigraphical evidence (Section 2.4).

- A number of inputs and processes operate within isolation basins when their sill lies inside the tidal regime. The precise balance of these varies temporally and spatially, within and between basins (Section 2.2). This balance needs to be determined as accurately as possible in order to increase the resolution of studies of former sea-levels from fossil isolation basins.
- The data from fossil isolation basins in Scotland has been used in the formulation and calibration of models of earth rheology, and ice sheet limits and dimensions.
- In considering the collection of data from, and the interpretation of fossil and modern isolation basins, the sources of a number of errors must be borne in mind, particularly in relation to the calculation of the indicative meaning, and corrective action taken where necessary / possible. The errors should be minimised through the use of a consistent methodology based upon accuracy of measurement and interpretation (Section 2.7; Chapter 3).

Methodology

3.1 INTRODUCTION

This research employs foraminiferal-based techniques to develop a high resolution record of late-Devensian and Holocene relative sea-level change from isolation basins in northwest Scotland, with the broad objective of developing a transfer function which can be applied to the interpretation of fossil isolation sequences. Previous isolation basin studies, in Scotland and further afield, have utilised the age-altitude methodology which has been so commonly applied in studies of relative sea-level change, normally using floral assemblages to infer palaeoenvironmental conditions (e.g. Kjemperud, 1981a, 1981b, 1986; Shennan *et al.* 1993, 1994, 1995, 1996a, 1996b; Long *et al.* 1999). The methodology employed in this thesis seeks to obtain the highest resolution record possible, given the techniques available, using statistical analysis to model the relationship between contemporary foraminifera and their environment. This relationship will then be used to explore the quantitative reconstruction of the indicative meaning of fossil isolation basin sediment sequences.

This chapter covers the following:

- A description of the process undertaken in selecting the sites for data collection;
- The methods involved in designing the sampling program;
- A detailed discussion of the use and benefits of foraminiferal assemblages in sea-level research, the environmental variables controlling their distribution and reproduction, and the validity of assemblages for statistical analyses;
- A brief introduction to statistical environment reconstruction.

3.2 SITE SELECTION

The site selection criteria was that basins should have sill elevations representing the full range of the tide. This should provide modern analogue data for a wide range of fossil basins, at as many stages of isolation and connection as is possible. It was also essential to avoid disturbed sequences, where sediment-mixing and inwash of foraminifera could have occurred. For this reason, sites on the west coast of the Hebridean islands were only selected if they have well protected sills. On the mainland, sites facing immediately onto exposed coastline were avoided.

Preliminary site selection was carried out using 1:25,000 Ordnance Survey maps and Marine Nature Conservation Reports on saline lagoons by Covey *et al.* (1998) and Thorpe *et al.* (1998), prior to reconnaissance visits. During these reconnaissance visits, water chemistry was recorded and three foraminifera samples were retrieved from each site for inspection in the laboratory. Analysis at this stage was primarily concerned with the presence and abundance of foraminifera in the basins, although note was also taken of any anthropogenic activity, such as past and present disturbance of the drainage system and/or modification of the sill, which were likely to affect the suitability of the site for environment reconstruction purposes. Final site selection was based upon these pilot studies.

Twenty sites were selected for detailed analysis, covering Argyll, Assynt and the surrounding area, and the Hebridean isles of North Uist and Skye (Figure 3.1.1 - 3.1.4). Of these basins, eighteen are still subject to tidal inundation, whilst the remaining two are freshwater, with the sill just above the level of tidal inundation. The freshwater basins provide information on recently isolated sites, and the changes that occur in the environment and microfossil community following isolation. In order to ensure information at the opposite end of the salinity scale one site was chosen which has a sill below MLWNT. This gives the least restricted exchange of water of all basins studied in this research, providing an analogue for basins at the end of the marine / beginning of the transitional stage.

3.3 SAMPLING DESIGN

This research employs a hypothesis-testing approach in seeking to develop a statistical model (transfer function), based upon modern isolation basin foraminiferal ecology, which can be used to reconstruct environmental parameters for fossil isolation basin foraminiferal assemblages. This relies upon Hutton's Principle of Uniformitarianism, where 'the present is the key to the past'.

The hypotheses being tested are:

- i. Salinity is the dominant control on foraminiferal assemblages within contemporary isolation basins.
- ii. The indicative meaning and range for fossil isolation basins can be estimated through the use of a transfer function, formulated from data on the species – environment relationship(s) in modern isolation basins.
- iii. The lowering of the indicative meaning by Shennan *et al.* (1995, 2000a) to account for freshwater input and basin size is accurate.

In order to provide a good modern analogue it was important in the selection of contemporary sites to ensure a distribution of environmental variables such as sill altitudes throughout the tidal regime (cf. section 3.2), acid and alkaline environments, and coarse and fine substrates. However, an attempt was also made to hold some variables approximately constant between sites, in order to provide an opportunity to focus on the remaining environmental parameters of the basins. Most often, the constant variable was geology (although this is also likely to be reflected in the water pH), but some attempt was also made to hold the reference water level of the sill constant between a number basins in the same area, providing an opportunity to examine the effects of freshwater input upon water salinity within the lagoons.

3.3.1 *Philosophical approach*

Until the early 1960s, the foundation of research into sea-level changes in Scotland was almost exclusively inductive (e.g. Chambers, 1848; Jamieson, 1865; Geikie, 1902; Earp *et al.*, 1962). Inductionists advocated the accumulation of knowledge through experience of observation and experimentation, with objectivity achieved through empirical generalisations being made only when all necessary details have

been assembled (Chorley, 1978; Haines-Young and Petch, 1986; Marshall, 1987). However, with the paradigm shift of the 'quantitative revolution' in geography during the late 1950s, Popper's (1959) critical rationalism (a hypothetic-deductive method) rapidly formed a large part of the scientific method which has been adopted by Sissons, Smith, Shennan and many other researchers.

One of the primary criticisms of the inductionist theory is a reliance upon the 'leap of faith' required to link observations with generalisations, which are then extended beyond the situation or area upon which they were originally based (Haines-Young and Petch, 1986). This procedure can be no better illustrated in this particular field of study than by the suppositions surrounding the nature and composition of the '25', '50' and '100ft.' shorelines prevalent in Scottish research during the early- to mid-twentieth century, where all of the raised platforms were (wrongly) assumed to be of marine origin, at a specified height, and near-horizontal along their entire length (cf. Earp *et al.*, 1962; Sissons, 1962a; 1962b; 1963).

Refutation and adaptation of positivist theories was strongly contested, with proponents such as Earp *et al.* (1962) disputing the interpretation and validity of new data provided by Sissons as he transformed the whole practice and techniques of field investigation towards a fallibilist way of thinking. It is through such criticism, Popper (1959) argued, that false ideas can be eliminated and hypotheses, theories and models gradually improved.

Critical rationalism has itself been criticised, most notably by Kuhn (1962) and Feyerabend (1975) on the basis that the method created irrationality in science. Feyerabend (1975) views science as an anarchistic undertaking, questioning not only the supposed superiority of science (a fair statement), but the very existence of any scientific method. He challenges the existence of all methodology, suggesting that any method throughout the history of science is mythical and that "the only methodological principle that can be defended in all circumstances is the principle that anything goes" (1975, p.28). Feyerabend also argues that 'progress' in science is determined not by method or reason, but in terms of the social processes operating within the scientific community (i.e. 'progress' is a social construct) (Feyerabend, 1975). Feyerabend's 'relativist' theory is regarded by some as extreme, on the basis

of several of his arguments detailed above (cf. Haines-Young and Petch, 1980, 1986); with the multiple perspectives of his postmodern-like approach, the dilemma for Feyerabend must be to explain how any 'progress' (however he may define it) can be achieved within science, in order that theory may develop.

Realists have suggested that taken to its limits, critical rationalism can lead to narrow 'scientism' (the single-minded pursuit of science in a quest for knowledge; with a view of superiority of science over all other methods). However, some aspects of the realist approach may also be taken to be similar to that of the approach of scientism. Its proponents believe the method can lead to the **true** explanation of the real world, and that it is the only philosophy that does not make the success of science a miracle (Putnam, 1971, p.73 (credited to Richard Boyd), emphasis added). van Fraassen (1987; emphasis added) has somewhat softened the former argument in suggesting that realism in science only **aims** to provide a literally true story of the world; it is only the scientific theory upon which the work is based that must be believed to be true.

Although one can accept van Fraassen's realist approach, the argument that models within scientific realism are experimental devices for probing understanding rather than a method for obtaining specific predictions (Richards *et al.*, 1997) cannot be maintained for the purposes of this research. Consequently, the realist approach is deemed unacceptable for the undertaking of this project.

Whilst it is acknowledged that the inductive method was necessary during the early work on sea-level and deglaciation, the deductive method (although certainly not the sole route to an advance in scientific knowledge) is advocated in further developing current theories. For this reason, the present study will continue with the critical rationalist approach, in an attempt to further cultivate greater verisimilitude within contemporary theory, through a strengthening of the associated methodology. What is not accepted, in full, from the fallibilist doctrine is the suggestion that refutation should lead to automatic rejection of a theory.

Alternatively, contrasting evidence should lead to refinement of a principle on a trial-and-error basis (Hay, 1987), using prevailing theory as a framework on which to base

further investigation (Haines-Young and Petch, 1980). *Ad hoc* changes in a vain attempt to avoid falsification should, however, be avoided on the basis that they are counter-productive, inhibiting progress and (potentially) creating unsafe or incorrect theory (Haines-Young and Petch, 1986). Such changes should be viewed on the same level as data manipulation (or “data torture” as Mills (1993) more appropriately describes it). The true fallibilist would attempt to investigate why rejection has occurred (Haines-Young and Petch, 1986).

Care must be taken within the critical rationalist approach to maintain an emphasis on an adequate resolution of time and space and to maintain a more interdisciplinary approach than is commonly associated with this method. The complexity of spatial and temporal variability suggests an empirical approach would be unsuccessful in adequately defining a landscape and its associated network of interactions. Empirical methods focus upon on the observable (e.g. isobase models (Sissons, 1963; 1983)), but research associated with previous events, such as those which occurred during the Holocene, must extend beyond this, using evidence from events which are not directly observable and / or evidence which must be uncovered (e.g. micro-organisms and material in sediment cores) in order to increase the resolution of models (e.g. Lambeck, 1993b; Shennan *et al.*, 1995).

3.4 FORAMINIFERAL ANALYSIS AND SEA-LEVEL RESEARCH

Foraminifera are uni-cellular (protozoan) marine organisms (Scott and Medioli, 1986), with the soft tissue (protoplasm) enclosed within a test, which reproduce asexually or, less commonly, sexually, through an alternation of generations (Murray, 1991). The test, composed of one or more chambers, may be constructed from secreted minerals (calcium carbonate, aragonite or silica) or agglutinated grains, such as quartz, mica, and diatoms, held together with an organic cement (Murray, 1991; de Rijk, 1995). The material and morphological features of the test are used in species identification. In the open ocean, foraminifera may be planktonic (living in suspension in the water column) or benthic (living in or on the sea floor). However, only benthic species are present in the more marginal brackish and nearshore areas, such as saltmarshes and saline lagoons. This research is therefore based exclusively on benthic foraminifera

Within the age-altitude methodology, pollen has traditionally been used as an indicator of the tendency of sea-level movement and as a dating proxy, whilst diatom analysis has often complimented this as an indicator of palaeosalinity (e.g. Shennan *et al.*, 1993) and other ecological parameters, such as pH and sediment type (Hendey, 1964; Palmer and Abbott, 1986; ter Braak and van Dam, 1989). Indeed, diatoms and pollen together were used extensively by Shennan *et al.* (1993, 1994, 1995, 1996a, 1996b) in establishing sea-level index points from fossil Scottish isolation basins.

Foraminifera, like diatoms, are used because of their capacity to indicate changes in salinity, but are also sensitive to other environmental parameters (Lloyd, 2000). Their use, however, has become increasingly important in recent years in the development of high resolution records of changes in relative sea-level. This is particularly apparent in studies of saltmarsh foraminifera from temperate coastlines, where Scott and Medioli (1978, 1986) believe them to be the most accurate sea-level indicators. This is because foraminiferal assemblages exhibit a strong relationship to elevation above MSL and, as such, have a high potential as tools in the accurate quantification of reference tide levels (Horton, 1997, 1999). Such high-resolution studies can also feedback into foraminiferal research, providing an increase in understanding of the ecology of the foraminifera themselves (Lloyd, 2000).

Foraminifera are used in this research for the above reasons, combined with the fact that diatoms would appear to be more susceptible to being washed into a basin by the marine input. Although there is no systematic interpretation of transport of diatoms in modern isolation basins, there was a growing impression during the fieldwork of such in-washing. Whilst foraminifera can also be transported, they will normally fall out of suspension in the area immediately behind the sill, when the water velocity reduces, and the capacity to carry the foraminifera is usually lost, due to their larger size, on average. Thus, it is considered that foraminifera will give more detailed, accurate results, given their sensitivity to changing environments and the lower probability of transportation over diatoms.

Some of the most recent studies of relative sea-level change have, in addition to foraminifera, utilised thecamoebians. These are used because of their predominance

in freshwater environments, and in the very highest zones of saltmarshes (where tides cover the marsh for less than a combined total of 7 days (1.9%) in a year (Gehrels *et al.*, 2001)) (e.g. Lloyd, 2000; Gehrels *et al.*, 2001). Like foraminifera, thecamoebians (or testate amoebae) are testate protozoans, with a test composed of secreted protein, silica or calcium, or agglutinated particles (Medioli and Scott, 1988). As two of the basins sampled during this research contain freshwater, samples were also checked for the presence of larger thecamoebians at the same time as counting foraminifera.

3.4.1 Foraminifera and environmental variables

Although distribution studies of benthic foraminifera have been undertaken for well over a century, including the seminal work of Brady (1884), a true ecological approach has only been developed since the introduction of the rose Bengal staining method by Walton (1952), which differentiates between those tests containing protoplasm (alive or recently living) and those which are empty (dead) (Murray, 1991). Such ecological studies are growing in importance and many are now being carried out with the aim of providing a contemporary dataset with which fossil foraminiferal assemblages can be interpreted (Murray, 1991).

Any palaeoecological investigation of fossil assemblages must first be based upon an understanding of the relationships between environmental parameters and the modern distribution of foraminifera (de Rijk, 1995) (Figure 3.2). Within this, studies of the environmental extremes are of great importance in determining distribution, particularly near the limits of their range (Bradshaw, 1968). In the case of foraminifera, Scott and Medioli (1986) believe that in marginal marine environments, where environmental variability is high (such as isolation basins), physical parameters such as salinity, temperature and elevation (or, perhaps, variable combinations of these factors through time) appear to have the strongest influence on the composition of an assemblage. Furthermore, Murray (1991) found the lowest diversity assemblages to be indicative of the most stressed environments (Figure 3.3).

Some degree of seasonal variation in the environmental parameters and the foraminifera will always occur, most probably on an annual basis (Murray and Alve, 2000). Any changes outside of the annual pattern must, therefore, be strong enough so as not to be masked by the underlying cyclicality (Murray, in press (source: Murray and Alve 2000)). Rapid changes in environmental parameters, however, are less frequent, and would generally be viewed as unfavourable for the site, often leading to deformed specimens (Boltovskoy *et al.*, 1991). In the case of isolation basins, particularly with respect to salinity, such rapid variation is likely to occur owing to the series of inputs and outputs during the tidal cycle. This should at least partly explain the generally low species diversity usually encountered in saline lagoons.

Clearly, therefore, the measurement of any pattern in foraminiferal distribution, and the environmental factors controlling this, is reliant upon a programme of systematic sampling, where environmental variables are measured repeatedly at the same place (Buzas, 1969). This is of especial importance in light of findings by numerous authors that a complex of biotic and abiotic parameters, specific to each individual site, determine foraminiferal distribution in terms of their ability not only to survive, but to reproduce and become the dominant species in an assemblage (e.g. Phleger, 1970; Murray, 1973; de Rijk, 1995; Murray and Alve, 2000; Gehrels *et al.*, 2001).

The following environmental variables (outlined in 3.4.1.1 – 3.4.1.9) were measured at each site during this research, with the methods involved in the measurement of each variable outlined in section 3.4.3.1: Water salinity, water pH, water dissolved oxygen, water temperature, organic content, particle size, sill dimensions, freshwater input and basin volume.

3.4.1.1 Water salinity

“For survival, growth, and reproduction, each benthic foraminiferal species has specific limits of tolerance to salinity” (Boltovskoy *et al.*, 1991, p.176).

Salinity varies considerably between isolation basins, depending upon the elevation of the sill with respect to its position in the tidal cycle (which determines the volume of saline water entering the basin), the salinity of the water entering the basin over the sill, and the amount of freshwater coming into the system. There is also a certain

amount of variation in salinity within each site, which is controlled by the degree of mixing of the saline and freshwater inside the lagoon. This, in turn, is influenced by the surface area and depth of the basin, the amount of marine and freshwater entering the basin, evaporation, and the strength of any currents associated with these inputs and outputs of water.

The effect of the range of salinity conditions within a basin upon foraminifera is unknown. However, as the band of salinity tolerance for each foraminiferal species is narrower for reproduction than survival (Bradshaw, 1968), the effects are likely to be significant. When species do experience salinity conditions outside of their lower limit or threshold, their physiological function is diminished, leading to smaller species, with thinner walls and decreased ornamentation (Buzas, 1969; Boltovskoy *et al.*, 1991). Bradshaw (1957) showed that levels of salinity consistently higher than an upper tolerance limit of a species may also hinder growth.

3.4.1.2 Water pH

The pH affects both the cell and test of calcareous foraminifera. The protoplasm of any foraminiferal species must remain within a narrow range of hydrogen ion concentration (pH) in order to survive (Bradshaw, 1968). Low pH, in particular, creates a stress situation for foraminifera, where calcareous types must expend considerable energy in recalcifying their test (Boltovskoy and Wright, 1976).

Even at a mildly alkaline pH 7.8, Boltovskoy and Wright (1976) found evidence of etching on calcareous tests. In an earlier experiment by Bradshaw (1961), at pH 2.0, the calcareous species *Ammonia beccarii* survived for less than 75 minutes, and for under 37 hours at pH 9.5. Unfortunately, there is little or no numerical data concerning the subtle effect of less extreme levels of pH on foraminiferal life processes over longer periods of time (Bradshaw, 1968).

Scott and Medioli (1980a) report a seasonal influence of pH, with high populations of calcareous foraminifera in the summer, but low populations in the winter. This, they conclude, is the product of lowered temperatures and salinity, leading to dramatically reduced levels of carbonate production and increased levels of CaCO₃

solubility (which is closely associated with salinity (Boltovskoy *et al.*, 1991)) during winter months.

Frequently, calcareous tests are not preserved in marsh / intertidal environments, owing to dissolution (Phleger, 1970) in a characteristically acidic environment. This is discussed in greater detail in section 3.4.2.1.

3.4.1.3 Water dissolved oxygen

The level of dissolved oxygen within a basin is related to photosynthesis and the supply of air-saturated water during tidal and freshwater inundation (Phleger, 1970). A lack of dissolved oxygen will contribute to reduced metabolic rates, producing dwarfed, thin-walled foraminiferal tests (Bradshaw, 1968; Boltovskoy *et al.*, 1991), and experiments have shown infaunal taxa becoming epifaunal as the availability of oxygen decreases, and they approach the redox boundary (Alve and Bernhard, 1995).

The pH and oxygen content are closely related (Bradshaw, 1968; Phleger, 1970), and Bradshaw (1968) reports their diurnal variation on a saltmarsh to be greater (due to lack of photosynthesis at night (Phleger, 1970)) than the observed seasonal change and variation caused by tidal factors. This large daily variation in levels of dissolved oxygen is in stark contrast to the relatively constant levels in the open ocean, and may partly explain why open ocean foraminiferal species cannot tolerate an intertidal habitat (Bradshaw, 1968).

3.4.1.4 Water temperature

Murray (1968), in a study of Christchurch Harbour, England, observed that each foraminiferal species had its own temperature range, and that the time of year for reproduction varied according to temperature and other requirements of the species. He also noted that some of the foraminifera, and most of the thecamoebians, appeared to go into near-hibernation during winter months, when temperatures and salinities were low.

In the case of isolation basins, the temperature control will still exist, but the diurnal variation is more closely linked to air temperature, especially in the shallower lagoons, as opposed to the greater inertia in water temperature (related to their

considerable volume) in the seas and oceans. The only exception to this observation is likely to be during stages of marine inundation in the saline lagoons. Therefore, the greater and more frequent input a basin has from the open ocean, the more detached the water temperature is likely to be from the prevailing air temperature.

3.4.1.5 Organic content

The influence of organic matter on foraminifera assemblages is variable (Boltovskoy and Wright, 1976). Decomposition of organic matter can acidify an environment, adversely affecting foraminifera as a result. Conversely, as most benthic foraminifera are detritus feeders (de Rijk, 1995), and organic debris is abundant in saltmarshes and intertidal areas generally, a high organic content can aid foraminiferal survival, reproduction and growth patterns. Nitrogen is the key nutrient in such environments (Valiela and Teal, 1979) as micro-organisms which are part of the food source for foraminifera use nitrogen in their metabolism to decompose organic matter (de Rijk and Troelstra, 1997).

3.4.1.6 Particle size

Agglutinated foraminifera use sediment particles of approximately 2 – 20 μm to build their tests. Therefore, an absence of particles of this size may limit the occurrence of agglutinates (de Rijk, 1995).

The predominant particle size, along with the depth of the redox boundary and the availability of food, also has an impact on the capacity of a foraminifer to live infaunally (Murray, 1991; Horton *et al.*, 1999a). Further information on infaunal habitats is provided in section 3.4.2.4.

3.4.1.7 Sill dimensions

The environmental conditions within an isolation basin are related to the characteristics of the sill, such as elevation and width, as it is these which control the marine input into the basin. Elevation in the sense of an isolation basin, like any other coastal feature, is essential when attempting to reconstruct relative sea-level history, or in comparing sites using a common datum in the tidal cycle (Jennings *et al.*, 1995; Gehrels *et al.*, 2001). Similarly, sill width acts as a controlling factor on the volume and rate of marine input and output.

Scott and Medioli (1978; 1980a) believe the duration and frequency of tidal exposure (i.e. those factors controlled by elevation and, in the case of isolation basins, sill width) to be the most important variables controlling the distribution of foraminifera within the intertidal zone, with salinity the next most important variable. Subsequent research, such as that by Patterson (1990), de Rijk (1995), de Rijk and Troelstra (1997, 1999) and Horton (1997, 1999a; Horton *et al.*, 1999b), has shown this view to be overly-simplistic in many cases, and that the most likely control on foraminiferal distribution is a combination of environmental variables, the specific blend often being controlled by site-specific factors.

3.4.1.8 Freshwater input

Jonasson and Patterson (1992) found that the effect of salinity on foraminiferal distribution is much more pronounced where there is considerable mixing with freshwater, such as at the landward margins of a saltmarsh. Although undoubtedly important, the exact influence of freshwater input on foraminiferal assemblages in an isolation basin is not known. In attempting to take account of a “significant freshwater input” into the Loch nan Eala basins, Shennan *et al.* (1995a, p.120) lowered the reference water level by 1.7m (the equivalent of reducing the reference tide level from HAT to MHWNT for the area), but no justification for why this exact figure was chosen is given. One of the objectives of this research is to attempt to improve this situation by collecting data from a range of sites with differing levels of freshwater input, in an attempt to ascertain the influence of freshwater input on foraminiferal assemblages.

3.4.1.9 Basin Volume

A small, shallow basin is much more susceptible to a change following a given input than a large, deep basin is given an identical input, and the resultant water within a smaller, shallower basin will also become mixed more readily than that in a large, deep basin. The water temperature of shallow basins also mirrors the prevailing air temperature more closely than that of a large basin. This all serves to indicate that basin volume plays a large role in determining the inertia or residence time of water within an isolation basin, as well as the overall water exchange and circulation processes. As a result, basin water volume will play a critical role in determining the isolation characteristics of any given basin.

3.4.2 Post-depositional change of foraminiferal assemblages

The reliability of palaeoecological reconstructions depend partly on post-depositional alteration, where the composition, diversity and/or density of a foraminiferal assemblage can be altered (de Rijk, 1995). A snapshot of the life assemblage at any one time gives information on the stages of growth and the relative and absolute abundance of the species (Murray, 1991). The ideal death assemblage (Murray, 1991) would give similar information, but is usually affected by life processes and post-depositional changes, causing it to differ (Horton, 1997).

The production rate of foraminifera depends upon the initial size of the life assemblage, the number of individuals that reproduce, the frequency of reproduction, and the number of progeny developed. One form of asexual reproduction (the division of the parent cytoplasm into agamonts rather than gametes) leads to the cell vacating the test, adding it to the death assemblage. Therefore, the death assemblage is initially controlled by the life processes of foraminifera, before further alteration by post-depositional changes, which will vary in their type and intensity within and between sites (Murray, 1991; de Rijk, 1995).

Post-depositional changes are the result of diagenetic processes (Murray, 1991), including selective preservation, transportation of tests, bioturbation, infaunal habitats, and predation.

3.4.2.1 Selective preservation

Selective preservation of foraminifera is caused by differences in test structure and composition (de Rijk, 1995; de Rijk and Troelstra, 1999). Calcareous foraminifera commonly undergo dissolution (carbonate solution) of the test, caused by organic matter or mineral oxidation (Green *et al.*, 1993). Even in a high pH marsh, if a calcareous species does manage to survive, the tests are dissolved rapidly once the specimens die (Green *et al.*, 1993; de Rijk and Troelstra, 1997). This is due to acute pH lowering at the sediment-water interface (Parker and Athearn, 1959; Phleger, 1970) and the removal of the limited protection of the test afforded by the protoplasm during life (Parker and Athearn, 1959; Bradshaw, 1968). Juveniles tend

not to be preserved at all, as they are uncalcified or only lightly calcified (Murray, 1991; Green *et al.*, 1993).

Bradshaw (1968) reports evidence of dissolution in tests to be apparent after ten days at pH 6.0 but, at pH 5.0, complete solution of the test occurs within one day. Indeed, Murray and Alve (1999), in examining a sediment core, found that at a depth of 1cm, a predominantly calcareous living surface assemblage became an almost completely agglutinated assemblage.

Agglutinated foraminifera are more widespread in intertidal environments, owing to their resistance to dissolution in low pH environments (Bradshaw, 1968; Phleger, 1970). They are not, however, invincible, and certain species with delicate tests are prone to disaggregation. Specimens particularly prone to this are those with loosely cemented, poorly sorted tests (Murray, 1991; de Rijk, 1995). As long as the grains are uniformly sorted, grain size alone does not seem to play a part. de Rijk (1995) reports disintegration of some coarse-grained species, with other coarse-grained types being more firm, whilst Murray (1991) believes fine-grained specimens to be more susceptible. It is more likely that poor cementation or sorting will be the main cause here. Agglutinates are also at greater risk of compaction and drying, often leading to the collapse of chamber walls (de Rijk, 1995).

3.4.2.2 Transportation

The autochthonous foraminiferal assemblage can be altered by transportation into (mixing) and out of (loss) an area (de Rijk, 1995), with no easy way of being able to recognise such movement when examining a sample. This is important in respect of being able to recognise those specimens which give a true reflection of the local environment (i.e. those *in situ*), and those which have been transported into the place of deposition, providing partial information on the wider environment (Horton, 1997).

Transport mechanisms include bed load, suspended load, ice or floating plants, with transport by water considered to be the most important (Murray, 1991). The transport itself is selective, and will depend upon foraminifera size and specific gravity (Murray, 1991), although test shape is also likely to be a factor.

Transport is most likely to be directly behind the sill, where flow velocity decreases on the rising tide, as the water is freed from the constriction, reducing its capacity to carry a suspended load, and increases on the rising tide. The main indication of this in examining samples is that the specimens tend to form a large death assemblage, in the area of the basin with the coarsest substrate where a shelly lag, such as that at Rumach VI in northwest Scotland (Shennan *et al.*, 1999), has often formed just landward of the sill.

3.4.2.3 Bioturbation

Bioturbation can lead to the upward or downward movement of particles (Murray, 1991) and the process may operate down to a depth of 10cm below the sediment surface (McCave, 1988). The most active bioturbation, however, is usually only found in the top 4cm, with slower, more episodic disturbance below this (Aller and Cochrane, 1976). Plant roots and the locomotion of foraminifera through the sediment can cause some bioturbation, but not on the scale of larger faunal organisms such as fiddler crabs (de Rijk, 1995). The rate of reworking varies on a seasonal basis, being highest in summer or early autumn in marsh sediments (Green *et al.*, 1993).

Bioturbation can promote the dissolution of calcareous foraminiferal tests, but it can also help in the preservation of smaller forms, in that reworking can allow tests to bypass the dissolution zone by biogenic subduction or falling into tubes and burrows (Green *et al.*, 1993).

3.4.2.4 Infaunal foraminifera

The presence of certain infaunal species can change the composition of the living surface and fossil assemblages (Goldstein and Harben, 1993; de Rijk, 1995). After selective preservation, infaunal foraminiferal habitats is the most common post-depositional change in literature dealing with modern foraminiferal ecology and palaeoecological reconstruction. The results of research examining the depth of infaunal habitat have been variable. Alve and Murray (2001) found the majority of foraminifera to be living in the top one centimetre of a muddy intertidal sediment over a one year survey, with the highest abundance of all species being in the top

0.25 cm, whilst Akers (1971) reported rose Bengal-stained specimens of agglutinated species to a depth of 30 – 35 cm in North Carolina.

The obvious control upon the depth of living is the depth of the oxygenated zone controlled by the particle size, with fine-grained marshes seeming to reduce the capacity for burrowing by foraminifera (e.g. Horton, 1997), whilst sandy substrates present a deeper oxygenated layer, allowing more abundant infaunal microhabitats (Kitazato, 1994). Severin (1987), however, reports that sandy substrates may also inhibit the capacity of a foraminifer to live infaunally if they are of a size which requires them to displace the sand grains as they burrow, thus constraining their rate of movement. The maximum abundance of benthic microalgae foraminifera feeders occurs a few millimetres immediately below the surface, irrespective of the position of the redox boundary (Alve and Murray, 2001).

3.4.2.5 Predation

Foraminifera in a subtidal surface sediment contribute 12% to the living biomass (Gerlach, 1978). Thus, when present in high densities, foraminifera provide a large food reserve (de Rijk, 1995). Predators include other foraminifera, nematodes, gastropods, crustaceans, fish, and fiddler crabs (Lipps and Valentine, 1970; Murray, 1991; Green *et al.*, 1993; de Rijk, 1995). Whilst the colour of some tests may be particularly attractive to predators, the majority of benthic foraminifera that are consumed are taken unselectively, and have holes bored in their tests, rather than solution of the test, in order to access the protoplasm. Therefore, predation should not cause significant alteration to the assemblage, unless the test is transported or destroyed (Murray, 1991).

3.4.3 Foraminifera and environmental parameters sampling design

Both the spatial distribution, and relative and absolute abundances of benthic foraminifera are affected by patchiness. An awareness of this is particularly important when dealing with living assemblages, where this a potential problem in evaluating results if the micro-scale spatial variability masks the effect of any underlying temporal cyclicity or trend (Murray and Alve, 2000).

3.4.3.1 Collection and preparation of samples

“High quality results can be obtained only from samples that are collected and handled with care” (Murray, 1991, p.313).

Each of the twenty sites, bar one (Dubh Loch, Argyll), was visited twice for foraminiferal sampling, with a gap of approximately three months between visits. The number of foraminiferal samples collected at each site varied from 7 to 48 during each visit. Water chemistry was measured at least twice during each visit (i.e. four times in all, per site), with the aim of establishing the extremes by sampling around the time of Neap tides and the time immediately following Spring tides. A safety line, with markers attached at regular intervals, was stretched out across each site, so as to identify the same sample points on each visit. Samples for sediment analyses and sill elevation data were collected only once for each site.

The collection of foraminiferal and sediment samples from the sediment/water interface was undertaken using a Russian corer in shallow water, and a grab sampler in deeper basins, from a small inflatable dinghy, anchored or tied into position on a safety line. Wherever possible, the Russian corer was used, as it appeared to cause less disturbance to the sediment. The top one centimetre of sediment was removed, and immediately placed in a pre-labelled storage vial. If material had been extracted by Russian corer, the process was repeated in order to retrieve material for analysis of particle size and organic content. Where the grab sampler had been used, sufficient material was available in one collection to fill vials for both foraminiferal and sedimentological analyses. Upon return to shore, each sample for foraminiferal analysis was placed in a rose Bengal solution (Walton, 1952) and the vial re-sealed, before being stored in cool conditions. Upon return to the laboratory, the samples were refrigerated. The exact make up of the rose Bengal solution used was 1 litre of 30 % ethanol with 1.5g of the protein stain rose Bengal ($C_2OH_2O_5T_4Cl_4Na_2$) and 1.5g of Sodium Hydrogen Carbonate ($NaHCO_3$) added.

Of the environmental parameters, most were measured in the field, but sedimentological analyses had to be undertaken in the laboratory. Measurements of salinity, pH, dissolved oxygen and water temperature were undertaken using Jenway meters, calibrated to, and beyond, the manufacturer's instructions. Further

information on the calibration process for the conductivity meter, and conversion of its readings to salinity, is provided in Appendix One. In water deeper than 2-3 metres, a halocline can develop with freshwater on the top (Barnes, 1980), so a one metre water sampler, triggered by a messenger attached to a cable, was used to reach the water at the bottom of the basin, and readings taken upon return to the shore. Freshwater input into the basins was measured using the average annual rainfall in the area of the basin in combination with the area of the basin catchment.

Sediments were subject to laboratory tests to determine the percentage organic content and particle size distribution, using loss on ignition (modified from Ball, 1964) and analysis in a Coulter laser granulometer respectively. Data from the laser granulometer was downloaded in British Standards format, and simplified into the percentage clay ($< 3.9\mu\text{m}$), silt ($4 - 63\mu\text{m}$), and sand ($63 - 200\mu\text{m}$) fractions. Details of sample preparation for these procedures are provided in Appendix One.

The elevation of the sills on North Uist were measured using a Leica 1010 total station, and tied into the Outer Hebrides datum using local benchmarks. Levelling on the mainland and Skye was undertaken using a Leica system 300 dual-frequency GPS system, with the results post-processed in SKI software by Leica technical support department, and tied into the Ordnance Survey National GPS Network of active stations, which converts the data to the Ordnance Survey National Grid system. The levelling on North Uist using the total station was checked with the GPS system, and the error margin of all measurements never exceeded 6.6 cm.

Once the foraminiferal samples were returned to the laboratory, a volume of 2cm^3 or 4cm^3 was removed, and wet-sieved through $500\mu\text{m}$ and $63\mu\text{m}$ sieves, using low water pressure in a fine spray, so as not to damage any foraminiferal tests. The material greater than $500\mu\text{m}$ was discarded. The material in the $63\mu\text{m}$ sieve was retained and refrigerated, prior to analysis under the microscope. Samples were wet-picked from a tray, and attached to a Chapman slide using diluted adhesive.

3.4.3.2 Determination of foraminiferal life forms

The rose Bengal method of staining has been widely used to differentiate living from dead foraminifera since its first description by Walton (1952). In this method, the

stain is absorbed onto proteins, which are major cytoplasmic components, rendering the cytoplasm a rose colour (Walton, 1952). The method is fairly quick, and inexpensive (Bernhard, 2000). There are, however, negative aspects to the method. Protoplasm can remain within a test, following death, for periods of several months (Bernhard, 1988) and will, therefore, stain. This is particularly apparent in poorly oxygenated environments, where decay is slow (Patterson *et al.*, 2000a). The organic lining of a test can also be stained, as can bacteria using the test as a refuge (Murray, 1991). The reverse can also occur, as the cytoplasm of some species can fail to take up the stain, and in some species (particularly agglutinates) the opaque nature of the test can make it difficult to determine the outcome of staining by the rose Bengal (Bernhard, 2000).

Despite its drawbacks, the rose Bengal staining technique is the most practical method of determining living forms (Murray and Bowser, 2000). It is good practice, however, to have an awareness of the method's limitations, including checking, where staining is present, that the last few chambers have absorbed the stain, before considering the specimen to have been alive at the time of sampling (Murray, 1991).

3.4.3.3 Total, live or dead foraminiferal assemblages?

Which components of a foraminiferal assemblage should be used in studies concerned with palaeoecological reconstruction is the subject of much ongoing debate. The debate is split between the use of the total (life plus death), life, and death assemblages.

Many use the total assemblage, as they believe it is the true modern analogue to buried total populations, serving as a time-averaged population which integrates the temporal and some of the spatial variability within a site (e.g. Scott and Medioli, 1980b; Jennings *et al.*, 1995; de Rijk, 1995; Gehrels *et al.*, 2001). Conversely, Murray (1973, 2000; Murray and Alve, 2000) criticises this approach, vehemently supporting the use of life assemblages, monitored in long-term seasonal studies, as the use of total and death assemblages disregards any post-depositional modifications, as outlined in 3.4.2. Horton (1997, 1999), however, in conducting a twelve month study of Cowpen Marsh, Teesside, concluded that the death assemblage most accurately represented the sub-surface assemblage, and was less

susceptible to seasonal variability. On this basis, Horton (1997, 1999) advocates the use of the foraminiferal death assemblage in palaeoecological reconstructions.

A pilot study was carried out on short cores collected from modern isolation basins by Dr Jeremy Lloyd, and compared to the surface assemblage, in order to determine their relationship.

- *Methods and results*

Cores of 50 cm length, together with Chapman slides containing rose Bengal-stained surface foraminiferal assemblages picked by Dr Jeremy Lloyd and Dr John Evans, were available from six modern isolation basins on North Uist.

One centimetre slices were cut from the cores with a sharp knife at the intervals 1-2 cm, 2-3 cm, 5-6cm and 10-11cm, and the samples were prepared following the method outlined in 3.4.3.1, barring the application of rose Bengal. Relative percentage species counts from the core and the surface dead, live, and total assemblages, were plotted in TILIA program v.2.0 b0.5 (Grimm, 1991-1993), and subjected to unconstrained cluster analysis in CONISS (Grimm, 1991-1993). The results are presented in Figure 3.4.1 –3.4.6.

In the clusters and the relative percentage data presented in Figures 3.4.1 – 3.4.6, the total assemblage appears to be the most closely linked to the sub-surface assemblages overall. This is not clear-cut in each individual basin, however, with some complex foraminiferal assemblages occurring and the live assemblage counts also reflecting the sub-surface assemblages in some of the basins. There are further problems introduced through the difference in species compositions between the surface and sub-surface assemblages. The most probable cause of this is dissolution of many of the calcareous tests which appear in surface assemblages, owing to the acidic substrate conditions (e.g. Green *et al.*, 1993). Whilst the life assemblage may present a more accurate picture of environmental conditions, if monitored regularly over at least a one-year time scale, the travelling distance to the sites involved rendered this impossible.

The primary argument against the use of the total assemblage in palaeoecological reconstructions is the unknown factor of post-depositional changes and, in particular, dissolution of calcareous tests, transport, and infaunal habitats. In recent work on fossil isolation basins, however, there are fossil records stretching up to *ca.* 9500 cal years BP containing abundant calcareous species, especially *Elphidium williamsoni* (Woodall, 1999; Lloyd, 2000). At the other extreme, whilst undertaking preliminary visits to sites on North Uist for this research, it was established that calcareous tests could rarely survive or be preserved immediately following death in modern assemblages, presumably because of the acidic rock type and dominance of the catchment areas by peat, leading to a sharp transition in pH at the sediment-water interface (e.g. Figures 3.4.1 – 3.4.6). On the basis of these two observations dissolution was not deemed to be a significant problem for the fossil data-set, although the lack of calcareous species in the modern data-set may present problems of its own during the reconstruction of fossil environments.

There is also little potential for large-scale transport of foraminifera within isolation basins, with basins on exposed coasts having been avoided, and the sill protecting all basins used from strong tidal currents. The only significant transport appears to be that carrying coarse material into the basin, with deposition occurring immediately behind the sill. Unfortunately, the short-cores used in the pilot study were collected approximately three years prior to the pilot study being carried out, so it was not possible to determine the infaunal characteristics of the foraminifera present.

On the basis of the above, it was decided that the total foraminiferal assemblage would be the most representative for this study. The use of the total assemblage, with the apparently low rates of dissolution involved in some fossil samples in isolation basins and the difficulty of survival / rapid dissolution of calcareous tests in some modern basins, removes this requirement by averaging out the temporal variability (it may represent several years of foraminiferal accumulation), whilst at the same time, the collection of two sets of samples from each basin, three months apart, still gives some indication of changes in the life assemblage during the spring and summer months, when most foraminifera will bloom.

3.4.3.4 *Foraminifera sample size*

The general agreement for a statistically significant foraminiferal sample size is between 300 and 400 specimens (Murray, 1991), depending upon the number of species present and the relative abundance of the most important minor species (Patterson and Fishbein, 1989). Whilst 500 specimens may be the ideal value, in giving slightly more accurate results, there is a large trade-off in terms of time taken for counting the samples (Murray, pers. comm. 2001).

Patterson and Fishbein (1989) noted that low counts will only affect quantitative assessment if important indicator species are present in small abundances. This is necessitated as smaller fractional abundances are seen as representing smaller differences in environment, thereby requiring smaller margins of error; large differences in environment can accept larger errors. Whilst a species accounting for 50% of the fractional abundance of a sample may require a count of as low as 50 specimens, greater than 500 specimens are required for an indicator species making up just 5% of the sample (Figure 3.5, from Patterson and Fishbein, 1989).

Given the low species diversity of most samples in this research, a target value of 300 specimens was selected for the data collection phase. However, many of the isolation basins have low counts towards the basin margins, particularly in those sites with sills in the higher reaches of the tidal regime. Automatic rejection of these samples would remove a vast proportion of the data, leaving a large amount of samples dominated by a single species. Therefore, a balance has to be struck between the two extremes of the removal of meaningful data and the inclusion of possibly inaccurate results. The minimum counts decided upon for this research, together with the margins of error around the 95% confidence interval, are presented in Table 3.1.

Relative Abundance (%)	Minimum Number of Specimens Required	% Error at 95% Confidence Interval
>95	30	± 8
50	70	± 12
25	100	± 9
10	200	± 4
4	300	± 2

Table 3.1 Minimum counts required for a sample with the indicator species at various percentage relative abundance values, together with error margins at the 95% confidence interval. Larger percentage errors are permitted at higher levels of abundance.

3.5 INTRODUCTION TO ENVIRONMENT RECONSTRUCTION

Statistical palaeoenvironmental reconstruction uses multivariate techniques to determine patterns and trends in complex systems, with the goal of reducing the dimensionality of the data, so that they can be more easily interpreted (Kovach, 1995). The primary aim is to identify the key environmental variables, and then to express these as a function of the biological data (in this case, quantitative values of foraminiferal assemblage) (Figure 3.6). This function is termed a transfer function, and it is constructed through the process of calibration (ter Braak, 1987b; ter Braak and Prentice, 1988; Birks, 1995). In terms of this study, the key environmental variables are those which control the foraminiferal ecology of the isolation basin environment, as outlined in 3.4.1.

The majority of quantitative environmental reconstructions involve two stages. First, the responses of the modern taxa or 'training set' to contemporary environments are modelled using regression techniques. Secondly, these modelled responses are used to infer past environmental variables from the composition of fossil assemblages, using calibration methods. Both regression and calibration may be conducted using classical or inverse approaches (Birks, 1995).

The first step in environmental reconstruction must be to discover whether linear or unimodal (Gaussian-like) statistical models are appropriate for the available training set, in relation to those environmental variables which are of interest. To determine

this, detrended canonical correspondence analysis (DCCA) may be employed (Birks, 1995).

In order to calculate the error of prediction, the root mean square error (RMSE) is commonly calculated for the modern training set of microfossils, and is used as a measure of its predictive ability (Birks, 1995). Usually, however, some form of cross-validation, such as jack-knifing or 'leave-one-out' is required to provide a more reliable and realistic prediction error (ter Braak and Juggins, 1993; Birks, 1995). Screening of the data set, prior to any regression or calibration is also often useful (Birks *et al.*, 1990), in order to determine any lack-of-fit in a sample to the environmental variable of interest, caused by a strong influence from other environmental factors (Birks, 1995).

If reconstructions are to be reliable, however, there are also a series of assumptions and basic requirements which must be borne in mind.

3.5.1 Basic Requirements and Assumptions

According to Birks (1994), there are at least seven major requirements in any quantitative palaeoenvironmental reconstruction:

- i. A biological system which produces abundant identifiable fossils and that is responsive and sensitive to the environmental variables of interest at the spatial and temporal scales of the study.
- ii. A large, high-quality, training set of modern surface-samples and associated environmental data should be available.
- iii. The fossil data-set should be of consistent taxonomy, and of comparable quality to the modern training set.
- iv. Good independent chronological control is required for fossil data-sets in order to permit correlation and comparison.
- v. Robust statistical methods are required that can model the complex, often unimodal relationships between modern taxa and their environment.
- vi. Reliable and realistic statistical estimation of standard errors of prediction for the modern training set, and for each reconstructed value, is required.

- vii. Critical ecological and statistical evaluations of all reconstructions are needed, as any statistical regression and calibration procedure will produce a result.

There are also five major assumptions which must be made, as detailed by Imbrie and Webb (1981) and Birks *et al.* (1990).

- i. The taxa in the modern training set are related to the environment in which they live.
- ii. The environmental variable being reconstructed is ecologically important in the system of interest.
- iii. The taxa in the training set are the same biological entities as in the fossil data, and their response(s) to the environmental variables have not changed significantly over time.
- iv. The statistical methods employed adequately model the response of the taxa to the environmental variable(s) of interest, with sufficient predictive power to allow useful and accurate reconstruction.
- v. Environmental variables other than the one of interest have negligible influence.

Obviously, the final assumption above is unlikely to be fulfilled in any environment reconstruction, given the relatively high amount of variance commonly left unexplained in transfer functions (e.g. Horton, 1997, 1999). Therefore, the emphasis here must be not so much to falsely assume negligible influence of other variables, but to state clearly the percentage variance left unexplained by the statistical methods.

All techniques, together with a discussion of their relative advantages and limitations, are outlined in chapters 5 and 6.

3.6 SUMMARY

- This research compiles and analyses data from modern isolation basins.

- Twenty sites around the west coast of Scotland and its islands were selected following the criteria and site reconnaissance strategy described above. Biological data were collected with a range of environmental variables measured at each site.
- Foraminifera are chosen in preference to other microfossil groups because of their sensitivity to change and resulting potential accuracy in reconstructions. The foraminiferal assemblages appear to be well preserved in cores from fossil isolation basins already examined, and occur in high numbers, thereby providing a good statistical basis for palaeoenvironmental interpretation (Horton, 1997).
- The total (live plus dead) foraminiferal assemblage is selected as the most representative of the fossil assemblages, whilst two visits to each site, three months apart, provides an indication of temporal variability of the foraminifera within basins.
- A minimum relative percentage abundance of $4\% \pm 2\%$ in any one sample has been selected as a cut-off value for indicator species. In this scenario, 300 specimens would also have to be counted in the sample, in order that the results can be deemed statistically significant.

Field Areas and Study Sites

4.1 INTRODUCTION

Having detailed the criteria used in the selection of sites in chapter three, chapter four provides more precise details of each of the twenty sites, as well as their regional context. The following information is considered:

- A summary of the dominant geological setting of the three separate field areas.
- A review of the work undertaken as part of the Marine Nature Conservation Review (MNCR) on those sites included in this research.
- The location, environmental setting, and characteristics of each modern isolation basin investigated in this research.

4.2 SUMMARY OF FIELD AREAS

This section summaries the relevant information available for the three areas (Skye and the Outer Hebrides, Assynt, and Argyll) outlined in Figures 3.1.1 – 3.1.4, based upon their geology and general environmental setting.

4.2.1 Skye and the Outer Hebrides

The Hebridean Islands are split into two chains, forming the Inner and Outer Hebrides. The Outer Hebrides (or Western Isles), including the Uists, Harris and Lewis, lie towards the periphery of western Europe, fully exposed to the Atlantic marine and climatic forces (Ritchie, 1996). They provide a degree of shelter for some of those islands forming the inner chain, such as the Isle of Skye. The islands covered in this research are the Isle of North Uist, Grimsay, and the Isle of Skye, with nine sample sites in the area (Figure 3.1.2).

The geography of the Hebrides has undergone profound changes during the last 14,000 years. On deglaciation there was one long Outer Hebridean island, which extended far west of the present Atlantic shoreline (Lambeck, 1995). A deep trough in the sea floor beneath the present Little Minch and North Minch had already flooded. Gradually, the western seaboard of the Outer Hebridean island became inundated by the rising ocean, causing re-working of the deposits laid down by the retreating ice mass, and the introduction of calcareous sands which now form the fertile machair environment with which the west coast of the Outer Hebrides is so frequently associated (Hall, 1996).

The islands themselves are varied in their landscape. The more mountainous Isles of Skye and Harris with their rugged cliffs are in stark contrast to the peat-covered, low-lying plateaus found on Lewis and the Uists. Much of the Uists and Benbecula lie close to sea-level, with ice-scoured rock hummocks and innumerable lochan-filled basins (Hall, 1996). This landscape characterises the Outer Hebrides as a whole, particularly on the rocky east coast, and provides the highest density of lagoonal habitats in Britain (Thorpe *et al.*, 1998). The maritime climate of the Hebrides today, as for much of the rest of western Scotland, is known for its unpredictability and occasional ferocity. There is only a small annual variation in temperature and precipitation, giving rise to cool, wet summers, and relatively mild winters, making the wind the most dominant climatic characteristic of the Hebrides, although Skye is somewhat more sheltered (Armit, 1996).

The Western Isles have seen little appreciable isostatic rebound since deglaciation, reflecting the relatively small volume of covering ice during the Devensian, to counteract the rising sea (Armit, 1996). The Outer Hebrides archipelago is presently undergoing very slow relative sea-level rise (Gilbertson *et al.*, 1996). This makes the shallow sloping west coast particularly vulnerable to land loss, with the machair environment in constant flux in order to readjust its landward configuration to the rising RSL (Armit, 1996), and the effects of reduced sand supply and increased storminess (Hansom and Angus, 2001). In contrast to the Western Isles, current uplift on Skye is estimated to approximate 1.5 mm/yr by Shennan (1992).

4.2.1.1 Geology

The Outer Hebrides are dominated by Lewisian Gneiss, some of the oldest rocks exposed in Europe, having formed around 2900 Ma (Fettes *et al.*, 1992). They are intensely metamorphosed basement rocks, with the islands representing the weathered surface remnants of a long ridge of gneiss, which has been eroded to form a series of low, fragmented islands (Armit, 1996). Locally, the gneisses are cut by dykes and irregular masses of acid and basic igneous rocks, with the east coast of the Outer Hebrides long island running parallel to the Minch fault, which lies just off-shore (Figure 4.1; Hall, 1996).

The Isle of Skye is formed of a series of jagged peninsulas, divided by long sea lochs, with a more complex geology than that of the Western Isles. Although Lewisian Gneiss is locally present, it does not dominate as it does in the Outer Hebrides. Rather, the predominant rock formations on Skye were created by volcanic activity in the Tertiary period, approximately 60 Ma (Figure 4.1), with the Cuillin mountains being formed at this time (Armit, 1996). Subsequently, like the Western Isles, the rock formations have been sculpted and scoured by the ice movements of the Quaternary period, with the carving of great gorges, now filled by the sea, such as that which separates Skye from the mainland (Armit, 1996).

The geology of both the Western Isles and the Isle of Skye produces a very thin soil, usually acidic and lacking in fertility (Armit, 1996). The acidity is likely to have implications for the survival of calcareous foraminifera, which are known to be vulnerable to dissolution under acidic conditions (cf. Sections 3.4.1.2 and 3.4.2.1).

4.2.2 Assynt

The eight sites in this area (Figure 3.1.3) are outside of Assynt in its strictest sense, and their geology is a little more straightforward than the that of the true Assynt area. For the purposes of this thesis (and for want of a more accurate descriptor), however, Assynt is taken to extend northwards from Ullapool, including all of the west coast up to Loch Laxford (Figure 4.2).

The relief of the land in Assynt is some of the most pronounced in Scotland, forming part of the Northern Highlands, with more coastal cliffs and more rugged coastline in this region than any of the other field areas, with the exception of the Isle of Skye. This has clear implications for the rate and volume of freshwater drainage into basins. With the rapid runoff caused by the topography, the geology will have a smaller effect on the chemistry of the water than the basic rocks on the plateaus of the Outer Hebrides, where water is more likely to be held in storage, and over a longer timescale.

The rate of Holocene uplift for the area is not apparent from the model proposed by Shennan (1992). However, the Moray Firth adjacent to Inverness was given a value of 1.6 mm/yr, so it can be expected to be slightly less than this, as one moves away from the centre of uplift.

4.2.2.1 Geology

Assynt is an area of complex metamorphosed rocks, dominated by the Moine Thrust. The basement rock for the area is Lewisian Gneiss, which is the product of a series of deformation and metamorphism events. This is cut by acid and basic igneous intrusions (Figure 4.2). Two major metamorphic, tectonic and intrusive events can be recognised. The earlier event, or migmatitisation (Fettes *et al.*, 1992) produced the Scourian Complex, generating high-grade gneisses, whilst the later event gave rise to the Laxfordian Complex, during which the original rock was reconstructed by tectonism and metamorphism to form lower-grade gneisses. These two events were separated by a period of crustal tension, during which a swarm of tholeiitic dykes (commonly known as the Scourie Dykes) was formed (Johnstone and Mykura, 1989).

Coastal locations have a simplified geology of Lewisian Gneiss, with Torridonian Sandstone resting unconformably above it (Figure 4.2; Horne, 1907). The isolated sandstone peaks which remain, such as Suilven, were once part of a continuous cover which buried the gneiss to a depth of 1 km or more. Much of the rock has been ground down to the now characteristic lochan-strewn surface by the passage of ice, exhuming the Lewisian Gneiss in the process (McKirdy and Crofts, 1999). Again,

this more recent geological background has created an ideal landscape for abundant isolation basins around the coast.

4.2.3 Argyll

The three sites in Argyll lie in an area from just south of Oban, in the north, to the immediate west of Lochgilphead in the south (Figure 3.1.4). Much of Argyll is covered by forested land, with high relief inland, but a relatively flat, more 'rolling' landscape towards the coastal margins (e.g. Stephenson and Gould, 1995).

The rate of present uplift for the Argyll area can be estimated from Shennan's (1992) model to be between 1.5 and 1.8 mm/yr.

4.2.3.1 Geology

As for the other field areas, the geological setting of Argyll is predominantly metamorphosed rock, intruded or overlain by igneous rocks in places. In this case, the metamorphosed rocks are of Dalradian age, represented mainly by schistose grit and mica-schist, becoming more influenced by epidiorite and chlorite-schists as one moves northwards, with occasional bands of modified, recrystallised limestone (Figure 4.3, Stephenson and Gould, 1995).

Like the Hebridean Isles and Assynt, there is a lack of calcareous parent material in most of the region, save some small areas of limestone, with rocks rich in bases, leading to an acidic soil and soil-forming mineral environment (O'Dell and Walton, 1962), with ramifications for the survival and preservation of calcareous foraminifera.

4.3 MARINE NATURE CONSERVATION REVIEW

The Marine Nature Conservation Review (MNCR) of Great Britain began in 1987. It complements the earlier Nature Conservation and Geological Conservation Reviews. Its primary objective was to extend the knowledge of benthic marine habitats, communities and species, and identify sites and species of nature conservation importance (Hiscock, 1998). As a contribution to the general MNCR survey programme as a whole, and in order to support the implementation of the

1992 EC Habitats Directive, in which saline lagoons are listed as the sole priority marine habitat requiring protection, the MNCR began a survey of lagoons in Scotland in 1993. The work included surveys of the shores (if tidal) and subtidal zone of each lagoon, describing their habitats and communities (collectively known as biotopes), and assessing their importance to the natural heritage (Covey, 1999). Thorpe *et al.* (1998) provide summaries of the basins in the Outer Hebrides, whilst Covey *et al.* (1998) covered the Inner Hebrides and mainland Scotland. All surveys were conducted in accordance with a standard MNCR rationale and methods procedure, described in Hiscock (1996).

For each basin, the biotopes present were determined and presented in maps. A basic description was also given of the location, date and type of biological survey carried out, type of lagoon (under the JNCC (1996) classification), area, maximum length and bathymetry of the lagoon, degree of wave and tidal stream exposure, tidal range at the site, and salinity of the water in the basin. In addition, the marine biology was summarised, together with details of any potential human influences on the site. Forty-seven biotopes and sub-biotopes were identified for mainland Scotland and the Inner Hebrides (Covey *et al.*, 1998), and 52 for the Outer Hebrides (Thorpe *et al.*, 1998), based upon the national biotope classification system of Connor *et al.* (1997a, 1997b).

The initial descriptions of the lagoons covered by the MNCR were used in the preliminary site selection process for this study, prior to reconnaissance fieldwork. This study therefore builds upon the information provided by the MNCR survey of saline lagoons, in covering the omissions from the summaries provided by Thorpe *et al.* (1998) and Covey *et al.* (1998), and in providing further information on the variability of the intra-basin environment. For those basins which were not included in the reports, their absence is highlighted in the relevant section below, where a brief outline of each basin used in this research is provided.

4.4 INDIVIDUAL BASINS

The lagoons around Scotland vary greatly in size and character. One common theme amongst most of the sites, however, as with most lagoons in Britain, is that they are

predominantly shallow, with only a few exceeding 5 m in depth, and many shallower than 0.5 m (Thorpe *et al.*, 1998). This variability between basins is likely to have an impact upon all aspects, and habitats within the basins, making each one unique. The general characteristics of all the basins studied in this thesis are outlined in the remainder of this section, with the main information summarised in Table 4.1 and each basin description accompanied by a site map (Figures 4.4.1 – 4.4.20).

4.4.1 Oban Trumisgarry

Oban Trumisgarry (Figure 4.4.1) is located on the Isle of North Uist (NF 873 745), fed by water from the sheltered Vallaquie Strand, via a culvert under the B893 road. A stream to the rear of the basin was dried-up during all visits to the site, but may provide a small freshwater input during winter and spring months. The basin lies adjacent to Oban nan Struthan (Section 4.4.2), with a small drainage divide between them. Other than this, the relief of the land surrounding the basin is minimal, with the only vegetation being grass, indicating little overland runoff of freshwater into the basin.

Thorpe *et al.* (1998) report the main body of the lagoon to be of a fine, sandy mud, colonised by dense patches of the tasselweed *Ruppia* sp. There are also casts of the lugworm *Arenicola* sp. in the sandy and muddy sediments. Other common fauna within the basin are the Oystercatcher *Haematopus ostralegus*, shore crabs *Carcinus maenas* and a breeding pair of Mute Swans *Cygnus olor*. There is a small amount of saltmarsh which fringes the basin.

The basin forms part of the South Lewis, Harris and North Uist National Scenic Area (NSA), based upon the area's landscape and scenery.

4.4.2 Oban nan Struthan

Oban nan Struthan (Figure 4.4.2) is located on the Isle of North Uist (NF 877 748), directly adjacent to Oban Trumisgarry (Section 4.4.1). Like Oban Trumisgarry, it receives its marine input through an under-road culvert from Vallaquie Strand and, as such, is protected from wave exposure, although the tidal stream from the culvert can be quite strong in the immediate vicinity of the sluice. There are two small

Basin	Sill Altitude (m OD)	Area (ha)	Max Length (m)	Max depth at low tide (m)	Max depth at high tide (m)	Water volume at low tide (m ³)	Water volume at high tide (m ³)	Catchment area freshwater input (m / yr)
Oban Trumisgarry	0.813	5	300	0.75	1	17,500	30,000	150,000
Oban nan Struthan	0.851	4	750	0.5	0.8	14,000	27,500	100,000
Alioter Lagoon	0.674	10	400	1	1.6 - 1.7	7,500	13,500	350,000
Bac-a-Stoc	0.653 / 1.707	3	300	0.5	1	9,000	24,000	60,000
Locheport 1	0.879 / 1.607	6	300	0.3	0.6	4,000	13,000	120,000
Locheport 2	0.417 / 0.602	1.5	250	1	2	9,000	24,000	22,500
Grimsay	1.035	0.6	125	0.2	1.2	1,200	7,200	9,000
Pool Roag	-0.707	40	1750	3	4.5	400,000	1,000,000	1,680,000
Loch na h'airde	1.851	6.5	300	2	2.3	32,500	52,000	341,250
Loch of Reiff	1.426	8	500	1	1.2	45,000	61,000	256,000
Lochan Sal	3.182	4	400	2	2	20,000	20,000	192,000
Loch an Eisg-brachaidh	0.801	2	200	0.75	1.75	7,000	27,000	96,000
Loch Roe Lagoon	0.477	4	300	5	6	30,000	70,000	250,000
Oldany	1.42 / 1.923	0.03	30	0.2	0.7 / 0.5	60	210 / 150	1920
Loch Nedd Lagoon	1.921	2.5	200	4.5	4.7	18,750	23,750	120,000
Lochan na Dubh Leitir	4.498	3.5	300	3	3	35,000	35,000	168,000
Duartmore	-0.546	0.7	150	2.5	3.5	6,000	13,000	50,400
Caithlim Lagoon	1.084	8	700	0.5	0.8	25,000	49,000	230,400
Craiglin Lagoon	1.417	6.5	500	5	5.15	40,000	50,000	182,000
Dubh Loch	1.193	24	1200	8	8.1	500,000	525,000	1,728,000

Table 4.1: Summary of basin dimensions, inputs, and sill elevations.

freshwater streams to the rear of the eastern basin and, as for Oban Trumisgarry, with the low relief and grass-covered surfaces surrounding the basin, freshwater input from overland flow will be minimal.

The lagoon is actually formed from two separate basins, with a rocky area in the middle, together with the remains of a dry-stone wall. No samples were taken from the shallow rocky area around the wall. Water exchange between the two basins occurs freely when the lagoon is inundated.

The basin has a fine muddy floor, dominated by the tasselweed *Ruppia* sp., with some lugworm *Arenicola* spp. casts. Some wrack such as the *Fucus serratus* serrated wrack can be found on boulders and cobbles near to the culvert (Thorpe *et al.*, 1998). Other common fauna within the basin are the Oystercatcher *Haematopus ostralegus* and shore crabs *Carcinus maenas*. There is a small amount of saltmarsh on the fringes of the basin, particularly towards the culvert, on which sheep graze.

This basin also forms part of the South Lewis, Harris and North Uist NSA.

4.4.3 Alioter Lagoon

Alioter Lagoon (Figure 4.4.3) is on the Isle of North Uist (NF 887 724). The basin receives its marine input through a culvert under the A865 road, from a sheltered area of Loch Blashaval, with ultra-sheltered wave exposure and negligible effect from tidal streams (Thorpe *et al.*, 1998). Freshwater is provided at the southwest corner of the basin by a stream fed by the comparatively large freshwater loch, Loch Veiravgat, with the relief here also likely to provide some freshwater input through overland flow and seepage from the peat.

The majority of the basin sediment is formed of a sublittoral mud, with a dense bed of *Ruppia* sp., with mats of the green alga *Cladophora* sp. between the tasselweed. The scarce foxtail stonewort *Lamprothamnium papulosum* also occurs in patches within this lagoon. Serrated wrack *Fucus serratus* is found towards the culvert (Thorpe *et al.*, 1998). Again, a breeding pair of Mute Swans *Cygnus olor* was

observed here, as was an otter *Lutra lutra* during one visit. Sea trout *Salmo trutta* are also reported to be found here (Thorpe *et al.*, 1998).

As well as being part of the South Lewis, Harris and North Uist NSA, this basin is part of the Loch Maddy Marine Conservation Area (MCA) and a component of the Loch nam Madadh (Loch Maddy) candidate Special Area of Conservation (cSAC) and Site of Special Scientific Interest (SSSI), based upon the marine fauna and flora of the lagoons in the area (Thorpe *et al.*, 1998).

4.4.4 *Bac-a-stoc Lagoon*

Bac-a-Stoc lagoon (Figure 4.4.4) is located on the Isle of North Uist (NF 898 723). Marine input into the basin is over two natural rock sills from the northwest of Loch Blashaval, close to the sheltered entrance to Alioter Lagoon (Section 4.4.3), although the second sill is so high that only MHWST is likely to breach it. Small amounts of freshwater are supplied through an overgrown channel from an adjacent, deep freshwater loch (Plate 4.1). A small step in the land surface to the rear (south-west) of the basin provides some freshwater input by seepage from the water-logged peat landscape.

The substrate is described as soft, flocculent mud by Thorpe *et al.* (1998), making the basin dangerous to wade into for samples. The substrate vegetation was dominated by the seagrass *Zostera noltii*, with the furoid *Fucus cottonii* present adjacent to areas of saltmarsh. The shore crab *Carcinus maenas* was the only fauna noted in this basin.

As well as being part of the South Lewis, Harris and North Uist NSA, this basin is part of the Loch Maddy Marine Conservation Area (MCA), a component of the Loch nam Madadh (Loch Maddy) candidate Special Area of Conservation (cSAC), and within the Loch an Dùin Site of Special Scientific Interest (SSSI) and Ramsar site, based upon the lagoon and coastal habitats, marine and coastal flora, the value to ornithology, and the presence of seals and otters in the area (Thorpe *et al.*, 1998).

4.4.5 *Locheport 1*

Locheport 1 (Figure 4.4.5) is located on the Isle of North Uist (NF 835 634). The marine input into the basin is from a sheltered area of Loch Eport over a natural boulder-strewn sill and a second, higher, bedrock sill (Plate 4.2). The basin would join naturally with the northern-most basin of Oban nam Fiadh, were the B894 road not built-up between them.

This basin is not covered by the MNCR review of Thorpe *et al.* (1998). However, the substrate is similar to that of Bac-a-Stoc (Section 4.4), being soft flocculent mud, which becomes coarser towards the sill. The basin is mainly surrounded by boulders, but there are some much softer saltmarsh areas along its margins.

Oban nam Fiadh, directly adjacent to and draining out past the sill of Locheport 1, is designated as a cSAC and SSSI under the Obain Loch Euphoirt (Loch Eport) site name, so it is highly probable that Locheport 1 is also covered under these designations.

4.4.6 *Locheport 2*

Locheport 2 (Figure 4.4.6) is on the Isle of North Uist (NF 841 636), a short distance from the Locheport 1 basin. There are two sills allowing marine input into the basin, one of which comes directly from Loch Eport, and the other indirectly from Loch Eport, via a series of basins which also receive the inputs and outputs for Oban nam Fiadh. Outflow from the basin on the falling tide produces tidal rapids (Plate 4.3).

This basin is not covered by the MNCR review of Thorpe *et al.* (1998). However, the substrate is similar to that of Locheport 1 (Section 4.4.5), being soft flocculent mud, which becomes coarser towards the sill. The basin is mainly surrounded by saltmarsh. Debris was also prevalent at this site at the time of the visits, with parts of the back-basin fringed with broken glass bottles and engine components, together with rusting parts of a vehicle chassis.

Oban nam Fiadh is very close to, and drains out past the sill of Locheport 2, and is designated as a cSAC and SSSI under the Obain Loch Euphoirt (Loch Eport) site

name. As for Locheport 1 it is, therefore, highly probable that Locheport 2 is also covered under these designations.

4.4.7 Grimsay

The Grimsay lagoon (Figure 4.4.7) lies on the Island of Grimsay, which is reached by road from North Uist or Benbecula. It is situated at the edge of Scotvein Bay (NF866 559). The marine input enters the basin over a natural rock sill.

Again, this basin was not included in the MNCR review by Thorpe *et al.* (1998), so there is no information readily available on the substrate, flora and fauna of the basin. The area immediately behind the sill is rocky, with coarse sand, before grading out into a soft organic mud as one moves into the basin. The basin is fringed with saltmarsh areas, which are covered by up to 0.3 m of water at MHWST. There is evidence of shore crabs *Carcinus maenas* living in the basin, with their empty carapaces along the edge of the basin shore.

There are no designated conservation sites reported for this area of Grimsay.

4.4.8 Pool Roag

Pool Roag (Figure 4.4.8) is located on the western coast of the Isle of Skye (NG 277 443), close to Dunvegan. It is a long, narrow lagoon, and the largest in the study by some considerable margin. The basin is connected during most stages of the tide.

Freshwater input is supplied into the basin from a number of small streams, with a larger stream at its head, producing a lowered salinity reported to be in the region of 3 by Covey *et al.* (1998). Samples were not collected so far north in the basin for this research, as the land immediately in front of the stream was intertidal, drying out at low tide. A small amount of freshwater input from the surrounding area is probable, given the relief and covering of grass to the north, east and west sides of the basin.

Covey *et al.* (1998) report a mixed substrate around the perimeter of the basin, comprising mud, with cobbles away from the shore. Vegetation ranges from the

wrack *Fucus cottonii* near the shore, the spiral wrack *Fucus spiralis* further offshore and, finally, serrated wrack *Fucus serratus* in the centre. Common fauna include lugworms *Arenicola* spp., periwinkles *Littorina littorea* and the otter *Lutra lutra*.

The site is reported by Covey *et al.* (1998) to be proposed as a Local Natural Heritage Site, for its saltmarsh areas which are locally important for waders and ducks.

4.4.9 Loch na h'Airde

Loch na h'Airde (Figure 4.4.9) is located on a south-western peninsula of the Isle of Skye (NG 394 163), close to the Black Cuillin and the Island of Soay, and immediately adjacent to Loch Brittle. The marine input for the basin comes direct from the open sea, but is fed along a narrow, rocky channel, 50 m in length, in which the sill is located (Plate 4.4). Freshwater input comes from two small streams, and runoff, particularly from land to the north-east and north-west of the basin.

Towards the front and rear of the basin, there are rocky areas, but the remainder of the basin substrate is composed of soft flocculent mud with the tasselweed *Ruppia spiralis*, and some green algae such as *Chaetomorpa linum* (Covey *et al.*, 1998).

Considering the remoteness of this site (4 km from the nearest settlement (Glen Brittle campsite)), it is perhaps surprising to find so much litter and debris around the fringes of this site. However, given the long, narrow channel through which the marine water enters this basin, it is likely that once material is washed into the basin, it cannot subsequently be removed by tidal action.

There are no conservation sites reported by Covey *et al.* (1998) covering this lagoon.

4.4.10 Loch of Reiff

The Loch of Reiff (Figure 4.4.10) is located on the Rubha Coiceach headland in Enard Bay, in the Assynt area (NB 965 145). The loch connects to the bay through a tidal channel, which is approximately 200 m in length, with a rocky sill at its head.

Freshwater input is provided by a stream and overland flow from a catchment of shallow relief.

The southern edge of the loch consists of coarse sand, with boulders and cobbles at the edge of the basin, which gradually grades into a substrate of softer, fine muddy sand, with saltmarsh at the basin periphery, as one moves north through the basin. No vegetation was observed to be growing on the substrate of the basin, other than some green algae on the softer sediments. Fauna such as the cockle *Cerastoderma edule* and lugworm *Arenicola* sp. are reported to be present by Covey *et al.* (1998).

The site forms part of the Assynt-Coryach NSA.

4.4.11 Lochan Sal

Lochan Sal (Figure 4.4.11) is a freshwater loch located in the southeast corner of Enard Bay (NC 071 152), immediately behind a fish farm. There is no marine input into the basin, but there is a controlled output of freshwater into Enard Bay through a notch in a stone wall (Plate 4.5). It is likely that the basin has been connected to the sea in the past, before this wall was built. Given the steep topography and sparse vegetation surrounding much of the basin, a significant input of freshwater will be provided by overland flow and through the two streams.

Being freshwater, the basin is not included in the MNCR review of lagoons by Covey *et al.* (1998), but the site is valuable for indicating the state of fossil basins when they were in a recently isolated phase. The substrate is composed of very soft mud, with filamentous green vegetation, most probably green algae. The south-eastern side of the basin has a steep rock face leading down into the basin, giving a deeper water environment and a more rocky substrate.

This basin is included in the Inverpolly National Nature Reserve (NNR) and SSSI, which were designated for the special upland, freshwater and woodland habitats in the area.

4.4.12 *Loch an Eisg-brachaidh Lagoon*

Loch an Eisg-brachaidh lagoon (Figure 4.4.12) is a series of three small basins, situated on the eastern shore of Enard Bay (NC 072 182). The first of these basins is separated from the Loch an Eisg-brachaidh by an artificial wall, with a culvert under a road bridge allowing marine input and basin output. The sills separating the basins are inundated at most high tides, with a strong tidal stream entering the outer basin during the initial inundation, and a small tidal rapids system operating between the middle and inner basins. A small amount of freshwater is provided by a stream to the rear of the site, although some of this water is used as the water supply for a nearby house. Freshwater input will be limited by the trees and long grass on the land surrounding the basins.

The basins are surrounded by boulders, colonised by channelled wrack *Pelvetia canaliculata* and the lichen *Lichina confines*. The substrate of the middle and inner basins is a coarse, muddy sand, with the green alga *Chaetomorpha linum* growing loosely upon it. On moving from the outer to the middle basin, the substratum changes to one of boulders and bedrock, with serrated wrack *Fucus serratus* and bladder wrack *Fucus vesiculosus*. Mussels *Mytilus edulis* and periwinkles *Littorina littorea* also occur here, and in the rapids system connecting the middle and inner basins (Covey *et al.*, 1998). Shore crabs *Carcinus maenas*, and some larger specimens of crabs, were observed within the basin, often being swept away by the tidal streams.

As for Lochan Sal (Section 4.4.11), Loch an Eisg-brachaidh is included in the Inverpolly NNR and SSSI, which was designated for the special upland, freshwater and woodland habitats in the area.

4.4.13 *Loch Roe Lagoon*

Loch Roe Lagoon (Figure 4.4.13) is located to the north of Lochinver, on the road to Achmelvich (NC 074 246). The basin is situated at the head of Loch Roe, connected to the loch by a channel which is 50 m in length, and is separated from a freshwater loch at the opposite end by a weir, which was always overflowing at the time of visits. This led to a drastically reduced salinity in the area of the outflow, and a

halocline in the remainder of the basin, marked by a severely lowered salinity in the upper section of the water column, particularly at low tide. The high relief along the eastern side of the basin will also provide an appreciable input of freshwater.

Covey *et al.* (1998) report the presence of only very weak tidal streams in the basin. However, the streams which occur coming into the basin during the rising tide, and leaving the basin during falling tides, are the most powerful observed in any basin in this research. These produce a white-water environment inside the basin within 25 m of the channel, which strips loose sediment from the basin floor and presents a hazard for anyone working in the vicinity.

In the shallow sublittoral area, Covey *et al.* (1998) report a mixture of bedrock and boulders supporting fucoids such as spiral wrack *Fucus spiralis* and, at greater depth, bladder wrack *Fucus vesiculosus*. The central and rear, shallower parts of the lagoon are filled with soft, muddy sediments, covered with casts of the lugworm *Arenicola* spp. (Covey *et al.*, 1998)

The lagoon is not included in any reported conservation sites.

4.4.14 Oldany Lagoons

The Oldany Lagoons (Figure 4.4.14) are located to the south-east of Oldany Island, in Eddrachillis Bay (NC 101 337). There are two small lagoons, positioned beside each other, separated by a small drainage divide of 3 m elevation, with marine input entering the basins over natural rock sills (Plate 4.6). There is no obvious source of freshwater input, other than directly by precipitation.

The basins have a soft muddy substrate, with small islands with saltmarsh grasses. The lagoons are not included in the MNCR review by Covey *et al.* (1998).

There are no reported conservation designations for this site.

4.4.15 Loch Nedd Lagoon

Loch Nedd Lagoon (Figure 4.4.15) is located on the western shore of Loch Nedd (NC 134 332), being separated from the loch by a channel containing a natural rock sill. A small stream and a vegetated slope on the land to the rear of the basin provide a freshwater input.

The lagoon has a narrow intertidal fringe of cobbles, with gravel and mud, which form part of the sill. The cobbles support bladder wrack *Fucus vesiculosus* and the green alga *Enteromorpha* spp. The main body of the lagoon is floored by soft, flocculent mud, which supports *Enteromorpha* (Covey *et al.*, 1998).

There are no conservation designations covering this lagoon.

4.4.16 Loch na Dubh Leitir

Loch na Dubh Leitir (Figure 4.4.16) is the second freshwater basin in this survey. Situated on the coastline of Eddrachillis Bay (NC 174 350), it is protected behind a shingle barrier (Plate 4.7), and does not receive marine input. Relatively steep topography to the rear of the basin, on a peat-covered slope, provides freshwater input into the basin.

Again, being a freshwater basin, the site is not covered in the MNCR review of Covey *et al.* (1998). The sediment is a deep, very soft, fine-grained organic mud, with some algae growing on the surface. At the northern margin of the basin there is a large area colonised by reeds. On the second visit to the site, in August 2000, water lilies *Nymphaea* spp. were abundant on the surface.

The site is not included in any conservation designations.

4.4.17 Duartmore Lagoon

Duartmore Lagoon (Figure 4.4.17) is located in Duartmore Bay, where Eddrachillis Bay narrows to enter Loch a' Chàirn Bhàin (NC 187 354). The marine input enters over a natural rock sill enclosed within a short channel, which also serves to protect the basin from tidal exposure (Plate 4.8). A small amount of freshwater enters the

basin from a stream to the rear of the basin, which comes down the hillside in a series of small cascades. The relief of the land surrounding the basin will also provide a significant amount of water *via* overland flow.

The substrate is largely coarse sand immediately behind the sill, which becomes finer further into the basin. Only the very rear margins of the basin have a more muddy layer, with vegetation being sparse. The only fauna observed within the basin were jellyfish during the second visit to the site in August 2000.

The site is not included in the MNCR survey report, and there are no apparent conservation designations covering this lagoon.

4.4.18 Loch Caithlim

Loch Caithlim (Figure 4.4.18) is located on the northern coast of the Isle of Seil, to the south-west of Oban (NM 765 185). The lagoon is connected to the sea by a culvert which passes under a private access road. Freshwater comes into the basin at the rear (western end), but other inputs will be minimal, given the relatively flat land which fringes the basin.

The majority of the basin has a substrate of extremely soft mud, which supports little biota. However, to the northern end of the basin, close to the culvert, serrated wrack *Fucus serratus* and other fucoids are present and, in the immediate vicinity of the culvert, there is also a dense bed of mussels *Mytilus edulis* (Covey *et al.*, 1998).

There are no reported conservation designations covering this lagoon.

4.4.19 Craiglin Lagoon

Craiglin Lagoon (Figure 4.4.19) is located on the margins of Loch Sween (NR 775 878). It is connected to Loch Sween via a narrow channel which passes through a culvert under a forestry road. Some freshwater input will come from the surrounding land, but this is likely to be limited by the forestry plantation.

Most of the lagoon has a bottom of fine mud, with tasselweed *Ruppia* spp. giving way to the seagrass *Zostera marina* at depth. The lagoon cockle *Cerastoderma glaucum* and the shore crab *Carcinus maenas* have both been recorded as living in the basin.

The basin is part of the Loch Sween Marine Consultation Area, identified for the rich and diverse marine communities within Loch Sween.

4.4.20 Dubh Loch

Dubh Loch (Figure 4.4.20) is located at the head of Loch Fyne (NN 115 110), to the north-east of Inverary. It is connected to Loch Fyne by a 300 m long meandering channel, which contains the sill. Freshwater enters the basin in the northeast corner from the River Shira, and undoubtedly from the steep catchment area immediately to the east and west of the basin.

The substrate grades from pebbles and cobbles along the periphery into fine, soft mud with occasional patches of the tasselweed *Ruppia* sp. (Covey *et al.*, 1998). When collecting a sample from 7 m depth, the top surface was covered in black tree leaves, with a strong smell suggesting anoxic conditions. Covey *et al.* (1998) report a halocline to be present in the basin.

There are no conservation designations reported for the site.

4.5 SUMMARY

- Twenty sites have been selected for the study of modern isolation basins. These basins are spread throughout three regions of Scotland, defined as Hebrides, Assynt and Argyll for the purposes of this study.
- The three regions have a relatively diverse geology between them, although extensive sequences of metamorphosed and acidic igneous rocks is a common theme. The glacial history of these three regions provided an ideal landscape for abundant isolation basins around the coastline.
- Between the twenty sites used in this research, there is a diversity in the depth and volume of water contained in the basins (Table 4.1). There is also a wide

spread of sill elevations and catchment characteristics. This should give a broad range of environmental conditions in the combined modern training set.

Contemporary Isolation Basins

5.1 INTRODUCTION

Chapters Three and Four describe the methodology and field sites used within this research. In this chapter the relationship between foraminifera and their environment is considered for contemporary isolation basins. The following points are considered:

- A description of the modern foraminiferal total assemblages. Three sites are detailed individually and then results for all of the basins combined.
- Clarification of the relationship between contemporary foraminiferal distribution and a series of environmental variables, using the contemporary training set.
- An attempt is made to refine the training set down to the eight most significant environmental variables. These are then used in Chapter Six to develop a transfer function, relating the biological data to a single environmental variable.

For each visit to each site, a TILIA graph is presented outlining the foraminiferal assemblages present, together with a graph matrix of the biological and environmental data. Unconstrained cluster analysis was performed on each data-set in order to detect zones within the foraminiferal assemblages present, using the unweighted Euclidean distance method, in which the data are not transformed or standardised. These were computed in the TILIA program of Grimm (1991-1993), with the analysis producing a nested series of clusters, represented as a dendrogram on the graphs (Prentice, 1986). All foraminiferal data collected during fieldwork is included in this analysis, irrespective of cut-off values.

Data from Oban nan Struthan (section 4.4.2), Duartmore Lagoon (section 4.4.17) and Loch Caithlim (section 4.4.18) are presented below as examples of the wider study.

These sites were chosen on the basis of one from each geographical area of this work (section 4.2). They are not necessarily representative of the environmental conditions and biological assemblages present within each area, but are intended to display some of the spatial and temporal diversity within the data. The biological and environmental data for the remaining seventeen sites are provided in Appendix Three.

5.2 OBAN NAN STRUTHAN

5.2.1 *Materials and methods*

Forty-eight sample points were used along three transects (Figure 4.4.2), covering the edges of the basin, in a small saltmarsh area, to the areas of deepest water. The points were chosen and identified based upon sampling at regular intervals along a safety line. Foraminiferal samples were collected twice, in May and September 1999, with samples for loss on ignition and particle size analyses collected in September 1999. Water chemistry measurements were taken four times in May and twice in September. As the basin is almost completely isolated from marine input at Neap Tide, the practice of measuring water chemistry around Neap Tide and at high tide within one day of Spring Tide should ensure that the extremes of the conditions within the basin are considered.

5.2.2 *Foraminiferal assemblages*

Eight foraminiferal species were identified within the samples collected during May (Figure 5.1.1), reducing to six species in September 1999 (Figure 5.1.2). The maximum number of species per sample is six, with no clear trend in the Fisher Index (α) of diversity along the transects, which ranges from 0.15 to 1.2; figures indicative of hypersaline or brackish lagoonal environments (Figure 3.3).

The foraminiferal assemblage is dominated by *Miliammina fusca*, with the assemblage only becoming more diverse and maintaining high numbers of total specimens in samples collected close to the sill. It is possible that specimens have been washed in over the sill, thus explaining the more diverse assemblage. However, only low currents through the culvert and calm conditions in the shallow waters of Vallaquie Strand were observed at the time of the survey. The ecological and /or

hydrological implications of this increase in foraminiferal species diversity towards the sill is, however, clear in terms of reconstructions from isolation basins, highlighting the potential problems of intra-basin variability in environmental reconstruction. Standard practice in recent years has been to sample in transects across basins or at the assumed centre of the basin, on the premise that this represents the true environmental conditions of the basin and hopefully avoids the effects of slopewash, and the inputs of sediment over the sill and through freshwater channels. However, in doing so, the often complex intra-basin variability of isolation basins is being ignored, particularly in large basins, and a true picture of hydrological conditions within isolation basins cannot be established.

5.2.3 Environmental variables

Water salinity in the basin, along a transect from the sill to the rear of the basin, is more uniform around Neap tide, when the basin is not receiving marine input, than Spring tide, when a drop in salinity of up to 15 is recorded between the front and rear sections of the basin (Figure 5.1.3). The divide is delineated by the shallow, narrower rocky section, on which the remains of two dry stone walls are situated (Figure 4.4.2).

Salinity values around Neap tide during the May visit were significantly lower than those during September. The most likely reason behind this is seasonal change due to differences in the precipitation rates between Spring and Summer.

The pH values for the site are all neutral to slightly alkaline (Figure 5.1.4), ranging from 7.06 to 9.05. Conditions remained relatively constant in May and June, regardless of flooding frequency. However, in September pH values were slightly more alkaline during Neap tide than during Spring tide.

Dissolved oxygen values are not available for May and June, owing to instrument malfunction. However, values recorded in September mirror the pH values, with levels at Neap tide being slightly higher than those at Spring tide (Figure 5.1.5). Water temperature also follows this trend, but this will be at least partly as a consequence of the air temperature prior to the time of sampling on each day, given

the shallow water depth within the basin (maximum of 0.5 m at low tide and 0.8 m at Spring tide), combined with the likely cooling effect of marine input. Freshwater input into the basin was not measurable, given the low amount of flow in the streams to the rear of the basin.

The particle size distribution of the site is dominated by sand, with a general trend of increased clay and silt components towards the centre of the rear section of the basin (i.e. that behind the dry stone wall remains). Any patterns between the sill and the wall are less distinguishable, with an increase in silt and clay towards the centre along transect C, but higher clay and silt values at the edge of the basin along transect A. Loss on ignition values show a broadly inverse relationship to sand content, albeit damped, with values ranging from 0.74 % to 14.94 % (Figure 5.1.6).

5.2.4 Foraminifera – Environment Relationships

A scatter plot matrix for all environmental variables and the seven most frequently occurring foraminiferal species is shown in Figure 5.1.7. These plots indicate that the vast majority of foraminifera – environment, environment – environment, and foraminifera – foraminifera relationships are non-linear, with the only notable exceptions being those between the percentage volume of organic content (loss on ignition), clay, silt and sand. The strong relationship between sand, silt and clay should always be expected, as there are implicit inter-relationships within their changing percentage contents.

5.3 DUARTMORE LAGOON

5.3.1 Materials and methods

Eight samples were collected from around the basin on each visit, with sample points following a curved transect from the sill area into the main body of the basin (Figure 4.4.17). No samples could be collected from the very centre of the basin, owing to the deep water and access difficulties with an inflatable. The samples were collected in April and August 2000, with water chemistry measured twice during each visit; once around the time of Neap tide, and again immediately after Spring tide.

5.3.2 Foraminiferal assemblages

Seven species were identified in samples collected in April (Figure 5.2.1), and six species in those collected during August (Figure 5.2.2). Of the twenty samples collected during the year, twelve contained foraminifera of which only seven remained following the screening for statistical significance. The maximum number of species per sample is five, with no clear trend in the Fisher index (α) of diversity along the transect, although species diversity was lower in those samples collected in August; values for α ranged from 0.75 – 1.75 in April, but only 0.18 – 0.6 in August.

The assemblage in April was largely dominated by *Cibicides lobatulus*, with *Miliammina fusca* taking over to the rear of the basin in the much finer, more organic sediments, although only one specimen was present in this sample. In August, the assemblage was more balanced between *Elphidium macellum* and *Cibicides lobatulus*, with one sample to the rear having *Elphidium williamsoni* as the dominant species. The number of total specimens was variable both within the basin and between visits to the site.

5.3.3 Environmental variables

Water salinity within the basin is more constant during the August visit than in April, with lower overall salinities also occurring during the April visit (range of 23.66 to 30.77 in April, compared to 27.51 to 33.40 in August) (Figure 5.2.3). There is no constant distinguishable trend in salinity along the sample transect. Again, some of the values obtained from the hand-held meter were checked using the titration method and with a laboratory bench-top meter. The titration method produced results slightly higher than the hand-held meter for both visits, with an error margin of up to ± 1.5 .

A probable explanation of the lowered salinity during the April visit is freshwater input into the site. A small stream flows into the rear of the basin, but its discharge was unmeasurable on all visits. However, the basin is enclosed by steep rocky slopes on three sides, with a high degree of overland runoff likely following precipitation.

The pH of the water within the basin, like salinity, varied between the seasons, with constant levels through the tidal cycle during August, but marginally lower levels in April (Figure 5.2.4), with the average in April being pH 0.6 lower than that in August.

Levels of dissolved oxygen were found to be higher around Spring tide than during Neap tide, although in absolute terms, the greater range in dissolved oxygen was found in August (Figure 5.2.5). The water temperature followed a similar pattern to the dissolved oxygen levels, in having higher values during Spring tide. This is the inverse of the expected pattern of an increase in the capacity of water to hold dissolved gases with decreasing salinity and temperature (Millero, 2001), suggesting that the higher levels of dissolved oxygen at Spring tide are more likely to have been caused by movement of the water over the sill at high tide. During this time, the oxygen-rich water at the surface is constantly moving and being replaced by water containing less oxygen as a result of turbulence, creating a greater potential for oxygen exchange across the air-water interface (Brown *et al.*, 1997).

Grain size analysis shows the first four samples (those closest to the sill; Figure 4.4.17) to be dominated by sand (94 to 97 %), with low organic content. After this, there is dramatic reduction in sand content, to a minimum of 29.3 %, with silt and clay both increasing significantly, along with the percentage of organic content (Figure 5.2.6).

5.3.4 Foraminifera – Environment Relationships

A scatter plot matrix for all environmental variables and the seven most frequently occurring foraminiferal species is shown in Figure 5.2.7. These plots indicate that the majority of foraminifera – environment, environment – environment, and foraminifera – foraminifera relationships are non-linear. As for Oban nan Struthan, the percentage of sand, silt, clay and organic content appear to have a strong relationship. However, a pattern is also evident between *Elphidium williamsoni* and *Haynesina germanica* with organic content, clay, silt and sand. An increase in any of the first three environmental parameters appears to be met by an increase in either or both of the species, whilst an increase in sand content correlates to a decrease in

either or both species. Conversely, high values of *Cibicides lobatulus* correlate strongly with samples with high sand content; an expected characteristic of the species (e.g. Murray, 1979).

5.4 CAITHLIM LAGOON

5.4.1 *Materials and methods*

Twelve foraminiferal samples were collected from the basin on each visit, with sampling arranged in two perpendicular transects (Figure 4.4.18). Sample collection was conducted in April and July / August 2000, with water samples collected twice during each visit, at around the time of Neap and Spring tides.

5.4.2 *Foraminiferal assemblages*

Only two species were identified in the samples collected in April (Figure 5.3.1), although this increased to five species in August 2000 (Figure 5.3.2), with a maximum of three species in any one sample. Of the twenty four samples collected during the year twelve contained foraminifera. However, none of these samples contained sufficient specimens to pass the statistical screening process (the maximum number of specimens within a sample being 25), meaning the site is disregarded in the combined dataset used in the statistical reconstruction. Species diversity within the site is poor, with Fisher indices (α) of diversity showing no pattern along the transects and values of α ranging from 0.21 to 3.17. *Miliammina fusca* dominates all but one of the samples, with an occasional occurrence of *Eggerelloides scabrus*.

5.4.3 *Environmental variables*

Salinity was almost equal throughout the basin during both visits around Spring tide, with a maximum variance of 0.8 and 0.15 along the transects in April and August respectively (Figure 5.3.3). Variation in salinity conditions around Neap tide is more pronounced, particularly towards the rear of the basin. This is especially true of the readings taken in August, with a maximum variance of 1.68 in April and 6.86 in August. A possible explanation for this could be the inflow of a small stream at the rear of the basin (Figure 4.4.18), of which the flow rate could not be determined.

pH throughout the basin at any given point in time is relatively constant, but displays variation between visits, with three of the four sets of readings within their own unique range of pH values (Figure 5.3.4). As was the case for the salinity values, only the readings taken during August Neap tide show greater variance along the transect. Again, this is towards the rear of the basin, and could again point to the input of freshwater from the stream. Another distinguishable pattern apparent within the readings is a greater range in pH between Spring and Neap tides in August than that during April.

Dissolved oxygen levels in the basin are variable through time but, as for pH and salinity, are relatively constant throughout the site at any given point in time (Figure 5.3.5), with the readings for Spring tides in both months higher than those for their respective Neap tides, in all but one sample. Water temperature is also relatively constant through the basin at a given time, with a maximum range of 2.3 °C between samples during April Spring tide, but 0.6 °C at all other times. Clearly, given the above information, the water chemistry points to a well-mixed basin at most times during the tidal cycle.

Grain size analysis shows mixed substrate conditions within the basin, with the typical coarse sediments immediately behind the sill and the dominant size alternating between sand and silt (Figure 5.3.6). The clay fraction and organic content mirror the fluctuations in the silt component, although in a damped fashion.

5.4.4 Foraminifera – Environment Relationships

A scatter plot matrix for all environmental variables and the seven most frequently occurring foraminiferal species is shown in Figure 5.3.7. Once again, the plots indicate that the majority of foraminifera – environment, environment – environment, and foraminifera – foraminifera relationships are non-linear. As was the case for the previous two sites, the only notable exceptions to the non-linear relationships are those between the percentage volume of organic content (loss on ignition), clay, silt and sand.

5.5 COMBINED RESULTS

All biological data for samples which exceed the cut-off thresholds outlined in Table 3.1 are displayed in Figures 5.4.1 and 5.4.2. Two hundred and sixty-six samples were found to be statistically significant using Table 3.1. For the remainder of this thesis, reference to the total or modern dataset refers to this dataset, screened for statistical significance.

5.5.1 *Multivariate analysis of the contemporary foraminiferal dataset*

The TILIA diagram for the total modern dataset is clustered using the unweighted Euclidean distance and unweighted Chord distance methods, with the data unconstrained. The unweighted Chord distance method utilises the square root percentage foraminiferal abundances, giving greater significance to the minor taxa. Identical zones picked out by both methods are considered to be statistically reliable, as they are deemed to be independent of the method used (Prentice, 1986). The clusters are tested further using Detrended Correspondence Analysis (DCA) in Chapter Six.

5.5.1.1 *Cluster Analysis*

Cluster analysis of the total dataset using the unweighted Euclidean distance method detects seven Foraminiferal Assemblage cluster zones (Figure 5.4.1).

- i. Foraminiferal Assemblage Zone **MF 1** contains only *Miliammina fusca*.
- ii. Foraminiferal Assemblage Zone **MF 2** is defined as a sub-zone of MF 1. Although CONISS does not pick out a separate cluster of samples for this sub-zone, it is differentiated from MF 1 as it does include other species, albeit in low percentage amounts (typically 2 – 5 %). MF 2 is dominated by *Miliammina fusca*, with small numbers of *Trochammina inflata*, *Jadammina macrescens* and *Eggerelloides scabrus*.
- iii. Foraminiferal Assemblage Zone **MF / ES** remains dominated by *Miliammina fusca*, but with an increasing proportion of *Eggerelloides scabrus*. Small numbers of *Elphidium williamsoni* or *Trochammina inflata* may also be present.
- iv. Foraminiferal Assemblage Zone **ES** is dominated by *Eggerelloides scabrus*, with up to 30 % *Miliammina fusca* in some samples. *Elphidium macellum*, *Trochammina inflata*, *Jadammina macrescens*, *Cibicides lobatulus*, and

- Ammonia beccarii* var. *batavus* are also present in some samples, although primarily in trace amounts.
- v. Foraminiferal Assemblage Zone **CL** is dominated by *Cibicides lobatulus*, but the assemblages within this zone are more diverse than those in the previous four. Other species present, and occasionally dominant, within the zone are *Ammonia beccarii* var. *batavus*, *Eggerelloides scabrus*, *Elphidium williamsoni*, *Haynesina germanica*, *Miliammina fusca* and *Elphidium macellum*.
 - vi. Foraminiferal Assemblage Zone **CL / AB** includes only five or six samples (depending on the method of cluster analysis), and is dominated by *Cibicides lobatulus* and *Ammonia beccarii* var. *batavus*. Also present are *Elphidium margaritaceum*, *Elphidium macellum*, *Miliammina fusca*, *Elphidium williamsoni* and *Haynesina germanica*.
 - vii. Foraminiferal Assemblage Zone **EW** has *Elphidium williamsoni* as the dominant species, with *Haynesina germanica* sub-dominant. It is the most diverse cluster within the dataset, some sample also having high abundances of *Cibicides lobatulus*, *Ammonia beccarii* var. *batavus*, and *Miliammina fusca*. Also present in low abundances are *Trochammina inflata*, *Haynesina depressula*, *Haynesina germanica*, *Jadammina macrescens*, *Eggerelloides scabrus*, *Elphidium macellum*, *Elphidium margaritaceum* and *Elphidium williamsoni*.

Cluster analysis using the second, unweighted chord distance, method detects seven virtually identical foraminiferal assemblage zones (Figure 5.4.2) in terms of species and sample composition, with the dominant species remaining the same for each cluster between the two methods.

The two methods of cluster analyses produce the same zones representing the species and sample composition, implying that the clusters are statistically reliable.

5.5.2 Environmental variables

5.5.2.1 Sill Altitude

As one of the principal aims of this thesis is to improve the resolution of relative sea-level reconstructions using the indicative meaning, it is important that the altitude of each basin sill is considered in the context of the local tidal range and elevation (m

OD) of the chart datum for each particular site. In order to enable comparison between sites (thus taking account of differences in tidal range between sites) the elevation of each sill must be standardised. As the indicative meaning is determined with reference to tidal levels, the altitudinal data can be converted to an index related to the tidal cycle, such as the Standardised Water Level Index (SWLI) of Horton (1997) and Horton *et al.* (1999).

Horton (1997) describes three possible methods of defining the SWLI of a given point, based upon computations of the SWLI using points in the tidal cycle. Appendix Four (sections 4.1 to 4.4) provides the equations for, and testing of all three methods. From the reconstruction of tide levels (Figure 5.5) and the strong relationship between the SWLI of each sill and the associated flooding frequency (Figure 5.6), it was determined that the most appropriate SWLI method for the range of sill elevations covered by this research is Horton's (1997) method three:

$$x_a = [((A_a - \text{MLWST}_a) / (\text{MHWST}_a - \text{MLWST}_a)] * 100 + 100 \quad (3)$$

where A_a is the altitude (m OD) of the sill at site a ; MLWST_a is the mean low water spring tide (m OD) at site a ; MHWST_a is the mean high water spring tide at site a ; and x_a is the SWLI of the sill of site a . The addition of the constant 100 ensures that all values are positive. Using this method, MHWST has a SWLI (x_a) of 200, whilst x_a is 100 if the measured elevation of the sill equals MLWST.

Comparisons of the constructed tidal levels using equation three indicate that the procedure is reliable (Figure 5.5). The tide levels are relatively stable throughout, with the exception of the last two sites. The sites in question are the two of the three used from the Argyll area. It is unclear, however, whether this is merely coincidental or a true reflection of differences between this and the other two field areas.

The SWLIs constructed using all three methods are also tested against the duration of flooding at Spring tide (Figures 5.6 and A4.3). All three methods exceed the critical value of r^2 required (0.41) at the 1 % significance level, indeed all exceed 0.91, with method three used here having an r^2 value of 0.92 and a root-mean square error (RMSE) of 7.66.

5.5.2.2 Foraminifera – Environment Relationships

A matrix of scatter plots for foraminifera – environment, foraminifera – foraminifera and environment – environment relationships for the total dataset is shown in Figure 5.7. The obvious linear relationships between loss on ignition (organic content), clay, silt and sand remain, as for the three individual sites outlined above. In addition to this, the only other reasonably clear relationships are those between different measures of given water chemistry components (e.g. average and maximum salinity, and average and minimum pH) and a negative linear correlation between *Eggerelloides scabrus* and *Miliammina fusca*. There do, however, appear to be some more tenuous relationships, such as between average temperature and average dissolved oxygen, and *Elphidium williamsoni* and *Cibicides lobatulus*.

The environmental variables within this matrix differ from those used in the analysis of data from individual sites. As there are several sets of water chemistry readings for every foraminiferal sample, it was necessary to reduce the number of readings for some environmental variables. This was done by taking values including the average (mean), range, and maximum and / or minimum values of each parameter, for each major field visit, at each sample point. Other variables standardised across the whole basin are also introduced for the purpose of inter-basin analyses, such as the freshwater input, sill elevation and basin volume of each site.

For the statistical reconstruction in Chapter Six, however, it is required to reduce the number of environmental variables, ideally to eight, from the present eighteen. Given the lack of visual relationships in the scatter plots, values of Pearson's Correlation Coefficient (r) and the Coefficient of Determination (r^2) were calculated for each environment – environment relationship within the matrix, with a set confidence interval of 99%, in an attempt to identify which variables can be used as a proxy for another and, thus, reduce the number of variables required within the reconstruction. The values of r and r^2 are displayed in Tables 5.2 and 5.3 respectively.

To determine whether stronger environmental relationships are present on a more regional basis, the environmental and foraminifera data for the Isles of North Uist and Skye (221 samples), and the mainland (45 samples) were split, and r values

calculated separately for each of the two datasets. The results are provided in Appendix Three. Whilst some r values lower down the scale (i.e. closer to zero or 'no correlation') appear to be stronger regionally, the relationships evident in the total dataset remain with little, if any, strengthening, whilst some are slightly reduced, particularly in the Uist and Skye dataset. Similarly, two separate matrix plots were created (Appendix Three), in order to try to identify patterns in the foraminifera – environment relationship on a more localised basis. Again there are no discernible differences between these and the total dataset.

From the r and r^2 values in Tables 5.1 and 5.2, proxies were identified which enabled the reduction of the number of variables from eighteen to eight. Table 5.3 highlights the variables which can be used as a proxy, together with information on which variables are covered by each of the proxies.

These eight variables can now be used as the environmental components in the environment reconstruction process. Ideally, dissolved oxygen would have been retained as an independent element, given the low value of r^2 obtained for its strongest relationship with another variable (in this case, an r^2 of 0.27 with average temperature). However, owing to repeated problems with the dissolved oxygen meter, and the need to collect these data *in situ* for accuracy, many readings were missing, which would create problems in the next stage of the statistical analysis. Given the above, the only way to utilise the dissolved oxygen data which was collected is to employ the proxy available, albeit with a relatively weak relationship in comparison to the others outlined in Table 5.3.

	Average Salinity	Maximum Salinity	Salinity Range	Minimum Salinity	Average pH	Minimum pH	pH range	Average temperature	Average Dissolved O ₂	% Organic Content	% Clay	% Silt	% Sand	Low tide volume	High tide volume	Basin surface area	Freshwater input	Sill elevation
Average Salinity																		
Maximum Salinity	0.7958*																	
Salinity Range	-0.4599*	0.1434																
Minimum Salinity	0.9497*	0.6238*	-0.6841*															
Average pH	0.4368*	0.2700*	-0.3206*	0.4522*														
Minimum pH	-0.4674*	0.1679*	-0.5097*	0.5263*	0.8594*													
pH range	-0.3051*	0.0808	0.6020*	-0.4159*	-0.2402*	-0.6670*												
Average Temperature	0.3673*	0.4223*	-0.0170	0.3247*	0.3028*	0.2511*	-0.0374											
Average Dissolved O ₂	-0.1529	-0.2347*	-0.0957	-0.1327	-0.0574	-0.0716	0.0668	-0.5232*										
% Organic Content	0.0487	-0.0519	-0.1250	0.0605	-0.0453	-0.0718	0.0198	-0.1037	0.0410									
% Clay	0.1028	0.0207	-0.0642	0.0660	0.0236	-0.0201	0.0516	-0.0230	0.0397	0.7160*								
% Silt	0.0744	0.0106	-0.0612	0.0561	0.0288	-0.0376	0.1009	0.0822	-0.0421	0.7004*	0.8834*							
% Sand	-0.0703	-0.0237	0.0211	-0.0341	-0.0067	0.0628	-0.1117	-0.0539	0.0256	-0.7438*	-0.9005*	0.9615*						
Low tide volume	0.0325	-0.0702	-0.1674*	0.0805	0.0813	0.1565	-0.2042*	-0.1714*	-0.0869	-0.0378	-0.0079	-0.0100	0.0163					
High tide volume	0.0659	-0.0104	-0.1391	0.1022	0.0563	0.1204	-0.1681*	-0.1406	-0.0893	-0.0296	-0.0001	0.0241	-0.0139	0.9907*				
Basin surface area	0.0866	0.0482	-0.0902	0.1068	0.2000*	0.1468	-0.0383	-0.0202	-0.0901	-0.0249	0.0516	0.0715	-0.0545	0.8423*	0.8403*			
Freshwater input	-0.2035*	-0.0874	0.1974*	-0.2203*	-0.0245	-0.1389	0.2278*	-0.0174	-0.2344*	0.3019*	0.3162*	0.3034*	-0.3070*	-0.0063	0.0067	0.090		
Sill elevation	-0.2059*	-0.3262*	-0.1113	-0.1524	-0.0148	0.0074	-0.0690	-0.0091	-0.0015	0.2095	0.0376	0.0264	-0.0346	-0.2458	-0.3275*	-0.1792	-0.2138*	

Table 5.1: Values of r (Pearson's Correlation Coefficient) for the relationship between environmental variables in the total modern dataset. * indicates 99% confidence interval.

	Average Salinity	Maximum Salinity	Salinity Range	Minimum Salinity	Average pH	Minimum pH	pH range	Average temperature	Average Dissolved O ₂	% Organic Content	% Clay	% Silt	% Sand	Low tide volume	High tide volume	Basin surface area	Freshwater input	Sill elevation
Average Salinity																		
Maximum Salinity	0.6333*																	
Salinity Range	0.2115*	0.0206																
Minimum Salinity	0.9019*	0.3891	0.4680															
Average pH	0.1908*	0.0729*	0.1028*	0.2045														
Minimum pH	0.2185*	0.0282*	0.2598*	0.2770	0.7386*													
pH range	0.0931*	0.0065	0.3624*	0.1730	0.0577*	0.4449*												
Average Temperature	0.1349*	0.1783*	0.0003	0.1054	0.0917*	0.0631*	0.0014											
Average Dissolved O ₂	0.0234	0.0551	0.0092	0.0176	0.0033	0.0051	0.0045	0.2737*										
% Organic Content	0.0024	0.0027	0.0156	0.0037	0.0021	0.0052	0.0004	0.0108	0.0017									
% Clay	0.0106	0.0004	0.0041	0.0044	0.0006	0.0004	0.0027	0.0005	0.0016	0.5127*								
% Silt	0.0055	0.0001	0.0037	0.0031	0.0008	0.0014	0.0102	0.0068	0.0018	0.4906*	0.7804*							
% Sand	0.0049	0.0006	0.0004	0.0012	0.0000	0.0039	0.0125	0.0029	0.0007	0.5532*	0.8109*	0.9245*						
Low tide volume	0.0011	0.0049	0.0280*	0.0065	0.0066	0.0245	0.0417*	0.0294*	0.0076	0.0014	0.0001	0.0001	0.0003					
High tide volume	0.0043	0.0001	0.0193	0.0104	0.0032	0.0145	0.0283*	0.0198	0.0080	0.0009	0.0000	0.0006	0.0002	0.9815*				
Basin surface area	0.0075	0.0023	0.0081	0.0114	0.0400*	0.0216	0.0015	0.0004	0.0081	0.0006	0.0027	0.0051	0.0030	0.7095*	0.7061*			
Freshwater input	0.0414*	0.0076	0.0390*	0.0485	0.0006	0.0193	0.0519*	0.0003	0.0549*	0.0911*	0.1000*	0.0921*	0.0942*	0.0000	0.0000	0.0081		
Sill elevation	0.0423*	0.1064*	0.0124	0.0232	0.0002	0.0001	0.0048	0.0001	0.0000	0.0439	0.0014	0.0007	0.0012	0.0604	0.1073*	0.0321*	0.0457	

Table S.2: Values of r² (Coefficient of Determination) for the relationship between environmental variables in the total modern dataset. * indicates 99% confidence interval.

Proxy	Variables covered	r ² value of relationship
Average Salinity	Average Salinity	1.00
	Maximum Salinity	0.63
	Minimum Salinity	0.90
Salinity Range	Salinity Range	1.00
Minimum pH	Minimum pH	1.00
	Average pH	0.74
	pH Range	0.44
Average Temperature	Average Temperature	1.00
	Average Dissolved Oxygen	0.27
Sand	Sand	1.00
	% Organic Content	0.55
	Clay	0.81
	Silt	0.92
Low Tide Basin Volume	Low Tide Basin Volume	1.00
	High Tide Basin Volume	0.98
	Basin Surface Area	0.71
Freshwater Input	Freshwater Input	1.00
Sill Elevation / SWLI	Sill Elevation / SWLI	1.00

Table 5.3: Environmental variables acting as proxies for other parameters, together with a list of which variables are accounted for by each proxy, and an r² value as an indication of the strength of that relationship. For 100 samples, the accepted value of r² for is 0.1031 at the 99.9% confidence interval (Fisher and Yates, 1963). As 266 samples are included here, and the minimum value of r² used to identify a relationship is 0.27, the relationships are interpreted as being statistically sound.

5.6 FORAMINIFERAL ECOLOGY

From the preceding sections, it can be seen that there are few straightforward relationships between foraminifera and their environment. However this is expected, as linear relationships are seldom found in an ecological study of species and their environment. Rather, Gaussian relationships are typical, with the abundance of taxa often a unimodal function of the environmental variables (Birks, 1995).

Examining the scatter plot matrices produced for each site, and that for the modern training set, it is evident that the foraminiferal species exist within a particular range of environmental variables, some having a wider-based tolerance than others. Some species are largely controlled by different ranges of the same variable, while other foraminifera will be primarily controlled by completely different environmental variables.

Whilst a foraminiferal species exists within a given range of an environmental variable within a site, it is not always found under the same conditions in another basin. For example, *Cibicides lobatulus* is dominant in some samples in the Loch of Reiff, where the average salinity value at the sample points was approximately 30.5 in August 2000. However, in Oban nan Struthan, some of the samples which experience almost identical average salinity conditions contain only *Miliammina fusca*. This is likely to be caused by the input of other variables, where the inter-correlation of environmental factors allows another species to become dominant and / or prevents the existence of that species. In the example above, the variation in species is likely to be controlled by differences in the sedimentological conditions.

From the data collected during this research, the ecological preferences of each foraminiferal assemblage identified in Figure 5.4.1 are outlined below, and compared to the findings of previous work on the ecology of the species. Table 5.4 identifies which zones are characteristic of each basin, or part of a basin, investigated during this research. This table highlights the dominance of *Miliammina fusca* in many of the basins, as well as the intra-basin variability and seasonal changes which can occur at some sites.

Isolation Basin	Closest matching Foraminiferal Assemblage Zone for overall basin	Closest matching Foraminiferal Assemblage Zone for areas within basin
Oban Trumisgarry	MF 1	EW (front), MF 1 (centre and rear)
Oban nan Struthan	MF 1	EW (front), MF 1 (centre and rear)
Alioter Lagoon	MF 2	MF / ES (front), MF2 (centre and rear)
Bac-a-Stoc	MF / ES	MF / ES (throughout)
Locheport 1	ES	ES (throughout)
Locheport 2	ES	ES (throughout)
Grimsay Lagoon	MF	MF / ES (centre), MF (front and rear)
Pool Roag	EW	EW (front, centre, rear), ES (SW corner)
Loch na h'airde	MF	MF (throughout), ES (1 sample in centre)
Loch of Reiff	CL	CL (throughout), MF (1 sample at rear)
Lochan Sal	MF	MF (throughout)
Loch an Eisg-brachaidh	MF and CL	CL (throughout in April), MF (throughout in August)
Loch Roe Lagoon	MF	MF (centre and rear), EW (front)
Oldany 1	n/a	n/a
Oldany 2	n/a	n/a
Loch Nedd Lagoon	CL / AB	CL / AB (throughout), MF (towards basin margins in August)
Loch na Dubh Leitir	MF	MF (throughout)
Duartmore Lagoon	CL	CL (front and centre), MF (rear)
Caithlim Lagoon	MF	MF (throughout), EW (front in August)
Craiglin Lagoon	MF	MF (front and rear), MF / ES (centre), EW (front in August)
Dubh Loch	MF	MF (front and centre), EW (rear)

Table 5.4: Foraminiferal Assemblage Zones and their relationship to contemporary isolation basins.

- i. Foraminiferal Assemblage Zone **MF 1**: Dominated by *Miliammina fusca*, which has the broadest tolerance of environmental variables of any species encountered in the modern basins. This confirms the suggested wide tolerance of Lloyd (2000). It was found in high abundances in freshwater conditions (146 specimens in water of 0.07 salinity) through to almost fully marine conditions (299 specimens in water of 29.7 salinity). More generally, however, although the species is found as a mono-specific at higher levels of salinity (up to 31.6), but with lower numbers of total specimens (typically 30 – 50), it is found in greatest numbers in water less than approximately 20 salinity. Typically, with the highest values of salinity, it would be, or begin to be succeeded as the dominant species by *Eggerelloides scabrus* (Zones MF / ES and ES), as discussed below.

Additionally, the matrix shows the species to tolerate a broad range of other water chemistry and sedimentological conditions. From observations made in the field, however, *Miliammina fusca* like other agglutinates, is intolerant of coarser sand substrates. An example of this is the shelly lag behind some of the basin sills, where calcareous types are dominant.

- ii. Foraminiferal Assemblage Sub-zone **MF 2**: This sub-zone is still dominated by *Miliammina fusca*, with only very small percentages of *Eggerelloides scabrus*, *Jadammina macrescens* and *Trochammina inflata*. As *Miliammina fusca* appears to be able to dominate in such a wide range of lagoonal environments, and *Jadammina macrescens* and *Trochammina inflata* are also tolerant of a wide range of environmental conditions, it is not possible to identify which environmental parameter(s) is / are changing in order to allow the small influx of other species. Again, the findings here with respect to the ecological preferences of *Jadammina macrescens* support those of Lloyd (2000), where it is found to tolerate low and / or variable salinity within the standing water environment of the modern basins (the common convention is that it is a species which inhabits only tidal marshes). In this present study, however, *Jadammina macrescens* is only found in very small relative abundances (< 7 %).

- iii. Foraminiferal Assemblage Zone **MF / ES**: This zone marks the samples at the beginning of the transition in dominance from *Miliammina fusca* to *Eggerelloides scabrus*. At this stage, the maximum salinity within the basin is generally higher (30 – 35) and more stable than that in MF1 and MF 2, although the average salinity can still vary by up to 20 between samples within the assemblage.

The general minimum value of organic content increases to almost 8 % with the appearance of *Eggerelloides scabrus*, with the percentage content of silt and clay also generally experiencing an increase, with a concomitant overall downward trend in sand content.

- iv. Foraminiferal Assemblage Zone **ES**: Although only one sample exists which is 100 % *Eggerelloides scabrus*, this zone marks the dominance of the foraminiferal assemblage by *Eggerelloides scabrus*, usually accompanied by *Miliammina fusca* as a sub-dominant species.

Following the narrowing of the range of salinity tolerance in the MF / ES zone, the salinity for this zone approaches the 29 – 35 specified as the tolerance for *Eggerelloides scabrus* by Murray (1979). The value of maximum salinity remains consistently between 30 - 35, with the range of average salinity also reduced considerably (typically 25 – 30). In line with this, the species is only dominant in those basins with sills low enough to allow sufficient marine input. The majority of the specimens of this species were collected from Locheport basins 1 and 2, in the Outer Hebrides, whose sills lie between MTL and MHWNT. However, as other basins also have sills in or below this range of tide levels, but do not include the species, other factors are clearly in operation in controlling the survival and reproduction of *Eggerelloides scabrus*.

As for MF / ES, the sediment trends are towards a more organic, finer grained sediment, although it is still dominated by sand in the majority of samples. Typical percentage values for organic content are 10 - 20 %, which supports suggestions in the literature that this is an organic-loving infaunal species

(e.g. Murray, 1979; Lloyd, 2000) whilst clay lies in the 5 – 15 % content band. As *Eggerelloides scabrus* is a sediment dwelling, agglutinated species, such a change in sediment properties to a finer, more organic composition is only to be expected.

- v. Foraminiferal Assemblage Zone **CL**: This zone is the first of three dominated by a calcareous assemblage. *Cibicides lobatulus* is by far the dominant species within the zone, although *Elphidium macellum* is dominant in two samples.

Cibicides lobatulus is characteristic of the shelly lag behind basin sills, but was also found further into basins such as the Loch of Reiff. By far the most apparent factor influencing its presence is grain size; more specifically, the sand content, as the species is known to attach itself to sand grains (Murray, 1979). Where the species represents at least 90 % of the assemblage within a sample, the sand content is also at least 90 %.

Salinity also appears to have a reasonably strong influence on the success of *Cibicides lobatulus*. The species only occurs as the dominant taxa where the average salinity lies between 21 and 32, although even this is lower than would be expected of a fully marine nearshore shelf species (Murray, 1979).

- vi. Foraminiferal Assemblage Zone **CL / AB**: Dominance within the zone is distributed between *Cibicides lobatulus* and *Ammonia beccarii* var. *batavus*, although they are never co-dominant within any one sample.

The ecological preferences of *Cibicides lobatulus* are discussed above. *Ammonia beccarii* var. *batavus*, to a large extent, appears to have similar requirements in the modern training set, although in one sample in which the species is dominant the average salinity reduces to below 10. This pattern of lower salinity follows published tolerance limits for this brackish infaunal species, which can tolerate daily variation of 0 – 35 salinity (Murray, 1979). Generally, the percentage content of sand is not as high in many of the

samples as in those where *Cibicides lobatulus* is dominant, altering between 25 and 95 %, although more typically it lies between 55 and 95 %.

- vii. Foraminiferal Assemblage Zone **EW**: The final zone from the modern training set is also the most diverse. The most common dominant species is *Elphidium williamsoni*, although *Haynesina germanica* also occurs in significant numbers in some samples.

The dominant environment characterised by *Elphidium williamsoni* within the zone is one similar to that of zone CL, with a band of average salinity tolerance between 18 – 32, and sand being the dominant particle size. For *Haynesina germanica* the salinity band remains the same, and sand is dominant in the majority of samples. Of the samples with low sand content, one contains only slightly in excess of 25 % sand, but also has the highest percentage of *Haynesina germanica* in the entire dataset. However, as there is only the one sample following this pattern, it is impossible to tell whether this is coincidence or a true ecological preference.

5.7 SUMMARY

All sites have been investigated in detail, in terms of the foraminifera present and the prevailing conditions within the basins. Three sites have been examined in greater detail in this chapter, as an indication of the range of species and conditions found within and between individual sites. All statistically significant data have also been analysed to determine the contemporary distribution of foraminifera and their associated environmental conditions within modern analogue isolation basins.

From the method employed within this chapter, the following conclusions can now be carried forward into subsequent chapters:

- Seven distinct clusters occur within the foraminiferal assemblages. These are identified using the multivariate techniques of unweighted Euclidean distance and Chord distance cluster analysis.

- The sill altitudes were standardised to take account of variations in tidal range around the Scottish coast. This was done using a Standardised Water Level Index (SWLI), with the method based upon the elevation of mean low water spring tide (MLWST) and mean high water spring tide (MHWST) at each site.
- Matrices of relationships between foraminifera and their associated environmental variables show few visible relationships. However, some are apparent between groups of foraminiferal species and between different environmental variables.
- The existence of relationships between different measured environmental variables permits the use of some environmental variables as a proxy for others. The detection of these patterns is reinforced by the use of Pearson's Correlation Coefficient (r). The existence of these surrogate relationships allows a reduction in the number of environmental variables to eight from the initial eighteen, which is a requirement of the statistical analysis contained in the Chapter Six.
- The ecology of the main foraminiferal species within each of the seven clusters in the modern training set is discussed. The ecological tolerances of *Miliammina fusca* are the broadest, particularly with regard to salinity. The main findings with regard to the ecological preferences of the foraminiferal species present within the basins are in agreement with those of Lloyd (2000), who estimates levels of salinity tolerance from a high-resolution fossil isolation basin record in Scotland.



Quantitative Reconstruction of Fossil Isolation Basin Environments

6.1 INTRODUCTION

The primary purpose of this chapter is to identify the controlling environmental variables in modern isolation basins, and to attempt to express their value quantitatively as a function of the biological data. This will be done through the use of a transfer function or biotic index (Figure 3.6; ter Braak, 1987a; Birks, 1995).

The training set of data used is that selected following the procedure outlined in Chapter Five, collected from a wide range of modern analogue sites, with the number of environmental variables reduced to eight and the foraminiferal samples screened according to Table 3.1. This enables the production of results which are potentially applicable on a regional, rather than local (individual site) basis.

The aims and objectives of the chapter are as follows:

- Test the foraminiferal assemblages defined by cluster analysis in Chapter Five.
- Determine the relationship between the modern combined foraminiferal training set and the eight environmental variables, selected in Chapter Five.
- Develop a transfer function from the training set of biological and environmental data, which can then be used to reconstruct former water levels in isolation basins from the fossil foraminiferal assemblages present.
- Assess the performance of any transfer function, and its likely potential for application to fossil sites, using Modern Analogue Technique (MAT).

6.2 DETRENDED CORRESPONDENCE ANALYSIS

Detrended Correspondence Analysis (DCA) is a commonly used ordination technique, applied to represent samples as points in a multi-dimensional space. Thus, similar samples are located together whilst dissimilar samples are placed apart. This complements the cluster analysis in that the cluster analysis classifies the samples according to their foraminiferal assemblage whilst DCA gives information about the pattern of variation within and between the groups (Birks, 1986, 1992; Prentice, 1986).

The first two DCA axes of the total modern training set account for 24.7 % and 10.4 % (35.1 % in all) of the total variance in the species data respectively (Figure 6.1). The loading of each species on the first three axes, and the percentage of variance explained by the first three detrended correspondence axes is shown in Table 6.1

Axis One, with an eigenvalue of 0.9754, has high positive loadings for all calcareous species and *Jadammina macrescens*, appearing to largely represent the dominant species from the last three cluster zones (CL, CL / AB, and EW). Low positive or zero loadings are calculated for the remaining agglutinated species (*Miliammina fusca*, *Trochammina inflata* and *Eggerelloides scabrus*), representing the first four cluster zones (MF 1, MF 2, MF / ES, and ES). Axis two has an eigenvalue of 0.4096, with a high loading for some calcareous species, such as *Cibicides lobatulus*, *Haynesina germanica* and *Elphidium williamsoni* and the agglutinate *Jadammina macrescens*, whilst the calcareous types *Ammonia beccarii* var. *batavus* and *Elphidium macellum* have low negative values.

The zonations produced by cluster analysis of the total dataset using the unweighted Euclidean and Chord distance methods correspond to the regions in the ordination diagram (Figure 6.1), supporting statistically the significance of the cluster analysis zonation. The zones MF 1, MF 2, MF / ES, and ES lie tightly constrained on Axis One (MF 1 is just one point on the diagram, as it is 100% *Miliammina fusca*), whilst CL, CL / AB, and EW are more widely scattered about both axes, with only two samples from the CL zone breaking the trend for high axis one loadings and entering the cluster of samples from the ES zone. The distribution of zones MF 1, MF 2 and

MF / ES overlap to a large extent, although these are, in all but one case, distinct from the ES cluster.

Species	Axis One	Axis Two	Axis Three
<i>Miliammina fusca</i>	1.2453	1.098	0.3321
<i>Elphidium williamsoni</i>	3.9541	2.6787	-0.0571
<i>Haynesina germanica</i>	3.8883	2.6047	0.3135
<i>Trochammina inflata</i>	2.2894	1.2606	2.4821
<i>Haynesina depressula</i>	4.1838	2.2947	-0.1334
<i>Jadammina macrescens</i>	3.2435	3.6097	-0.1367
<i>Eggerelloides scabrus</i>	0	1.0883	0.4019
<i>Cibicides lobatulus</i>	5.275	2.9224	1.6728
<i>Ammonia beccarii</i> var. <i>batavus</i>	3.6983	-0.0877	1.2675
<i>Elphidium macellum</i>	5.5426	-0.3402	-1.6274
<i>Elphidium margaritaceum</i>	4.3005	2.0354	2.0354
Variance (Eigenvalues)	0.9754	0.4096	0.098
Percent total variance	24.7	10.4	7.9
Cumulative percent of total variance	24.7	35.1	43.0

Table 6.1 Species loading and percentage of variance explained by the first three axes of detrended correspondence analysis from the total foraminiferal assemblage.

6.3 RELATIONSHIP BETWEEN FORAMINIFERA AND ENVIRONMENTAL VARIABLES

Canonical Correspondence Analysis (CCA) is employed here to test the hypothesis that the foraminiferal assemblage within each sample, and as a whole, is related in some way to the environmental parameters measured during the fieldwork.

CCA is an ordination technique, converted into multivariate direct gradient analysis by interpretation of the environmental gradient (ter Braak, 1986, 1987b). It has become widely used in ecological studies in the short time since it has been developed (Kovach, 1995). It permits the display of the main trends of variation within a multi-dimensional dataset in the reduced space of two axes on a biplot, with the dispersal of site or sample scores restricted to being oriented as linear combinations of the environmental variables. In this way, variation within the biological community can be directly related to variation in the environment (ter

Braak, 1986), based upon the assumption (implicit in all ordination techniques) of the existence of a single set of environmental gradients to which all the species respond.

6.3.1 Methods

CCA was used to extract environmental gradients from the modern training set, and to calculate values for individual samples and foraminiferal species along the axes created by the environmental variables. All computations were made through the CANOCO program of ter Braak, release 3.12, 1991 (ter Braak, 1988, 1990).

From the eight environmental variables selected in Chapter Five, a process of pre-selection was carried out during the first CCA run, which identified salinity range and pH as having the lowest eigenvalues (i.e. the most tenuous relationships with the samples). These two variables were consequently excluded from the dataset, leaving six remaining for the CCA technique to utilise.

The canonical eigenvalues are compared against the sum of unconstrained eigenvalues and used as a measure of the amount of variation accounted for by the environmental variables. These measures are then transformed into percentages explaining the total variance of species data.

6.3.2 Results

The CCA sample – environment and species – environment biplots are shown in Figure 6.2. Axis One (eigenvalue 0.431) and Axis Two (eigenvalue 0.369) of the CCA biplot explain 20.3 % of the total variance in the foraminiferal data (Table 6.2).

Within the biplots (Figure 6.2), the length of the arrow (environmental vector) approximates the relative importance of that variable in explaining the variance in the biological assemblages. The orientation of the arrow shows the approximate correlation of the variable to the ordination axes and other environmental factors. Those environmental variables with the longest arrows are most strongly correlated with the ordination axes, and so more closely related to the pattern of community

variation shown in the ordination diagram. Vectors moving in opposite directions to each other indicate a negative correlation (e.g. Average Salinity and Freshwater).

Axes	1	2	3	4	Total Inertia
Eigenvalues	0.431	0.369	0.222	0.07	3.949
Species-Environment correlations	0.694	0.697	0.592	0.407	
Cumulative percentage variance :					
- of species data	10.9	20.3	25.9	27.6	
- of species – environment relationship	38.7	71.9	91.9	98.2	
Sum of all unconstrained eigenvalues					3.949
Sum of all canonical eigenvalues					1.113

Table 6.2: Summary of CCA results from the modern training set. The associated biplots appear in Figure 6.2.

On the species – environment biplot (Figure 6.2b), the position of the species is projected perpendicularly onto the environmental vectors, approximating their weighted average optima along the environmental variable. Thus, species which are characteristic of a particular environment may be identified.

The six pre-selected environmental variables account for 28.2 % of the explained variance within the foraminiferal dataset. Within this, some of the explanation will be through inter-correlation of environmental variables, whereby more than one environmental variable is influencing a given assemblage. This is to be expected, however, given that Tables 5.2 and 5.3 showed some pair-wise correlation between all combinations of the environmental variables.

6.3.3 Synopsis

From the CCA results, basin volume is the most influential environmental variable, followed by freshwater input. There are, however, problems in the measurement of both of these variables (Sections 6.3.3.1 and 6.3.3.2).

6.3.3.1 Basin Volume

The figures for basin volume used in the statistics are only an approximate measure, as detailed surveys of water depth (basin cross-sectional profiles) and accurate

measurement of the basin surface area (such as by digitising) were not carried out. Consequently, no data are available to check the accuracy of the current estimates.

Basin dimensions are already estimated during the study of fossil sites when borehole transects are made across basins to achieve an approximate picture of the basin substrate. However, basin volume needs to be studied in greater detail with regard to modern isolation basins, and its control upon environmental conditions within them. One major factor is the inertia or residence time of a system, which is primarily controlled by basin volume. A large, deep basin will be less susceptible to a change or instability following a given input than a small, shallow basin will be.

It is likely that a greater understanding of isolation basin environments will come through the study and quantification of marine and freshwater inputs in relation to basin volume, as it is the variable interaction of marine and freshwater conditions within isolation basins, over a broad range of spatial and temporal scales, that gives rise to much of the complexity and diversity of the isolation basin system. However, as reliable data for marine input and basin volume is lacking at this time, no attempt is made here to develop a transfer function for the reconstruction of the volume of fossil basins.

6.3.3.2 Freshwater Input

A given freshwater input will have a direct but variable impact on salinity, depending on the volume of water held within the basin and the high temporal variability in the freshwater input which can occur depending upon weather conditions. Some consideration should also be given within this to inter-annual variation in the climate system, such as the North Atlantic Oscillation, and its effects on precipitation.

While freshwater input is desirable information for fossil sites, it is more practicable in combination with information on its precise impact on water chemistry in a basin of a given volume. With longer-term studies, some understanding may be also be gained of the impact of inter-annual variations in precipitation.

6.3.3.3 Solution

As salinity is likely to be strongly influenced by both basin volume and freshwater input, it was decided to attempt to develop a transfer function based upon salinity, which is the next largest environmental vector in the CCA biplot (Figure 6.2a). Although Chapter 5 shows the salinity tolerance of the foraminiferal species to be diverse, particularly in the case of *Miliammina fusca*, it is anticipated that the combination of foraminiferal species in each sample assemblage will provide greater definition of the salinity tolerances and preferences of each assemblage and / or cluster zone.

Salinity will not allow the quantitative reconstruction of the indicative meaning of isolation basins sills called for by Shennan *et al.* (1995, 2000); SWLI is likely to be the best measure of the indicative meaning of sills, but the strength of the vector in the CCA analysis for this particular environmental variable is negligible. The most probable reason for the poor performance of SWLI in CCA is because it is not simply the sill elevation which is important in isolation basins; overall sill dimensions are as, if not more important, as it is these which control the marine input into a basin (a narrow sill will restrict water inputs and outputs to a much greater extent than a wide sill).

Although SWLI undoubtedly exercises some control on salinity, it is one of many factors, with other variables such as basin volume (controlling the inertia or residence time of the system) and the volume of marine and freshwater inputs likely to be much more significant. The relationship between salinity and SWLI is certainly not a straightforward one (The r^2 value of their relationship is only 0.04; Table 5.3), and salinity can act only as a very weak proxy for SWLI and *vice versa* (Figure 6.3). From Figure 6.3, one can also conclude that:

- There is a bias in the sampling in this research in favour of basins with their sill higher than MLWNT.
- the call by Shennan *et al.* (1995, 2000) for the more accurate identification of the indicative meaning of isolation basin sills is likely to be somewhat misleading in terms of gaining a greater understanding of the processes occurring within basins during isolation.

A transfer function which is successfully based on salinity will provide information on the salinity within the fossil basins at different stages in the basin history (for example, the salinity range at the point of isolation indicated by the foraminiferal assemblage). However, the control of salinity conditions within any isolation basin would appear to be the result of a complex interaction of factors such as basin volume, and the volume of marine and freshwater inputs. The latter are, in turn, controlled by sill dimensions and SWLI, precipitation, and the area and morphology of the catchment. Until such time as these factors are precisely quantified and the interplay between them understood, it is unlikely to be possible to accurately reconstruct salinity conditions within isolation basins.

6.4 QUANTITATIVE RECONSTRUCTION FROM MODERN ISOLATION BASIN FORAMINIFERAL ASSEMBLAGES

The expression of salinity as a function of foraminiferal assemblages will enable quantitative reconstruction of salinity for a range of fossil isolation basins, at different points in their history. To achieve this, the modern foraminiferal data set used so far in this thesis is retained, but the environmental data set is reduced to the average salinity variable only.

6.4.1 Gaussian or linear response models of foraminifera – average salinity?

A number of statistical techniques are used in ecological studies to reconstruct past environments. The first step in such a study should be to decide upon the underlying model of species – environment response (Birks, 1995). Some methods assume a unimodal (Gaussian) model of species response to their environment (Figure 6.4a) while others assume a linear response of species to their environment (Figure 6.4b). Detrended Canonical Correspondence Analysis (DCCA; ter Braak, 1986) is used to estimate the nature of the taxa – environment relationship present here.

DCCA uses the environmental variable of interest (x) as the only environmental variable, to estimate (as the length of DCCA Axis One) the gradient length in relation to x in terms of standard deviation (SD) units (Birks, 1995). If the gradient length is shorter than 2 SD units, then the taxa are generally behaving monotonically

along the gradient, and linear regression and calibration methods are appropriate. If, however, the gradient length is longer than 2 SD units, several taxa will have their optima located within the gradient, and unimodal-based (Gaussian) methods of regression and calibration are applicable (Birks, 1995).

Species – environment relationships are usually unimodal, as each taxon grows and reproduces best at a particular optimum value of an environmental variable, and cannot survive where the value of that environmental variable is either too high or too low (ter Braak, 1987b). Strictly speaking, ecological response curves are not quite so straightforward as portrayed by the Gaussian-type unimodal models (Birks, 1995; Figure 6.4a). However, just as linear models are appropriate for data that are only approximately linear, unimodal models are useful in developing statistical techniques for data showing mostly unimodal responses (ter Braak and Prentice, 1988). This makes the Gaussian unimodal model a convenient and robust approximation for the analysis of biological data that span gradients in excess of 2 SD units (Birks, 1995).

DCCA of the modern training set with average salinity as the only environmental variable produces an environmental gradient length of 8.32 SD. This indicates that the relationship between the foraminifera and average salinity is of a unimodal nature, and unimodal-based methods of regression and calibration are therefore used. The two techniques chosen are Weighted Averaging – Partial Least Squares (WA - PLS) regression and calibration, and testing of the resultant transfer function by use of the Modern Analogue Technique (MAT).

6.4.2 Weighted Averaging – Partial Least Squares (WA-PLS) regression

6.4.2.1 Method

Weighted Average – Partial Least Squares regression (WA-PLS), developed by ter Braak and Juggins (1993), is an inverse procedure, which can be regarded as the unimodal equivalent of the linear-based Partial Least Squares regression technique. As such, it is derived from the principle of maximum likelihood, whereby the value

of y (average salinity) can be estimated from precisely known values of x (foraminiferal assemblage; Barlow, 1998).

In past ecological studies, inverse and classical methods of Weighted Averaging (WA) have been used extensively as a means to develop transfer functions for taxon – environment relationships. However, a primary assumption within the WA method is that environmental variables other than the one of interest (x) have negligible influence (section 3.5.1), thus ignoring any residual correlations among the biological data once they have been fitted to x (ter Braak and Juggins, 1993; Birks, 1995). Clearly this could be problematic for studies such as this one, where it appears that no single environmental variable acts independently of others (for example, section 5.6). Conversely, WA-PLS utilises the residual correlation structure in the data to improve the fit between the biological data and x in the modern training set.

In taking account of residual correlations, WA-PLS can greatly reduce the Root Mean Square Error of the Prediction (RMSEP) for a test set of data with low noise. Noise which is structured in the form of secondary environmental gradients will also significantly reduce the RMSEP, as it provides additional structure in the data for WA-PLS to exploit. With increasing or unstructured noise, the reduction in RMSEP will decline, but even then it will remain as low as, or lower than, the value for RMSEP which would be obtained if inverse and classical WA methods were used (Birks, 1995).

As well as accounting for additional environmental variables which influence the composition and abundance of the biological assemblages, WA-PLS can also outperform WA in certain instances because the WA method suffers from ‘edge effects’ (Mohler, 1983), where the optima of taxa are overestimated at the low end of the scale, and underestimated at the high end (Hill and Gauch, 1980).

WA-PLS is performed on the dataset using the CALIBRATE program (Version 0.70, Juggins and ter Braak, 1992, 1997). From this, results are returned on the basis of:

- i. the correlation (r) and the coefficient of determination (r^2), which act as measures of the strength of the relationship between transfer functions for different environmental variables (Gasse *et al.*, 1995).
- ii. the RMSEP, which compares the observed and predicted values of x_i and in doing so provides a measure of the overall predictive abilities of the transfer function.

The results are also cross-validated using the simple jack-knifing or 'leave-one-out' method (ter Braak and Juggins, 1993), where the reconstruction procedure is applied n times to a training set of size $n-1$. In each of the predictions one sample is removed and the value of the environmental variable of interest (x) for that sample is predicted using the remaining data in the training set. By subtracting the predicted value from the observed value (x_i), a prediction error for the sample can be determined. The prediction errors are then accumulated to form $\text{RMSEP}_{(\text{jack})}$ (Birks, 1995).

As a large foraminiferal training set is being used, it will inevitably contain some samples that show a poor relationship to average salinity. The reason for the poor fit with salinity is because other environmental factors are dominant in influencing or controlling the assemblage. The samples showing a weak relationship with salinity will be those with the highest residual distance from the first ordination axis, which is itself constrained by average salinity. These samples can reduce the predictive ability of a transfer function (Martens and Naes, 1989) and should, therefore, be identified and removed from the training set (Gasse *et al.*, 1995; Jones and Juggins, 1995). After an initial run of the training set using WA-PLS, the data were screened. Those samples with an absolute residual (observed minus predicted) greater than the standard deviation of average salinity in the training set were deleted, following the recommendations of Jones and Juggins (1995).

6.4.2.2 Results

Data screening for high residuals in the foraminiferal data when plotted against average salinity identified 72 samples (27 % of the dataset) with an absolute residual greater than the standard deviation of the environmental variable of interest in the training set (SD = 8.32). The distribution within the training set of those deleted

samples is largely random, although for those data collected from the Isle of North Uist, more samples were removed from the August data (particularly Oban nan Struthan). All remaining samples from Loch Roe Lagoon and Lochan Sal were also removed. High numbers of *Miliammina fusca* were found in Lochan Sal, despite the freshwater environment. This predictably shows cases of the occurrence of species at extreme values of the environmental variable of interest to be leading to the exclusion of sample from the transfer function.

Using the remaining 194 samples, a WA-PLS transfer function was developed. However, in order to ensure that the removal of the 72 samples would not have adverse effects on the performance of the WA-PLS regression and calibration, the WA-PLS coefficients for the 194 remaining samples were plotted using values of average salinity predicted by the transfer function when the original modern training set of 266 samples was used, versus the values of average salinity predicted by the transfer function when the screened data-set of 194 samples was used (Figure 6.5). The value of the Coefficient of Determination (r^2) is 0.988, showing that the removal of those foraminiferal samples which showed a poor relationship with average salinity has not adversely affected the estimation of species' coefficients using the WA-PLS method. However, the very high value of r^2 also suggests that, in this case, the removal of the 72 samples in the screening process changed the predictions so little for the remaining 194 samples that all 266 samples could have remained in the data-set, with little probable impact on the accuracy of the transfer function.

The performance of the transfer function is summarised in Table 6.3, with $RMSEP_{(jack)}$ an indicator of the overall predictive abilities of the training set when using the WA-PLS method (Birks, 1995), whilst $r^2_{(jack)}$ shows the strength of the relationship between the observed and predicted values when using the model (Gasse *et al.*, 1995). Figure 6.6 provides a graphical indication of the performance of the transfer function, with observed values plotted against those predicted using the WA-PLS model.

Using the WA method for inverse deshrinking regression, it is possible to obtain information on species optima and tolerance to average salinity (Jones and Juggins, 1995), which can then be used in the ecological interpretation of the species.

Variable	Number of Samples	Number of Species	RMSE	r^2	RMSEP _{jack}	r^2_{jack}
Average Salinity	194	11	3.81	0.73	3.993	0.70

Table 6.3: Summary statistics of the performance of a WA-PLS transfer function for average salinity using the new screened training set.

The optima of a species is its weighted average, whilst the tolerance is the standard deviation. Table 6.4 presents information on the number of occurrences of each taxon, its maximum relative abundance in any assemblage, and the WA optima and tolerance of each species. Figure 6.7 presents graphically the eleven species with their optima plotted, together with error bars for the species tolerance of average salinity in the screened training set. Screening of the dataset is likely to have reduced the standard deviation of some of the species, making the tolerance bands narrower than was actually observed in the field; for purely ecological purposes the model would be best run on the original modern training set, rather than the screened data-set, in order that the full range of each species' tolerance may be established. From Figure 6.7, it can be seen that each species has a range of salinity tolerance which overlaps with the majority of the other species, indicating that a transfer function based on average salinity is unlikely to be highly effective.

Species	N	Max	Opt	Tol
<i>Miliammina fusca</i>	162	100	17.833	6.2339
<i>Haynesina depressula</i>	4	5.03	19.4494	1.1181
<i>Elphidium margaritaceum</i>	5	26.53	22.4227	2.8175
<i>Trochammina inflata</i>	24	33.30	24.219	9.7354
<i>Cibicides lobatulus</i>	36	99.46	25.4993	5.1266
<i>Elphidium williamsoni</i>	36	73.10	26.2804	6.116
<i>Jadammina macrescens</i>	7	7.50	27.0323	7.6926
<i>Haynesina germanica</i>	20	63.46	27.7424	6.4401
<i>Eggerelloides scabrous</i>	101	100	29.6511	2.8108
<i>Ammonia beccarii</i> var. <i>batavus</i>	22	95.56	29.774	4.6621
<i>Elphidium macellum</i>	19	50	31.6761	3.0928

Table 6.4: Summary statistics for the WA optima and tolerance value of salinity for each foraminiferal species in the screened modern training set. Number of occurrences of each taxon (N), its maximum relative abundance in any assemblage (Max), and the WA optima (Opt) and tolerance (Tol) of each species are shown.

For the purposes of the calibration of a fossil dataset using the transfer function, data from three sites were used in WA-PLS calibration and Modern Analogue Technique:

- i. Rumach VI (Douthwaite, 1999)

- ii. Loch nan Corr (Lloyd, 2000)
- iii. Dubh Lochan (Shennan *et al.*, 2000a)

The salinity values predicted by WA-PLS calibration of cores from Rumach VI are displayed in Table 6.5, with the values for Dubh Lochan and Loch nan Corr in Appendix Five. The thecamoebian and foraminiferal assemblages from each core, together with the predicted salinity values, are shown graphically in Figures 6.8, 6.9 and 6.10 respectively. Thecamoebians were omitted from the WA-PLS calibration data-set, as no thecamoebians are present in the modern training set, and their presence in the fossil data-set prevented the calibration from running. The only implication of this is for the top foraminiferal sample in Dubh Lochan, and the top two foraminiferal samples in Loch nan Corr, where *Miliammina fusca* was found together with thecamoebian species. The removal of the thecamoebians will cause the calibration program to predict average salinity values based only on the *Miliammina fusca*, which is unlikely to be accurate.

Sample Number	Sample Depth	PLS Predicted Salinity
1	252	15.71
2	284	15.71
3	316	21.01
4	348	16.83
5	380	24.64
6	412	26.85
7	444	24.04
8	476	15.71
9	508	23.20
10	540	15.71
11	572	26.09
12	604	28.61
13	636	28.47
14	668	28.79
15	700	28.78
16	732	28.56
17	764	28.86
18	796	29.37
19	828	28.92
20	860	28.64
21	892	28.85

Table 6.5: Summary of salinity values predicted for samples in a fossil core from Rumach VI basin, Arisaig.

6.4.2.3 Synopsis

WA-PLS regression on a screened modern training set shows a strong relationship between foraminiferal species and average salinity, in comparison to some other studies using foraminifera in an environment such as a saltmarsh. For example, using PLS, Gehrels *et al.* (2001) achieved an r^2 value of only 0.386 when trying to relate total foraminiferal assemblages to elevation. However, their training set has an RMSEP of 0.386, indicating that their transfer function would perform better than the one created here.

Using WA-PLS calibration, the transfer function certainly does not appear to have performed well in terms of picking up changes in the foraminiferal assemblages and translating these into changes in salinity (Figures 6.8 - 6.10). In Dubh Lochan (Figure 6.9) and Loch nan Corr (Figure 6.10) the dominance of *Haynesina germanica* signifies the end of the fully marine stage and the beginning of the isolation process. Using this information, and AMS ^{14}C dates and biostratigraphy based on diatoms for Rumach VI published by Shennan *et al.* (1999), the age at 604 cm depth (Figure 6.8) is inferred to be 5690 ± 50 ^{14}C yr BP. Whilst a reduction in predicted average salinity does occur at this point, the transition only appears to be detected where *Miliammina fusca* is abundant. A similar pattern is evident in the reconstructions for Dubh Lochan (Figure 6.9) and Loch nan Corr (Figure 6.10). The most probable reason for this is the range of species which are present and controlling the assemblage in the fossil data-set in comparison to the modern training set; a transfer function can not accurately predict the average salinity of an assemblage dominated by a particular foraminiferal species if that same species does not dominate an assemblage in the modern training set.

The fact that WA-PLS calibration of average salinity does not appear to detect many of the major changes in the foraminiferal assemblages suggests that it will not be possible to successfully apply the transfer function to fossil data. In order to test this, and determine whether it is a flaw in the WA-PLS calibration technique or the transfer function and modern data-set used, the values of predicted salinity in fossil samples obtained by WA-PLS calibration will now be tested using Modern Analogue Technique (MAT). This method independently predicts average salinity values for the samples, and also determines if the modern training set contains

samples which are good analogues for the fossil data, or whether there are no close analogues, in which case the reconstructions should be ignored.

6.4.3 Modern Analogue Technique (MAT)

6.4.3.1 Method

Modern Analogue Technique (MAT) compares numerically the similarity (or dissimilarity) between fossil biological data and the modern training set of biological assemblages and associated environmental data. Having found the modern sample(s) that is / are most similar to the fossil sample, the past environment for that fossil sample is then inferred to be the modern environmental variable(s) for the analogous modern sample(s) (Birks, 1995). As such, it provides an independent assessment of the reliability of predictions from WA-PLS (Edwards, 1998).

In order to predict the environmental variable(s) of interest for a fossil biological assemblage, it is necessary that a good modern analogue exists within the dataset. Thus, the technique, as is the case for any other method of reconstruction, relies upon the assumption that:

- i. the species – environment relationships have not changed through time.
- ii. the modern training set covers the full range of environments which the fossil samples were subject to, and the likely range of biotic assemblages contained within the fossil samples. This assumption can create serious limitations for MAT (Birks, 1995).

MAT is performed here using the MODERN ANALOG TECHNIQUE program (release 1.1, Juggins, 1997). Average salinity reconstruction is based upon the weighted average of the ten most similar modern samples. Squared chord distance was selected as the dissimilarity coefficient, as this provides the optimum 'signal-to-noise' ratio when used with percentage data (Prentice, 1980; Overpeck *et al.*, 1985).

The modern training set screened during WA-PLS is run through MAT alone first, in order to calculate dissimilarity percentiles. Dissimilarities below the 20th percentile threshold are indicative of good analogues (Horton, 1997). Any samples with a dissimilarity coefficient (DC) greater than the value of the 20th percentile is deemed

to have no close analogue, indicating that the WA-PLS calibration predictions may be erroneous and should not be used.

6.4.3.2 Results

Percentile of MAT data for the modern training set, and a value of r^2 for the strength of the relationship between observed and weighted mean predicted values of average salinity are shown in Table 6.6.

r^2	1 st Percentile	2 nd Percentile	5 th Percentile	10 th Percentile	20 th Percentile
0.71	0.000000	0.000000	0.001095	0.006009	0.036432

Table 6.6: Summary of MAT predictions for average salinity and dissimilarity percentiles.

The relationship between the observed and weighted mean predicted average salinity values for each sample are also presented in Figure 6.11. MAT displays a pattern of relationship between the observed and predicted values which is very similar to that from the WA-PLS model (Figure 6.6), with an almost identical value of r^2 at 0.71.

Testing of the three fossil datasets using MAT, against the results from the modern training set, reveal that only four of the samples in the Rumach VI basin (Table 6.7) and six of the samples in Dubh Lochan (Table 6.8) have a modern analogue. No modern analogues exist for any of the samples in Loch nan Corr (Appendix Five), even though visual matches may be made, particularly where *Miliammina fusca* dominates with a small abundance of *Jadammina macrescens*. All of the samples in Rumach VI which have a good modern analogue in this dataset have a foraminiferal assemblage of 100 % *Miliammina fusca* (Figure 6.8), while those in Dubh Lochan are dominated by *Miliammina fusca*, in some cases with a very small proportion of *Jadammina macrescens*, or *Cibicides lobatulus*, with trace amounts of other species (Figure 6.9). Considering the dominance of *Miliammina fusca* in the modern training set, and the number of samples in which it was mono-specific, it is unsurprising that fossil samples dominated by this species register as having a good modern analogue.

6.4.3.3 Synopsis

MAT is the least-valid statistical technique of the reconstruction methods, in that it does not have an underlying statistical model of taxon-environment response. The main disadvantage of this is that MAT depends entirely upon the range and composition of the modern training set.

Sample	Depth	PLS Calibration	Weighted Mean	Min DC	Analogue
1		15.71	16.2	0.0000	Good
2		15.71	16.2	0.0000	Good
3		21.01	16.2	0.4508	No Close
4		16.83	16.2	0.0931	No Close
5		24.64	27.3293	0.3993	No Close
6		26.85	27.4511	0.3233	No Close
7		24.04	27.4675	0.3099	No Close
8		15.71	16.2	0.0000	Good
9		23.20	26.0673	0.2580	No Close
10		15.71	16.2	0.0000	Good
11		26.09	27.3855	0.4838	No Close
12		28.61	28.0342	0.1899	No Close
13		28.47	27.1828	0.3134	No Close
14		28.79	26.7876	0.3516	No Close
15		28.78	27.3754	0.3873	No Close
16		28.56	27.1247	0.4494	No Close
17		28.86	27.3544	0.3809	No Close
18		29.37	26.2657	0.3998	No Close
19		28.92	27.6694	0.2933	No Close
20		28.64	26.9571	0.5047	No Close
21		28.85	26.8676	0.6201	No Close

Table 6.7: MAT Assessment of PLS Calibration predictions for samples from Rumach VI fossil isolation basin. The 4 highlighted rows are those which have a DC (Dissimilarity Coefficient) lower than the 20th percentile (Table 6.6) and, as such, have good analogue samples in the modern training set.

Of the 120 fossil samples tested using MAT, only 10 have a good modern analogue. This match is accounted for by only three species (*Miliammina fusca*, *Jadammina macrescens*, and *Cibicides lobatulus*). Clearly, at least one of the assumptions on which MAT is based has not been reached. The most likely explanation is that the modern training set simply does not have the biotic diversity (it has only 11 species) required to calibrate parts of the fossil assemblages (such as the nearshore shelf stage, where assemblages are typically at their most diverse). More simply, it may be that the actual species which dominate parts of the fossil assemblages are either not present, or not present in sufficient amounts in the modern training set to allow accurate reconstruction. This trend is particularly evident when comparing the

dominance of *Jadammina macrescens* and *Haynesina germanica* in the transitional stage of fossil assemblages, in comparison to their relatively low abundance in the modern training set.

Sample	Depth	PLS Calibration	Weighted Mean	Min DC	Analogue
1	110		20.17	2.0000	No Close
2	118		23.65	2.0000	No Close
3	122		16.20	1.2440	No Close
4	126		16.20	0.0000	Good
5	134		16.94	0.1316	No Close
6	142		16.80	0.0489	No Close
7	150		16.88	0.0788	No Close
8	158		16.61	0.0242	Good
9	166		16.73	0.0387	No Close
10	174		16.65	0.0256	Good
11	182		16.95	0.1488	No Close
12	190		15.06	0.4599	No Close
13	198		17.03	0.5663	No Close
14	206		17.03	0.5878	No Close
15	214		17.02	0.4200	No Close
16	222		17.01	0.3207	No Close
17	230		15.07	0.3846	No Close
18	238		16.94	0.1367	No Close
19	242		15.02	0.5795	No Close
20	246		16.66	0.9513	No Close
21	248		27.60	0.3202	No Close
22	250		28.04	0.2332	No Close
23	252		26.04	0.3160	No Close
24	254		25.51	0.0719	No Close
25	262		26.18	0.0129	Good
26	266		24.28	0.0023	Good
27	269		23.50	0.0017	Good

Table 6.8: MAT Assessment of PLS Calibration predictions for samples from Dubh Lochan fossil isolation basin. The 6 highlighted rows are those which have a DC (Dissimilarity Coefficient) lower than the 20th percentile (Table 6.6) and, as such, have good analogue samples in the modern training set.

6.5 DISCUSSION

There are many methods of quantitative environment reconstruction available, but Weighted Averaging – Partial Least Squares regression (WA-PLS) and Modern Analogue Technique were chosen here to act as independent tests of each other, whilst WA-PLS also took account of the residual correlations within the foraminiferal assemblages which are not accounted for by average salinity.

In terms of calibration of the fossil dataset using PLS, and matching samples from the fossil dataset to those in the screened modern training set using MAT, the

exercise was unsuccessful; it has not been possible to develop a transfer function for foraminifera based upon average salinity for isolation basin environments. The most probable explanation for this is the role of as yet unquantified environmental variables which are controlling the basin environment and foraminiferal assemblages, together with severe overlap in the optima and tolerance values of average salinity for each species. There is also the possibility that the foraminiferal assemblages in modern and fossil basins simply do not match up, because the species are not present in similar relative abundances within the assemblages. This issue is discussed further in Chapter Seven.

Whilst PLS calibration allowed the prediction of average salinity values for all of the fossil samples from Rumach VI, and MAT provided predictions of average salinity levels for both Rumach VI and Dubh Lochan, MAT also revealed that only 10 of the 48 samples from the two sites had a good analogue in the modern training set, represented by only three foraminiferal species, whilst none of the samples from Loch nan Corr have a good analogue in the modern training set.

However, although a transfer function based upon average salinity is not possible, the findings from the WA-PLS and inverse WA models are significant in terms of the ecology of modern isolation basin environments. Using the inverse WA technique the optima and tolerance values of average salinity for each of the foraminiferal species in the modern training set have been identified from the screened data-set (Figure 6.7; Table 6.4). The potential of this method for increasing the understanding of the foraminiferal ecology of the modern isolation basin environments is explored further in Chapter Seven, using the original modern training set.

6.6 SUMMARY

- DCA using the modern training set allowed the testing of the clusters in the total foraminiferal assemblage which were identified in Chapter Five. This identified similar clusters in the data to the cluster analysis, with a reasonably strong eigenvalue on axis one, suggesting a definite environmental gradient.

- CCA shows that only 28.2 % of the variation in the foraminiferal assemblages is explained by the six environmental variables chosen. The most significant of these environmental vectors acting on the foraminiferal assemblages is the volume of water held within the modern basin, with freshwater input the next most important factor. It was decided that the quality of these data is not of the standard of the other environmental readings, however. Basin volume is only an approximation, and not the result of detailed measurement of water depth around the basin, whilst the likely impact of freshwater can only be reliably measured when in comparison to basin volume and the likely inertia of the system. The influence of sill elevation, focused upon by Shennan *et al.* (1995, 2000), standardised using the SWLI methodology, was determined to be negligible. Given these considerations, it was decided that average salinity was the statistically strongest of the useful variables, in terms of reconstruction from fossil environments.
- Owing to the apparent correlations between some variables in the CCA biplot, WA-PLS was used to develop the transfer function, in preference to inverse and classical WA models, as it takes account of residual correlations. Component one of the WA-PLS model accounted for the greatest amount of jack-knifed variance in the screened modern training set, so estimates calculated using this component were used in developing the transfer function.
- WA-PLS regression and MAT both show a strong relationship between the observed and estimated average salinity value for the screened modern training set. Unfortunately, calibration and matching analogue techniques were not successful in identifying statistically significant average salinity conditions for the fossil dataset, and the development of a transfer function for fossil isolation basins is abandoned at this point.
- Whilst it is not possible to develop a useful transfer function, the inverse WA method has allowed the identification of optima and tolerance values of average salinity for each species. The potential of this technique will be explored further in Chapter Seven.

Discussion: Implications for Sea-Level Reconstruction and Foraminiferal Ecology

7.1 INTRODUCTION

Chapter Six outlined the process of developing a foraminiferal-based transfer function which could then be used to strengthen the interpretation of fossil isolation basin environments. However, the testing of the transfer function using fossil samples show that it provides few good modern analogues.

Clearly there are important implications from these findings which must be borne in mind for future research, both in refining this work prior to further attempts to develop a more comprehensive transfer function, and in the use of isolation basins for the reconstruction of RSL.

This chapter focuses on the following issues:

- The considerations which were made in the sampling strategy of this thesis in an attempt to develop a reliable transfer function.
- Potential improvements to the sampling strategy which could increase the applicability of a foraminiferal-based transfer function developed from isolation basin environments.
- The use of the transfer function in relation to the interpretation of RSL from isolation basin environments.
- The implications for quantitative environmental reconstruction techniques used in Quaternary ecological studies, and the assumptions and requirements therein.
- Developments in the understanding of isolation basin environments gained through this research, and the associated foraminiferal ecology.

7.2 A FORAMINIFERAL-BASED TRANSFER FUNCTION FOR ISOLATION BASINS: WHY DIDN'T IT WORK?

Foraminiferal transfer functions have been successfully developed in the past for saltmarsh environments (e.g. Horton, 1997, 1999; Edwards, 1998; Horton *et al.*, 1999a), using SWLI as the environmental variable of interest. The development of the transfer function allowed the quantification of the distinct altitudinal zones which occur in saltmarsh environments, as indicated by the foraminiferal assemblages.

However, in relation to this, the fundamental difference between isolation basin environments and other types of site in RSL studies, such as saltmarsh, is that all of the foraminiferal samples within a basin are related to one common altitude at any given time (that of the sill) and not to their own measured elevation. Clearly, this dictates that intra-basin variability in the modern environment and foraminiferal species of isolation basins cannot be accounted for by SWLI. In addition to this, the very strong inter-correlation (44.1 %) between the environmental variable of interest and the other environmental variables found by Horton (1997, 1999) does not appear to exist to such a large extent in the data collected from isolation basins. For example, on saltmarshes there is likely to be a strong correlation between SWLI and salinity, pH, the grain size distribution, and the percentage organic content, where a change in one variable will be mirrored in the other components. Whilst such patterns can be detected in modern isolation basins, they do not occur on such a uniform basis.

The other apparent problem in successful transfer function development for isolation basins is thought to be related to this variability in the intra-basin environment, and low levels of correlation between the environmental parameters. This is represented by the extremely low range of foraminiferal species found both within and throughout the basins investigated, similar to the transitional (variable salinity) stage found within fossil cores. The proposed explanation for this is threefold:

First, that the species contained within the top one centimetre of sediment on any given day, which was identified as being the modern sample, are still just a very

small 'snapshot' in time in comparison to those contained within 1cm of consolidated sediment in a fossil core. This is despite the fact that two sets of foraminiferal samples were collected from all but one of the basins in an attempt to determine some sense of seasonal trends in the foraminifera.

Second, that the basins which have been sampled have typically been shallow in comparison to the estimated maximum depth of fossil basins. For example, during the early Holocene, the substrate of Loch nan Corr is thought to have been under 12 metres of water (4 metres of water over the sill, and an 8 metre deep basin). The deepest basin in this study (Dubh Loch; Section 4.4.20) is under 9 metres deep at its maximum point, but few foraminifera were found on a substrate which was covered with decomposing leaves. The majority of the contemporary basins are considerably shallower than this (Figure 7.1). It is therefore probable that none of the basins represent the fully marine or nearshore shelf phase (stages 1 and 2, Figure 2.1), when foraminiferal diversity is at its maximum in the fossil basins (Figure 7.2). It is also probable that this lack of water depth leads to the different levels of abundance found for the same species between modern and fossil cores. For example, *Jadammina macrescens* is a species indicative of the transitional stage in fossil basins, but is seldom found in modern basins. *Miliammina fusca* dominates this phase in the modern basins, with *Eggerelloides scabrus* replacing it under more saline conditions, pointing to their tolerance of the more variable conditions which are likely in shallower water.

Third, and following on from the point above, the environment within the modern isolation basins sampled appears to be in the upper half of the transitional phase between nearshore shelf and freshwater conditions (all of stages 4 and 5, and the latter parts of stage 3; Figure 2.1), creating very stressful conditions for foraminifera, given the highly variable environment. This is likely to restrict faunal diversity to those species that can tolerate a wide range of conditions, particularly with regard to salinity, or to those that can adapt to minimise the variability, through such methods as living in a shallow infaunal habitat (e.g. *Miliammina fusca*; Murray and Alve, 1999).

The above suggests that it is the uniqueness of the isolation basin environment, and the lack of representation of the fully marine phase in this study which can account for the fact that a transfer function could not be developed for isolation basins, but could be for the more straightforward saltmarsh environment. It also points to the fact that there is a need for analogue samples from basins with their sills lower in the tidal cycle (i.e. stages 1, 2, and 3 in Figure 2.1), in order to obtain data on the fully marine end member seen in fossil sites, and to determine the indicative meaning of the fully marine stage in fossil sites. Previously, this has thought to have been around MTL – 1.5 m (*ca.* MLWNT) for some basins (e.g. Loch nan Corr; Lloyd, 2000; Shennan *et al.*, 2000a). The variable conditions found within modern basins whose sills lies around MLWNT suggest that this estimate of the reference water level may well be higher than is actually the case, although much will depend upon the role that the inertia of the water body will have played in maintaining salinity levels in such a relatively deep basin.

Finally, consideration must be given to the fact that a truly accurate transfer function may not be possible due to changes in the hydrology of isolation basins through catchment modification. Whilst the Outer Hebrides may have been the same peat-covered catchments for much of the Holocene, sites on the mainland (including all fossil sites) are likely to have had forested catchments. The exact impact of this is indeterminable, but should be considered, given likely changes in freshwater input and the potential of indirect anthropogenic impacts on the survival and preservation of calcareous foraminifera.

7.2.1 Considerations in the Sampling Strategy

The basic sampling methodology employed in this research followed that of Horton (1997) and Edwards (1998) for saltmarsh environments, in the sense that it allowed for the study of foraminiferal assemblages and measurement of environmental variables, with an objective to statistically reconstruct the environment.

However, as the environment was expected to be more complicated than saltmarsh, a more comprehensive sampling strategy was undertaken for this research, involving the collection of more samples (532 foraminiferal samples in all, of which 266 (50

%) passed the first data screening), from a larger number of sites. A greater number of environmental variables were also measured, using more modern methods. For example, a calibrated pH meter was used rather than litmus paper, a conductivity meter was taken into the field and results run through a conversion program, rather than laboratory-based porewater salinity tests, a laser granulometer was used for particle size analysis rather than sieving and weighing the sediment, and GPS surveying equipment was used on many of the sills instead of relying on unmaintained benchmarks in an area of Scotland where some of the largest errors in the benchmark system are thought to be by the Ordnance Survey.

The most important aim within this strategy was to gain as much understanding of the isolation basin environment as was possible. This served two main purposes in that a greater understanding would be developed of the ecology of isolation basins and the comprehensive data-set would also afford the greatest opportunity to develop a transfer function for the reconstruction of fossil basin environmental conditions. In order to achieve this, as many environmental variables were measured as was possible, balanced with coverage of a large number of sites, in order that an understanding could be achieved of the true range of the conditions within isolation basins.

7.2.2 Potential Solutions.

The considerations outlined in Section 7.2.1 led to the meeting of the objectives, in terms of gaining a more detailed understanding of the processes within, and ecological characteristics of, a large range of modern isolation basins, and their foraminiferal assemblages. However, as the data-set could not support the development of a transfer function, potential developments in the sampling strategy must be investigated if future work is to build upon the findings of this research. These additions would allow the focus of future research to be oriented towards the greater understanding of the volume of the inputs into an isolation basin system.

This would require a further phase of fieldwork, arranged over a longer, more regular time period similar to that reported by Murray and Alve (2000) and Alve and Murray (2001). Their research was on the Hamble Estuary in southern England,

where a time series survey was carried out over 27 months in order to examine the abundance, infaunal characteristics and species diversity of the foraminifera. Even a study over one year would allow more consistent monitoring of the range of environmental conditions and inputs through all seasons, and give a greater insight into the foraminiferal ecology such as infaunal habitat, and changing species diversity and abundance characteristics throughout the seasonal cycle. Such a time-intensive study would have to be carried out on a smaller number of basins.

Some deeper basins, with a greater degree of connection to the marine environment (and, therefore, higher salinity conditions) also need to be investigated in order to provide a full analogue for reconstructions from fossil sites. Nearshore shelf species are present in the modern basins sampled, but only in those basins with the lower sills and, even then, in the areas with the coarser-grained sandy substrate. This is normally close to the sill, such as in Duartmore Lagoon (Figures 5.2.1, 5.2.2 and 5.2.6) and the Loch of Reiff (Figures A3.9.1, A3.9.2 and A3.9.3). There are some suitable sites available in Scotland for this, but many may be too deep to safely sample; Loch Obisary on the Isle of North Uist has a reported maximum depth of 45.3 metres in the North basin (Dipper *et al.*, 1987), which is unpractical for sampling, although the South basin has a more manageable depth of 19 metres (Dipper *et al.*, 1987). The sill, however, is around MHWST, giving slightly reduced salinity, reported to be anywhere from 10 in the southern basin to 30 close to the sill in the northern basin (the sill is in the northern basin; Mitchell *et al.*, 1980). More suitable deep modern basins can be found off to the sides of sea lochs on the west coast of Scotland (Austin, pers. comm., 2002) and in Greenland and Norway (Long, pers. comm., 2001).

Another complicating factor is the configuration of the sill of the basin. Although two sills may have the same SWLI, the volume of marine input coming into each basin may be significantly different, depending upon the cross-sectional shape or area of the sill. Similarly, even if the volume of marine input is identical over the entire tidal cycle and all other factors are equal, the marine input will have a greater effect upon a basin containing a small volume of water than it will on a basin with a large volume of water, owing to the inertia within the larger system. This has not been considered in this research in terms of foraminiferal ecology, although the

differences in the temporal variability of salinity between small and large basins were clear during sampling of the basins.

Clearly then, a valuable alteration to the sampling strategy for future research would be to concentrate on the volume of the marine input over the whole tidal cycle, relative to the volume of water in the basin, rather than simply measuring the normalised elevation of the sill. This would be incredibly time-consuming and, given the flow rates of the input and output over some of the sills, could potentially be very dangerous or even impossible (e.g. Loch Roe lagoon, Section 4.4.13). The next best alternative to this would be to calculate the maximum wetted cross-sectional area for each sill, to give a proxy for the maximum likely volume of marine input into the basin, and to calculate the ratio of this versus the estimated volume of water held in the basin at the same point in the tidal cycle. Such a 'marine input – basin volume ratio' would also easily allow the consideration of the extra input received into those basins with more than one sill. The raw data for calculating the cross-sectional area could be collected very quickly, easily and accurately using GPS equipment.

A similar ratio, based on input volume, could be calculated for freshwater input through streams and rivers into the basin. The most simple and effective way of calculating the freshwater input accurately would be to install a simplified gauging station, such as a 'V-notch' channel, where the flow is controlled through a purpose-built single regular-shaped notch and measured by volume using data-loggers.

In combination with information on the SWLI of the sill and the water chemistry during the tidal cycle, the marine and freshwater input – basin volume ratios should give a strong indication of the variability and / or inertia within each basin system. This information would then have clear benefits in improving the understanding of the environment and its associated foraminiferal ecology within isolation basins.

If this work were to be carried out, it would also be prudent to place greater emphasis on using a series of basins in which one or more variable can be held constant. For example, similar water volume held in the basins, but different sill cross-sectional areas, or different freshwater inputs. This was attempted in this

research, but the scarcity of basins rarely permitted such an ideal approach. For this reason, it may prove necessary to look elsewhere, such as Norway or Greenland, where there are not only abundant modern isolation basins, but more extensive sequences of fossil basins available, some in staircase sequences such as those found in the Arisaig area of Scotland (Shennan *et al.*, 1993, 1994, 1995, 1999) and on Arveprinsen Ejland in west Greenland (Long *et al.*, 1999), the foraminifera from which can then be used in the calibration of any transfer functions developed.

7.3 IMPLICATIONS FOR ENVIRONMENTAL RECONSTRUCTION

7.3.1 RSL reconstruction using isolation basin environments

Fossil isolation basins have been used extensively in the reconstruction of RSL change (cf. Chapter Two), with the radiocarbon dated, long transitional sequences examined by Shennan *et al.* (1999, 2000a) and Lloyd (2000), from Rumach VI, Dubh Lochan and Loch nan Corr respectively. However, whilst giving the most detailed record from isolation basins, it is these extended sequences, more than other isolation basin records, which also create problems in the estimation of the indicative meaning of the basin sills (e.g. Shennan *et al.*, 1995, 1999, 2000a; Lloyd, 2000). This was the primary reason why this research was conducted, with Shennan *et al.* (1995) and Lloyd (2000) identifying modern analogue studies as a requirement for increasing the precision in reconstructions of RSL.

Given the findings of this research and the unsuccessful attempts to statistically reconstruct fossil isolation basin environments, there are two major implications which must be considered with regard to the interpretation of RSL using fossil isolation basin sequences.

7.3.1.1 The use of foraminifera

Although the Scandinavian work and much of the Scottish work on isolation basins has been carried out using diatoms and pollen, some of the more recent Scottish studies have used foraminiferal and thecamoebian assemblages. The appearance of the changes in salinity groups, with the characteristic transition moving up the core being nearshore shelf into variable salinity foraminiferal species, then into

freshwater thecamoebians with a decrease in RSL. This is illustrated in a fossil core from Loch nan Corr (Figure 6.10).

In light of the ecological considerations of Lloyd (2000), and the outline of foraminiferal ecology and species – salinity optima and tolerance values for isolation basins in Chapters Five and Six of this volume, care should be exercised in the interpretation of such diagrams based solely on salinity as the controlling factor. The traditional boundaries of salinity preference and tolerance for foraminifera in open-water environments (e.g. Murray, 1973, 1979) do not appear to be wholly applicable to the more closed-system, isolation basin environments. The most obvious example of this is the tolerance of extremely low salinity conditions by *Miliammina fusca* to a greater extent than *Jadammina macrescens*; a reversal of the trend found globally in saltmarshes (Lloyd, 2000). This suggestion is strongly supported by the contemporary samples from this study.

In examining the low species diversity of the modern isolation basin samples, it appears that few species are successfully adapted to tolerate the range of conditions in an isolation basin environment; for those species which do exist, there would seem to be little competition. However, what remains to be determined is whether those species which do survive and successfully reproduce do so because they can naturally tolerate the range of water conditions, or because they are adapted to living in a shallow infaunal habitat, thus lowering the variation in conditions which they experience.

7.3.1.2 The use of the indicative meaning for isolation basins

In the CCA carried out in Section 6.3, it was clear from the biplots (Figure 6.2) that the SWLI was not singularly important to the foraminifera in modern isolation basins. Although the elevation of the sill may play an indirect role in controlling other parameters, such as salinity and sediment composition (a lower sill allowing a larger proportion of sand to enter the basin, all other factors being constant), the primary control on the foraminifera and indicative meaning of an isolation basin is clearly more than just the SWLI of the sill, even with any freshwater input taken into account as advocated by Shennan *et al.* (1995).

The primary reason behind this is that isolation basins are much more of a closed and complex system than say, saltmarshes. They have a greater number, and more complex controls on the marine inundation characteristics which, in combination with basin volume and surface area, give differing levels of inertia within a given basin.

This lack of importance of SWLI is, perhaps, not surprising however, given the closed nature of the isolation basin system, and the fact that each basin has only one SWLI measurement taken account of in the statistics (that of the lower sill), but has many foraminiferal samples. This can lead to very different foraminiferal assemblages being compared to the same SWLI, therefore eliminating the identification of intra-basin variability using this parameter.

Because of this, it is much more likely that the marine input ratio of a basin will have to be considered, as outlined in Section 7.2.2, before being related to an indicative meaning. Whilst this, like SWLI, is just one measurement related to many foraminiferal assemblages, there is likely to be greater diversity between basins in terms of its actual value. SWLI values for the majority of basins are concentrated within a small band of the tidal range, but there is likely to be a wider range of marine input – basin water volume ratios between these same basins. The sampling of deeper, fully marine basins should widen this diversity further.

The standard practice in determining the elevation of a sill for a fossil basin which has become covered in sediment and / or vegetation has been to make boreholes down to the bedrock surface across the area above the sill, in a grid network. The minimum and maximum values of the bedrock surface would then be recorded (Long *et al.*, 1999) or perhaps even just the minimum elevation (Shennan *et al.*, 1994). As can be witnessed in the field today, some basins have sills composed of more than one material or have another point of weakness through which water has drained, eroding the sill at that (often narrow) point over time. This can lower the minimum elevation of the sill, yet little water exchange occurs through such a small space (particularly with a basin containing a large volume of water) in comparison to a basin with a much wider sill at that low level (Figure 7.3). In other cases, sills can be strewn with boulders. If boulders were to be encountered in boreholes, they can

not easily be differentiated from bedrock, which can lead to the under-estimation of the minimum elevation or the over-estimation of the maximum elevation.

Considering these potential sources of error, the simplest and most effective way to minimise them would be to use all of the measurements along a transect across the sill, to give an approximate cross-sectional area as a guide to the possible marine input for the basin. There may also be the potential for the application of ground penetrating radar in identifying the sill profile prior to, or instead of making borehole measurements. As for the modern basins, this information could then be related to the probable water volume held within the basin at different times in the basin history, to give a marine input – basin volume ratio for different points during the basin isolation record (Figure 7.4). Such a reconstruction should show a decreasing ratio of marine input relative to the basin water volume as the isolation process occurs; although both the marine input and basin water volume will gradually decrease during isolation, the marine input should fall by a greater amount relative to the volume of water held within the basin, allowing a reduction in salinity.

Estimates of the marine and freshwater input – basin volume ratios would lead to much more ‘individual’ indicative meanings for each basin, in what is a more complex system than other environments used in RSL reconstruction. In this way, the procedure of determining the indicative meaning of a basin sill would remove some of the simplification of the environment which is currently applied, and more would be considered of the processes in operation in isolation basins and the differences therein.

This is **not** to say, however, that it would be unwise to use isolation basins in the reconstruction of former RSL until such a time as a suitable transfer function is developed for the indicative meaning. As outlined in Chapter Two, fossil records from isolation basins already provide a valuable, high-resolution record of RSL change. Instead, what the findings and recommendations of this research **do** imply is that until such a time that a transfer function is developed, the desired increase in resolution for sites with long transitional sequences, based on the accurate definition of the indicative meaning for each fossil basin, cannot be satisfactorily achieved.

7.3.2 Quantitative environmental reconstruction techniques

Section 3.5.1 outlined seven major requirements which must be met, and five primary assumptions which must be considered in any quantitative palaeoenvironmental reconstructions. Using the results presented in Chapters Five and Six, this section considers whether these requirements and assumptions can legitimately be met when reconstructing isolation basin environments. For ease of reference, the requirements and assumptions are repeated in Sections 7.3.2.1 and 7.3.2.2, with discussion of those points worthy of note in 7.3.2.3.

7.3.2.1 Requirements in quantitative palaeoenvironmental reconstruction (Birks, 1994)

- i. A biological system which produces abundant identifiable fossils and that is responsive and sensitive to the environmental variables of interest at the spatial and temporal scales of the study.
- ii. A large, high-quality, training set of modern surface-samples and associated environmental data should be available.
- iii. The fossil data-set should be of consistent taxonomy, and of comparable quality to the modern training set.
- iv. Good independent chronological control is required for fossil data-sets in order to permit correlation and comparison.
- v. Robust statistical methods are required that can model the complex, often unimodal relationships between modern taxa and their environment.
- vi. Reliable and realistic statistical estimation of standard errors of prediction for the modern training set, and for each reconstructed value, is required.
- vii. Critical ecological and statistical evaluations of all reconstructions are needed, as any statistical regression and calibration procedure will produce a result.

7.3.2.2 Assumptions in quantitative palaeoenvironmental reconstruction (Imbrie and Webb, 1981; Birks *et al.* 1990)

- i. The taxa in the modern training set are related to the environment in which they live.

- ii. The environmental variable being reconstructed is ecologically important in the system of interest.
- iii. The taxa in the training set are the same biological entities as in the fossil data, and their response(s) to the environmental variables have not changed significantly over time.
- iv. The statistical methods employed adequately model the response of the taxa to the environmental variable(s) of interest, with sufficient predictive power to allow useful and accurate reconstruction.
- v. Environmental variables other than the one of interest have negligible influence.

7.3.2.3 Discussion

Many of the requirements and assumptions do appear to have been met in the statistical analyses used in this research. The issues discussed here are areas where there is a doubt as to the validity of the requirement or assumption being met, or where the importance of the requirement or assumption has been emphasised by the investigations.

The first requirement states the need for a biological system which is responsive and sensitive to the environmental system. Whilst isolation basins clearly fulfil this criteria, the low species diversity and dominance of species which are highly tolerant of variability in the modern isolation basins sampled suggest that the response of many foraminiferal species is so sensitive to such a variable environment, that only the hardiest of transitional species remain, such as *Miliammina fusca*. This is typical of the transitional stage of fossil isolation basins. The fossil basins appear to be much more diverse during the fully marine stage (Figure 7.2). However, until such a time as deep, more saline modern analogue basins (i.e. those with their sill lower in the tidal cycle than MLWST) can be sampled, requirement two is breached by this study.

Whilst the modern training set is undoubtedly of high-quality, of consistent taxonomy, and large enough to fulfil the task, with sampling methods to match the rigour of those employed in the collection of the fossil data, there simply are too few indicator species in the modern training set to be able to provide an acceptable

modern analogue for all of the fossil data-set. This problem is intensified by the fact that *Jadammina macrescens*, one of the main indicator species in fossil transitional sequences (e.g. Dubh Lochan and Loch nan Corr; Figures 6.9 and 6.10 respectively), rarely occurs in the modern training set (Figure 5.4.1) and when it does, it is only present in trace amounts. Similarly, the dominance of *Eggerelloides scabrus* in some of the more saline modern basins, particularly on North Uist, is not a typical pattern in fossil basins.

The final requirement details the need for an independent evaluation of the results of any statistical test. This prerequisite was met within this research, with the results of MAT for Rumach VI and Dubh Lochan emphasising its importance. While PLS calibration provided predictions of the average salinity conditions for each of the samples in the fossil data, MAT showed only 10 of the 48 samples to actually have a good modern analogue in the screened modern training set.

Of the assumptions made in the reconstruction, this research should have satisfied the final statement to a greater degree than many other ecological studies. As has already been discussed in Chapter Six, the WA-PLS method used takes any residual correlation of environmental variables into account, along with the defined environmental variable of interest. Whilst this still does not entirely meet the supposition, it is the most effective method available at present, and is certainly more preferable than methods such as WA, where transfer functions are based solely on the environmental variable of interest.

Finally, the second assumption requires that the environmental variable of interest is important in terms of controlling the ecological system of interest. The initial aim of reconstructing SWLI using a transfer function was not possible, as SWLI was shown to be of negligible importance by CCA, while the variable identified by CCA as the most important was not useful in the interpretation of fossil sites. For reasons outlined in Section 6.3.3, average salinity was chosen as the environmental variable likely to be the most informative in terms of modern and fossil isolation basin environments. Given the recommendations for the development of the sampling strategy given earlier in this chapter, and the logic behind them, one would expect a

function such as the marine input – basin volume ratio to exercise a greater control on the ecological system within isolation basins.

7.4 FORAMINIFERAL ECOLOGY

7.4.1 Introduction

One of the most difficult exercises in this research has been to try to identify patterns or correlations between foraminiferal species within an assemblage. Examining the scatter plot matrices provided for each basin in Chapter Five and Appendix Three, and the total modern data-set in Section 5.5, there are few clear correlations evident in species – species relationships.

The most likely reason for the lack of inter-basin relationships in the total modern data-set is the changing balance and influence of the environmental variables between basins. This is further complicated by trying to differentiate between those changes which are caused by differences in marine input between sites, and those which are caused by within-basin variability or patchiness in the environment.

One simple way to look at this to see if more obvious patterns should be evident is to take fossil cores, and plot the foraminiferal assemblage from every sample. Alternatively, the use of weighted mean and standard deviation values for foraminifera – environment relationships can be developed for the modern training set, to give a further insight into the ecological controls. This serves two purposes: First, it gives detailed quantitative information on foraminifera – environment relationships. Second, the use of this information can assist in the explanation of patterns in species – species relationships, and how these are controlled by combinations of environmental variables.

7.4.2 Fossil Data

The primary advantage of using a series of foraminiferal assemblages from the same core within a fossil basin is that it would allow the separation of many of the changes which occur during the isolation process from those changes which result from the naturally occurring intra-basin variability in environment which exists throughout a site at any given time. By holding components such as the basin

geology constant, this practice would permit the examination of the genuine changes brought about directly, and indirectly, through a varying marine input during the isolation process.

Fossil foraminiferal sequences are available from Loch nan Corr (Lloyd, 2000; Figure 6.10), Dubh Lochan (Shennan *et al.*, 2000a; Figure 6.9) and Rumach VI (Douthwaite, 1999). The complete sequences of Loch nan Corr and Dubh Lochan are used here. As there were too many species to display in a matrix for Loch nan Corr, the species with lowest maximum percentage values ($< 4\%$) and all thecamoebians were removed for the purposes of this exercise. A small number of species were also removed from the Dubh Lochan data-set, to a level of lowest maximum percentage of $< 2\%$. The scatter plot matrices for Loch nan Corr and Dubh Lochan are shown in Figures 7.5 and 7.6 respectively.

From the two matrices in Figures 7.5 and 7.6, it can be seen that there are as few clear correlations between the foraminiferal and thecamoebian species in the fossil data as there are in the modern training set. While there is one obvious linear relationship between *Miliammina fusca* and *Jadammina macrescens* in Dubh Lochan (Figure 7.6), all other associations would appear to be of low correlation or Gaussian type, as would normally be expected of ecological data.

Figure 7.5, covering the data from Loch nan Corr, does appear to show a greater degree of linearity in the relationship between some of the species, such as between *Elphidium macellum* and *Elphidium gerthi*, and between *Cibicides lobatulus* and *Brizalina variabilis*, and more of what could be loosely defined as unimodal relationships.

From observations made when collecting the modern data, the most likely reason behind the linear relationship is subtle changes in the environment of a basin, which allows two foraminiferal species with similar tolerances to co-exist. Gradual changes in one or two environmental parameters through the basin lead to changing relative abundances of the two species. The most obvious example of this is *Miliammina fusca* and *Eggerelloides scabrus* in the modern training set, particularly in Locheport basin 1 on the Isle of North Uist (Figures 4.4.5, A3.4.1 and A3.4.2),

where very small changes in salinity and sedimentology within the basin lead to a changing relative abundance between the two species. The unimodal or Gaussian relationships suggest that there are some species – species relationships which are maximised at optimum percentage values for each species, whilst in other cases the presence of one species at a relatively high percentage appears to provide enough competition to preclude the survival or reproduction of other selected species at anything other than very low levels.

There are also clear bimodal patterns in some of the species, both in the modern and fossil data-sets, indicating that samples may simply have not been collected containing mid-range percentage abundances of that species. More probable, however, is that it is difficult for some species to be co-dominant with another, whereby a threshold is crossed when one species replaces another, with only low residual abundances of the replaced species remaining.

Although predictably, the fossil data matrices show identical types of relationships to the patterns found in the modern training set, it is perhaps more surprising to have found such patterns in the modern data-set, given the much lower species diversity and apparent overlap in the tolerance of environmental variables between species. This would appear to suggest that it is indeed the combination or interaction of several environmental variables which controls the presence, dominance or absence of individual species, manipulating both inter- and intra-basin variability in the foraminiferal assemblages. The marine input – basin volume ratio is likely to play a significant role in controlling such interactions in the environment.

7.4.3 Modern Training Set

7.4.3.1 Introduction

In order to gain a more detailed understanding of more of the effects of the environmental variables, and their resultant control on foraminiferal ecology, further tolerance and optima values for each species can be investigated. Information on the overlaps between these tolerance limits will also be valuable.

Going back to the original environmental data-set from the CCA model in Chapter Six, it is possible to choose any one environmental variable to run through the inverse WA model, and identify its optima and tolerance based on the data available. As an initial test, the procedure has been performed on the average salinity (Figure 7.7), percentage sand content (Figure 7.8) and SWLI (Figure 7.9) for all 266 samples of the modern training set.

In this instance, the test was carried out without the further screening of the data by WA-PLS which was carried out in Chapter Six for average salinity (Figure 6.7). For this reason, a greater range of tolerance by each species of each environmental variable is likely, as the extremes are still included. This should show a more realistic range of values for each of the environmental variables in modern isolation basins, and a greater (more realistic) degree of overlap in tolerance levels between species. As for average salinity there is, indeed, significant overlap for both sand content and SWLI between species. No single species has an exclusive range of tolerance, or an optima which is outside of the range of tolerance of a significant number of other species, providing yet further evidence that it is the combination of the many variables which control the presence or absence of foraminiferal species in isolation basins.

Observations on the ecological preferences of species within each of the seven cluster zones were made in Section 5.6. Here, the ecological limits of the most frequently occurring foraminiferal species, highlighted by WA inverse regression (Figures 7.7 - 7.9), are discussed with reference to previously published findings on foraminiferal ecology and the general trends in species preference outlined in Section 5.6. It should be noted that the tolerance range in particular is not necessarily indicative of the foraminiferal species as a whole, only for the conditions sampled within the twenty contemporary isolation basins. If a species occurs only a few times within the data-set, such as *Haynesina depressula*, it is impossible to determine its true range of tolerance for environmental parameters.

7.4.3.2 *Miliammina fusca*

Miliammina fusca is the species tolerant of the broadest range of water conditions in modern isolation basins (cf. Section 5.6). Murray and Alve (1999) consider this

trend to extend further, stating that *Miliammina fusca* can represent a wide range of marginal marine environments, from marsh edge to waters of up to 6 m depth. From the raw data, it was stated in Chapter Five that the species occurs in greatest numbers in water below 20 salinity. The species optimum salinity level identified by WA inverse regression at 19.9 (Figure 7.7) concurs with this, and the findings of Murray (1991) and Murray and Alve (1999). Average salinity tolerance levels (± 8.8) follow the general findings in published literature that *Miliammina fusca* is a euryhaline species (e.g. Murray, 1979; Murray and Alve, 1999; Lloyd, 2000; Alve and Murray, 2001).

Similarly, the broad tolerance limits of substrate conditions (35 – 85 % sand content; Figure 7.8) support previous findings (e.g. Murray and Alve, 1999) that *Miliammina fusca* can support a wide range of sediment conditions, from sands to organic-rich muds. However, in comparison to many other species in the modern training set, *Miliammina fusca* is largely intolerant of the coarsest-grained sediments (it has the third-lowest maximum sand percentage tolerance of the eleven species). The species appears to maintain its highest levels in the finer, more organic sediments in isolation basins, where it often co-exists with *Eggerelloides scabrus*. It is this characteristic association with the finer-grained sediments which is likely to lead to the success of this species, along with *Eggerelloides scabrus*, in modern isolation basins, allowing the foraminifera to live infaunally and, thus, remove themselves from some of the variability in water conditions.

7.4.3.3 *Eggerelloides scabrus*

It is extremely rare in modern isolation basins for *Eggerelloides scabrus* to be found in a sample without *Miliammina fusca* also being present (Figure 5.4.1). This points to the relationship outlined in Section 7.4.2, whereby the two species clearly prefer a very similar environment, with a change in only one or two parameters causing dominance to switch between the species. From the evidence in the modern training set, the trigger for the changing relative abundance appears to be salinity, with the optimum salinity value for *Eggerelloides scabrus* (29.6) lying beyond the upper salinity tolerance limit of *Miliammina fusca*. The tolerance limits (± 3.1) are largely in agreement with the salinity tolerance figures of 29 – 35 suggested by Murray (1979, 1991). The findings in relation to the percentage sand content optima and

tolerance levels (53.8 ± 17 %; Figure 7.8) also fully supports the trends suggested in Section 5.6 and by Murray (1979) and Lloyd (2000), of a sediment dwelling species which prefers fine-grained, high organic content sediments.

Eggerelloides scabrus dominates the more marine assemblages in basins on North Uist, where calcareous species (e.g. *Cibicides lobatulus*) would be typically found in fossil cores and other modern basins. The most probable explanation for this is the lack of calcareous species within the Hebridean basins as whole, suggesting acidity conditions which prevent the survival and reproduction of calcareous forms. However, if acidity is the reason behind this a sharp transition (lowering) in pH must occur across the water – sediment interface, as the water pH in the Hebrides basins is similar to, if not slightly closer to pH 7.0 than that in the mainland sites. Alternatively, the fact that the species is infaunal, whilst many of the calcareous forms characteristic of the fully marine stage are epifaunal, suggests that *Eggerelloides scabrus* dominates these marine conditions because it is an infaunal species which thrives on high salinity. If water conditions are still variable beyond the species' range, or the water body too shallow, it can remove itself from some of the variability of the environment through living in the sediment, whilst the epifaunal types remain more vulnerable.

7.4.3.4 *Cibicides lobatulus*

In accordance with field observations and initial findings in Section 5.6, *Cibicides lobatulus* prefers substrates with a high percentage sand content, the species optima and tolerance lying at 90 ± 19.2 % sand. The species was found to be most abundant in the sandy or shelly lag areas directly behind the sill, predominantly in those basins whose sills lie relatively low in the tidal cycle (e.g. Duartmore Lagoon, Section 4.4.17). However, the average salinity optima (25.5) and tolerance values (± 5.2) for this species are identified as being slightly lower than levels for some species classed as variable salinity types, such as *Elphidium williamsoni* and *Haynesina germanica* (Figure 7.7).

Figure 7.9 plots *Cibicides lobatulus* as having the second highest optimum value for SWLI in the modern training set (i.e. it prefers basins with sill higher in the tidal cycle). However, after taking into account the large SWLI tolerance range attached

to *Cibicides lobatulus*, only three other species reach lower values of SWLI in their tolerance bands (*Elphidium macellum*, *Elphidium margaritaceum* and *Ammonia beccarii* var. *batavus*; Figure 7.9), all of which occur in only a small number of samples.

Many of the basins in which the species is found (e.g. the Loch of Reiff) do not have the fully marine average salinity conditions associated with this fully marine species (e.g. Murray, 1979, 1991). As a significant proportion of the tests of this species were unstained by rose Bengal, it can be assumed that many of these irregular occurrences were caused by the tests being washed into basins. This assertion is reinforced by the presence of tests only in the shelly lag behind the sill of such basins, and would explain the anomaly of its reduced average salinity value in the statistical analyses (Figure 7.7). This obviously has implications for the comparisons of the ecological tolerances of *Cibicides lobatulus* with other species, such as *Elphidium williamsoni*, which appear below. The apparent relationships with other species should, therefore, be treated with care.

7.4.3.5 *Elphidium williamsoni*

The results from this research for *Elphidium williamsoni* show it to have similar optima (25.5 and 82.3 %) and tolerance bands (± 6.8 and ± 17.7 %) for average salinity and percentage sand content to *Cibicides lobatulus*. Much like *Eggerelloides scabrus* with *Miliammina fusca*, *Elphidium williamsoni* is rarely found in samples in the modern training without *Cibicides lobatulus* also being present, suggesting that a similar relationship whereby a small change in one or two parameters allows a threshold to be crossed and the dominance to switch between the two species.

Unlike *Eggerelloides scabrus* and *Miliammina fusca* however, it is not entirely clear from the optima and tolerance bands exactly which parameter(s) is / are required to change in order to cause the switch between the two species, other than a slightly reduced percentage sand content for *Elphidium williamsoni*. The relationship between *Elphidium williamsoni* and *Cibicides lobatulus* is also likely to be complicated by the apparent interaction of other species, such as *Ammonia beccarii* var. *batavus* and *Haynesina germanica* in some samples. These latter two species

are both infaunal and can tolerate diurnal salinity variation similar to that of *Elphidium williamsoni* (0 – 32; Murray, 1991) from 0 – 35 (Murray, 1979), so it is a little surprising that they were not found more frequently in the contemporary isolation basins. The likely reason for this is that they were out-competed by the combination of *Miliammina fusca* and *Eggerelloides scabrus*, perhaps owing to the sediment type or acidic conditions which infiltrate through to their shallow infaunal habitat.

Alternatively, if the optima and tolerance values for *Cibicides lobatulus* are largely incorrect owing to the washing of specimens into basins, the occurrence of the two species together can be put down to little more than coincidence in at least some of the cases. Removal of data where only *Cibicides lobatulus* tests are found in a basin may lead to more clearly defined tolerance values for *Cibicides lobatulus*, with a higher optimum value for average salinity.

7.4.3.6 *Haynesina germanica* and *Jadammina macrescens*

Haynesina germanica shares similar optima (26.8) and tolerance levels (± 7.5) for average salinity and percentage sand content with *Cibicides lobatulus* and *Elphidium williamsoni*, and is always present when *Elphidium williamsoni* dominates the assemblage, generally increasing its relative abundance whenever *Elphidium williamsoni* declines. Again, this suggests a close relationship between the species, with the link between *Haynesina germanica* and *Elphidium williamsoni* also present in the Loch nan Corr fossil core (Lloyd, 2000; Figure 6.10), although in this case *Haynesina germanica* is always the more abundant of the two species.

The average salinity and optima values for *Haynesina germanica* do not reflect the full diurnal range of 0 – 35 suggested by Murray (1979). As a wide range of salinity conditions were sampled within the twenty basins, this is probably owing to the competition from other transitional or variable salinity species, particularly *Miliammina fusca*, rather than a simple lack of diversity in the selection of sites.

Haynesina germanica, like *Jadammina macrescens* is a classic transitional species in fossil isolation basin cores, and listed as a brackish species in published literature (e.g. Murray, 1979, 1991). Typically, *Haynesina germanica* becomes dominant

immediately following the fully marine stage in fossil cores, before *Jadammina macrescens* takes over later in the sequence (e.g. Figures 6.9 and 6.10).

Like *Jadammina macrescens*, *Haynesina germanica* does not dominate the modern training set in the same way as it dominates large sections of some fossil cores, with the optima and tolerance values for average salinity (26.8 ± 6.7 *Jadammina Macrescens*; 26.8 ± 7.5 *Haynesina germanica*) for both species offering little evidence to suggest that *Jadammina macrescens* would take over from *Haynesina germanica* in an isolation sequence. The low numbers or absence of *Jadammina macrescens* and *Haynesina germanica* in most samples is likely to create problems for application of a transfer function to fossil data, as the fossil data currently has no effective analogue within the modern training set. This problem is intensified by the fact that the patterns in the modern training set for these two species do not appear to accurately represent the environmental changes which occur in the transitional sequence of fossil cores. One possible reason why this problem may occur between the fossil and modern data-sets is the issue of water depth. *Miliammina fusca* and *Eggerelloides scabrus* have been shown in the modern training set to be able to dominate in shallow-water modern isolation basins, perhaps allowing them to out-compete other characteristic transitional species. This argument is reinforced in the case of *Jadammina macrescens* as it is an epifaunal species and, therefore, less likely to be able to protect itself from the variation within a brackish environment to the extent that *Miliammina fusca* and *Eggerelloides scabrus* can.

An alternative suggestion has been put forward with regard to *Jadammina macrescens*, this time in relation to its presence in the fossil data-set, where it was suggested that the species may have been washed into the Loch nan Corr assemblage from fringing saltmarsh (Lloyd, pers. comm., 2001). This is considered to be highly unlikely, however, given the dominance of the species over such a long section of the core. The core was also taken towards the centre of the basin and, whilst tidal currents may have caused some mixing during the fully marine stage, little sediment disturbance is likely to have occurred during the latter stages of the transitional phase of basin isolation.

7.4.3.7 Determining ecological optima and tolerance limits

The graphs presented in Figures 7.7 to 7.9 each have the x-axis arranged in ascending order of the species optima. However, for ecological investigations, leaving the species in a set order on every graph, should make it easier to compare each species' tolerance and optima values for combinations of variables. This would allow the relatively easy identification of those species which have little overlap in their tolerance values, and those which seem to prefer similar environments.

As there are several reasons as to why some foraminifera are present in an assemblage while others are not, this simple procedure is a highly beneficial exercise to improve our understanding of the ecology of environments such as isolation basins. For example, of the species which have little or no overlap in their tolerance of environmental variables, they are unlikely to be seen in the same assemblage for the simple reason that they can not tolerate the same environment. However, if two species were to have very similar tolerance values for water chemistry components, it is still unlikely that both species would be co-dominant in a given assemblage. Rather, the interaction of other environmental variables, such as sediment properties, would allow one species to become dominant at the expense of the other.

The WA method used here, and the procedures leading up to this method in the preparation and testing of the data-set are, whilst being very useful, a rather circuitous route to obtaining values for the weighted mean and standard deviation of each species against each environmental variable, if the only objective of the research is to gain quantitative information on the modern environment. Both measures can be relatively quickly and simply obtained through more straightforward computer-driven statistical packages. However, an initial process of data screening, such as that outlined in Table 3.1, should not be ignored in the preparation of the data for statistical testing if misleading results are to be minimised.

The decision to use the WA model or a more accessible and less time-consuming technique is likely to be controlled by the desired definition of the species tolerance values. If the removal of extreme values to produce narrower tolerance bands is required, as was performed for average salinity in Chapter Six, the full WA model is

necessary, in order to calculate the residual of each sample. From the point of removing those samples with a residual greater than the standard deviation, it is a very brief process to then run the WA model again in order to obtain the revised values for species optima and tolerance against the environmental variable of interest. However, for ecological purposes a true picture of the species and the range of conditions in which they can survive and reproduce should be sought, and the data should be used without running this final screening process.

7.4.4 Synopsis

The sampling strategy and statistical methods used in this research have provided a valuable qualitative and quantitative insight into the ecology of isolation basins, and the complexity and diversity of their environment. However, it is only through the further investigation of species – environment preferences and controls, using methods and techniques such as those outlined above, that a truly definitive understanding of the ecology of isolation basins can be achieved.

7.5 SUMMARY

- The complexity of the isolation basin environment is much greater than that of other environments, such as saltmarshes, for which transfer functions have been successfully developed. Much of this complexity comes from the fact that isolation basins are more of a closed system, which can be highly variable over a short distance within a given site.
- The low species diversity in comparison to the fully marine and freshwater stages of the fossil data-set, coupled with a range of dominant species in the modern training set which appear to have a broad tolerance of their environment, dictate that few good modern analogues could be found using the current modern training set. Even where the species diversity is lower in the fossil assemblages (normally during the transitional phase), differences in the dominant species between the modern and fossil data-sets still lead to a low number of valid analogues in the modern training set. The problem is exacerbated, in particular, by the dominance of *Miliammina fusca*, which appears to be able to tolerate a wide range of water and sediment conditions within contemporary isolation basins.

- Given the level of complexity in the environment, it appears that inter-relationships between environmental components, rather than single variables, appear to control the foraminiferal assemblages. Therefore, further consideration needs to be given to defining a suitable environmental control which accounts for a greater range of the variance in the other environmental variables, and the associated foraminiferal assemblages, in the same way that SWLI was shown to exert such a large control on the other environmental variables in the work of Horton (1997) and Edwards (1998). Such a controlling factor could then be used as the environmental variable of interest in the development of a more successful transfer function. This would be best achieved through more focused research, on a lower number of modern isolation basins, over an entire seasonal cycle.
- It is suggested that a suitable environmental control for isolation basins would be found through the development of an accurate measure of the maximum possible marine input into a basin. A 'marine input – basin volume ratio' is recommended as a suitable measure of this, as it also considers the inertia present within the system caused by the volume of water in the basin.
- Deeper basins, and basins with their sill elevation lower in the tidal cycle must still be identified and investigated in order to provide a modern analogue environment for the fully marine or nearshore shelf stage of fossil isolation basins.
- The use of weighted mean and standard deviation for defining the optima and tolerance of species to a series of environmental variables is advocated. By considering the range of tolerance bands for each species to the series of variables, more can be determined about the main controlling variables for each species.
- Only when a greater quantitative understanding of the isolation basin environment is reached, can a significant increase in resolution of the RSL reconstructions using isolation basins be satisfactorily achieved.

The Conservation of Isolation Basins

8.1 INTRODUCTION

Saline lagoons are already recognised as important habitats on biological grounds, by virtue of their priority status under the European Community Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (the 'Habitats Directive'; Council of the European Communities, 1992), and the resultant in-depth study of their biotopes under the Marine Nature Conservation Review (MNCR). Some of the more remarkable examples, such as Loch Maddy on North Uist, have been proposed as marine candidate Special Areas of Conservation (cSACs) in response to the Habitats Directive, and have existing protection through Site of Special Scientific Interest (SSSI) designation.

With regard to isolation basins, however, this interest and protection is deficient in two respects:

- i. The focus on biology in the MNCR survey of saline lagoons has been at the expense of gaining a detailed understanding of the complex and diverse range of environments which exist within isolation basins, and the processes operating within them and their catchment. This research has sought to address this, presenting findings on foraminiferal ecology (sections 5.6 and 7.4) within the isolation basin system as a whole, and making recommendations with regard to approaches for further developing our understanding of the complex processes and interactions involved in isolation basin environments.
- ii. The protection of fossil isolation basins, which contain records of past changes in relative sea-level (RSL) and climate, has been ignored thus far. Fossil sites are beyond the remit of the MNCR, but their importance should be recognised through the assessment and inclusion of key sites in updates to the Geological

Conservation Review (GCR), and their consideration for protection under statutory conservation designations.

The issue of conserving modern isolation basins is covered only briefly in this chapter. While only the biological aspects of the conservation of modern isolation basins were addressed through the MNCR (e.g. Hiscock, 1996; Covey *et al.*, 1998; Thorpe *et al.*, 1998), the integrated management of these sites in relation to the processes occurring within the basins and their catchment area is a priority, as already promoted for freshwater management (e.g. Maitland and Morgan, 1997; Carvalho and Anderson, 2001; Leys, 2001; Soulsby and Boon, 2001).

By contrast, no recommendations have, thus far, been made for the conservation of fossil isolation basins. As a programme of updates is currently planned for the GCR, the primary aim of this chapter is to provide recommendations for the conservation of fossil isolation basin sites. This includes an inventory of known sites, together with the type of information currently available from each of them which can be used in the reconstruction of past environments.

8.2 MODERN ISOLATION BASINS

8.2.1 Introduction

In comparison to other marine and brackish environments, modern isolation basins are a less open system. The degree of interaction with the fully marine and freshwater environments changes through time (Figure 2.1). This interaction is controlled by the dimensions of the sill and its position in relation to the tidal cycle, together with the morphology of, and vegetation within the drainage basin. The volume of water held within the basin will also affect the impact of marine or freshwater influx. Typically, a smaller basin will react to a given input to a greater degree, and more quickly, than a larger basin, as larger basins have greater inertia to overcome. This variable interaction with the marine and freshwater environment, over a broad range of spatial and temporal scales, gives rise to much of the complexity and diversity of the isolation basin system.

From this simplified explanation of the modern isolation basin environment, and that of Covey (1999), it is clear that it is not sufficient to consider just the basins and / or the biological assemblages which they contain in isolation. Rather, it is the physical setting of the basin and its relationship to the local environment, along with the interaction between the biological assemblages and their physical environment which must be considered. In order to achieve this, the processes and controlling factors in operation within the isolation basin environment, and its local setting, must first be identified and then understood. This is especially crucial given the large overlap and interaction between the physical and biological environment (Gordon and Leys, 2001a), and with the links between the two being essential in the interpretation of palaeoenvironmental records and changes in relative sea-level (Laidler, 2001).

8.2.2 Changes in the isolation basin environment

Changes occur in isolation basins over a broad range of temporal scales, from the approximately semi-diurnal tidal input into many basins, through the fortnightly tidal cycle, to more long-term changes on a seasonal or annual basis, arising from such factors as precipitation and the resultant freshwater input. Superimposed upon this pattern are those changes brought about by extreme or unique events, such as storms, tsunamis, or the impact of human activity on the catchment area of a basin. Many of these changes are recorded through changes in the basin sediment and / or biostratigraphy.

These changes also operate at a variety of spatial scales, from those patterns such as the natural patchiness in a basin environment, through a small amount of freshwater input causing localised lowering of the water salinity, to basin-wide changes caused by a large marine input. Again, this pattern is overlain by one-off or extreme events, such as modification of the sill (thereby altering the marine input) or pollution. The impact and speed of any change will be determined by the processes operating within the basin, the inertia within the system, and its connectivity with the local setting. The causes of changes in the system may be split into natural changes, and those brought about through anthropogenic activity.

8.2.2.1 Natural changes

Natural changes within an isolation basin system come from the interplay of the lake basin and its surrounding marine and drainage basin environment, or more directly through interaction with the atmosphere. The changes in a marine basin are largely controlled by the tidal input across the sill, and the input of freshwater in those basins where it is significant, and have been discussed in previous chapters. However, as the tidal input reduces, and the basins become more brackish than freshwater, so the control of natural change gradually switches to the catchment area and the prevailing climate. Examples of natural changes in an isolation basin system include:

- i. Basin infilling (e.g. Shennan *et al.*, 1993, 1994, 1995, 1996a, 1996b, 1999, 2000a). Through time, basins naturally become silted up with material from the catchment area. Successional changes are then accelerated through the availability of potential nutrients locked up in the deposits. When shallow water permits the utilisation of these nutrients, rapid colonisation and acceleration of the infilling process can occur, otherwise known as eutrophication (Maitland and Morgan, 1997; Carvalho and Anderson, 2001).
- ii. The impacts of a changing climate. This can directly and indirectly affect lake basin physics (water flushing or recycling rates, and stratification), chemistry (pH, nutrients, and dissolved oxygen content) and biology (e.g. Carvalho and Anderson, 2001).

The degree of connection to marine and freshwater environments, in combination with the prevailing climate, also impacts the isolation basin system in terms of flushing of the basin (Carvalho and Anderson, 2001) or the water turnover period (Maitland and Morgan, 1997). In turn, the flushing rate of a system is important in the estimation of its sensitivity to environmental change, particularly in terms of eutrophication; the lower the flushing rate, the more sensitive a site will be to eutrophication, as the residence time of nutrients is increased. The flushing rate has a similar impact on the potential of a basin for acidification (Carvalho and Anderson, 2001).

8.2.2.2 Anthropogenic changes

Anthropogenic changes can simply accelerate or alter those changes which occur naturally within an isolation basin system, such as eutrophication and climate change. They can also introduce a small number of additional changes into the natural system, such as through modification of the catchment or the basin sill (which, in turn, affects the size, salinity, morphology and flushing rate of the basin), and processes such as acidification from atmospheric pollution on the global scale. The four main examples of potential human impact on modern isolation basins are eutrophication, acidification, catchment modification, and basin modification:

- i. Although eutrophication is a natural process, it has been greatly accelerated by human activity, particularly through agriculture and the excessive use of fertilisers. The effects include increased algal growths and, eventually, the deoxygenation of the lower, cooler water in stratified basins (Maitland and Morgan, 1997). The vast majority of the land surrounding modern isolation basins in Scotland is used in sheep and cattle farming. The droppings from these animals washed into the basins from fringing saltmarsh, together with septic tank outflows which feed directly into basins, can lead to the increased nutrient input and build-up required for eutrophication, rather than input from fertilisers. There are also potential inputs of nutrients and pollutants from fish farms in sea lochs around the Scottish coast (e.g. Scott, 1997), forestry (e.g. Kreiser *et al.*, 1990; Patrick *et al.*, 1990), and any changes in farming practice which alter the current balance, such as increased agricultural yields.
- ii. Acidification is caused primarily by acid deposition resulting from the burning of fossil fuels. It is mainly characterised in lake basins by severe damage to fish stocks, but the biological impacts of acidification are wide-ranging. The effects of acid deposition are reported to have become increasingly noticeable in many lochs throughout Scotland (e.g. Battarbee, 1990). Impacts include possible changes in, or damage to, the flora and fauna (e.g. Howells, 1990, Battarbee, 1990), with basins in areas of base-poor geology being particularly vulnerable owing to their low buffering capacity (Carvalho and Anderson, 2001). The largest potential impact of this

on isolation basins would be on the sometimes rare flora and fauna which occur within saline lagoons and, in the context of this research, the preservation of microfossil records which are used in palaeoenvironmental reconstruction, particularly calcareous foraminifera.

- iii. The processes in operation within a basin are inexorably linked with the catchment area, with the relationship between the two increasing as a basin becomes isolated. Therefore, any modification of the catchment area will have impacts on the basin system and the interplay between a basin and its surroundings is fundamental to the conservation of that basin. The most common change within the catchment area is in the drainage pattern which feeds freshwater into the isolation basin. The drainage system in itself carries not only freshwater into the basin, but also sediment, nutrients and pollutants which can lead to the infilling, eutrophication and acidification of the basin (e.g. Maitland and Morgan, 1997; Carvalho and Anderson, 2001).

Physical impacts also lead to the alteration of the catchment drainage system. These include the use of all-terrain vehicles in farming, the grazing of cattle and sheep, the cutting of peat (for fuel), and afforestation. With the continued uncertainty surrounding livestock farming, some farmers in the Outer Hebrides are considering a move to commercial afforestation of their land (A. Rodger, pers. comm., 1999). This would have a much greater, and more variable impact on drainage (and the resultant flushing rate of the basin), and the supply of sediment and nutrients, with the size of the effect dependent upon the stage of rotation of the plantation (Laidler, 2001).

- iv. Both fossil and modern isolation basins have been affected by modification of the basin sill. The most frequent cause is road construction, with the introduction or enlarging of culverts for modern basins, or the removal, lowering, or covering of the sill of fossil basins. This can either heavily modify modern basin environments or can, indeed, create new saline lagoons if no control on marine input was present before the construction.

In the case of fossil basins, the modification of the sill for road construction or land drainage, such as on the Ru peninsula in Arisaig (Figure 8.1), has implications for the future palaeoenvironmental interpretation of these sites for purposes of reconstructing former relative sea-levels. Any removal or lowering of the sill, either detected or undetected, will lead to reductions in the accuracy of reconstructions or erroneous results.

Whilst the problems of catchment and basin modification can be relatively easily addressed through local management responses such as promoting public education and awareness, impacts such as acidification through global atmospheric pollution have more widespread impacts, producing more severe changes in the isolation basins system as a whole. These changes require the co-ordination of management responses at national and international levels (cf. Gordon *et al.*, 1998).

8.2.3 Marine Nature Conservation Review (MNCR) of saline lagoons

Of the twenty basins investigated as part of this research, seven were not included in the MNCR surveys of saline lagoons by Thorpe *et al.* (1998) or Covey *et al.* (1998). Of these seven, two are freshwater environments, with the elevation of their sill just outside the range of the contemporary tidal cycle, but the other five receive regular marine input across natural rock sills. Several other basins were observed during the undertaking of this research which were excluded from the MNCR reports, particularly in the Uists. The impact of this will depend upon the precise objectives of the MNCR saline lagoon survey. If the intention was to determine the range of biotopes present within saline lagoons in Scotland, the implications of omitting basins from the study are likely to be minimal, as a broad range of environments was covered in the MNCR study. However, if the purpose of the survey was to include an environmental audit of all lagoons, then the ramifications may be a little more significant for the conservation of saline lagoon habitats, as many basins currently lie unrecognised.

The MNCR survey of saline lagoons had an immediate priority to focus on gaining an understanding of the biological habitats and communities (or biotopes) contained within the basins, and the rarity and / or diversity of these biotopes (Hiscock and

O'Connor, 1996; Hiscock, 1998; Covey, 1999). As a result, the processes occurring within the basins were largely ignored through an over-simplification of the environment. For example, only one value for the salinity of a basin is often stated, measured at a random point in the tidal cycle. In some cases, this figure was only an estimated value. The research reported in this thesis, and the report of Covey (1999), has shown that isolation basin environments can be highly variable in both space and time, and that no real indication of the environmental conditions and processes within a basin can be determined by a single measurement. There was also no requirement in the MNCR survey to consider the interaction of the basin with its local environment, such as the amount of marine and freshwater input into the basin, and the impacts that this would have on the biotopes present.

In order to conserve these basins successfully, they must be treated as part of the wider environmental system, with a similar management approach, in many respects, to that taken for freshwater management (e.g. Maitland and Morgan, 1997; Carvalho and Anderson, 2001; Leys, 2001; Soulsby and Boon, 2001). For this reason, integrated management is required, based on an holistic interpretation and sound understanding of the physical and biological processes operating within the basins and their catchment area (cf. Gordon and Leys, 2001a, 2001b).

8.2.4 The conservation of modern isolation basins

Those marine sites identified under the *Natura 2000* network of the 1992 EC Habitats Directive are currently designated as marine candidate Special Areas of Conservation (marine cSAC), where rare, endangered or vulnerable natural habitats and species (other than birds) are supported (Scottish Natural Heritage, 1995). An example of such a site is Loch Maddy, which is a large shallow marine inlet and bay, comprising thirteen saline lagoons, reefs and intertidal sand and mudflats. Bamber *et al.* (1992) and Covey (1999) believe that it is saline lagoons of this type (large size, with numerous basins and a convoluted shape, including those broken up by islands) which support the most diverse lagoonal communities.

Parts of the Loch Maddy area are already protected as a biological SSSI. Other marine cSACs are in a similar situation in already having SSSI designation covering

at least part of their area. The criteria for SSSI designation for saline lagoons is outlined by the Joint Nature Conservation Committee (1996), although these only emphasise the biological interests.

While many larger basins are protected for their complex lagoon systems and high level of species diversity, many smaller basins, which have less inertia within their system, remain vulnerable to the direct and indirect effects of human activity. In the case of Loch Maddy and the Alioter and Bac-a-Stoc Lagoons, they lie inside the Loch nam Madadh marine cSAC, Loch an Duin SSSI, and Loch Maddy Marine Conservation Area (MCA), but the vast majority of smaller modern isolation basins are unprotected.

Some of these smaller sites are particularly valuable for the accurate interpretation of palaeoenvironments and relative sea-level changes, and for educational purposes, and merit consideration for some form of protection (Laidler, 2001), in order to maintain the modern natural processes occurring within the environment (c.f. Leys, 2001; Soulsby and Boon, 2001). One approach would be to conserve those sites close to protected fossil isolation basin sequences, to allow direct comparisons during interpretation. This may not always be possible, or provide the best examples of basins, however.

The obvious individual basins to consider for conservation on geological (modern process) grounds are those already protected on biological grounds, such as Alioter Lagoon and Bac-a-stoc Lagoon, within the Loch Maddy cSAC and SSSI. This would allow more integrated management, linking conservation of biological interests to maintenance of the natural processes. These basins illustrate the processes involved in modern isolation basins / sluiced and silled saline lagoons, whilst also being important habitats for the flora and fauna of the Loch Maddy area, although the foraminifera contained within them are relatively poor as modern analogue sites for RSL reconstruction.

On the mainland, the Loch Roe, Loch Nedd and Duartmore Lagoons, and the Loch of Reiff, all clearly illustrate the processes occurring within modern isolation basins. Between them, they have a good range of sill elevations within the tidal cycle, have

varying degrees of freshwater input (from the high volume entering Loch Roe Lagoon through the steep catchment around Duartmore Lagoon, to the shallow catchment surrounding the Loch of Reiff; cf. Chapter 4), and display a relatively diverse range of foraminifera for reconstruction purposes. None are currently covered by conservation designations, but merit consideration on the grounds of their modern process environments and foraminiferal diversity.

There is a case for the conservation of these modern isolation basin sites, not only through statutory protection but also through the voluntary sector Regionally Important Geological and Geomorphological Sites (RIGS) programme. This should allow not only the protection of the sites, but also allow inclusion of their interests in public education and awareness programmes and in site interpretation. However, whatever methods of conservation are employed, management must recognise the temporal and spatial variability of the biological and physical environment.

8.3 FOSSIL ISOLATION BASINS

8.3.1 Introduction

The geological records of fossil isolation basins on the western coast of Scotland are currently unprotected from human impact. However, the basins provide valuable, and often high-resolution evidence for the reconstruction of past RSL and other changes in environment. The Geological Conservation Review (GCR) does include a network of conservation sites throughout Scotland for Lateglacial and Holocene relative sea-level changes, as reported in the Quaternary of Scotland GCR volume (Gordon and Sutherland, 1993). However, the selection of sites for the GCR was undertaken before the start of the main research focus on isolation basins in the early 1990s. There is now a need to update the GCR site coverage in the light of the results of this research, and that of Shennan *et al.* (e.g. 1993, 1994, 1995, 1996a, 1996b, 1999, 2000a) and Lloyd (2000). This section identifies a number of key individual sites and / or areas with several sites in close proximity. It is recommended that these be considered for inclusion in the GCR during the forthcoming programme of updates.

8.3.2 *Fossil basins in Scotland*

At present, the only inventory of fossil isolation basins is provided by Shennan *et al.* (2000a), as part of a summary of sea-level index points from isolation basin and tidal marsh environments for northwest Scotland. It is, therefore, a valuable exercise to develop this list explicitly for isolation basins, and to provide further information, such as the types of microfossil records available, and the measured elevation of the sill, as well as supplying references to the original work for each site, where the results and analyses for each basin can be found (Table 8.1). The location of each of the sites included in Table 8.1 is indicated in Figure 8.1. This information provides a basis for assessing the conservation importance of the sites.

8.3.3 *The conservation of fossil basins*

Whilst a real threat of change in process or impacts on biological assemblages is only possible in those fossil isolation basins which still contain freshwater (e.g. Loch nan Corr; Lloyd, 2000), human impacts can affect the usefulness of a site for the interpretation of past changes in climate and the environment. The most obvious of these impacts within Scottish fossil isolation basins is the removal or modification of the rock sill for road construction or land drainage.

RSL reconstructions from isolation basins rely upon the accurate determination of the elevation of the sill. This information, when combined with the dating of sediments or microfossils within cores, is used to determine former relative sea-level at the site, for different points in time during the Late Devensian and Holocene. By combining the results from a number of basins, local relative sea-level (age-altitude) curves can then be constructed. Clearly, any removal or lowering of the sill would lead to erroneous results. Even where sill modification is detected (e.g. Shennan *et al.*, 1996a), significant error margins must normally be introduced into elevation estimates of the sill, affecting the resolution of reconstruction possible from the basin. Examples of this include margins of ± 0.5 m used by Shennan *et al.* (1994), and ± 1.0 m by Woodall (1999).

Site Name	Number in Figure 8.1	Sill Elevation (m OD)	Pollen	Diatoms	Foraminifera / Thecamoebian	Dinoflagellate Cysts	References	Importance to Earth Heritage
Loch Cill an Aonghais	1	19.61 ± 1 m	✓		✓		Woodall (1999)	d
Ardtoe	2	20.6 m	✓	✓	✓		Shennan <i>et al.</i> (1996a, 2000a)	d
Rumach Iochdar	3	9.3 m	✓	✓			Shennan <i>et al.</i> (1993, 1995, 2000a)	d, e
Rumach Meadhonach	4	17.8 m	✓	✓			Shennan <i>et al.</i> (1993, 1995, 2000a)	d, e
Rumach IV	5	16.3 m		✓		✓	Shennan <i>et al.</i> (1996b)	d, e
Rumach V	6	16.3 m *		✓		✓	Shennan <i>et al.</i> (1996b)	d, e
Rumach VI	7	4.8 m	✓	✓	✓		Shennan <i>et al.</i> (1999), Douthwaite (1999)	a, b, c, e
Loch nan Eala (upper)	8	6.3 m	✓	✓			Shennan <i>et al.</i> (1994, 1995, 2000a)	b, c, e
Loch nan Eala (main)	9	5.2 ± 0.5 m	✓	✓			Shennan <i>et al.</i> (1994, 1995, 2000a)	b, c, e
Loch Dubh	10	20.4 m		✓		✓	Shennan <i>et al.</i> (2000a)	d, e
Upper Loch Dubh	11	36.5 m		✓			Shennan <i>et al.</i> (2000a)	d, e
Lochan nan Tri Chriochan	12	33.4 m		✓			Shennan <i>et al.</i> (2000a)	d, e
Loch Torr A' Bheithe	13	33.2 m		✓			Shennan <i>et al.</i> (2000a)	d, e
Loch A' Mhuilinn	14	15.5 m		✓			Shennan <i>et al.</i> (2000a)	d, e
Loch nan Corr	15	2.7 m			✓		Lloyd (2000)	a, b, c
Fearnbeg	16	5.7 m	✓	✓		✓	Shennan <i>et al.</i> (1996b)	d
Dubh Lochan	17	3.7 m	✓	✓	✓		Shennan <i>et al.</i> (2000a)	b, c

Table 8.1: Fossil isolation basins investigated in western Scotland. The type of evidence collected is indicated, together with the elevation of the sill (m OD) and a reference to the original research publication or report. * The sill for Rumach V lies at 13.8 m, but water must first enter through Rumach IV, with its sill at 16.3 m. There are also further sills within Rumach V, at approximately 16.3 m elevation. In the 'Importance to Earth Heritage' column, a = high-resolution record; b = Early Holocene rise; c = Late Holocene fall; d = Lateglacial RSL changes and / or local marine limit; e = part of the Arisaig staircase of basins.

Obviously, it is not practical to recommend every site for conservation, or inclusion in the Geological Conservation Review. Sites may be recommended on the basis of two criteria (cf. Ellis *et al.*, 1996):

- i. Representativeness of the fossil record contained in the basin.
- ii. Uniqueness of the record contained within the basin.

In sum, the sites selected should form part of a network of sites representing the key features of RSL changes in Scotland.

8.3.3.1 Representativeness

The records within each fossil basin all provide similar information in terms of the isolation history of that basin and, hence, the local sea-level history. However, the elevation of the sill determines the age and duration of that record, whilst the depth of the basin and the sedimentation rates within it, in combination with the age of the deposits, determine the resolution of the record contained within the basin. For example, the Ardtoe basin, with its sill at 20.6 m OD, was isolated rapidly by $12,540 \pm 90$ ^{14}C yr BP, with a relatively compact (low resolution) sedimentary record covering the rapid transition from marine to freshwater conditions. Conversely, Loch nan Corr, with its sill at 2.7 m OD, provides a high-resolution record. The transitional sequence there covers almost 5 m of sediment, from the end of the fully marine stage at 6085 ± 75 ^{14}C yr BP, to the beginning of the freshwater stage at 710 ± 60 ^{14}C yr BP (Lloyd, 2000).

There is, therefore, a problem in identifying precisely what a representative or typical isolation basin record is. In this case, the most valuable way to approach a requirement for representativeness of fossil isolation basin environments would seem to be to recommend those basins with long isolation records stretching back to the Younger Dryas or beyond, such as Loch nan Corr and Rumach VI. This would also serve to protect those basins with the high-resolution transitional sequences which are so valuable in the interpretation of former changes in RSL and environment.

8.3.3.2 Uniqueness

Each isolation basin record covers a unique period of time, and has its own microfossil (biostratigraphical) and sedimentary (lithostratigraphical) record. However, some basins record unique events, such as the Younger Dryas, and the mid-Holocene highstand. Work is also currently in progress to attempt to locate unique content in the form of tephra shards, which can be used for accurate dating of the horizon in which they were found (Mackie, in prep.). Other basins provide valuable information owing to the elevation of their sill. For example, high basins, which isolated early, provide information to constrain the altitude of the marine limit and the timing of deglaciation, whilst also giving indications of early environmental change. Some basins also contain multiple incursions of marine water, detected in the litho- and biostratigraphy, which is vital in constraining the interaction of eustasy and isostasy.

There is clearly a need to protect some of these basins containing information on unique events. Basins such as Upper Loch Dubh, Lochan nan Tri Chriochan, Loch Torr A'Bheithe, and Ardtoe provide records covering early RSL changes following deglaciation, whilst these and others (e.g. Loch nan Corr, Rumach IV and V, Rumach VI, and Loch Cill an Aonghais) cover the Younger Dryas. Information on multiple incursions are covered by basins with sills at lower elevations, such as Loch nan Eala upper basin and Rumach Iochdar, between which the mid-Holocene highstand is constrained (Shennan *et al.*, 1993, 1994, 1995).

Certain areas are particularly outstanding for their assemblages of sites. For example, the Arisaig area provides an impressive staircase of isolation basins, running from a modern isolation basin in the form of Rumach Tidal Pond (Zong, 1997) through the high-resolution record of Rumach VI and other Rumach and Loch nan Eala basin sequences, to Upper Loch Dubh, which provides one of the earliest records available from an isolation basin in Scotland. Whilst the tidal pond is not a good example of a modern isolation basin, as it is very shallow, from an interpretation perspective it illustrates well the processes involved in regular tidal inundation across a solid rock sill, with a variety of substrates from a shelly lag behind the sill to finer, more organic sediments towards its southern edges.

8.3.3.3 Recommendations

Sections 8.3.3.1 and 8.3.3.2 outline cases for the inclusion of particular isolation basins in the GCR from two perspectives: the uniqueness of the record contained within some basins, and the representativeness of the record contained within others. The extensive, high-resolution transitional sequences of Loch nan Corr and Rumach VI provide long, detailed records representative of RSL changes during the Lateglacial and Holocene in areas intermediate between the centre and periphery of isostatic uplift. Basins within the Arisaig staircase, particularly those in the Rumach and Loch nan Eala sequences and Upper Loch Dubh provide information on unique events, such as constraining the altitude of the local marine limit and the mid-Holocene transgression, whilst also covering changes during the Younger Dryas. These Arisaig basins in particular, together with Rumach Tidal Pond and Loch nan Corr, are recommended for inclusion in updates to the Geological Conservation Review, and for some form of protection, on the grounds of their value in the interpretation of past changes in RSL. Specifically, it is important that the sills of such basins are protected from modification, or a permanent, in-depth record made of their elevation, profile, and cross-sectional area before any changes are made.

The value of some individual sites may warrant consideration for statutory protection. All of the sites named in this section, however, should be considered for conservation through at least the voluntary sector RIGS initiative, as there is a value to all of these sites, particularly the Arisaig staircase, for interpretative and awareness purposes, both at the academic and public level.

For the purposes of public education, Earth heritage has become more accessible at the local level through the direction and presentation of the styles of interpretation boards developed for some sites of Earth heritage interest, the publication of *A Landscape Fashioned by Geology* booklets (e.g. McKirdy and Crofts, 1999), and through RIGS geological trail leaflets, such as that produced by Batchelor and Browne (1999). It is through the use of these types of resources, for the Arisaig suite of sites in particular, that the Earth heritage value of modern and fossil isolation basins can be most effectively communicated to the public.

8.4 SUMMARY

- There is a large overlap and interaction between the physical and biological environment within isolation basins, giving rise to a complex system. This dynamic environment is overlain by a series of natural changes which occur through inputs from the catchment and the atmosphere. These changes are further complicated by human activity, which largely serves to accelerate the speed at which natural changes take place.
- The remit of the MNCR survey of saline lagoons focused on the biotopes present within them, neglecting the detailed monitoring required to understand the processes in operation. However, the dynamic aspect of isolation basins, their relationship with the local environment (including human impact), and the variability of the environment in space and time all must be understood and taken into account in the conservation management of these sites; approaching the management of a saline lagoon in isolation from its processes, inputs and local catchment environment offers very little hope for its successful conservation.
- The inventory of fossil isolation basins in Table 8.1 and Figure 8.1 provides information on the types of microfossil records available from each site, together with the elevation of the sill and the scientific value.
- Conservation management is recommended for some modern and fossil isolation basins, on the grounds of protecting sites of unique or representative value as key reference sites for Late Devensian and Holocene RSL, and public education based around this.
- The successful conservation management of modern and fossil isolation basins, regardless of the type of designation, must be founded on better public education and awareness.

Conclusions

9.1 INTRODUCTION

This chapter concludes the thesis by summarising the main findings, and assessing the extent to which the aims and objectives of the research outlined in Chapter One have been met. The chapter concludes with recommendations for future research.

9.2 SUMMARY OF THE THESIS

This thesis represents the first attempt to examine, in detail, the foraminiferal ecology of modern isolation basins, and to then use this information to try to reconstruct the environment in fossil isolation basins using statistical methods (Chapter Two). A comprehensive methodology was developed for the sampling of twenty modern isolation basins (Chapters Three and Four). The data in the modern training set covered fifteen of these sites. The remaining five sites had very low abundances of foraminifera, so could not be used in the statistical analyses following the data screening carried out according to Table 3.1. It was intended to produce a transfer function using this data, based upon the Standardised Water Level Index (SWLI) of the basin sills, but Canonical Correspondence Analysis (CCA) showed SWLI to be an insignificant factor in controlling foraminiferal distribution. Instead, a transfer function was developed based upon average salinity, using the total foraminiferal assemblages (Chapters Five and Six). The foraminiferal data from three fossil isolation basins sites was used in the calibration of this transfer function.

There were clear problems in the statistical analyses, however, in relating the faunal assemblages from modern isolation basins to those from fossil sites. Two major reasons have been suggested for this (Chapter Seven):

First, some of the main indicator species are not common between the modern and fossil data-sets. The best example of this is the high numbers of *Jadammina macrescens* and *Haynesina germanica* present in the fossil sequences, characteristic of the transitional sequence. Whilst the modern basins sampled during this research are analogues of points in that transitional stage, occurrences of *Jadammina macrescens* and *Haynesina germanica* are rare in the modern training set. The species have been replaced by *Miliammina fusca* and, in the more saline basins, *Eggerelloides scabrus*. The most likely reason for this is the resilience of these latter two species, owing to their infaunal microhabitat which allows them to partially remove themselves from the extreme variability of the transitional stage within such shallow basins. Although *Jadammina macrescens* and *Haynesina germanica* are indicative of the transitional sequences in fossil basins, reconstructions of water depth for fossil sites (Figure 7.2) show them to have been deeper than many of the modern basins sampled. Consequently, the fossil sites are likely to have had less variability in their environments, allowing *Jadammina macrescens* and *Haynesina germanica* to survive.

Second, the bias in sampling basins with sills above MLWNT has led to the lack of a modern analogue for the fully marine stage in fossil isolation sequences. This is characterised by the shallow modern basins which were sampled and the low foraminiferal species diversity. The problem was precipitated by the absence of deep, fully marine modern isolation basins in Scotland, with their sill(s) at or below MLWST. What this problem does show, however, is that the estimate of the indicative meaning for the fully marine stage of Loch nan Corr, placed at MTL -1.5 m (ca. MLWNT) by Shennan *et al.* (2000a) and Lloyd (2000), is likely to be too high. Loch nan Corr had a greater water depth (approximately 11 m; Figure 7.2) at this point than any basin in the modern training set (Figure 7.1), with a greater degree of inertia in the system as a result. However, as those modern basins with sills around MLWNT display more of a transitional than fully marine foraminiferal assemblage, it can be assumed, even with the effects of the inertia of the water body, that the indicative meaning of the fully marine stage of Loch nan Corr is likely to be below MLWNT, especially given the slow isolation process which occurred in the basin.

The findings from the statistical analyses for modern isolation basins were more successful than those for the palaeoenvironmental reconstruction of fossil sites, with the possibility to calculate species optima and tolerance values for different environmental variables. This allows the development of an accurate understanding of foraminiferal ecology in modern isolation basins (Chapter Seven). These findings can be compared with existing literature on the ecology of shallow water foraminifera (e.g. Murray, 1979; Alve and Murray, 2001), and the assessments of foraminiferal ecology made from high-resolution records from fossil isolation basins (e.g. Lloyd, 2000).

Finally, recommendations were made for the conservation of modern and fossil isolation basins (Chapter Eight). A small number of modern isolation basins are already afforded a high level of protection through their inclusion in SSSIs or marine candidate Special Areas of Conservation (cSAC) on biological grounds. A case is put forward for more integrated management, however, particularly for some of the smaller basins, in a similar approach to that taken for freshwater lakes. In contrast, fossil sites currently have no protection. As existing literature shows (e.g. Shennan *et al.*, 1995, 1996; Woodall, 1999), the removal or modification of basin sills has clear implications for the accuracy of RSL reconstructions using these sites, given the significant error margins which must be introduced. A number of isolation basins, including the impressive staircase of sites in the Arisaig area, are named and recommended for inclusion in the planned updates to the Geological Conservation Review, and possible protection through statutory or voluntary conservation designations, on the grounds of their value to Earth heritage as interpretation sites for Late Devensian and Holocene changes in RSL.

9.3 THESIS AND METHODOLOGICAL EVALUATION

The following research aims were identified in Chapter One:

- i. Identify and quantify the importance of the variables that control patterns of isolation basin sedimentation, including the presence and distribution of their biota, in order that the precision of sea-level and environmental reconstructions may be improved.

- ii. Evaluate the applicability of presently used methods of statistical environmental reconstruction methods to isolation basin environments, and assess the importance of sill elevation in determining the indicative meaning of a basin.
- iii. Identify those isolation basins sites with the best regional, national and international records of RSL changes, and develop recommendations for their conservation management.

This section evaluates the extent to which these research aims have been realised.

9.3.1 Aim i.

The foraminifera in transects through twenty basins were identified, and the results provided in Chapter Five and Appendices Two and Three. Alongside this, a series of environmental variables to be measured during the field surveys were outlined in Chapter Three, with the results of their relationship with each other and the foraminifera provided in Chapter Five and Appendix Three. Combined, they allowed the development of the modern training set for the statistical analyses. From this, basin volume and freshwater input were identified to have the greatest influence on the foraminifera within the basins, based on the CCA statistical technique. However, as there was problems in checking the accuracy of these parameters and missing data, and they are of little value in reconstructions for fossil sites, the next variable identified by the statistical technique (average salinity), was used to develop a transfer function.

As the environmental variable of choice, in combination with the foraminifera present in the modern isolation basins, failed to accurately quantify the relationship between foraminifera and their environment, the thesis fails to meet this part of the research aim. The quantification of the indicative meaning of isolation basin samples called for by Shennan *et al.* (1995, 1999, 2000a), which takes account of the impact of a given freshwater input, over-simplifies the processes operating within an isolation basin environment. The sensitivity or inertia within the system (most

probably the volume of water held in the basin) must be considered, and the relationship between this and the marine and freshwater inputs quantified.

Chapter Seven makes recommendations to improve the sampling strategy, particularly in locating deeper basins as analogues for the fully marine stage and examining accurately the volume of inputs in relation to the volume of water held within the basin. Through this development, it is anticipated that the precision of the relationship between the isolation basin environment and foraminifera will be improved. This will give greater potential for improving the resolution of RSL and environmental reconstructions from fossil basins.

9.3.2 Aim ii.

From the WA-PLS method used to develop the transfer function from the modern training set, and the assessment of its applicability in Section 7.3.2, there is no reason to doubt the effectiveness of this method in reconstructing the environment in isolation basins. The fact that the reconstruction did not work in this particular case would appear to be more than adequately explained through the complicated isolation basin environment, and the need to identify and accurately measure a variable which controls the environment, in the way that Horton (1997) and Edwards (1998) found SWLI to dominate and control (or act as a proxy for) other environmental factors in saltmarsh environments. The ratio between the marine input and water volume within the basin is suggested as such a measure, and should be investigated in future research.

From this, it can be concluded that sill elevation alone can not be identified as an important factor in controlling the isolation basin environment; the SWLI of the basins sills was scarcely picked up on the CCA biplots in Figure 6.2, suggesting minimal influence on the foraminifera.

The other method of reconstruction used, MAT, also worked successfully, although the sensitivity of the method to the presence of very small abundances of species not present in the modern training set is surprising. This stresses the need for a more diverse modern training set, despite the high number of samples in the current data-

set. It may also suggest that the use of the 20th percentile in the method for the acceptance or rejection of a modern analogue is a little too severe, as assemblages within the fossil data-set which appeared to have a reasonable match by eye were not accepted as good modern analogues by the Modern Analogue Technique. Obviously, there is a danger of going to the other extreme in relaxing the standard, but the issue is certainly one which should be experimented with in future research.

9.3.3 Aim iii.

Chapter Eight outlines the conservation issues and recommendations for both modern and fossil isolation basins. However, as fossil basins are currently unprotected, whilst some examples of modern basins are protected to the highest levels of statutory designation, and involved in public consultation and awareness programmes (e.g. those surrounding Loch Maddy), the focus on recommendations was for fossil basins.

An inventory of fossil basins is supplied in Chapter Eight, and named sites are identified for their representativeness and / or uniqueness, on the grounds of their value in the interpretation of Late Devensian and Holocene RSL and environmental change. The primary aim of this exercise is to identify type-sites for inclusion in the update of the Geological Conservation Review, although it is clear that some sites should also be conserved through statutory designations to protect the high-resolution of the record which is currently available. There is also a case for the recognition of the Arisaig staircase of isolation basins as a suite of basins which can be used for interpretation and to increase academic and public awareness of the value of these sites, possibly through use of the RIGS system.

9.4 SUMMARY OF MAIN FINDINGS

The main findings of the research presented in this thesis are:

- Isolation basin environments are more complex than many other coastal environments, such as saltmarsh, for which transfer functions have previously been successfully developed. Much of this complexity is introduced by the relatively closed, but variable nature of the system.

Because of this variability and complexity, it is not possible to produce a general transfer function for all isolation basins which is based upon the elevation of the sill with reference to the tidal cycle, onto which freshwater is then superimposed.

- If a general transfer function for the reconstruction of past RSL change from fossil isolation basins is to be developed, the inter-relationships between environmental components must be understood. In order to achieve this the wetted cross-sectional area of the sill should be quantified (as a proxy for marine input) in relation to the volume of water held within the basin. A similar measure must also be made of freshwater input into basins if its potential impact is to be understood.
- The indicative meaning of the fully marine stage in the Loch nan Corr isolation sequence, suggested to be MTL -1.5 m by Shennan *et al.* (2000a) and Lloyd (2000), appears to have been over-estimated. The lowest sills in the modern training set lie close to MLWNT, but the foraminifera contained within these two basins do not reflect fully marine conditions. Loch nan Corr will have had more inertia in its system, owing to deeper water within the basin, but as the isolation process itself was slow, with high sedimentation rates during this time, it is argued that the indicative meaning should still be lowered.
- Although the calibration of a foraminiferal transfer function based upon average salinity was not successful, the Weighted Averaging (WA) method used in developing the transfer function gives valuable quantitative information on the foraminiferal ecology of modern isolation basins, with reference to their tolerance and optima of individual environmental variables.
- The main findings on foraminiferal ecology within modern isolation basins relate to those foraminifera indicative of the transitional or variable salinity stage, although some nearshore shelf species were also present in the modern training set.
- The main problem for the modern data-set providing a good analogue for fossil transitional sequences is the rarity of *Jadammina macrescens* in modern isolation basins, despite the fact that it dominates the fossil transitional stage, such as in Loch nan Corr (Figure 6.10; Lloyd, 2000). It is

most commonly replaced by *Miliammina fusca* in the modern basins. The proposed explanation for this is the infaunal habitat preferred by *Miliammina fusca*, which removes it from some of the environmental variability in the system. *Miliammina fusca* also prefers relatively shallow water depths (Murray, 1991; Murray and Alve, 1999), which makes it well suited to the majority of basins sampled during this research. These characteristics, together with its broad tolerance of salinity (11 - 28 in the statistical analysis, but down to 0.01 in the modern data-set) and sediment conditions (35 – 85 % sand), allow this euryhaline species to out-compete other typical transitional species which prefer deeper or more stable water conditions.

- *Eggerelloides scabrus* is another dominant species in the modern training set, representing more saline conditions. Inverse WA identifies the species' optimum average salinity value at 29.6, with its tolerance values (± 3.1) showing it to take over from *Miliammina fusca* as the dominant species as *Miliammina fusca* approaches the upper limits of its own salinity tolerance. This is particularly apparent in the Hebridean sites, where calcareous species are rare, and *Eggerelloides scabrus* is left to typify the more saline basins. The species is assisted in this by the fine (53.8 ± 17 % sand) organic sediments in these basins, and its infaunal habitat which removes it from the extremes of basin variability.
- *Cibicides lobatulus* is shown to have similar average salinity optima and tolerance values (25.5 ± 5.2) to brackish species, such as *Elphidium williamsoni* (25.5 ± 6.8) and *Haynesina germanica* (26.8 ± 7.5). As *Cibicides lobatulus* is a nearshore shelf species, many of the tests were not stained by the rose Bengal, and it was most frequently found on shelly lags behind basin sills, it is concluded that the species was often washed into basins, leading to the lowering of its true average salinity preferences.
- In order to develop the understanding of foraminiferal ecology in modern isolation basins, and to increase the effectiveness of quantitative palaeoenvironmental reconstructions for fossil sites, deeper, more saline basins, with their sill at or below MLWST, must be sampled. This will give ecological data on the more diverse, fully marine foraminiferal assemblages which are absent in this research, and provide an effective analogue for the

fully marine stage in fossil isolation sequences. Only with this development, and those outlined in Chapter Seven and below, can a greater quantitative understanding of the isolation basin environment be reached, and a significant increase in the resolution of RSL reconstructions using isolation basins be achieved.

9.5 RECOMMENDATIONS FOR FUTURE RESEARCH

In this thesis, the diversity of the environment within isolation basins is demonstrated, primarily representing the transitional phase of a fossil sequence, where foraminiferal diversity is low. Although most components of the research aims and objectives are met in the thesis, there is a requirement to conduct further work before accurate environment reconstructions can be made from the foraminiferal assemblages contained within fossil isolation basins.

Further work should revolve around modifications to the sampling strategy employed in this thesis. These changes should be threefold.

First, Gehrels *et al.* (2001) identify diatoms as the most reliable microfossil indicator in saltmarsh environments. Whilst a potential problem with diatoms being washed into basins is outlined in Section 3.4, a pilot-study covering a small number of basins at different points in the isolation cycle would be worthwhile as a comparative and / or combined study. This should follow the improved sampling strategy outlined below for foraminifera.

Second, there is a need to expand the diversity of foraminifera within the modern training set. In particular, this should focus upon the sampling of deeper basins, under fully marine conditions (those in stages 1, 2 and the earlier part of stage 3, Figure 2.1), in order to obtain more nearshore shelf foraminiferal assemblages and provide a good modern analogue for the fully marine stage of fossil basins. There are some potential contemporary sites off sea lochs on the west coast of Scotland, although there may also be a need to look abroad, most probably in Scandinavia or Greenland.

Finally, an environmental variable must be identified which, to a large extent, controls the other environmental variables within isolation basins. The marine input – basin water volume ratio, as outlined in Section 7.2.2 and Figure 7.4, is recommended as the likely control, and warrants further investigation. It is hoped that this ratio, in combination with one for freshwater input – basin water volume, will be shown to act as reliable proxies for isolation basin environmental conditions as a whole.

References

Admiralty Tide Tables. 2000. *United Kingdom and Ireland (including European Channel Ports)*, 1. Hydrographer of the Navy, Somerset: 440pp.

Akers, W.H. 1971. Estuarine foraminiferal associations in the Beaufort area, North Carolina. *Tulane studies in Geology and Paleontology*, 8: pp.147-215.

Aller, R.C. and Cochrane, J.K. 1976. ^{234}Th : ^{238}U disequilibrium in nearshore sediment: particle reworking and diagenic time scales. *Earth Planet. Sci. Lett.*, 20: pp.37-50.

Alve, E. and Bernhard, J.M. 1995. Vertical migratory response of benthic foraminifera to controlled oxygen concentrations in an experimental mesocosm. *Marine Ecology Progress Series*, 116: pp.137-307.

Alve, E and Murray, J.W. 2001. Temporal variability in vertical distributions of live (stained) intertidal foraminifera, southern England. *Journal of Foraminiferal Research*, 31: pp.12-24.

Armit, I. 1996. *The archaeology of Skye and the Western Isles*. Edinburgh University Press, Edinburgh: 264pp.

Austin, R.M. 1991. Modelling Holocene tides on the northwest European continental shelf. *Terra Nova*, 3: pp.276-288.

Ball, D.F. 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Journal of Soil Science*, 15: pp.84-92.

- Ballantyne, C.K., McCarroll, D., Nesje, A., Dahl, S.O. and Stone, J.O.** 1998. The last ice sheet in north-west Scotland: reconstructions and implications. *Quaternary Science Reviews*, **17**: pp.1149-1184.
- Bamber, R.N., Batten, S.D., Shearer, M. and Bridgwater, N.D.** 1992. On the ecology of brackish water lagoons in Great Britain. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **2**: pp.65-94.
- Barlow, R.J.** 1998. *Statistics: a guide to the use of statistical methods in the physical sciences*. The Manchester Physics Series. John Wiley & Sons Ltd, Chichester: 204pp.
- Barnes, R.S.K.** 1980. *Coastal lagoons: the natural history of a neglected habitat*. Cambridge University Press, Cambridge.
- Batchelor, R.A. and Browne, M.A.E.** 1999. *St Andrews geological trail*. Fife RIGS Group, St Andrews.
- Battarbee, R.W.** 1990. The causes of lake acidification with special reference to the role of acid deposition. *Philosophical Transactions of the Royal Society of London B*, **327**: pp.339-347.
- Bennike, O.** 1995. Palaeoecology of two lake basins from Disko, West Greenland. *Journal of Quaternary Science*, **10**: pp.149-155.
- Bernhard, J.M.** 1988. Postmortem vital staining in benthic foraminifera: Duration and importance in population and distributional studies. *Journal of Foraminiferal Research*, **18**: pp.143-146.
- Bernhard, J.M.** 2000. Distinguishing live from dead foraminifera: methods review and proper applications. *Micropaleontology*, **46**: pp.38-46.

- Birks, H.J.B.** 1986. Numerical zonations, comparison and correlation of Quaternary pollen-stratigraphical data. *In*: Berglund, B.E. (Ed.). *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley & Sons Ltd, London: pp.743-773.
- Birks, H.J.B.** 1992. Some reflections on the application of numerical methods in Quaternary palaeoecology. *Publication Karelian Institute, University of Joensuu*, **102**: pp.7-20.
- Birks, H.J.B.** 1994. The importance of pollen and diatom taxonomic precision in quantitative palaeoenvironmental reconstruction. *Review of Palaeobotany and Palynology*, **83**: pp.107-117.
- Birks, H.J.B.** 1995. Quantitative palaeoenvironmental reconstructions. *In* Maddy, D. and Brew, D.S. (Eds.). *Statistical modelling of Quaternary Science data*. Technical Guide 5. Quaternary Research Association, Cambridge: pp.161-236.
- Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C. and ter Braak, C.J.F.** 1990. Diatom and pH reconstruction. *Philosophical Transactions of the Royal Society of London*, **327**: pp.263-278.
- Bjorck, S., Bennike, O., Possnert, G., Wohlfarth, B. and Digerfeldt, G.** 1998. A high-resolution ¹⁴C dated sediment sequence from southwest Sweden: age comparisons between different components of the sediment. *Journal of Quaternary Science*, **13**: pp.85-89.
- Boltovskoy, E. and Wright, R.** 1976. *Recent foraminifera*. Dr W. Junk b.v., The Hague, the Netherlands: 515pp.
- Boltovskoy, E., Scott, D.B. and Medioli, F.S.** 1991. Morphological variations of benthic foraminiferal tests in response to changes in ecological parameters: a review. *Journal of Paleontology*, **65**: pp.175-185.

- Bondevik, S., Svendsen, J.I., Johnsen, G., Mangerud, J. and Kaland, P.E.** 1997a. The Storegga tsunami along the Norwegian coast, its age and runup. *Boreas*, **26**: pp.29-53.
- Bondevik, S., Svendsen, J.I. and Mangerud, J.** 1997b. Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway. *Sedimentology*, **44**: pp.1115-1131.
- Bondevik, S., Svendsen, J.I., and Mangerud, J.** 1998. Distinction between the Storegga tsunami and the Holocene marine transgression in coastal basin deposits of western Norway. *Journal of Quaternary Science*, **13**: pp.529-537.
- 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, R.W. (Ed.). *British Quaternary studies: recent advances*. Clarendon Press, Oxford: pp.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**: pp.447-474.
- ter Braak, C.J.F.** 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate gradient analysis. *Ecology*, **67**: pp.1167-1179.
- ter Braak, C.J.F.** 1987a. The analysis of vegetation-environment relationships by canonical correspondence analysis, *Vegetatio*, **69**: pp.69-77
- ter Braak, C.J.F.** 1987b. Ordination. *In*: Jongman, R.H.G., ter Braak, C.J.F. and van Tongeren, O.F.R. (Eds.). *Data analysis in community and landscape ecology*. AC Wageningen: pp.91-173.

ter Braak, C.J.F. 1988. *CANOCO – a FORTRAN program for canonical community ordination by [partial] [detrended] [canonical] correspondence analysis, principle component analysis and redundancy analysis (Version 2.1). Technical Report LWA-88-02.* TNO Institute of Applied Computer Science Statistics Department, AC Wageningen: 95pp.

ter Braak, C.J.F. 1990. *Update notes: CANOCO Version 3.10.* Agricultural Mathematics Group, AC Wageningen: 35pp.

ter Braak, C.J.F. 1991. *CANOCO Version 3.12.* Agricultural Mathematics Group, AC Wageningen.

ter Braak, C.J.F. and Prentice, I.C. 1988. A theory of gradient analysis. *Advances in Ecological Research*, **18**: pp.271-317.

ter Braak, C.J.F. and van Dam, H. 1989. Inferring pH from diatoms: comparison of old and new calibration methods. *Hydrobiologia*, **178**: pp.209-223.

ter Braak, C.J.F. and Juggins, S. 1993. Weighted averaging partial least squares regression (WA-PLS): an improved method for reconstructing environmental variables from species assemblages. *Hydrobiologia*, **269/270**: pp.485-502.

Bradshaw, J.S. 1957. Laboratory studies on the rate of growth of the foraminifer “*Strebulus beccarii* (Linne) var. *tepida* (Cushman).” *Journal of Paleontology*, **31**: pp.1138-1147.

Bradshaw, J.S. 1961. Laboratory experiments on the ecology of foraminifera. *Contributions of the Cushman Foundation for Foraminiferal Research*, **12**: pp.87-106.

Bradshaw, J.S. 1968. Environmental parameters and marsh foraminifera. *Limnology and Oceanography*, **13**: pp.26-38.

Brady, H.B. 1884. Report on the foraminifera dredged by HMS Challenger during the years 1873-1876. Reports of the scientific results of the voyage of HMS Challenger during the years 1873-1876. *Reports of the scientific results of the voyage of the HMS Challenger*, **9** (zoology): 814pp.

Brown, E., Colling, A., Park, D., Phillips, J., Rothery, D. and Wright, J. 1997. *Seawater: its composition, properties and behaviour*. 2nd Edition. Butterman-Heinemann, Oxford: 168pp.

Buzas, M.A. 1969. Foraminiferal species densities and environmental variables in an estuary. *Limnology and Oceanography*, **14**: pp.411-422.

Carvalho, L. and Anderson, N.J. 2001. Lakes. *In* Warren, A. and French, J.R. (Eds.). *Habitat conservation: managing the physical environment*. John Wiley and Sons Ltd., Chichester: pp.123-146.

Chambers, R. 1848. *Ancient sea margins: as memorials of change in the relative relief of sea and land*. W.S. Orr and co., London: 337pp.

Chorley, R.J. 1978. Bases for theory in geomorphology. *In* Embleton, C., Brunsden, D. and Jones, D.K.C. (eds.), *Geomorphology: present problems and future prospects*. Oxford University Press, Oxford.

Connor, D.W., Brazier, D.P., Hill, T.O. and Northen, K.O. 1997a. Marine Nature Conservation Review: marine biotope classification for Britain and Ireland. Volume 1. Littoral biotopes. Version 97.06. *JNCC Report*, **229**.

Connor, D.W., Dalkin, M.J., Hill, T.O., Holt, R.H.F. and Sanderson, W.G. 1997b. Marine Nature Conservation Review: marine biotope classification for Britain and Ireland. Volume 2. Sublittoral biotopes. Version 97.06. *JNCC Report*, **230**.

Corner, G.D. and Haugane, E. 1993. Marine-lacustrine stratigraphy of raised coastal basins and postglacial sea-level change at Lyngen and Vanna, Troms, northern Norway. *Norsk Geologisk Tidsskrift*, **73**: pp.175-197.

Corner, G.D., Yevzerov, V.Y., Kolka, V.V. and Møller, J.J. 1999. Isolation basin stratigraphy and Holocene relative sea-level change at the Norwegian-Russian border north of Nikel, northwest Russia. *Boreas*, **28**: pp.146-166.

Council of the European Communities. 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Communities, Series L*, **206**: pp.7-50.

Covey, R. 1999. The saline lagoon survey of Scotland. *In* Baxter, J.M., Duncan, K., Atkins, S., and Lees, G. (Eds.). *Scotland's living coastline*. The Stationery Office, London: pp.150-165.

Covey, R., Fortune, F., Nichols, D.M. and Thorpe, K. 1998. *Marine Nature Conservation Review Sectors 3, 4, 12, 13 and 15. Lagoons in mainland Scotland and the Inner Hebrides: area summaries*. Joint Nature Conservation Committee, Peterborough. (Coasts and seas of the United Kingdom. MNCR Series). 139pp.

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

Davies, P. and Haslett, S.K. 2000. Identifying storm or tsunami events in coastal basin sediments. *Area*, **32**: pp.335-336.

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**: pp.548-553.

Dipper, F.A., Lumb, C.M. and Palmer, M.A. 1987. A littoral, sublittoral and limnological survey of Loch Obisary, North Uist. 21 to 29 June 1985. (Contractor F.A. Dipper, Huntingdon.) *Nature Conservancy Council, CSD Report, 275.*

Douthwaite, T. 1999. *Relative sea-level changes during the Late Devensian and Holocene at Rumach VI, NW Scotland: A foraminiferal study.* Unpublished M.Sc. Dissertation, University of Durham.

Earp, J.R., Francis, E.H. and Read, W.A. 1962. Discussion on J.B. Sissons' paper on Lateglacial shorelines in Transactions of the Edinburgh Geological Society, 19(1). *Transactions of the Edinburgh Geographical Society, 19(2):* pp.216-220.

Edwards, R.J. 1998. *Late Holocene relative sea-level change and climate in southern Britain.* Unpublished Ph.D. thesis, University of Durham. 2 Volumes.

Ellis, N.V., Bowen, D.Q., Campbell, S., Knill, J.L., McKirdy, A.P., Prosser, C.D., Vincent, M.A. and Wilson, R.C.L. 1996. *An introduction to the Geological Conservation Review* Joint Nature Conservation Committee, Peterborough.

Eronen, M., Glückert, G., Hatakka, L., van de Plassche, O., van der Plicht, J. and Rantala, P. 2001. Rates of Holocene isostatic uplift and relative sea-level lowering of the Baltic in SW Finland based on studies of isolation contacts. *Boreas, 30:* pp.17-30.

European Commission. 1996. *Interpretation manual of European Union habitats. Annex 1 of Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora.* European Commission (Directorate-General XI), Brussels.

Fægri, K. 1940. Quartärgeologische Untersuchungen im westlichen Norwegen. II. Zur spätquartären Geschichte Jærens. Bergens Mus. Årb. 1939-1940. *Naturvitensk, 7:* 201pp.

Fettes, D.J., Mendum, J.R., Smith, D.I. and Watson, J.V. 1992. *Geology of the Outer Hebrides.* Memoirs of the Geological Survey, sheets (solid edition), Lewis and Harris, Uist and Barra (Scotland). HMSO, London.

- Feyerabend, P.** 1975. *Against Method*. Verso, London.
- Firth, C.R., Smith, D.E. and Cullingford, R.A.** 1993. Late Quaternary glacio-isostatic uplift patterns for Scotland. *In* Owen, L.A., Stewart, I., and Vita-Finzi, C. (Eds.). *Neotectonics: Recent advances*. Quaternary Proceedings, vol 3. Quaternary Research Association, Cambridge: pp.1-14.
- Fisher, R.A. and Yates. F.** 1963. *Statistical tables for biological, agricultural and medical research*. Oliver and Boyd.
- Foged, N.** 1972. The diatoms in four postglacial deposits in Greenland. *Meddelelser om Grønland*, **194**(4): pp.1-66.
- Foged, N.** 1973. Diatoms from Southwest Greenland. *Meddelelser om Grønland*, **194**(5): pp.1-84.
- Foged, N.** 1977. The diatoms in four postglacial deposits at Godthåbsfjord, West Greenland. *Meddelelser om Grønland*, **199**(4): pp.1-64.
- van Fraassen, B.** 1987. Arguments concerning scientific realism. *In* Kourany, J.A. (Ed.) *Scientific Knowledge: Basic Issues in the Philosophy of Science*. Wadsworth, California: pp.343-358.
- Gasse, F., Juggins, S. and Khelifa, L.B.** 1995. Diatom-based transfer functions for inferring past hydrochemical characteristics of African lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **117**: pp.31-54.
- Gehrels, W.R., Roe, H.M. and Charman, D.J.** 2001. Foraminifera, testate amoebae and diatoms as sea-level indicators in UK saltmarshes: a quantitative multiproxy approach. *Journal of Quaternary Science*, **16**: pp.201-220.
- Geikie, A.** 1902. *The geology of eastern Fife: being a description of sheet 41 and parts of sheets 40, 48 and 49 of the geological map*. Memoirs of the Geological Survey of Scotland. H.M.S.O., Glasgow: 421pp.

Gerlach, S.A. 1978. Food chain relationships in subtidal silty sand marine sediments and the role of meiofauna in stimulating bacterial productivity. *Oecologia*, **33**: pp.55-69.

Gilbertson, D., Kent, M. and Grattan, J. 1996. The Sheffield Environment and Archaeology Research Campaign in the Outer Hebrides. *In* Gilbertson, D., Kent, M. and Grattan, J. (Eds.). *The Outer Hebrides: The last 14, 000 years*. Sheffield Environmental and Archaeological Research Campaign in the Hebrides, Volume 2. Sheffield Academic Press, Sheffield: pp. 1-4.

Godwin, H. 1940. Studies in the post-glacial history of British vegetation. III: Fenland pollen diagrams. IV: Post-glacial changes of relative land and sea level in the English Fenland. *Philosophical Transactions of the Royal Society of London B*, **230**: pp.239-303.

Goldstein, S.T. and Harben, E.B. 1993. Taphofacies implications of infaunal foraminiferal assemblages in a Georgia salt marsh, Sapelo Island. *Micropaleontology*, **39**: pp.53-62.

Gordon, J.E. and Sutherland, D.G. (Eds.). 1993. *Quaternary of Scotland*. Geological Conservation Review Series, **6**. Chapman and Hall, London: 695pp.

Gordon, J.E., Thompson, D.B.A., Haynes, V.M., Brazier, V. and MacDonald, R. 1998. Environmental sensitivity in the Cairngorm Mountains, Scotland. *Ambio*, **27**: pp.335-344.

Gordon, J.E. and Leys, K.F. 2001a. Earth science and the natural heritage: pressures and sustainable management. *In* Gordon, J.E. and Leys, K.F. (Eds.). *Earth science and the natural heritage: interactions and integrated management*. The Stationery Office, Edinburgh: pp.126-129.

Gordon, J.E. and Leys, K.F. 2001b. Earth science and the natural heritage: developing a more holistic approach. *In* Gordon, J.E. and Leys, K.F. (Eds.). *Earth science and the natural heritage: interactions and integrated management*. The Stationery Office, Edinburgh: pp.5-18.

Gray, J.M. 1983. The measurement of relict 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. Institute of British Geographers Special Publication, 16*. Academic Press, London: pp.97-127.

Green, M.A., Aller, R.C. and Aller, J.Y. 1993. Carbonate dissolution and temporal abundances of foraminifera in Long Island Sound sediments. *Limnology and Oceanography, 38*: pp.331-345.

Grimm, E. 1991-1993. *Tilia*. Illinois State Museum, Springfield, USA.

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, vol. 16. Academic Press, London: pp.161-181.

Hafsten, U. and Tallantire, P.A. 1978. Palaeoecology and post-Weichselian shore-level changes on the coast of Møre, western Norway. *Boreas, 7*: pp.109-122.

Haines-Young, R. and Petch, J. 1980. The challenge of critical rationalism in methodology for physical geography. *Progress in Physical Geography 4*: pp.63-77.

Haines-Young, R. and Petch, J. 1986. *Physical geography: its nature and methods*. Harper and Row, London: pp. 24-73.

Hall, A. 1996. Quaternary geomorphology of the Outer Hebrides. *In* Gilbertson, D., Kent, M. and Grattan, J. (Eds.). *The Outer Hebrides: The last 14, 000 years*. Sheffield Environmental and Archaeological Research Campaign in the Hebrides, Volume 2. Sheffield Academic Press, Sheffield: pp. 5-12.

- Hansom, J.D. and Angus, S.** 2001. Tir a'Mhachair (Land of the Machair): sediment supply and climate change scenarios for the future of the Outer Hebrides machair. *In* Gordon, J.E. and Leys, K.F. (Eds.). *Earth science and the natural heritage: interactions and integrated management*. The Stationery Office, Edinburgh: pp.68-81.
- Hay, A.** 1987. Scientific method in geography. *In* Johnston, R.J. (ed.). *The future of geography*. Methuen, London: pp.129-142.
- Hendey, N.I.** 1964. *An introductory account of the smaller algae of British coastal waters, Bacillariophyceae (Diatoms)*. Fishery Investigation Series, N. London. HMSO: 19pp.
- Hill, M.O. and Gauch, H.G.** 1980. Detrended correspondence analysis: an improved ordination technique. *Vegetatio*, **42**: pp.47-58.
- Hiscock, K.** (Ed.). 1996. *Marine Nature Conservation Review: rationale and methods*. Joint Nature Conservation Committee, Peterborough (Coasts and seas of the United Kingdom. MNCR series).
- Hiscock, K.** 1998. Preface. *In* Covey, R., Fortune, F., Nichols, D.M. and Thorpe, K. (Eds.). *Marine Nature Conservation Review Sectors 3, 4, 12, 13, 15. Lagoons in mainland Scotland and the Inner Hebrides: area summaries* (MNCR Series). Joint Nature Conservation Committee, Peterborough: p.5.
- Hiscock, K. and O'Connor, D.** 1996. Scope and structure of the Marine Nature Conservation Review. *In* Hiscock, K. (Ed.). 1996. *Marine Nature Conservation Review: rationale and methods*. Joint Nature Conservation Committee, Peterborough (Coasts and seas of the United Kingdom. MNCR series): pp.45-50.
- Horne, J.** 1907. Introductory. *In* Geikie, A. (Ed.). *The geological structure of the north-west Highlands of Scotland*. Memoirs of the geological survey of Great Britain. HMSO, London: pp.1-10.

- Horton, B.P.** 1997. *Quantification of the indicative meaning of a range of Holocene sea-level index points from the western North Sea*. Unpublished Ph.D. thesis, University of Durham. 2 volumes.
- Horton, B.P.** 1999. The distribution of contemporary intertidal foraminifera at Cowpen Marsh, Tees Estuary, UK: implications for studies of Holocene sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **149**: pp.127-149
- Horton, B.P., Edwards, R.J. and Lloyd, J.M.** 1999a. A foraminiferal-based transfer function: implications for sea-level studies. *Journal of Foraminiferal Research*, **29**: pp. 117-129.
- Horton, B.P., Innes, J.B. and Shennan, I.** 1999b. Late Devensian and Holocene relative sea-level changes in Northumberland, England. *In* Bridgland, D.R., Horton, B.P., and Innes, J.B. (Eds.). *The Quaternary of north-east England*. Field Guide, Quaternary Research Association, London: pp.35-47.
- Imbrie, J. and Webb, T.** 1981. Transfer functions: calibrating micropalaeontological data in climatic terms. *In* Berger, A. (Eds.). *Climate variations and variability: facts and theories*. D. Reidel, Dordrecht: pp.125-134.
- Jamieson, T.F.** 1865. On the history of the last geological changes in Scotland. *Quarterly Journal of the Geological Society of London*, **21**: pp.161-203.
- Jardine, W.G.** 1986. Determination of altitude. *In* van de Plassche, O. (Ed.). *Sea-level research: a manual for the collection and evaluation of data*. Geobooks, Norwich: pp.569-590.
- Jelgersma, S.** 1961. Holocene sea-level changes in the Holocene. *Meded. Geol. Sticht., C VI*: pp.1-100.
- Jennings, A.E., Nelson, A.R., Scott, D.B. and Aravena, J.C.** 1995. Marsh foraminiferal assemblages in the Valdivia Estuary, South-central Chile, relative to vascular plants and sea-level. *Journal of Coastal Research*, **11**: pp.107-123.

Johnstone, G.S. and Mykura, W. 1989. *British Regional Geology: The Northern Highlands of Scotland* (4th Edition). HMSO, London: 219pp.

Joint Nature Conservation Committee. 1996. *Guidelines for the selection of biological SSSIs: intertidal marine habitats and saline lagoons*. Joint Nature Conservation Committee, Peterborough.

Jonasson, K.E. and Patterson, R.T. 1992. Preservation potential of salt marsh foraminifera from the Fraser River delta, British Columbia. *Micropaleontology*, **38**: pp.289-301.

Jones, V.J. and Juggins, S. 1995. The construction of a diatom-based chlorophyll transfer function and its application at three lakes on Signy Island (maritime Antarctic) subject to differing degrees of nutrient enrichment. *Freshwater Biology*, **34**: pp.433-445.

Juggins, S. 1997. *Modern Analog Technique (Release 1.1)*. Department of Geography, University of Newcastle.

Juggins, S. and ter Braak, C.J.F. 1992. *CALIBRATE – program for species-environment calibration by [weighted-averaging] partial least squares regression*. Environmental Change Research Centre, University College London: 20pp.

Juggins, S. and ter Braak, C.J.F. 1997. *CALIBRATE*. Department of Geography, University of Newcastle.

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**: pp.243-258.

Kiden, P. 1995. Holocene relative sea-level changes and crustal movement in the southwestern Netherlands. *Marine Geology*, **124**: pp.21-41.

- Kitazato, H.** 1994. Foraminiferal microhabitats in four marine environments around Japan. *Marine micropaleontology*, **24**: pp.29-41.
- Kjemperud, A.** 1981a. A shoreline displacement investigation from Frosta in Trondheimsfjorden, Nord-Trøndelag, Norway. *Norsk Geologisk Tidsskrift*, **61**: pp.1-15.
- Kjemperud, A.** 1981b. Diatom changes in sediments from basins possessing marine/lacustrine transitions in Frosta, Nord-Trøndelag, Norway. *Boreas*, **10**: pp.27-38.
- Kjemperud, A.** 1986. Late Weichselian and Holocene shoreline displacement in the Trondheimsfjord area, central Norway. *Boreas*, **15**: pp.61-82.
- Kovach, W.L.** 1995. Multivariate data analysis. *In* Maddy, D. and Brew, J.S. (Eds.). *Statistical modelling of Quaternary science data*. Technical Guide 5. Quaternary Research Association, Cambridge: pp.1-38.
- Kreiser, A.M., Appleby, P.G., Natkanski, J., Rippey, B. and Battarbee, R.W.** 1990. Afforestation and lake acidification: a comparison of four sites in Scotland. *Philosophical Transactions of the Royal Society of London B*, **327**: pp.377-383.
- Kuhn, T.S.** 1962. *The Structure of Scientific Revolutions*. University of Chicago Press, Chicago.
- Laidler, P.D.** 2001. Hydrology, palaeohydrology and conservation of isolation basins in north-west Scotland. *In* Gordon, J.E. and Leys, K.F. (Eds.). *Earth science and the natural heritage: interactions and integrated management*. The Stationery Office, Edinburgh: pp.165-168.
- Lambeck, K.** 1991. Glacial rebound and sea-level change in the British Isles. *Terra Nova*, **3**(4): pp.379-389.

- Lambeck, K.** 1993a. Glacial rebound of the British Isles - I. Preliminary model results. *Geophysical Journal International*, **115**: pp.941-959.
- Lambeck, K.** 1993b. Glacial rebound of the British Isles - II. A high-resolution, high-precision model. *Geophysical Journal International*, **115**: pp.960-990.
- Lambeck, K.** 1995. Late-Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society of London*, **152**: pp.437-448.
- Leys, K.F.** 2001 The sustainable use of freshwater resources: a case study from the River Spey. *In* Gordon, J.E. and Leys, K.F. (Eds.). *Earth science and the natural heritage: interactions and integrated management*. The Stationery Office, Edinburgh: pp.169-179.
- Lipps, J.H. and Valentine, J.W.** 1970. The role of foraminifera in the trophic structure of marine communities. *Lethaia*, **3**: pp.279-286.
- Lloyd, J.M.** 2000. Combined foraminiferal and thecamoebian environmental reconstruction from an isolation basin in NW Scotland: implications for sea-level studies. *Journal of Foraminiferal Research*, **30**: pp.294-305.
- Long, A.J., Roberts, D.H. and Wright, M.R.** 1999. Isolation basin stratigraphy and Holocene relative sea-level change on Arveprinsen Ejland, Disko Bugt, West Greenland. *Journal of Quaternary Science*, **14**: pp.323-345.
- Lowe, J.J. and Walker, M.J.C.** 1997. *Reconstructing Quaternary Environments* (2nd edition). Longman.
- Mackie, E.A.V.** in prep. High resolution palaeoenvironmental reconstructions from northwest Scotland since the Lateglacial (working title). Ph.D. thesis, University of Durham.

- Maitland, P.S. and Morgan, N.C.** 1997. *Conservation management of freshwater habitats: lakes, rivers and wetlands*. Chapman and Hall, London: 233pp.
- Marshall, J.U.** 1987. Geography as a scientific enterprise. *In* Johnston, R.J. (ed.). *The future of geography*. Methuen, London: pp. 113-128.
- Martens, H. and Naes, T.** 1989. *Multivariate calibration*. John Wiley & Sons Ltd, London: 419pp.
- McCave, N.** 1988. Biological pumping upwards of the coarse fraction of deep-sea sediments. *Journal of Sedimentary Petrology*, **58**: pp.148-158.
- McKirdy, A. and Crofts, R.** 1999. *Scotland: The Creation of its Natural Landscape*. Scottish Natural Heritage, Battleby (A Landscape Fashioned by Geology Series): 64pp.
- Medioli, F.S. and Scott, D.B.** 1988. Lacustrine thecamoebians (mainly arcellaceans) as potential tools for palaeolimnological interpretations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **62**: 361-386.
- Millero, F.J.** 2001. *Physical chemistry of natural waters*. Wiley-Interscience, New York: 654pp.
- Mills, J.L.** 1993. Data torturing. *New England Journal of Medicine*, **329**: pp.1196-1199.
- Mitchell, R., Dipper, F.A., Earll, R. and Rowe, S.** 1980. A preliminary study of Loch Obisary: a brackish Hebridean loch. *Progress in Underwater Science*, **5**: pp.99-118.
- Mohler, C.L.** 1983. Effects of sampling pattern on estimation of species distribution along gradients. *Vegetatio*, **54**: pp.97-102.

- Murray, J.W.** 1968. The living foraminiferida of Christchurch Harbour, England. *Micropaleontology*, **14**: pp.83-96.
- Murray, J.W.** 1971. *An atlas of British recent foraminiferids*. Heinemann Educational Books, London: 244pp.
- Murray, J.W.** 1973. *Distribution and ecology of living foraminiferids*. Heinemann Educational Books, London: 274pp.
- Murray, J.W.** 1979. *British nearshore foraminiferids: keys and notes for the identification of the species*. Academic Press, London: 68pp.
- Murray, J.W.** 1991. *Ecology and palaeoecology of benthic foraminifera*. Longman, Essex: 397pp.
- Murray, J.W.** 2000. JFR Comment: The enigma of the continued use of total assemblages in ecological studies of benthic foraminifera. *Journal of Foraminiferal Research*, **30**: pp.244-245.
- Murray, J.W.** in press. When does environmental variability become environmental change? The proxy record of benthic foraminifera. *In* Martin, R. (Ed.). *Environmental Micropalaeontology*. Plenum Press.
- Murray J.W. and Alve, E.** 1999. Taphonomic experiments on marginal marine foraminiferal assemblages: how much ecological information is preserved? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **149**: pp.183-197.
- Murray, J.W. and Alve, E.** 2000. Major aspects of foraminiferal variability (standing crop and biomass) on a monthly scale in an intertidal zone. *Journal of Foraminiferal Research*, **30**: pp.177-191.
- Murray, J.W. and Bowser, S.S.** 2000. Mortality, protoplasm decay rate, and reliability of staining techniques to recognize 'living' foraminifera. *Journal of Foraminiferal Research*, **30**: pp.66-70.

- O'Dell, A.C. and Walton, K.** 1962. *The Highlands and Islands of Scotland*. Regions of the British Isles Series. Thomas Nelson and Sons Ltd., Edinburgh: 353pp.
- Overpeck, J.T., Webb, T. and Prentice, I.C.** 1985. Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogues. *Quaternary Research*, **23**: pp.87-108.
- Palmer, A.J.M. and Abbott, W.H.** 1986. Diatoms as indicators of sea-level change. *In* van de Plassche, O. (Ed.). *Sea-level research: a manual for the collection and evaluation of data*. Geobooks, Norwich: pp.457-488.
- Parker, F.L. and Athearn, W.D.** 1959. Ecology of marsh foraminifera in Poponessett Bay, Massachusetts. *Journal of Paleontology*, **33**: pp.333-343.
- Patrick, S.T., Timberlid, J.A. and Stevenson, A.C.** 1990. The significance of land-use and land-management change in the acidification of lakes in Scotland and Norway: an assessment utilising documentary sources and pollen analysis. *Philosophical Transactions of the Royal Society of London B*, **327**: pp.363-367.
- Patterson, R.T.** 1990. Intertidal benthic foraminiferal biofacies on the Fraser River Delta, British Columbia: modern distribution and palaeoecological importance. *Micropaleontology*, **36**: pp.229-244.
- Patterson, R.T. and Fishbein, E.** 1989. Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. *Journal of Paleontology*, **63**: pp.245-248.
- Patterson, R.T., Guilbault, J.P., and Thomson, R.E.** 2000. Oxygen level control on foraminiferal distribution in Effingham Inlet, Vancouver Island, British Columbia, Canada. *Journal of Foraminiferal Research*, **30**: pp.321-335.
- Phleger, F.B.** 1970. Foraminiferal populations and marine marsh processes. *Limnology and Oceanography*, **15**: pp.522-534.

- van de Plassche, O.** 1979. Sea-level research in the provinces of south Holland, Netherlands. *Proceedings of the "1978 international symposium of coastal evolution in the Quaternary"*, Sao Paulo, Brazil: pp.534-551.
- van de Plassche, O.** 1986. Introduction. *In* Plassche, O. van de. (Ed.). *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Geo Books, Norwich.
- van de Plassche, O.** 1991. Late Holocene sea-level fluctuation on the shore of Connecticut inferred from transgressive and regressive overlap boundaries in salt-marsh deposits. *Journal of Coastal Research*, **11**: pp.159-179.
- Popper, K.R.** 1959. *The logic of scientific discovery*, Hutchinson, London: 480pp.
- Prentice, I.C.** 1980. Multidimensional scaling as a research tool in Quaternary palynology: a review of theory and methods. *Review of Palaeobotany and Palynology*, **31**: pp.71-104.
- Prentice, I.C.** 1986. Multivariate methods for data analysis. *In* Berglund, B.E. (Ed.). *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley and Sons Ltd, London: pp. 775-797.
- Putnam, H.** 1975. *Mathematics, Matter and Method*. Cambridge University Press, Cambridge: vol. 1.
- Rasch, M. and Nielsen, N.** 1995. Coastal morpho-stratigraphy and Holocene relative sea-level changes at Tuapaat, southeastern Disko Island, central West Greenland. *Polar Research*, **14**: pp.277-289.
- Retelle, M.J., Bradley, R.S. and Stuckenrath, R.** 1989. Relative sea-level chronology determined from raised marine sediments and coastal isolation basins, northern Ellesmere Island, Arctic Canada. *Arctic and Alpine Research*, **21**: pp113-125.

- Richards, K. Brooks, S., Clifford, N., Harris, T. and Lane, S.** 1997. Theory, measurement and testing in 'real' geomorphology and physical geography. *In*, Stoddart, D.R. (Ed.) *Process and Form in Geomorphology*. Routledge, London: pp.265-292.
- de Rijk, S.** 1995. *Agglutinated foraminifera as indicators of saltmarsh development in relation to late Holocene sea-level rise (Great Marshes at Barnstable, Massachusetts)*. PhD Thesis, Free University, Amsterdam. 188pp.
- de Rijk, S. and Troelstra, S.R.** 1997. Salt marsh foraminifera from the Great Marshes, Massachusetts: environmental controls. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **130**: pp.81-112.
- de Rijk, S. and Troelstra, S.R.** 1999. The application of a foraminiferal actuo-facies model to salt-marsh cores. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **149**: pp.59-66.
- Ritchie, W.** 1996. Foreward. *In* Gilbertson, D., Kent, M. and Grattan, J. (Eds.). *The Outer Hebrides: The last 14, 000 years*. Sheffield Environmental and Archaeological Research Campaign in the Hebrides, Volume 2. Sheffield Academic Press, Sheffield: p. xi.
- Roep, Th. B.** 1986. Sea-level markers in coastal barrier sands: examples from North Sea coast. *In* Plassche, O. van de. (Ed.). *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Geo Books, Norwich: pp.97-128.
- Roep, Th.B. and Beets, D.J.** 1988. Sea-level rise and palaeotidal levels from sedimentary structures in coastal barriers in the western Netherlands since 5600 BP. *Geologie en Mijnbouw*, **67**: pp.53-60.
- Scott, D.B. and Medioli, F.S.** 1978. Vertical zonations of marsh foraminifera as accurate indicators of former sea-levels. *Nature*, **272**: pp.528-531.

- Scott, D.B. and Medioli, F.S.** 1980a. Living vs. total foraminifera populations: their relative usefulness in palaeoecology. *Journal of Palaeontology*, **54**: pp.814-831.
- Scott, D.B. and Medioli, F.S.** 1980b. Quantitative studies of marsh foraminifera distribution in Nova Scotia: implications for sea-level studies. *Journal of Foraminiferal Research, Special Publication*, **17**: pp.1-58.
- Scott, D.B. and Medioli, F.S.** 1986. Foraminifera as sea-level indicators. *In* van de Plassche, O. (Ed.). *Sea-level research: a manual for the collection and evaluation of data*. Geobooks, Norwich: pp.435-456.
- Scott, D.B. and Greenberg, D.A.** 1993. Relative sea-level rise and tidal development in the Fundy tidal system. *Canadian Journal of Earth Sciences*, **20**: pp.1554-1564.
- Scott, S.** 1997. *Sea Lochs*. Scotland's Living Landscape Series. Scottish Natural Heritage, Battleby: 24pp.
- Scottish Natural Heritage.** 1995. *Natura 2000: a guide to the 1992 EC Habitats Directive in Scotland's marine environment*. SNH Publications, Battleby: 19pp.
- Seppä, H., Tikkanen, M. and Shemeikka, P.** 2000. Late-Holocene shore displacement of the Finnish south coast: diatom, litho- and chemostratigraphic evidence from three isolation basins. *Boreas*, **29**: pp.219-231.
- Severin, K.P.** 1987. Laboratory observations on the rate of movement of a small miliolid foraminifer. *Journal of Foraminiferal Research*, **17**: pp.110-116.
- Shennan, I.** 1980. *Flandrian sea-level changes in the Fenland*. Unpublished Ph.D. thesis, University of Durham.
- Shennan, I.** 1982. Interpretation of Flandrian sea-level data from the Fenland, England. *Proceedings of the Geologists' Association*, **93**: pp.53-63.

- Shennan, I.** 1986. Flandrian sea-level changes in the Fenland. II: Tendencies of sea-level movement, altitudinal changes, and local and regional factors. *Journal of Quaternary Science*, **1**: pp.155-179.
- Shennan, I.** 1989. Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science*, **4**: pp.77-89.
- Shennan, I.** 1992. Late Quaternary sea-level changes and crustal movements in eastern England and eastern Scotland: an assessment of models of coastal evolution. *Quaternary International*, **15/16**: pp.161-173.
- Shennan, I., Tooley, M.J., Davis, M.J., and Haggart, B.A.** 1983. Analysis and interpretation of Holocene sea-level data. *Nature*, **302**: pp.404-406.
- 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**: pp.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**: pp.261-283.
- Shennan, I., Innes, J.B., Long, A.J. and Zong, Y.** 1995. Late Devensian and Holocene relative sea-level changes in northwestern Scotland: new data to test existing models. *Quaternary International*, **26**: pp.97-123.
- Shennan, I., Green, F., Innes, J.B., Lloyd, J.M., Rutherford, M.M. and Walker, K.J.** 1996a. Evaluation of rapid relative sea-level changes in northwest Scotland during the last glacial-interglacial transition: evidence from Ardtoe and other isolation basins. *Journal of Coastal Research*, **12(4)**: pp.862-874.

Shennan, I., Rutherford, M.M., Innes, J.B. and Walker, K.J. 1996b. Lateglacial sea-level 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, **111**: pp.229-244.

Shennan, I., Long, A.J., Rutherford, M.M., Green, F.M., Innes, J.B., Lloyd, J.M., Zong, Y., and Walker, K.J. 1996c. Tidal marsh stratigraphy, sea-level change and large earthquakes: a 5000 year record in Washington, USA. *Quaternary Science Reviews*, **15**: pp.1023-1059.

Shennan, I., Tooley, M.J., Green, F., Innes, J.B., Kennington, K, Lloyd, J.M. and Rutherford, M.M. 1999. Sea level, climate change and coastal evolution in Morar, northwest Scotland. *Geologie en Mijnbouw*, **77**: pp.247-262.

Shennan, I., Lambeck, K., Horton, B.P., Innes, J.B., Lloyd, J.M., McArthur, J., Purcell, T. and Rutherford, M.M. 2000a. Late Devensian and Holocene records of relative sea-level changes in northwest Scotland and their implications for glacio-hydro-isostatic modelling. *Quaternary Science Reviews*, **19**: pp.1103-1135.

Shennan, I., Lambeck, K., Horton, B.P., Innes, J.B., Lloyd, J.M., McArthur, J. and Rutherford, M.M. 2000b. Holocene isostasy and relative sea-level changes on the east coast of England. *In* Shennan, I. and Andrews, J. (Eds.). *Holocene land-ocean interaction and environmental change around the North Sea*. Geological Society, London, Special Publications, **166**: pp.275-298.

Shennan, I., Lambeck, K., Flather, R., Horton, B.P., McArthur, J., Innes, J.B., Lloyd, J.M., Rutherford, M.M. and Wingfield, R. 2000c. Modelling western North Sea palaeogeographies and tidal changes during the Holocene. *In* Shennan, I. and Andrews, J. (Eds.). *Holocene land-ocean interaction and environmental change around the North Sea*. Geological Society, London, Special Publications, **166**: pp.299-319.

- Sissons, J.B.** 1962a. A re-interpretation of the literature on Lateglacial shorelines in Scotland, with particular reference to the Forth area. *Transactions of the Edinburgh Geological Society*, **19**(1): pp.83-99.
- Sissons, J.B.** 1962b. Reply to J.R. Earp, E.H. Francis and W.A. Read in T.E.G.S. 19(2). *Transactions of the Edinburgh Geological Society*, **19**(2): pp.221-224.
- Sissons, J.B.** 1963. Scottish raised shoreline heights with particular reference to the Forth Valley. *Geografiska Annaler*, **45**: pp.180-185.
- Sissons, J.B.** 1966. Relative sea-level changes between 10,300 and 8,300 BP in part of the Carse of Stirling. *Transactions of the Institute of British Geographers*, **39**: pp.19-29.
- 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**: pp.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**: pp.145-159.
- Sissons, J.B.** 1983. Shorelines and isostasy in Scotland. *In* Smith D.E. and Dawson, A.G. (Eds.). *Shorelines and Isostasy. Institute of British Geographers Special Publication*, **16**. Academic Press, London: pp.209-225.
- Skempton, A.W.** 1970. The consolidation of clays by gravitational compaction. *Quarterly Journal of the Geological Society of London*, **125**: pp.373-412.
- Smith, D.E., Sissons, J.B. and Cullingford, R.A.** 1969. Isobases for the Main-Perth Shoreline in south-east Scotland as determined by trend-surface analysis. *Transactions of the Institute of British Geographers*, **46**(1): pp.45-52.

- Snyder, J.A., Forman, S.L., Mode, W.N. and Tarasov, G.A.** 1997. Postglacial relative sea-level history: sediment and diatom records of emerged coastal lakes, north-central Kola Peninsula, Russia. *Boreas*, 26: pp.329-346.
- Soulsby, C. and Boon, P.** 2001. Freshwater environments: an Earth science perspective on the natural heritage of Scotland's rivers. *In* Gordon, J.E. and Leys, K.F. (Eds.). *Earth science and the natural heritage: interactions and integrated management*. The Stationery Office, Edinburgh: pp.82-104.
- Stabell, B.** 1985. The development and succession of taxa within the diatom genus *Fragilaria* Lyngbye as a response to isolation from the sea. *Boreas*, 14: pp.273-286.
- Stephenson, D. and Gould, D.** 1995. *British Regional Geology: The Grampian Highlands* (4th Edition). HMSO, London.
- Stone, J., Lambeck, K., Fifield, L.K., Evans, J.M. and Cresswell, R.G.** 1996. A Lateglacial age for the Main Rock Platform, western Scotland. *Geology*, 24: pp.707-710.
- van Straaten, L.M.J.U.** 1954. Radiocarbon dates and changes of sea-level at Velzen (Netherlands). *Geologie en Mijnbouw*, 16: pp.247-253.
- Svendsen, J.I. and Mangerud, J.** 1987. Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *Journal of Quaternary Science*, 2: pp.113-132.
- Thomson, R. and Wain-Hobson, T.** 1979. Palaeomagnetic and stratigraphic study of the Loch Shiel marine regression and overlying gyttja. *Journal of the Geological Society of London*, 136: pp.383-388.
- Thorpe, K., Dalkin, M.J., Fortune, F., & Nichols, D.M.** 1998. *Marine Nature Conservation Review Sector 14. Lagoons in the Outer Hebrides: area summaries*. Joint Nature Conservation Committee, Peterborough. (Coasts and seas of the United Kingdom. MNCR Series). 289pp.

- Tooley, M.J.** 1978. *Sea-level changes: northwest England during the Flandrian Stage*. Clarendon Press, Oxford.
- Tooley, M.J.** 1981. Methods of reconstruction. *In* Simmons, I.G. and Tooley, M.J. (eds.) *The environment in British prehistory*. Duckworth, London: pp.1-48.
- Tooley, M.J.** 1982. Interpretation of Holocene sea-level changes. *Geografiska Foreningens i Stockholm Forhandlingar*, **100**: pp.203-212.
- Troels-Smith, J.** 1955. Characterisation of unconsolidated sediments. *Danmarks Geologiske Undersøgelse IV* **3**: pp.1-73.
- Valiela, I. and Teal, J.M.** 1979. Inputs, outputs and interconversions of nitrogen in a saltmarsh ecosystem. *In* Jeffries, R.L. and Davy, A.J. (Eds.). *Ecological processes in coastal environments*. Blackwell, Oxford: pp.399-419.
- Walton, W.R.** 1952. Techniques for the recognition of living foraminifera. *Contributions of the Cushman Foundation for Foraminiferal Research*, **3**: pp.56-60.
- Weidick, A.** 1993. Neoglacial change of ice cover and the related response of the Earth's crust in West Greenland. *Rapport Grønland Geologiske Undersøgelse*, **159**: pp.121-126.
- Weidick, A.** 1996. Neoglacial changes of ice cover and sea-level in Greenland - a classical enigma. *In* Grønnow, B. (Ed.). *The palaeo-Eskimo cultures of Greenland: new perspectives in Greenlandic archaeology*. Danish Polar Centre, Copenhagen: pp.257-270.
- Woodall, R.** 1999. *Isolation basin stratigraphy and late Devensian relative sea-level change at Loch Cill' an Aonghais, Knapdale, western Scotland*. Unpublished MSc thesis, University of Durham.
- Wright, W.B.** 1914. *The Quaternary Ice Age*. Macmillan, London: 464pp.

Zong, Y. 1993. *Flandrian sea-level changes and impacts of projected sea-level rise on the coastal lowlands of Morecambe Bay and the Thames Estuary, UK.* Unpublished Ph.D. Thesis, University of Durham.

Zong, Y. 1997. Implications of *Paralia sulcata* abundance in Scottish isolation basins. *Diatom Research*, **12**: pp.125-150.

