

A Reconstruction of the Eastern Margin of
the late Weichselian Ice Sheet in
Northern Britain

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DECLARATION

This thesis has been composed solely by myself. The work presented is my own unless otherwise acknowledged.

Fiona S. Stewart

ABSTRACT

The eastern margin of the last ice sheet to cover northern Britain has been subject to much speculation since it was recognised, in 1840, that this area has been subject to glacial modification. Several reconstructions of the margin have been proposed which range from restricted ice cover of the mainland, with ice-free areas, to complete ice cover by ice sheets coalescing over the central North Sea.

This study aims to reconstruct the eastern margin of the north British ice sheet by examining data collected onshore and offshore along the east coast of mainland Scotland. Looking at the offshore evidence has given an insight into the onshore areas to explain unknown and confusing glacial evidence. This highlights the importance of combining the two sources of evidence.

The reconstruction is based on data collected at a regional scale, augmented by detailed sites both onshore and offshore. The empirical evidence is used to test simple theoretical ice sheet reconstructions of palaeo ice-flow.

The offshore dataset consists of 1KJ analogue, sparker seismic records collected by the British Geological Survey (BGS) continental mapping programme. These are spaced at approximately 10km intervals. Site specific 1KJ sparker seismics provide detailed ice margin information.

A seismostratigraphy has been constructed. Sedimentological control is provided by borehole and vibrocore data, collected by the BGS, and tied into the seismic grid.

The onshore dataset consists of regional geomorphological maps compiled from aerial photographs and topographical maps. They are augmented by site specific data which provides detailed information about localised ice behaviour.

Two possible ice sheet reconstructions have been compiled. Amino acid racemisation ratios from key sites constrain the reconstructions. The preferred reconstruction consists of an ice margin which terminates in a marine environment, at a maximum of

50km from the present-day coastline. The margin consists of three forms which relate to the basal thermal regime of the ice sheet.

The Moray Firth embayment was a critical area of the ice sheet. The extent of ice cover and type of ice margin in this area significantly affected the distribution of erosional features. It is suggested that the ice margin

location cycled between a minimum, inshore grounded ice margin at the present 40m bathymetry depth, with a maximum, floating calving margin position constrained by the Southern Trench, and pinned to the 40m bathymetry depth offshore north-east Caithness. The ice covering north-east Caithness and Buchan was warm-based in the initial stages of ice expansion, but became cold-based and protected the landscape, as a result of diverging ice-flow. The ice extended further to the east during the maximum reconstruction and created another erosion pattern preserved within the Moray Firth Basin.

Dating evidence would suggest that the maximum reconstruction pre-dates the more restricted reconstruction. However, given the problems of reworking of dateable material within glacigenic environments both reconstructions are presented as a maximum and minimum option.

It is suggested that the controlling factor on the behaviour of both reconstructions is the relationship between glacio-isostatic loading, crustal downwarping, eustatic sea level, and the buoyancy of the ice sheet margin terminating in a glaciomarine environment.

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A RECONSTRUCTION OF THE EASTERN MARGIN OF THE LATE WEICHSELIAN, NORTH BRITISH ICE SHEET

CHAPTER 1

INTRODUCTION

1.1 AIM

The overall aim of this thesis is to present a reconstruction of the eastern margin of the late Weichselian north British ice sheet. More specifically the aims are:

- 1). locate the margin of the ice sheet and determine the areal extent of ice cover,
- 2). establish the processes affecting the margin and base, and the affects that these will have on ice behaviour,
- 3). provide chronological control for the margin position at the maximum.

1.2 BACKGROUND

Many reconstructions of the extent and behaviour of the former ice sheet over Scotland have been proposed since Agassiz recognised that the landscape had been affected by glaciations in 1840 (Agassiz 1840). The first reconstructions, e.g. Geikie (1863a), Jamieson (1865), were based on empirical evidence of glacial erosion, transportation and deposition of sediment. The centre of ice accumulation was established as Rannoch Moor and the main drainage routes identified as the Midland Valley, the Great Glen, and Strathmore. Although no eastern margin was proposed it was recognised that the ice extended to the present day coastline. Further work (Bremner 1932, Charlesworth 1926, Simpson 1933,

Sissons 1963, 1965, 1976 and 1981) was specific, with the main aim being the acquisition of data to resolve localised glacial behaviour. Reinterpretation of earlier work did not significantly affect the reconstruction of overall ice sheet extent proposed by the early workers, although the extent of the ice offshore remained open to supposition. However, reinterpretation of the evidence created further problems by recognising that some areas exhibited evidence of possible multiple glaciations through time, or had been affected by different directions of ice movement within the same glaciation.

The problems of chronological and stratigraphical correlation, and the dynamism of ice sheets became of prime importance. For example, the ice coverage of Scotland was re-examined using evidence from the Cairngorm plateau (Linton 1959, Sissons 1973) as well as the coverage of 'moraineless' Buchan, and Caithness, based on the intensity of the glacial ^{and periglacial} modification of the landscape (Synge 1956, Charlesworth 1956, Hall 1984, and Fitzpatrick 1972).

The availability of offshore data from the early 1970s, collected during the hydrocarbon exploration of the North Sea basin and the BGS Regional Mapping Project of the continental shelf, resulted in the development of an offshore Quaternary stratigraphy, incorporating the sediments thought to be associated with the late Weichselian glaciation (Thomson and Eden 1977, Holmes 1977). As geophysical techniques have improved the initial work has been extended to involve more detailed examination of forms and processes, with chronology becoming increasingly more important. Various dating techniques were applied to the recovered sediments, e.g in 1981 Quaternary stratigraphy control sites were proposed and drilled. The more complete parts of the record preserved in the offshore area have proved to be a valuable source of data for reconstructing palaeoenvironments. A number of reconstructions of ice extent now exist, based on offshore evidence alone (Stoker *et al.* 1985, Sejrup *et al.* 1987, Cameron *et al.* 1987).

With the advent of mathematical modelling of ice sheets, a series of theoretical regional reconstructions of the ice sheet have been developed. These are based on the laws of ice flow, mass balance reconstructions, and thermal regimes, which affect the behaviour of ice sheets. Variables such as bed type, and margin environment (subaerial or subaquatic) have also been incorporated into models (Boulton *et al.* 1977, Boulton *et al.* 1985, Denton and Hughes 1981).

Attempts have been made to compare field evidence with models of ice cover, for example, the work carried out on the Trotternish Escarpment of Skye (Ballantyne 1990). This has shown that the field evidence and theoretical models of ice coverage do not agree. This was also found by Price (1983) and Sutherland (1984) in their reviews of the late Weichselian glaciation of Scotland.

None of the reconstructions of the late Weichselian north British ice sheet has specifically linked the land and sea records. This study aims to achieve this, and to produce a reconstruction of the ice margin, and the processes affecting it, which satisfies the onshore and offshore evidence. By considering the onshore and offshore evidence any reconstruction of the late Weichselian ice sheet will be potentially more rigorously constrained, and should, for example, add a new perspective on problem coastal areas such as Caithness and Buchan.

It is valid to combine the onshore and offshore evidence because the present day offshore environment contains deposits laid down in a non-marine environment, and therefore are comparable. However, both advantages and disadvantages are present in this approach. The advantages relate to the increased data set, especially the more complete record of sedimentation offshore. The seismics allow a three dimensional study of the deposit which is not often possible onshore. At the same time, the onshore environment allows more detailed work at particular sites with which to constrain the overall picture. The disadvantages of working with information from two environments relate to the contrasts in the two datasets. Seismic interpretation is constrained by the limitations of the acquisition systems,

particularly with regard to detail, whilst borehole information is constrained by the sampling techniques, and the applicability of the derived information outwith the immediate sampling area. Limitations onshore also relate to access to, and level of preservation of, suitable sediment sections in both two and three dimensions. Where boreholes are used the limitations encountered are similar, although the sampling method of the recovered material is different. In an onshore borehole, for example, not all the material is extracted as a continuous core. These problems place limitations on the inferences made from the combined data set. However, as long as they are recognised, their effects can be borne in mind and they should not denigrate the quality of the research produced.

Reconstructions of the late Weichselian Ice Sheet Maximum Position

Existing reconstructions fall into two groups; those which advocate complete ice sheet coverage of the eastern coastal strip of Scotland and the North Sea basin, (Fig 1.1 part a), and those which suggest a more restricted and incomplete coverage (Fig. 1.1 part b).

There are five recent reconstructions which indicate total coverage, Flinn (1967), Boulton *et al.* (1977), Andersen (1981), Denton and Hughes (1981) and Price (1983). These are derived from theoretical mathematical models of ice sheet behaviour with the exception of Price (1983). They present the late Weichselian North British ice sheet as either an extension of the Fennoscandian ice sheet, or, as an ice dome centred on Rannoch Moor or the Cairngorms, which coalesced with the Fennoscandian ice sheet. The parameters and assumptions used to generate the ice sheets are presented in table 1.1. Subsequent alteration of the model used by Boulton *et al.* (1977), incorporated different bed conditions, and resulted in a more restricted ice cover of the North Sea basin. However, all the land areas were still covered (Boulton *et al.* 1985).

Historically, Scandinavian erratics on the east coast of England have led to the idea that the Scandinavian ice extended a significant distance into the North Sea. However, this need not have been during the late Weichselian glaciation.

Fig 1.1 part b, and table 1.2 show restricted or incomplete ice cover reconstructions of the late Weichselian ice sheet, and list the main sources of evidence used. The reconstructions show that the regional limits of ice cover have been established and confirmed, with the exception of three areas. These are; 1) 'moraineless Buchan' (Synge 1957, Charlesworth 1957, Hall and Connell 1982, Hall 1984), 2) Caithness (Sutherland 1984, Hall and Whittington 1989), and 3) the location of the margin in the North Sea (Stoker *et al.* 1985, Cameron *et al.* 1987, Sejrup *et al.* 1987, Wingfield 1989, Hall and Bent 1990, Andrews *et al.* 1991).

The main priority of late Quaternary research relating to the eastern margin of the last British ice sheet is to establish the margin position. Study can then turn to consider questions of chronology of the development of the ice sheet, and the processes active at the margin.

1.3 REGIONAL FRAMEWORK

This research focuses directly on the onshore/offshore links in the key areas of controversy. The study area lies between 56° and 59°N, and 0° and 4°W (Fig. 1.2). It is composed of the 10km coastal strip of the mainland and the sea area extending east to the 0° line of longitude. The area incorporates parts of the Caithness, Bosies Bank, Moray-Buchan, Peterhead, Tay-Forth and Marr Bank map areas, as delineated by the British Geological Survey (BGS). The area has been divided into five separate study areas. These are 'Wee Bankie' (56-59°N, 3°W-0°E), 'Peterhead' (57-58°N, 2°W-0°E), 'Moray Firth' (57°40'-58°40'N, 3°30'W-0°E), 'Bosies' Bank' (58-59°N, 2°W-0°E), and the onshore sector, also shown in Fig. 1.2.

The pre-Quaternary structure is shown on Fig. 1.3. This is simplified to show the positions of the basins and platforms

present in the area, within the regional structural framework. The offshore area lies on the western margin of the North Sea Basin; this basin has been a major depocentre since the late Palaeozoic, with subsidence continuing into the Quaternary (Sclater and Christie 1980). Fig 1.4. shows the pre-Quaternary solid geology and Fig. 1.5 shows the present day bathymetry of the area.

The Quaternary sediment forms a wedge which thickens to the north east and extends into the centre of the North Sea, and the main depositional centre where Quaternary sediment thicknesses exceed 1000m. The wedge of sediment in the study area reaches a maximum of 180m in the north-east (Stoker 1985a, 1987).

It is important to establish background environmental detail, such as the pre-Quaternary and Quaternary geology, the present-day bathymetry, topography, and sea-bed surface, for each of the five areas;

i) Wee Bankie

This includes estuarine (Firth of Forth and Firth of Tay), nearshore, and shallow shelf environments. General water depth increases eastward to a maximum of 80m. The seabed surface undulates and is broken up by channels which are up to 120m deep and are eroded into both unlithified and lithified strata. The channels are most common inshore, and occur in close proximity to mounded and hummocky topography.

Rockhead is composed of Tertiary, Cretaceous and Permo-Triassic igneous and sedimentary strata, including mudstones, siltstones and sandstones. The area is affected by caledonoid (north-east trending) fault and fold structures and forms part of the margin of the subsiding North Sea basin (Chesher, Fannin and Thomson 1986, Stoker 1983).

Quaternary sediment thicknesses vary, they range from thin-to-absent, blanket deposits to ~50km east of the present coastline. Thick accumulations of sediment, up to 80m, occur within the channels in the mounded and incised topography, while some of the mounds contain up to 50m of sediment.

ii) Peterhead

This area includes nearshore and shallow shelf environments. The nearshore area is subject to sediment transport, indicated by active bedforms, such as sandwaves and dunes. Water depth increases from 50m at the break of slope at the coast, to 120m in the north-east, coincident with the Outer Moray Firth Basin. Local depressions range between 100m and 120m deep, such as the Buchan Deep and Dog Hole. Areas of shallow water occur to the south-east of the Southern Trench (60m) and at the Aberdeen Bank (70m). As well as troughs and ridges, the area exhibits numerous channels and small ridges trending in a south-west to north-east direction. This assemblage of features is restricted to the area to the west of $1^{\circ}30'W$, where the seabed topography undulates.

The area can be divided into four structural geology zones; the Aberdeen Platform, the Peterhead Ridge, the Buchan Graben and the southern margin of the Moray Firth Basin. These form a series of small depocentres and highs within the North Sea Basin. The pre-Quaternary sedimentary rocks range from Devonian to Neogene in age. The Devonian (Old Red Sandstone facies) rocks crop out near the coast. The sedimentary rocks onlap onto Dalradian metamorphic rocks, including semi-pelites and pelitic metamorphics, and Southern Highland Group metamorphics. Igneous rocks crop out at the coast between Peterhead and Cruden Bay which are composed of coarse-grained acidic material (usually granite). Two major faults occur within the area, the Highland Boundary Fault and the Banff Fault. The Banff Fault forms the margin of Moray Firth Basin (Fettes and Chesher 1982).

Quaternary sediments form an onlapping wedge which thickens to the north-east of the area. The sediment cover ranges from thin-to-absent on the Peterhead Ridge bedrock high, to over 200m thick in the north-east. The base of the succession in the east is too deep to accurately position it below the seismic multiple.

However, where present, the base of the sequence is uneven and erosive, with channels and small depressions eroded into the bedrock. Rockhead dips gently to the north-east.

iii) Moray Firth

The bathymetry of the area is complex (Fig. 1.5). The water depth increases gradually from 50m at the inshore break of slope, to 90m at the eastern boundary. Banks rising to 40m beneath O.D. occur frequently, and small isolated depressions 80m deep occur off the Caithness coast. Rockhead rises sharply to crop out at the surface at Muckle Skerry, immediately to the north of the project area. Isolated deeps up to 200m exist which parallel the coast, e.g. the Southern Trench. These are steep-sided, narrow, and are up to 20km long. They are partially infilled with up to 70m of Quaternary deposits, and are associated with fault zones.

The pre-Quaternary structure consists of sedimentary basins and ridges. The basins contain Palaeozoic and Mesozoic strata. Palaeocene rocks are found in the north-east, with Jurassic rocks found in the vicinity of the Beaully Firth. Three faults affect the rocks, namely; the Wick Fault, the Great Glen Fault and the Banff Fault (Fettes and Chesher 1977).

The Quaternary sediments are deposited on an uneven rockhead. The depth of sediment present ranges from thin-to-absent, off the coast of northern Caithness, to over 70m in the Quaternary depocentres. The Inner Moray Firth basin contains five Quaternary Basins with depths of sediment as follows; Nairn (70m), South Lossiemouth (50m), North Lossiemouth (60m), Banff (50m), and Fraserburgh (30m). Between the basins sediment cover is rarely greater than 10m thick (Chesher 1984, Ruckley and Chesher 1987).

iv) Bosies' Bank

Bosies' Bank includes part of the Inner Moray Firth Basin, and a small part of the Outer Moray Firth Basin (Fig. 1.3). It consists of an eastward thickening sediment wedge, overlying

Palaeozoic and Mesozoic sedimentary strata. The bathymetry is partially dependent on structural controls relating to the solid geology, which have affected the subsequent deposition of the Quaternary sediments. Water depths range from 60m to 220m, the former occurring on small highs in the south-west, and the latter occurring within linear deeps found in the north-east. In general the seabed dips gently to the east to an average depth of 120m. The seabed topography, is slightly undulating, with the incised channels, or deeps, trending north-north-west to south-south-east. Rockhead geometry is dictated by a series of basins and highs, some of which are continuations of features present in the Moray Firth area.

The sedimentary strata which crop out at rockhead are predominantly Tertiary shales and sandstones. However, in the north-west quadrant the rockhead is composed of Devonian, Triassic and Cretaceous strata. The Devonian rocks, red micaceous sandstones, form the Caithness Ridge (Skinner and Arthur 1987).

Quaternary sediments form an easterly thickening wedge, up to 120m thick, deposited onto uneven rockhead incised by deep channels. In the east of the area rockhead is found within 10-15m of the surface (Skinner and Bent 1988).

v. Onshore

The sub-Pleistocene geology of the mainland is summarised in Fig. 1.4. This shows that the coastline is composed of Moinian, Dalradian, Devonian, Carboniferous, Permo-Triassic, Jurassic, and Cretaceous rocks. The sedimentary rocks include sandstones, mudstones, siltstones, and limestones and shales, whilst the Moinian rocks are schistose. Igneous intrusions range from acidic granites in the basement material, to basic and intermediate intrusions associated with the Carboniferous sediments in the Central Valley. The main fault complexes are the Southern Upland Fault, the Highland Boundary Fault and the Great Glen Fault. The landscape is dominated by a caledonoid (south-west to north-east) trend.

Quaternary sediments cover all the onshore area (Fig. 1.6), except where bedrock crops out, and on the foreshore. The sedimentary sequence is more fragmentary than offshore.

Offshore Quaternary Succession

The BGS offshore Quaternary stratigraphy, which is summarised in Figures 1.4, 1.7, 1.8, and table 1.3, is common to several of the offshore areas, and it is helpful to discuss it as a whole.

The succession contains sediment possibly ranging from early Pleistocene (Eburion), to Holocene in age. The stratigraphic succession has, however, been subject to episodes of erosion, which have removed parts of the sequence. The sediments were deposited in both glacial and interglacial subaerial and aqueous environments (Stoker *et al.* 1985, Andrews *et al.* 1991).

The chronostratigraphy suggests that only the following seismo-stratigraphic formations are relevant to this study, Forth Formation, St. Abbs Formation, Witch Ground Formation, Wee Bankie Formation, Marr Bank Formation, Swatchway Formation, and the upper part of the Coal Pit Formation. These are formations which are defined by seismic stratigraphy characteristics, rather than sediment characteristics.

The sedimentary succession is shown in Fig. 1.9, and the general characteristics are summarised in table 1.3. Given this information, the formations have been interpreted by Holmes (1977), Thomson and Eden (1977), Stoker (1983, 1985a and b, and 1987), and Skinner and Bent (1988) in the following way:

Forth Formation

In the 'Wee Bankie' and 'Peterhead' areas this has been locally subdivided into the St. Andrews and Largo Bay members, which are interpreted as a fluviomarine sand body and a transitional assemblage of glaciomarine and marine muds, respectively. Where the formation is undivided it occurs as a channel infill, or a sheet sand deposit. In the east it consists

of marine and ice-distal, glaciomarine facies, with the possible inclusion of some fluviatile facies. It is thought to be the lateral equivalent of part of the Witch Ground Formation.

Witch Ground Formation

The Witch Ground Formation is found in the north-east of the area. It is a basin-fill deposit, interpreted as an ice-distal glaciomarine facies which grades upward to a temperate marine facies. The younger sediments are thought to be the lateral equivalents of the Forth Formation, whilst the older glaciomarine facies is thought to be equivalent to the St. Abbs Formation, in the 'Peterhead' area. Note that this has been ascribed an older age than suggested by Stoker *et al.* (1985), from work carried out by King (*pers comm*) on a borehole to the east of the study area.

St. Abbs Formation

This formation is restricted to the inshore area of the 'Wee Bankie' area, and the extreme south-west of the 'Peterhead' area. It is interpreted as an inshore sheet and channel infill deposited under shallow marine conditions, in the 'Wee Bankie' area, but as a thin glaciomarine deposit in the 'Peterhead' area.

Wee Bankie Formation

This formation is found parallel to the coastline in both the 'Wee Bankie' and 'Peterhead' areas. It has been interpreted as consisting of a glacial diamict and glaciomarine deposits. Thomson and Eden (1977) describe it as the, 'moraine and channel', topography which is a, 'till deposited under the last Devensian ice sheet which incorporates moraine, at the margin of the ice sheet.' This is thought to be laterally equivalent to the Marr Bank and Swatchway formations.

Marr Bank Formation

This formation is interpreted as a glaciomarine deposit of sands and silts, deposited in shallow water, adjacent to the margin of the late Weichselian ice sheet. It is restricted to the 'Wee Bankie' and 'Peterhead' areas.

Swatchway Formation

This is restricted to the eastern part of the study area, in the 'Peterhead' and Bosies' Bank areas. It is interpreted as a more ice-distal, and deeper glaciomarine deposit, equivalent of the Marr Bank Formation. In the Bosies' Bank area a crenulate micro-relief characterises its upper surface; this has been interpreted as ice loading and/or ploughmarks resulting from grounding of sea ice in shallow water. To the west, the water was too shallow to allow iceberg access. Alternately, part of the succession has been interpreted as a possible tide-water ice sheet margin associated with the late Weichselian maximum (Bent 1986, Hall and Bent 1990).

Coal Pit Formation (Upper)

The upper part of the Coal Pit Formation is incorporated into the late Weichselian stratigraphy, because it is proposed that this sequence of marine and pebbly glaciomarine sediment was reworked in the late Weichselian.

Moray Firth Quaternary Stratigraphy

The sequence of Quaternary sediments in the 'Moray Firth', is more complicated because it cannot be incorporated into the regional seismostratigraphy with confidence. From lithological evidence it has been interpreted as a series of subglacial tills, overlain by glaciomarine and possibly ablation till, in the inner Moray Firth (Chesher and Lawson 1983). Up to seven late Quaternary lithofacies are present, which date (lowest unit) from the mid-Devensian (Weichselian) c. 43ka BP. This lowest unit is thought to be the most widely distributed unit over the inner Moray Firth. Younger sediment units are only found within the basins. The

second common unit in the area has been dated to 12.4ka BP +/- 100 (C¹⁴). It is thought to be related to a restricted deposit of till(?) which is thought to be younger than 16ka BP. This is also shown in Fig. 1.6.

1.4 RESEARCH APPROACH

Two main approaches were considered at the outset of research. One was to use a systematic approach considering each data source in turn, for example, the seismic evidence, provenance studies, and borehole data. The problem with this approach is that the relative importance of different data sources varies from place to place, and that key data sources in some areas did not exist in others. This makes integration of the results difficult, hence, a regional approach has been adopted. All the evidence for a particular area is considered and an interpretation made for that area as a whole. Subsequently the reconstructions for individual areas are integrated into an overall ice sheet reconstruction.

The sequence of regional studies is designed to move from the known to unknown. Thus the first to be considered is the Wee Bankie area. Here there are both general and specific seismic studies relatively well constrained by borehole data, and linked to a distinctive bottom morphology. The availability of the different studies allows interpretations to be relatively tightly constrained before extending the techniques into less well-known areas, or areas with poor data.

Two particular problems were identified: a) the interpretation of North Sea sediments in terms of contemporary glacial and glaciomarine process models and b) the chronological control on the reconstructions. The first problem was tackled by the use of analogues in Iceland. The second was approached by the use of thermoluminescence dating and amino acid racemisation techniques on mollusca.

1.5 THESIS STRUCTURE

The thesis structure reflects the research design (Fig. 1.10). Chapter 2 presents the techniques used to examine both the onshore and offshore data. This includes the evaluation and theory of seismic acquisition. Chapter 3 exemplifies the required approach and presents the seismic, sedimentary, provenance and particle size analyses results obtained for each offshore area, followed by the onshore results. The dating results are presented separately. An overall interpretation for each area is presented, which includes discussion of the results and interpretations from the detailed sites.

Chapter 4 integrates the results obtained from each area with regard to the areal and temporal extent of the icesheet as a whole. Chapter four also includes a glaciological reconstruction of the palaeo-iceflow of the eastern margin of the Scottish late Weichselian ice sheet.

Chapter 5 considers the implications of the reconstruction, both in terms of alternative reconstructions, and also existing theoretical models of icesheet behaviour and the study of former glaciated areas.

CHAPTER 2

DATA ANALYSIS STRATEGY AND TECHNIQUES

2.1 INTRODUCTION

This chapter outlines the techniques used to interpret the offshore and land evidence. It stresses the theory, assumptions, and problems inherent in the use of the techniques, as well as the difficulties of correlation.

Fig 2.1 summarises the sampling and analysis programme. It distinguishes the onshore and offshore evidence, and the methods by which the two datasets have been utilised to produce information. The different scales of analysis of the evidence become apparent, with stress on the detailed work within a regional framework. The integration of the two datasets is then linked to the chronological interpretation, and theoretical reconstruction.

2.2 TECHNIQUES

2.2.1 OFFSHORE

This section contains a résumé of the theory of seismic acquisition and interpretation, and outlines the techniques used to analyse the cored material.

The offshore data are composed of analogue, single channel, 1kJ, deep tow sparker (DTS) seismograms, bathymetric, side scan sonar data, borehole, gravity core, vibrocore and grab sample reference material available from the BGS offshore database. The database contains the results of BGS analyses of the recovered material for sedimentological, geotechnical, geochemical, lithological and palaeontological characteristics. Further examination of selected boreholes and vibrocores, by the author, provided additional data specific to this project.

The seismic data have provided most evidence, with the cored material acting primarily as a control on lithological interpretations based on the reflection pattern recorded on the seismic lines. Two scales of seismic coverage have been used: the regional (1:250 000) scale collected by the BGS in several cruises, since 1970, and local (1:10 000) scale, provided by commercial data from sites within the North Sea and Moray Firth basin. The line spacing between the BGS lines is typically 10km, whilst the commercial lines are 150-500m apart. The BGS data provides the regional overview which gives the general setting of the ice margin location, and the seismic facies units which occur in this environment, whilst the commercial data allow detailed study of specific parts of the ice margin.

Seismic Theory

Subsurface data are acquired by geophysical investigation using seismic surveying. Several seismic acquisition systems exist which operate on the same principle, the response of an acoustic energy signal to differences in the physical properties of the subsurface geology. The subsurface geology is assumed to consist of layers with marked vertical, and smooth lateral, changes. Structure is examined by reflecting acoustic energy off interfaces between the layers and recording the results on a seismic record. From this it is possible to calculate the depth to the interface using the relationship between the velocity of the acoustic energy through the rock and the time taken for the signal to travel to and from the interface, the two way travel time (TWT). The depth (d) is found from the equation;

$$d = \text{TWT} \times V_p \times 0.5$$

where, d is depth (m), TWT is two way travel time (s), and V_p is the compressional wave velocity through a given lithology.

TWT is obtained as a direct measure from the seismic record, which is calibrated in time along the vertical axis. The velocity

(v_p) is obtained from either tables of velocities of known rock types (Press 1966), or from direct downhole velocity measurements. Using the above relationship it is possible to estimate the depths at which interfaces occur within the section. Where borehole control exists the seismic response of the lithologies can be used to calibrate the seismic line and infer lithologies along the line where sediment samples have not been collected.

Seismic acquisition is based on the physics of energy wave transmission through solids, the behaviour of the energy wave where it encounters an interface and the reflection back to a recorder. Many factors affect the way the acoustic energy is transmitted and this affects the validity of the information shown on the record. It is important to understand these before considering the analysis of the record.

The seismic signal is generated from an exploding source which results in a plane compressional wave (P wave). This propagates down through the water column until it encounters the seabed. Transmission of the energy through the medium occurs under perfect elastic conditions, defined in terms of stress and strain. Stress is the force which is a balance of internal action and reaction between different parts of a body at a general internal point. Strain is the deformation of a body resulting from the applied stress (Fig 2.2). The components of strain can be expressed as linear functions of the components of stress (Hookes' Law). When dealing with an isotropic solid it is assumed that perfect elastic deformation, resulting from the input of energy into a body is transmitted linearly. Change in the other component axes is confined to volume reduction. Motion, due to the applied force of the energy input, results. The speed of this motion (velocity) through the solid is related to the density of the material.

Expansion to the three dimensional case is complicated. Difficulties arise from both the nature of the medium through which the wave is propagating and the nature of the wave itself. The wave is not always a P wave. At an interface the P wave can generate shear (S) waves which travel through (and deform) the

medium normal to the direction of propagation, and vice versa. The S waves can have different polarities which will affect the magnitude and strength of the returning signal. Near-surface Rayleigh and Love waves (Davies 1968) exist which, although confined to the upper layers, have large amplitudes which obscure deeper reflection signals.

The medium through which the energy is transmitted, is rarely an isotropic solid. The solid is often crystalline with an anisotropic crystal lattice and inhomogeneous rock structure. The anisotropy of the crystal lattice leads to potential differences in the propagation of the waves and therefore the seismic velocity of the solid. Pore spaces may be filled with a liquid, gas or a different solid with different transmission properties. This alters the seismic velocity of the solid. The variations in the velocities for a solid can be such that it is impossible to infer lithologies from the seismic velocity alone, lithological control is also needed. However it is possible to infer the effects that porosity, for example, will have on the velocity for a given 'solid' and the effects of either a liquid or gas fill. Empirical relationships also exist between the velocity and density of rock types.

Three dimensional consideration of energy transfer utilises the concept of the 'wavefront', i.e. the positions in space where the displacement caused by the disturbance at a given time is equal. This is then used as the source point for the next wavefront to develop. In an homogeneous medium the wavefront is spherical and expands with distance from the source. The energy at any point diminishes over time as the wavefront expands because the area over which it is distributed is greater. This results in a decrease in the amplitude of reflections from deeper within the profile and a loss of strength in the reflected signal.

To simplify the physics and apply Snells reflection principles to the seismics, lines normal to the advancing wavefront 'rays' are drawn. This is the path along which the energy is transmitted. Normal reflection and refraction physics utilising Snell's Law at an interface can be applied to the rays,

with wave velocity, wavelength, and densities of the different transmission media being the important factors affecting the behaviour (Fig. 2.3).

Reflection physics are dependent upon the acoustic impedance across an interface i.e. the density of the medium and the velocity of the wave passing through it. These parameters also dictate the transmission coefficient R which is related to the amplitude of the transmitted wave. If there is a large transmission coefficient and a distinct difference between the density and amplitude parameters associated with that medium, then a strong reflector will be recorded on the seismic record. If there is little difference in the transmission coefficient then it is unlikely that the reflector will appear. Complicating factors in this exist. At depth the reflected signal can be reduced due to the number of interfaces encountered. The signal is dampened as its energy becomes dissipated either as heat or in complicated internal reverberations between closely spaced interfaces, known as ringing.

Seismic Stratigraphy Interpretation

The seismic data in this thesis have been interpreted using the methods developed by Vail *et al.* (1977) and Mitchum *et al.* (1977). The basic principle is to identify and interpret structures and associated lithological units as defined by their seismic reflection response. Vail *et al.* (1977) and Mitchum *et al.* (1977) examine the seismic data in two ways; seismic sequence analysis, and seismic facies unit analysis;

Seismic Sequence Analysis

This identifies seismic sequences. A seismic sequence is a genetically related assemblage of reflectors. The sequence is delineated by the configuration of reflector terminations as summarised in Fig. 2.4. Definitive assemblages of reflectors occur at the base and top of the sequence. The reflector pattern within the unit indicates the environmental changes associated with the

sequence through time. The eustatic application of the Vail sequence model is inappropriate here because only one sequence is considered, the late Weichselian.

Seismic Facies Analysis

This is the "description and interpretation of seismic reflection parameters, including configuration, continuity, amplitude, frequency, and interval velocity." (Mitchum *et al.* 1977, p121). The main parameters used in this study are the reflection configuration, i.e. gross stratification patterns, continuity and amplitude. This includes information such as the seismic contrasts between different strata and the areal extent of specific seismic units (Fig 2.5). These give information about the energy regimes in the environment of deposition (Fig. 2.6).

Sangree and Widmier (1977) have adapted this method for clastic shelf facies, and Stewart and Stoker (1990) have extended this to include diamicton deposits. When considered in three dimensions these factors allow distinct seismic facies units to be mapped. Bouma *et al.* (1987) present a useful reference study of applied seismic stratigraphic interpretation on the regional scale.

The technique has been adapted in this thesis so it is applicable to data of different scales. A relative classification system for the reflectors is used, namely:-

- First Order* High amplitude, strong, laterally continuous over large areas i.e. can be traced over several intersecting seismic lines
- Second Order* Less strong, laterally continuous/neocontinuous but over a smaller area than above. May be traced over adjacent seismic lines
- Third Order* Weak, short, low amplitude events, often of localised importance only associated with channel features etc.

Other Reflectors which give some structural control but do not fall into the above categories e.g. infill within a channel.

A seismic stratigraphy for the study area was derived by identifying and delineating seismic facies units and complementing this with detailed seismostratigraphies of particular sites. By following structural reflectors at cross ties, fence diagrams were constructed to illustrate the areal extent of the different facies units (plate 2.i). This was most successful in areas with good quality data, such as the 'Wee Bankie' area. Problems of correlation between lines occurred in areas where older, less abundant data were available.

Problems in Interpretation

It is important to highlight the limitations which affect the interpretation of seismic data:-

1. Resolution : This limits the size of the features which can be recorded on the seismic line. Different systems have different vertical resolutions which are a function of the wavelength of the acoustic signal. For example the Hunttec DTS used by GEOTEAM (1984) was limited to 5m vertical resolution, whereas the DTS system used by RACAL (1988) in the Moray Firth had a resolution of 30cm. Many important sedimentary features are finer than the resolution of the coarser systems, resulting in oversimplification.

The horizontal resolution of the line is limited, depending on the frequency of shot and the speed and course of the ship. Different methods of measuring distances cause exaggeration of features and hinder detection of steeply dipping reflectors.

2. Acoustic Impedance : The relative impedance of adjacent seismic facies within the seismic sequence may be insufficient to register as an interface. This means that the reflector would be

absent from the record. Alternately the relative impedance may be so great that the resulting high amplitude reflector masks the reflected signals from immediately beneath it, e.g. a gas bright spot (Fig. 2.7a).

3. Distortion : The seismic line is affected by poor return of energy from deeper within the strata as a result of the loss of energy and decreasing amplitude of the returning signal. This results in 'poor penetration' and non recovery of information. At inclined interfaces, where there is a large change in the velocity, it is possible to get pull-up or down-pull of the seismic signal beneath that interface. One example is hyperbolic reflectors from point sources at the base of, or within, a diamicton unit (Fig 2.7b and 2.7c). Absorption of energy by gas in pore spaces also has a 'blanking' effect which creates distortion of the record.

4. Velocity Variation : One of the assumptions implicit in seismic interpretation is that there is little velocity variation in the lateral direction. However this is not necessarily the case in reality.

5. Depth Calculations : The signals do not follow a simple vertical, linear pathway. This makes calculations of the depth of the deeper reflectors subject to inaccuracies (see Sharma 1986).

6. Borehole Control : Sometimes there is a mismatch between seismic interpretation and borehole evidence. Work carried out in the central North Sea by the British Geological Survey as part of the regional mapping project indicates that there is good agreement between the seismic and core interpretation. However, in some cases the opposite holds true, and the seismic record indicates that there is considerable variation within the seismic facies with many reflectors, while analysis of the core shows that there does not seem to be such a high degree of variability within the sediments (Paul and Jobson 1989).

7. Reproducibility : Seismic stratigraphic interpretation is a subjective technique dependent upon the experience of the interpreter. The interpreter has to be able to distinguish between reflectors which are meaningful and those which are spurious.

8. Location : The accuracy of the location systems used to record the position of the ship and the fish with regard to the actual position of the track of the seismic survey is a problem, compounded by the difficulty of locating a core site accurately. This links into the spatial variation of the sediments deposited at a site and how representative of the sediment body is the survey line? Some systems can locate the actual seismic track to within +/- 15m of a borehole (RACAL 1988), although the BGS lines can be +/- 400m from a borehole. In a high energy sedimentary environment even the former accuracy of positioning may be insufficient to constrain the data given rapid lateral changes in glacial and glaciomarine environments (Stewart, 1989, Appendix 4).

9. Generic Assumptions : In seismic interpretation, it is assumed that a given seismic facies extending across a large area does not change its general sedimentological properties and that similar seismic 'signatures' represent similar sediments e.g. sand, silts and clays, diamicts (Mitchum *et al.* 1977). There is the problem of equifinality in that different generic sediments may have identical seismic signatures. This casts doubt on the glacial till generic interpretation favoured by King *et al.* (1987).

Seismic Stratigraphy : adopted procedure

Forty nine single channel, analogue, 1kJ Sparker seismic lines covering 3650 line kilometres were selected to provide regional coverage for the study area. These were shot on a series of BGS cruises covering the continental shelf since 1970 (table 2.2). The best quality data were provided by the 80/03 survey. Lines were selected to give the best areal coverage given the availability of sediment sample points required for lithological and sedimentological control. Additional considerations were the quality of the lines and the location of the lines with regard to different working hypotheses. Twenty four high resolution DTS lines were studied from the commercial site 40km east of Montrose, covering 60km (9km²).

To test the reproducibility of the seismic interpretation in this project an area initially analysed as part of the BGS regional mapping of the UK continental shelf, namely the Marr Bank and Tay-Forth sheets (Stoker 1985a, 1987) was reanalysed. Fig. 2.8. shows the original and authors' analysis of line 80/03 36. Comparison of the lines indicate that although some of the deeper structure of the sediment succession is missing in the latter line, the main reflectors and channels have been identified. This lends support to the interpretations elsewhere within the thesis.

The seismic lines have been drawn up as part of a three dimensional network. It has been possible to establish the spatial relationships between structures and deposits, for example, channels, ridges, basins, seabed sediment waves, ripples, dunes, faulting, and deformation. These have been used to infer the processes likely to have been active.

Vertical measurements have been made in TWT for ease of comparison and to reduce the inaccuracies associated with conversion to true depth measures.

Laboratory Analysis

Core Preparation

Sediments in 13 boreholes and 1 vibrocore were examined in the laboratory. Logs of 7 boreholes, 7 vibrocores and 1 gravity core were also consulted (Table 3). Commercial and BGS reports were consulted for geotechnical descriptions of sedimentary material collected within the project area. The BGS descriptions included colour (Munsell), lithology (mud, diamicton, sand etc.), presence of organic material, bioturbation and structure. Shear strength, palaeomagnetic tests, grain size analysis, micropalaeontology, triaxial testing and moisture content results were also consulted.

The 14 cores were analysed in the laboratory as follows:

The core was split in half, cleaned with an osmotic knife, and x-rayed using the Danish Scanray AC 120L system, manufactured by Scandinavian X-Ray A/S. The x-rays revealed structure, bioturbation, clastic and shell positions within the core without disturbing the surrounding sediments (Fig. 2.9). This helped establish whether clasts within the core were dropstones, as indicated by the bedding structures (Thomas 1984), and whether shells were *in situ*. The core was then photographed, and described including; colour (Munsell), sediment type, structure and composition. The presence of organic material and artifacts was noted. This was then compared with the BGS log and additions were made to the latter. Shelly material was removed for identification and relative dating by amino acid racemisation, where appropriate. Finally, sediment samples were selected for further laboratory analysis. Originally selection was systematic at 10cm interval down the core. However, this was changed to sampling at boundaries of sedimentary units and representative sites within them, because the systematic sampling interval did not include all the important lithological changes.

Laboratory Analyses of Sediment Samples

Each sediment sample was analysed for particle size, pH, Calcium Carbonate content, clastic shape and surface morphology, and the lithology of the >10mm and 3-5mm size fractions. The purpose of the analysis and the techniques used are described below:-

Particle Size Analysis (PSA)

PSA has been used to describe the sediment size distribution and as an aid in inferring process. Samples were wet sieved to 63 μ m using standard sieves (BS3406). The <63 μ m fines were freeze dried and analysed using a SediGraph 5000ET Particle Size Analyser

(MICROMERITICS 1984). This system was chosen as a quick, effective method of analysing the fine fraction of the samples. The system assumes that the absorption of x-radiation is proportional to particle mass. The system was chosen after extensive testing of alternate systems, including laser diffraction techniques. Appendix 1 outlines the theory and selection criteria in more detail. Statistical analyses of the psa curves included kurtosis, skewness and modality (Pettijohn 1957, Briggs 1977, Bridgland 1986). Since the maximum size of the clasts is limited by the method of sampling and the width of the recovery tube, this creates a positively skewed psa distribution for the fraction coarser than 10cm.

pH

The pH of the sediment was used to establish the ionic content of the sediment. This can reveal the transport path of the sediment (Andrews and Sim 1964).

% Calcium Carbonate Content (CaCO₃)

This was measured using a Calcium Bomb (Muller and Gastner 1980) which indicates the amount of carbonate displaced from a sediment on the addition of HCl. The CaCO₃ content can indicate a provenance for the matrix, as discussed above (Andrews and Sim, 1964).

Clast Shape and Surface Morphology

The clast shape (angular, sub-angular, sub-rounded and rounded) was recorded for the clasts of >10mm axis, and the presence of striae, broken clasts and 'flat-iron' shaped clasts was noted. Boulton (1978) suggested that there was a link between the shape of a clast and the probability of it having been transported through a glacier via different subglacial, englacial and supraglacial pathways. Each transport path produces characteristic shapes as follows:

<u>Pathway</u>	<u>Shape Criteria</u>
Supraglacial	Coarse fraction, angular to subangular clasts
Englacial	Coarse fraction, angular to subangular clasts.
Subglacial	Fine fraction, finely comminuted. Clasts become rounded with striae on their surfaces due to basal transport mechanics. They may also exhibit polished surfaces and a roche moutonnée profile.

Meltwater transport is indicated by sub-rounded to rounded clasts, the degree of rounding being dependent on lithology and the length of time the clast is subject to glaciofluvial erosion.

A relative indicator of entrainment time (short to long!) can be derived from the Reichelt classification of clast shape and the resistance of a clast to glaciofluvial erosion and solution which is dependent on rock hardness (Mohs Scale in Cox *et al.* 1974, p106). The classification is transitional and grades from angular, subangular to subrounded and rounded. Results are presented as a percentage histogram and compared with type histograms of clastic assemblages representing different sedimentary environments (Fig. 2.10). Reworking of the clasts was shown by the presence of sub-rounded and rounded clasts with chipped and broken surfaces.

Provenance Studies

Provenance studies identify, '...the source area or areas of the material making up a sediment,...', (Whitten and Brooks, 1972 p 366).

Rock type was identified in hand specimens, using a microscope where necessary. Where rock type was unknown, the clast was examined in thin section to establish the petrology. Two clast sizes were examined for the provenance study, >10mm and the 3-5mm sand fraction. The clasts were grouped into ten lithological classes and histograms of the percentage of each class were

constructed. The clasts of >10mm in the 'c' axis were examined to identify their source within the diamictons and also the fine matrix-supported sediments where clastic material is scarce. The 3-5mm size clasts were examined by The Dutch Method (Ehlers 1979) in an attempt to distinguish between different facies in areas of cyclic sedimentation, especially where larger clasts are rare. This involves identification of at least 300 examples of the 3 - 5mm sized clasts in the sample. Smaller numbers were used in fine samples where less than 300 particles existed, but the analysis was still valid in that the population rather than a statistical sample was examined. In diamictons this can provide information about different sediment sources for possible polymodal sedimentation (Ehlers 1979). Ten classes were employed:

Quartz(ite), Sandstone, Pelites, Limestone, Coal, Devonian/Old Red Sandstone Series, 'Sedimentary', 'Igneous', 'Metamorphic', and 'Others' (includes unknowns). Some of classes are not mutually exclusive, however, the clast would be categorised in the most applicable class.

Some clasts were too small to indicate whether they were fragments of the source rock, or whether they related to intrusive and extrusive elements. For this reason general groups exist for 'sedimentary' clasts etc. If a clast did not fall into any category it was classified as an 'Other' clast.

All the techniques produce results which describe the individual sample, but which can also be used for intercore correlations. Each technique provides information which is valid in itself but, when in combination with the information from intra and intercore comparisons provides much stronger evidence to describe and explain the sedimentary environment. For this reason the results from each analysis are presented for each borehole. Intracore consideration of the results is followed by intercore comparison of the results with conclusions being drawn for the sedimentary environment of the study area as an integrated unit.

Core analysis was restricted by the following problems:-

- 1) Core availability: the composite log was the only record of some of the cores, which would have otherwise been sampled.
- 2) Condition: the cores have been stored for between 9 and 18 years and are in a poor condition. Some material has been removed in the past for subsampling and dehydration and shrinkage during storage has reduced the information available from the core, especially the geotechnical properties.
- 3) Poor recovery: several boreholes had incomplete recovery with important sections of the sequence missing. This reduced the number of downcore sample points drastically. The average recovery for the boreholes in this study was <20%.
- 4) Site location: the lack of proximity of cores to seismic lines and their location in relevant sites for testing the working hypotheses further limited the number of suitable cores.

2.2.2 ONSHORE

The onshore data were obtained by mapping evidence of glacial modification of the landscape. The scales were chosen to match the regional studies offshore. Sedimentary successions in key locations provided the onshore sedimentary evidence to match the offshore borehole records. The geomorphic maps were compiled at a scale of 1:25 000 from the interpretation of aerial photographs and 1:50 000 from the Ordnance Survey maps. Sedimentary evidence was obtained from the field description of sections and detailed lithological analyses of samples. This included *in situ* and laboratory based analysis using some of the methods cited for the offshore sediment analysis. These techniques were also used for the onshore boreholes.

Sedimentary processes and forms from contemporary mid-latitude ice marginal glacial environments in Iceland were

examined in the field as analogues for the glacial environments present in the study area during the maximum of the late Weichselian glacial.

Interpretation of Remotely Sensed Imagery

A composite Landsat 1:1 000 000 image of Scotland (RAE Farnborough 1984) was used to identify the macroscale pattern of lineations in the landscape. The lineations were mapped and identified as a basis for examination of aerial photographs at 1:24 000 scale (SDD 1988) (Fig. 2.11). The features identified and mapped from the aerial photographs were roches moutonnées, ice moulded and streamlined hills, ice scoured bedrock, linear rock basins, rock meltwater channels, and ice-plucked surfaces. These were identified from their planform and relief on the aerial photographs (Fig. 2.12). Ice-scoured bedrock was identified by the smooth, occasionally fluted surface texture. Alternately ice-plucked surfaces were identified by an uneven texture. Paleo ice-flow directions have been reconstructed from the orientation of these features, assuming that the direction of ice flow can be derived from streamlining of its bed.

The validity of this approach was field-tested using 1:10 000 scale aerial photographs (RAF 1942) in sample situations, namely Helmsdale, Strathpeffer, Banff, the Montrose Basin area, Fife Ness, Hope Reservoir Gifford, and Edinburgh (Fig. 2.13). Field checking of the geomorphic map tested the effectiveness of the interpretation of the photographs in a range of different environments e.g. upland areas and intensely farmed coastal areas. Comparison shows that geomorphic mapping from aerial photographic interpretation provides the effective evidence.

Topographic Map Analysis.

Geomorphological mapping of glacial erosional features was also undertaken for the onshore area using the Ordnance Survey, 1:50 000 map sheets (2nd edition). The planform shape of the

landforms was used as the primary identification criteria (Fig. 2.12). However, it is difficult to distinguish between some of the erosional and depositional features. Site visits clarified the origin of some of the landforms.

Exposures and Boreholes

Exposures of the sedimentary succession in 13 key sites were photographed and logged. Sedimentary structures were identified and described, namely; bedding, syn and post depositional deformation structures associated with loading and glaciotectionic activities; faulting, boudinage and flame structures, evidence of slumping and liquifaction of the sediments. Brodzikowski and Van Loon (1984) have shown the importance of these structures in understanding the glacial geology of an area, especially as glaciotectionic deformation is more common than previously thought. Sediment unit boundaries were identified and mapped out. Facies descriptions were applied, as used for the offshore sediment (Eyles *et al* 1983). Fabric analysis of the clasts provided evidence of the direction of movement of the ice sheet (Bridgland 1986). *In situ* examination of clasts was used to indicate the presence of dropstones and rafted units within the matrix (Thomas 1984).

Samples of sediment and organic material were removed for laboratory analysis as described above. Six onshore 'shell and auger' boreholes and several trial pits were also examined in the field. Note that the maximum clast size collected in the onshore boreholes was limited to 25cm.

2.3 DATING

Three dating techniques were considered as possible chronological constraints for the project. These were Thermoluminescence dating of sediments, Amino Acid Racemization dating of shells and/or foraminifera, and Radiocarbon dating of organic material. The rationale was to adopt methods which were

applicable to the onshore and offshore environments and which could be interchanged. The methods were to be standardised relative to amino acid ratios, by duplicate dating of a single core. Variations between dates obtained from different methods would then be quantified. The chronology derived using this system would link with wider Northern European Quaternary research via the aminostratigraphy derived by Miller and Mangerud (1985).

In practice radiocarbon dating and thermoluminescence dating were found to be inappropriate to the samples available. Radiocarbon dating by conventional isotopic decay methods required larger samples than were available from any core material. Two sediment samples were analysed by the author at the thermoluminescence laboratory in Aberdeen; a till and a glaciomarine sediment. Several different methods for deriving a T.L. date were applied to the samples. Unfortunately the technique proved inapplicable for tills (Gemmell 1988), although meaningful dates for the glaciomarine sediments should have been possible. A full discussion of the techniques and their problems are outlined in Appendix 1.

Amino acid racemisation dating was applied to molluscs chosen to comply with the requirements outlined by Sejrup (*pers comm*). Molluscs of the following species were preferentially selected, because a large database exists with which to integrate and constrain the the results: *Arctica islandica*, *Mya truncata*, *Hiatella arctica*, *Macoma calcarea*. The small taxodont species, *Yoldiella lenticula* and *Portlandia arctica* although useable do not have a great deal of data for comparison (Sejrup, *pers comm*). The dating technique is based on the rate at which amino acids within the skeletal structure of organic material epimerise on death of the organism. Epimerisation occurs at a known rate for each amino acid, which is dependent on temperature. When the burial temperature is known or can be approximated, the rate of epimerisation through time is known. The ratio of the two forms of the amino acids is measured, and it is possible to calculate the length of time since death. In reality the technique is used for relative rather than absolute dating because assumptions exist

within the derivation of the epimerisation rates and the change in environmental conditions over time which make absolute dates open to question. Amino acid racemisation is also dealt with in more detail in appendix 1 (Stewart 1988a).

CHAPTER 3

RESULTS

3.1 INTRODUCTION

This chapter is split into three sections; 1) offshore results, 2) onshore results, and 3) dating results. The offshore section is divided into four subsections which contain the seismic and sedimentology results from each of the offshore areas. Each subsection is concluded with an interpretation of the results presented for that area, as is section 2, the onshore results. The dating section contains the amino acid racemisation ratios obtained from the collected shells.

3.2 SECTION 1 - OFFSHORE RESULTS

REGIONAL STRATIGRAPHY

Composite profiles of the regional stratigraphy have been compiled from the seismic facies analysis of 3650km of 1kJ, sparker seismic lines in the study area. In complex areas stratigraphic relationships and/or specific features of interest are illustrated using the actual seismic line. The profiles have been described using the seismic analysis parameters and descriptors of Mitchum *et al.* (1977), and Sangree and Widmier (1977), shown in chapter 2, and the terminology of Mitchum Jr. (1977). Specific reference is made to the following figures which illustrate the reflector configurations and descriptive terminology employed in the seismic interpretations (Figs. 2.5 and 2.6). Note that some of the descriptive terms are applied to reflector configurations as examples of the geometry and internal architecture, and do not relate to the scale *sensu stricto* of the Vail Sequence Model (updated: Vail 1987), or to the location of the feature, e.g. those defined as being applied to the shelf break and slope.

The sedimentological results provide control for the seismostratigraphy. They also provide detailed information about spatial variation in sediment size and sediment distribution.

Figure 3.1 shows the locations of the seismic lines and the seismic sections referred to in the text, together with borehole and vibrocore sites.

'Wee Bankie' and 'Peterhead' contain the systematic description and interpretation of the evidence in order to test the existing interpretation of the offshore record in terms of glacial deposits and ice margin location. 'Moray Firth' and 'Bosies' Bank' contain the results of specific studies which try to extend the known position of the ice margin.

3.2.1

WEE BANKIE (56-57°N, 0-3°W)

3.2.1.1 SEISMIC PROFILES

The west-east composite profile (Fig. 3.2) has been compiled from BGS project 80/03, lines 15, 30, 34, 36 and those shown on the Tay-Forth and Marr Bank BGS 1:250 000 Quaternary map sheets (Stoker 1985, 1987). It has been divided into three zones; WBA, WBB, and WBC:-

Zone WBA

This zone extends from the estuarine environment in the west, to the eastern limit of the inshore area, approximately 40km from the coastline, as marked by the eastern edge of the hummocky mound and channel topography.

Water depth rarely exceeds 60m except within channels, where it is up to 120m deep. Sediment cover is thin and patchy and ranges from 0-25m. It is commonly 10-20m thick, except where it infills channels to 80m or forms mounds in the east up to 40m thick. The seabed reflector is strong and in places obscures the top 5-6m of the underlying seismic facies unit. The reflector shows that the seabed is smooth, exhibits no sediment transport structures, and is probably an armoured relict surface. It is relatively flat within the estuarine areas, but undulates in the inshore area, except where the channel and hummocky mounded topography occurs.

Rockhead (the interface between unlithified and lithified strata) is an undulating, smooth, first order reflector where it truncates the Permo-Triassic strata. It is a second order reflector in the north, where an irregular-floored basin occurs. Rockhead is uneven in the south, where shallow basins and steep-sided, 'V'-shaped channels are eroded in the rock. The seismic facies units are delineated by second order reflectors. Second order reflectors also delineate the major incised channels in the zone. The internal structure of the seismic facies is indicated by

the third order reflectors. The reflectors and seismic response configurations indicate that three seismic facies units exist, WBA1, WBA2, and WBA3, as shown in Fig 3.2 :-

WBA1

Description This is the main unit in this zone. It extends from the estuarine area to the contact with zone WBB. The upper boundary of the unit forms the first order seabed reflector, except where recent channels incise 5-15m into the unit or extend into rockhead up to 20m below seabed. The lower boundary is the rockhead reflector.

The seabed reflector is hummocky and consists of up to three discrete, asymmetric mounds in the east which are up to 20m high and which trend approximately parallel to the coastline (Fig 3.3). The mounds sometimes overlie a strong, but short reflector, which is horizontal and planar. Rockhead is uneven and composed of a series of eroded basins and channels.

The unit is thin to absent, and forms a discontinuous blanket over the zone, with rockhead locally cropping out at the surface. The seismic response is structureless and chaotic, with low to moderate amplitude sporadic reflectors, giving a patchy seismic record. Point-source reflectors (hyperbolics) occur throughout the unit.

Interpretation This seismic facies unit gives the 'type' response of a diamicton-dominated, shelf, glacigenic facies, as shown in Fig 2.6 (Stewart and Stoker 1990: Appendix 4). This facies displays a mounded external form and is characterised internally by a patchy, chaotic to structureless seismic response, with common point-source reflectors. The base of the unit is marked by a strong reflector which appears to represent an erosive surface.

The mounded morphology of this facies and its lithological composition, a diamicton, is consistent with a glacigenic origin. The widespread distribution and overconsolidated nature of the unit suggests that it is a till deposited at the base of an icesheet.

WBA2

Description This unit is restricted to discrete pockets in the Tay and Forth approaches. It is found within channels and shallow depressions eroded up to 10m into the upper part of WBA1. In the mouth of the Firth of Forth it forms a more continuous deposit onlapping bedrock and overlying WBA1. The upper boundary forms the seabed surface, but does not indicate subsurface irregularities, except within partially infilled channels. This is a strong, slightly undulatory, first order reflector. The basal reflectors defining the channels and depressions are third order, and poorly defined, especially in some of the smaller channels. The basal reflector of the more continuous deposit is either first or second order and uneven.

The facies displays an homogenous, low amplitude seismic response, with rare truncated and disturbed third order internal reflectors showing random orientation. At the base of some of the channels there are rare point-source reflectors.

Interpretation This is a blanket deposit which covers WBA1 and infills channels and shallow depressions. The internal structure of disturbed third order reflectors suggests that the deposit has undergone post-depositional change. The unit is also present within the channels and depressions, but has a completely chaotic response with no third order reflectors. However the point-source reflectors indicate coarser material.

The amplitude and homogeneity of the seismic response represent a medium energy depositional environment, such as a sand-dominated sub-littoral deposit.

WBA3

Description This unit is found throughout zone WBA as a thin drape, and is also found within some of the channels, depressions and small basins eroded between 5-10m into unit WBA1. It is found in association with WBA2 in the Tay and Forth approaches.

The strong first order reflector is the seabed, whilst the basal reflectors are smooth third order reflectors which

indicate the base of the channel or depression. Low amplitude, laterally continuous, parallel-bedded reflectors exhibiting onlap and draped fill characterise the seismic response of the sediment in the channels and depressions. The thin drape has a low amplitude seismic response, but is not thick enough to display any reflectors.

Interpretation This unit occurs as: 1) a discontinuous drape, 2) an onlapping deposit in the channels, and 3) as both a draped and onlapping fill in the depressions and basins. The channels and depressions were eroded prior to deposition of the unit. The depositional environment was of low, uniform energy, indicated by the reflector patterns, although the variable geometry of the sediment fill indicates different sedimentation processes.

The draped infill suggests that the deposit may be composed of fine silts and clays deposited by suspension sedimentation. The onlapping pattern is more indicative of localised along-channel sediment deposition, and may include coarser sandy material. This unit may be laterally equivalent to WBA2, but this cannot be confirmed from the evidence available.

Figure 3.3 shows sections of project 80/03 lines 16 and 36. The inset of the three dimensional relationship of the lines illustrates the local variations of the unit described. The line 16 example shows the crenulated seabed surface related to sediment transport processes in the Firth of Tay. Line 36 illustrates the west-east unit distribution and seismic responses. It shows the morphology of the ridges and infill deposits, as well as the inshore rock platform.

Zone WBA / Zone WBB Contact

The contact between zones WBA and WBB is transitional. There is no evidence of a sharp contact, and only localised evidence of interdigitation. However topographic change is associated with the contact zone. A ridge and basin topography occurs at, or close

to, the contact. Site investigation data from this zone allowed the detailed examination of the contact. The results are reported in section 3.2.1.4.

Zone WBB

This zone is located on the shelf, as shown in Fig. 3.2. Its western contact is marked by the distal edge of the mounded topography. Its contact with zone WBC is transitional.

Water depths range from 60m in the west to 75m in the east. Sediment cover is thin, and forms a sheet ~25 metres thick, increasing to 30m in the east. The seabed reflector is strong, and obscures up to 8m of the underlying facies unit. The seabed surface is relatively smooth and undulates slightly, but less than in zone WBA. In the north of the Wee Bankie area the seabed is deeply incised by open and partially-filled channels cut into bedrock. Banks and basins occur, locally such as the Montrose Bank (Fig. 1.5). The seabed dips slightly to the north-east with a gradient of 1:2 300. The rockhead reflector is strong (first order), planar and truncates the underlying Permo-Triassic sequence. It mirrors the surface gradient and dip direction.

Figure 3.2 shows that the rockhead reflector becomes less distinct (second or third order) and the gradient of the eastward dip increases to 1:825, where the sediment thickens. The rockhead is dissected by deep (40m), steep-sided channels in the north where sediment cover is thin. It is eroded into a series of shallow (10-15m) depressions near the contact with zone WBA. Rockhead is obscured by the first multiple to the east.

A first order reflector can be traced throughout the zone, except where it has been removed by deep (<75m) 'V'-shaped channels in the east. The reflector is planar and dips to the north-east, with a gradient of 1:4 250. Second order reflectors delineate the major channels and basins. Cuspate third order reflectors indicate the presence of minor channels, within the sediment. They also indicate the type of infill structure, within the shallow basins and depressions, and the structures within the ridge deposits.

The sediments in zone WBB are divided up into three relevant seismic facies units; WBB1, WBB2 and WBB3:-

WBB1

Description This unit is a sheet deposit 20-35m thick. In the west of the zone it is the major unit; to the east it overlies a thickening wedge of older sediment (Stoker *et al.* 1985).

The upper boundary of the unit is a smooth, undulating, first order reflector which forms the seabed, except where this has been cut into by channels or depressions. The lower boundary is the very strong, first order planar reflector, which truncates all underlying strata and sediment.

Proximal to the contact with zone WBA, moderate amplitude, laterally continuous, subparallel prograding reflectors downlap onto the planar reflector, becoming parallel to the planar reflector away from the contact. The acoustic response is locally more variable, particularly associated with the cusped reflectors. The response from within the cusps is of a higher amplitude and is chaotic. The response is similar to occasional beds occurring within the downlapping, and subhorizontal reflectors. Point source reflectors occur sporadically through the unit, with a decrease in occurrence distal to the contact with zone WBA.

Interpretation The unit is a prograding sheet deposit, with a sediment source at the contact with zone WBA, which becomes more drape-like distal to the source. The strength and the undulating morphology of the seabed reflector would suggest that it is composed of a coarse lag deposit, due to winnowing of fines by currents. This may indicate armouring of the surface with the preservation of the original morphology (Owens 1977). The lower primary reflector is probably also composed of a coarse lag deposit because cores penetrating this reflector contain a distinct gravel bed correlated to this reflector (Thomson and Eden 1977).

The overall seismic response indicates interbedding of medium and low energy environments. Within the cusped reflectors the

response becomes more variable suggesting a higher energy system. The lithofacies within the cusate reflectors are suggested to be coarser sands or gravel proximal to the sediment source, fining to sands distally. It is suggested that the cusate reflectors delineate former channel cross sections, as a result of their geometry, and the higher energy sediments within them are interpreted as channel-fill deposits. The inclusion of infill-type material within the parallel bedded reflectors is suggested to be indicative of channels occurring parallel to the line of the geophysical survey.

The point-source reflectors indicate oversized clasts, or clastic deposits within the unit (e.g. gravel within silts).

This unit is interpreted as an ice-proximal glaciomarine unit.

WBB2

Description This unit is found within the shallow, surface depressions and basins which cut up to 10m in unit WBB1 in the south of the area. The upper boundary of the unit is the first order seabed reflector, while the lower boundary is a well defined third order reflector. Minor parallel-bedded reflectors indicate both draped and onlapping fill within the channels and depressions. The low amplitude, but high continuity of internal reflectors' seismic response characterises this unit. This would suggest a uniform, low energy environment. Occasional randomly distributed lenses of higher amplitude reflecting bodies occur within this unit (Fig. 3.4).

Interpretation This is a basin infill deposit, which occurs as both a draped and onlapping unit. The low energy regime would suggest that the lithofacies should be composed of sands, silts and clays.

The differences in the pattern of infill suggests that two processes would have operated; sedimentation of silts and clays from suspension to create drapes, whilst the onlapping fill indicates a higher energy environment and deposition within channelised flow.

WBB3

Description This unit occurs within the shallow channels (<10m) at the seabed surface. It is most common in the north of the Wee Bankie area. The upper reflector is the first order seabed reflector. The lower reflectors are third order, with variable definition, and indicate small, 'V'-shaped channels. The seismic response of the unit displays discontinuous, variable amplitude internal reflectors. Occasional single or multiple, oblique third order reflectors occur within the unit, but it does not have a well-bedded internal structure.

Interpretation This unit is a channel-fill deposit. The seismic response is indicative of a variable energy depositional regime. The lack of regular internal structure suggests that this was deposited in an environment where depositional processes varied, but were dominated by high energy events which removed any structure within channel. The occasional third order, oblique reflectors may represent preserved infill structures. However the general structure would suggest a deposit laid down as a single event, or one which has been reworked. Interestingly there is no evidence of oversized clastic material, as would be expected in a high energy environment.

Zone WBC

This zone extends beyond the 0°00' line of longitude, and outwith the study area to the east (Fig. 3.2).

Water depth ranges from 75m in the west to 90m in the east. The sediment cover comprises a thickening onlapping sequence overlying a prograding wedge, which is thickest in the north-east, where up to 180m of sediment occur. The seabed dips to the north-east as a smooth, undulating continuation of the surface in Zone WBB. One deep, open, channel occurs in this zone, as shown on line 34 in the inset in Fig. 3.3.

Rockhead is only detected in the south; elsewhere it is obscured by the seabed multiple. It is a strong first or second

order reflector, which dips to the north-east, with the same gradient as in zone WBB. Rockhead is uneven and is interrupted by 'V'-shaped single channels and depressions.

The geometry of the reflectors within the sediment units become more numerous with complex internal structure. The first order reflector continues from zone WBB, but becomes more fragmented having been removed by infilled channels. This reflector loses strength in the south-east and eventually peters out. In the north of the area it can be traced to the east, where it rises to the surface near the 0°00' line. This may be due to thinning of the overlying unit.

The unit boundary reflectors delineate two seismic facies units, with the possible inclusion of the upper part of an older unit in the south-east, where the first order reflector is absent. The seismic facies units are WBC1 and WBC2:-

WBC1

Description This is the main seismic facies unit in zone WBC (Fig. 3.5). It occurs throughout the zone, except in the south-east where it pinches out beneath an extensive deposit of unit WBC2.

The upper boundary is the first order seabed reflector and the lower boundary is the primary, planar reflector. In the south east the lower reflector becomes weaker, rises up towards the surface, but is truncated by the erosion surface at the base of WBC2. The unit is only 20m thick in the south, as opposed to nearly 40m thick in the north-east.

The unit exhibits a medium amplitude, laterally continuous, parallel-bedded internal seismic response. There is more internal structure present to the north with third order reflectors occurring as both parallel-bedded and occasionally cusped and prograding reflectors. Occasional point-source reflectors occur, which become rare to the east. In the south the structure decreases as the unit pinches out.

Interpretation This unit is interpreted as an ice distal glaciomarine sheet deposit. The environment of deposition was of low to medium energy producing a prograding to draped deposit of

fine material. Ice rafted debris is present but rare, and also decreases to the east. Rare cusped reflectors with higher amplitude seismic responses within their boundaries are interpreted as channel cross-sections. These would be expected to contain coarser sediment. This interpretation is extended to the prograding reflectors with higher amplitude seismic responses, which indicate coarser sediment building out from a source in the west.

WBC2

Description This unit occurs within deep, steep sided, 'V'-shaped, symmetrical and asymmetric, single and multiple channels, which become more common in the north-east of the zone. The channels are up to 95m deep, and are all infilled, except for one at the eastern end of line 34, which is partially filled with onlapping sediment.

The upper boundary is the smooth first order reflector which forms the seabed. The lower boundary is usually a second order reflector, but can be a third order reflector. This reflector delineates the channel boundary, and can be very uneven in the complex multiple channel incisions. The channels can incise into all the units, including the oldest Aberdeen Ground Formation (Stoker *et al.* 1985). However, they do not extend into the rockhead.

The seismic response of the unit indicates variable amplitude and continuity. Third order reflectors occur as both parallel-bedded onlapping infill, and complex multi-phase infill. Third order internal reflectors within the multi-phase infill indicate that up to three infill events are preserved in different channels. The infill ranges from draped fines to coarse diamicton, indicated by the chaotic-signature with hyperbolic reflectors (Fig. 3.5). The deep channels in the north-east of the zone do not show this three phase infill pattern. They are infilled with a sandy unit which grades to a chaotic diamict-type unit, or to muds with no visible internal structure and no point-source reflectors.

Interpretation This is an infill deposit within channels which

postdates the last significant depositional episode associated with WBC1. The size of the channels would suggest that they were cut in a very high energy incision phase in the sediment history of the North Sea.

The seismic response suggests that the infilling events occurred in rapidly changing energy regimes. In some of the channels third order discontinuous onlapping reflectors suggest a draped deposit, indicating a decrease in the energy regime and possibly the presence of silts and clays. Where the third order reflectors within the channels are prograding this suggests bedforms within the channel infill and point-bar sediment assemblages. In the south-east, it is suggested that the erosive event which cut the channels, also created a basin eroded into unit WBC1, which was infilled with this unit. This is illustrated on Line 27 in Fig. 3.3.

3.2.1.2 CORE ANALYSIS RESULTS

Five boreholes from this area have been analysed in the laboratory. The results from these, along with reference material from 4 boreholes and 8 vibrocores, have been used to produce the composite logs for zones WBA-WBC, shown in Fig 3.6. The raw data are shown in appendix 3.

Three lithologies are present in the boreholes; diamictons, sand and mud (silts and clays). The lithofacies which these represent have been derived by looking at the sedimentary characteristics, as outlined in chapter 2. Five units have been found in the boreholes:-

Unit 1

Description This is found in boreholes 81/27, 81/36 and 81/40, in zone WBC. It is the lowest unit resting on rockhead, or above the older Quaternary sediment. It varies in thickness from 15-25m, but increases to the east, consistent with the seismic data.

The lithology of the unit is muds, and some fine sands. The size distribution curves (Fig. 3.7) indicate a coarsening upwards

through the unit. In 81/27 there appears to be cyclicity over a distance of 40cm within the finer sediment of the lower part of the unit. This is also mirrored by the CaCO_3 percentages in this core. The number and size of clasts increases upwards. This affects the size distribution curves.

The unit becomes less structured upwards, from well-laminated with rare or absent clasts in the lower part, to a disturbed (loading structures only), or structureless unit in the upper part. The clasts are small (5-2mm in diameter), and vary from angular to sub-angular. Provenance studies show that some of the clasts are far-travelled and include non-local metamorphic and igneous rocks originating from Highland Series and Midland Valley Series rocks (Fig 3.8b). Micaceous material is found within the laminae, these are <500µm and occur throughout the lower part of the unit. Shell fragments have been found, most too small or abraded to be identified. They may reflect contamination of the material at a depth of 9m in 81/36 during collection (Graham, 1989b). However, material in borehole 81/27 includes *Astarte borealis*, at a depth of 6.3m, which suggest a colder environment than present day conditions. It is possible that the fauna at this depth is Pleistocene (Graham 1989e).

Interpretation This unit is interpreted as a glaciomarine deposit, which was deposited distal to the margin of an advancing ice sheet, with its source on the Scottish mainland. Through time, the environment became relatively less distal, but was still dominated by fine sands to clays, with up to 25% of the unit composed of clay.

Sedimentation rates increased through time resulting in a less structured deposit, especially closer to the margin. This resulted in loading structures in some areas. In the extreme distal areas the presence of laminae suggest that sediment input was pulsed, as would the cyclicity indicated by the particle size distributions for 81/27. Faunal material is rare in this unit. There is no evidence of reworking and the removal or destruction of shells. This suggests that either fauna was rare, due to an extreme climate, or that the sedimentation rate was too high, or

both. The sediment sizes indicate that it is likely that two processes of sedimentation were in operation, namely sediment transported by bottom currents and suspension sedimentation, from plumes of fine sediment.

Unit 2

Description This unit is found in zone WB3 immediately to the east of the mounded topography. It has been penetrated in boreholes 73/27 and 81/36. The unit varies in thickness from 10m in the west to a thin to absent deposit in the east. Lithologically it is composed of medium sands, silts and a small percentage of clay, with 5% clasts, some of which exceed 10mm in diameter. The clasts are located randomly throughout the unit (Fig. 3.7). The lower boundary of the unit is transitional with unit 1. Near the base of unit 2 there are some laminated sections. These are composed of silt and fine sand. Laminae are sometimes disturbed by dropstones, indicated by impact disturbance of the underlying material and silt cappings overlying the clasts (Fig. 3.9).

Provenance studies suggest that the clasts originate from the Scottish mainland. The clasts are igneous and metamorphic rocks from the Highland and Midland Valley Series rocks (Fig 3.8a and b.). The clast shapes and surface morphology, including striated and 'flat-iron' clasts, suggests subglacial transport. The 2-5mm clasts tend to be angular to subrounded. Shell fragments are found scattered throughout the unit.

Interpretation This unit is interpreted as an ice-proximal glaciomarine deposit. It exhibits many of the characteristics of unit 1, but is coarser, with a greater number of clasts. The morphology of the clasts indicate glacial transportation. The presence of 'outsized' clasts in the particle size distribution which are found as dropstones, show that ice rafting of debris has occurred. Some of the coarser sand-dominated sediment within the unit may have been reworked by, for example, slumping and localised fluviglacial derived currents at the margin, thus removing the mud component of the particle size distribution (Fig. 3.7). This is best illustrated in the base of 81/33, where the mud

is still present in the unit because it has been protected from reworking at the margin of an advancing ice sheet, by being deposited in a depression.

Unit 3

Description This unit is located in zone WBA, and forms the mounded topography shown on the seismic sections. The unit thickness is 10-15m thick.

The sediment is composed of a very poorly sorted admixture of clasts set in a sandy and muddy matrix, a classic diamicton as shown in Fig. 3.7 (Miall *et al.* 1983). The unit is overconsolidated, massive and contains no internal structures, or fabric. The clasts are matrix supported. Analyses of the clasts shows that they are predominantly sub-angular, with smaller proportions of angular and sub-rounded clasts. The clasts often showed the striated, 'flat-iron' and reworked indicators (broken well rounded clasts) of glacial transport (Boulton 1978).

Provenance studies show that the clasts <10mm, and those 2-5mm in size originate from the Scottish mainland. However the likely source of the clasts is more restricted than for the ice rafted debris of units 1 and 2 (Fig. 3.8a and b). Matching the lithology of the clasts to the solid geology (Fig. 1.4) indicates that the clasts have been derived from deposits immediately onshore. Although an exception is shown within 81/33, which contains a fragment of coal in the 2-5mm fraction which has been transported from the Midland Valley Coal Measures, outwith the local sediment source area which includes the Devonian strata of Strathmore, and the igneous and metamorphics associated with the Highland Boundary Series. Clastic material has also been incorporated from erosion of the underlying Permo-Triassic rockhead, and includes sandstones, siltstones and mudstones.

The different clast sizes do not automatically indicate the same source for the sediment; the smaller clasts show larger possible source areas, although there is good agreement on the general localities. This may relate to the small size of the clasts, making identification difficult. However the sediment may

have been transported further and become more eroded. Minor fluctuations in the dominant rock classes within the core suggest minor fluctuations in the dominant direction of the ice, through time. However with the exception of 81/33, no major changes in ice flow direction have occurred.

Subtle differences occur in the mud fraction. The mud, especially the clay, dictates the colour of boreholes 81/31 and 81/33. When wet sieved, the sediment in these cores change from light brown, through reddish brown, to grey and dark olive grey, as found in the other cores, but the <63 μ m residue is red.

The unit contains rare reworked shell fragments which are highly abraded, and include *Chlamys islandica*, in 81/33 at 5.6m (Graham 1989d), and possibly 72/21 at 2.5m (Graham 1989f), although most fragments are unidentifiable in these boreholes. However, in 81/32 samples of *Macoma balthica* (9.55m) and *Macoma* ? (9.65m) indicate colder conditions (Graham 1990).

Interpretation This unit is interpreted as a glacial diamict, probably a basal lodgement till, deposited beneath an ice sheet. It is overconsolidated, possesses no structure, is very poorly sorted and contains clasts which have been transported from outwith the area of deposition. Shells within the diamicton are reworked and have been highly abraded and crushed.

Unit 4

Description This unit is found in the base of vibrocores and consists of mud, overlain by recent sediments. In BGS logs it has been correlated to the Forth Formation. It is suggested that this unit represents the fining-up glaciomarine mud associated with a retreating ice front, marking the transition from a glaciomarine to ice distal marine setting, especially as glaciomarine sediments are known to exist onshore. This unit may be part of the draped infill within the shallow depressions seen in the seismic lines. If this is the case, then it is possible that this unit has been reworked, or eroded in places. Evidence for this, however, was not actually found within the boreholes examined.

Unit 5

Description This is the uppermost sediment unit found in the area. It occurs as a veneer ranging from a few centimetres to 1m thick, but is usually about 0.5m thick. It is composed of moderately well-sorted sands (Fig. 3.7), with a very high shell content. The shelly material includes fragments such as echinoid spines, as well as complete shells, which indicate marine fauna present today, although some are unidentifiable (Graham 1989a,c,d, 1990).

Interpretation This unit is interpreted as Holocene seabed sands and muds, based on the macrofauna present. These have probably formed from reworking and winnowing of the diamicton and glaciomarine sediments, with additional inputs from fluvial sediment transport.

3.2.1.3 REGIONAL INTERPRETATION

The Wee Bankie area can be divided into three distinct zones, WBA, WBB, and WBC. Within each zone a number of seismic facies units have been identified and described. Lithological descriptions of the seismic facies units within each zone have been made, on the basis of the lithological control provided by boreholes and vibrocores. From the evidence presented it is possible to suggest how the sedimentary succession was deposited.

The distribution of the zones is sub-parallel to the coast, with a north-easterly influence exerted by the dip in the rockhead and bathymetry to the Fladen basin in the north-east. Strong caledonoid structural trends further influence this orientation.

Zone WBA contains subglacial till (WBA1), deposited on eroded bedrock, which has subsequently been overlain by draped and onlapping sediment units WBA2 and WBA3, interpreted as veneer and infill deposits. Prior to the deposition of the younger units (WBA2 and WBA3) an episode of erosion took place which cut the deep channels. The glacial diamict unit (WBA1), blankets this



zone, and has an uneven surface topography, which includes mounds, at the junction with zone WBB. These have been interpreted as moraines, deposited at the margin of an ice sheet. The ice sheet was supplied with sediment from the Scottish mainland. In this zone the material was transported both englacially and subglacially, as shown by the clast shape and surface morphology data. The ice sheet also incorporated local material, eroded from the bedrock, and reworked sediment. This is shown by the reworked macrofauna, and broken clasts found within the diamict. Although the seabed surface undulates, there is no evidence of standstill positions between the moraines in the channel and hummock topography, and the present day coastline, such as smaller, stacked, mounds.

The deep channels are filled with an onlapping and occasionally complex, infill unit, which suggests a flow of material along the channel. It is suggested that these may represent subglacial meltwater drainage channels, given their morphology and location within the diamict-dominated zone. The draped units may represent the upward transition from ice-proximal to ice-distal and then marine conditions, as the ice sheet retreated from this zone. Contemporary seabed sediments form a thin (0.5m) surface veneer overlying the seismic facies and sediment units identified in this zone, except within the estuaries, where it would be expected that estuarine muds are deposited.

Zone WBB contains 3 seismic facies units which have been interpreted as; 1) a prograding ice proximal glaciomarine unit, which fines to the east (WBB1), and 2) and 3) as onlapping and drape units infilling depressions, basins and channels eroded into the surface of WBB1 (WBB2 and WBB3), as outlined in the seismic facies and sediment descriptions.

It is suggested that unit WBB1 developed as a prograding outwash fan, in front of an ice sheet grounded in zone WBA, but which ended, or became uncoupled from the seabed in the contact area between zones WBA and WBB. The prograding sequence was supplied with sediment from meltwater. The subhorizontal sediments

distal to the contact relate to plumes of fine silts and clays which were deposited by suspension sedimentation processes. Point-source reflectors relate to coarse ice-rafted debris originating from the Scottish mainland, and/or reworked sediment at the base of the grounded ice sheet. Alternately it is suggested that the ridge-proximal, prograding sequence may represent a subaerial outwash plain which graded into a glaciomarine environment.

The depression in front of the ridge, associated with the transition between zones WBA and WBB, and extant in the rockhead, relates to ice proximal erosion both by proglacial meltwater and basal erosion at the ice margin. The structures in the prograded section may also include post-depositional glaciotectonic structures due to slumping and / or overriding of the sediments by further ice activity. However the majority of the deposit is glaciomarine as is shown by the structures within the cores, and the particle size distributions which are indicative of waterlain deposition. WBB1 contains Pleistocene colder climate faunal indicators in comparison to the present day faunal assemblage in the sampling locality.

The presence or absence of the first order reflector shown on Fig. 3.3 at the base of the glaciomarine unit is important. It is suggested that the western limit of this reflector marks the maximum eastern extent of the ice sheet where it was in contact with its base. Thomson and Eden (1977) suggest that this reflector relates to a marine transgression which predates the late Weichselian glaciation. Further to this I would suggest that this reflector originally extended to the present day coastline. When the ice sheet advanced into the present day marine environment the basal processes and loading effect of the ice sheet either removed the reflector by reworking the sediment, or eroding rockhead, or altering the geotechnical properties such that the strength and continuity of the reflector was lost. Thus, where the reflector is absent in the west, and the seismics suggest a diamict facies unit, the ice sheet was present and in contact with the base. The eastern transition to a glaciomarine seismic facies unit overlying the first order reflector indicates the boundary between an ice

sheet in contact with its bed, and an ice sheet that has become uncoupled from its base, as a function of terminating in water deep enough to allow the ice to float. This is used to define the eastern margin of the ice sheet, assuming that the diamict and glaciomarine units are lateral equivalents.

Zone WBC is the eastward extension of the glaciomarine environment. It contains two seismic facies units WBC1 and WBC2. WBC1 is interpreted as the ice distal continuation of WBB1. The sediments within this unit are finer and contain rare, small clasts which have an ice rafted origin, probably derived from the east coast of the Scottish mainland. The first order reflector still occurs as a marker horizon for the base of the sediments of interest, although it is not as continuous. The surface veneer and channel infill sediments are thinner and are restricted to channels in the north-east of the area. In the south-east, however a substantial structureless basin-fill deposit of WBC2 occurs, with part of the underlying WBC1 unit eroded and removed during the basin forming event. The energy regime associated with the deposition of unit WBC2 is higher than the energy regimes which resulted in the shallow channels in zone WBB and those in zone WBA, which postdate the erosion of the deep subglacial meltwater channels. These channels are of an intermediate scale compared to the features. If they related to the same event, one would expect a similar magnitude of erosion, regardless of location.

The channels in zone WBC cut down through the first order marker reflector which is thought to relate to the marine transgression which pre-dates the deposition of the units examined here (Thomson and Eden 1977). The deep channels may represent channels incised by the meltwater released from the ice sheet (Wingfield 1990). These have undergone a complicated infill history, as indicated by the triple infill styles.

Table 3.1 summarises the results from the seismic facies analyses and the sedimentary analyses, for the Wee Bankie area.

Table 3.2 attempts to correlate the results of the seismic facies unit and lithofacies unit definitions, with the existing

BGS stratigraphy for the Tay-Forth approaches and Marr Bank area (Stoker *et al.* 1985). This has been achieved by comparing the seismic facies units and the sedimentary units summarised in table 3.1, and Figures 3.2, 3.6 and 3.7, with the BGS defined stratigraphy as summarised in chapter 2 (Figs. 1.7, 1.8 and 1.9, and table 1.4). Units WBA3 and WBB3 are correlated with sediment unit 4, the St. Abbs Formation. WBA2, WBB2 and WBC2 are all correlated with the Forth Formation. WBA1 is correlated with sediment unit 3 and is thought to be the glacial diamict of the Wee Bankie Formation, whilst WBB1 and WBC1 are correlated with the Marr Bank Formation. WBB1 is correlated with sediment unit 2, which is an ice-proximal glaciomarine unit, whilst WBC1 is correlated with the ice-distal glaciomarine unit, unit 1.

3.2.1.4 DETAILED INVESTIGATION OF THE ICE MARGIN

From the regional seismic survey, it is suggested that the area of hummocks and channels topography represents the boundary position between subglacial deposition at the base of an ice sheet, and proglacial deposition into a glaciomarine environment. However, the regional seismic survey does not provide sufficient coverage and resolution to enable detailed examination of the margin area, although, it does show interesting geometric relationships between the units, for example, interdigitating subglacial and glaciomarine units occur in line 36 (Fig 3.10). This suggests that this area contains a complicated record of ice-marginal perturbations, as well as genetic evidence of the type of ice margin present, and the processes affecting it, which have been preserved within the local and regional sediment record.

Data collected from a detailed seismic survey across this area has been analysed to reconstruct and classify the margin, and dominant processes active in its formation. The survey was commissioned by BP and completed by GEOTEAM UK Ltd. The data consists of high resolution, 1KJ analogue, sparker seismics, shot in 1984, using a Hunttec Deep Tow Sparker system. Twenty four seismic lines oriented north-south and east-west, at a 120-500m line spacing, have been interpreted (Stewart 1988b).

The survey site is located approximately 40km east of Montrose, centred on $56^{\circ}46'57.8N$, $1^{\circ}41'32W$. Water depth ranges from 40m-50m, with localised troughs 65m below the sea surface. The seabed is marked by a strong, uneven first order reflector. Seabed sediments are composed of sands and sand and gravel mixtures. The seabed topography consists of localised discontinuous ridges in the centre, small, deep troughs in the west, and a group of streamlined mounds, aligned north-south, in the east (Fig 3.11). The ridges are asymmetric, with steep-sides on the western side, with small mounded outliers, forming a discontinuous double-ridged arc. The secondary ridge occurs behind the main ridge and accentuates the arcuate system. These ridges are only 4m high compared to the 7-8m height of the main ridge. The internal seismic structure of the ridges is chaotic with occasional random seismic reflectors, some of very high amplitude. The ridges are related to a channel network developed at the same level. A channel 100m wide separates them.

Rockhead is irregular and reflects the underlying Triassic strata which are deformed with varying intensity. The deformation has been mapped (Fig. 3.12). On the seismic profiles rockhead is generally marked by an uneven second order reflector except in the south-east and extreme north-west, where it is marked by a planar, first order reflector. Rockhead topography can be divided into two types; in the north-west and south-east the rockhead undulates slightly with depths of 70m, +/- 9m, whilst the rest of the area is dominated by a deep, steep-sided, channel trending south-southwest to north-northeast. This channel is located partly along a fault, and partly within the areas of severe rockhead deformation. The depth of the channel ranges between 130m, in the south-west, to 85m. The channel lip occurs at 80m below sea level. The average depth of the channel base is ~100m, below sea level. The channel floor is uneven and includes two enclosed deeps, up to 130m below sea level (Fig 3.13).

Sediment cover ranges from 10-15m, where it overlies the slightly undulating bedrock, to 55m, where the infill within the channel is thickest. This does not coincide with the deepest

basin, which lies beneath a depression at the surface.

Third order reflectors indicate an internal structure which can be traced across the area, namely a system of wide, shallow channels, which occur at 65m (70ms TWT) within the sediment (Fig. 3.14).

Four seismic facies units have been identified; GEO1, GEO2, GEO3, and GEO4; their distribution is shown in Fig. 3.15. Figure 3.16 shows an interpreted seismic section illustrating the different seismic facies units;

GEO1

Description This unit is found in the north-west and east of the area. The upper boundary is the second order seabed reflector, and the base of the unit is marked by a strong, first order reflector, cut into rockhead. The unit occurs as a drape deposit, with a high degree of internal structure. Subparallel- to parallel-bedded reflectors indicate either prograding downlapping, or onlapping internal structures. In addition, small, cusped reflectors and local unconformities which are present and are thought to represent wide, shallow buried channels. These channels can be linked to form a network at some depths (Fig. 3.14), although within most of the sequence this cannot be achieved with much confidence. Occasional point-source reflectors occur. High amplitude and good continuity, characterise reflections in this unit, except where cusped reflectors and channel sections are infilled by a more chaotic response.

Interpretation This unit has the same seismic facies characteristics as WBB1 and is suggested to be the Marr Bank Formation, a glaciomarine unit.

GEO2

Description This unit is a sheet deposit which infills the deep channel cut into the rockhead. The upper first order reflector, is the seabed, which includes the upstanding ridges shown in Fig. 3.11. The base of the unit is the uneven, poorly defined, second order rockhead reflector. Laterally, the unit interdigitates with,

or overtops unit GEO1. The two boundary types are shown on Fig. 3.16. The internal structure of the unit is variable. It ranges from a locally seismically transparent unit, especially at the base of the main channel feature, through a hummocky chaotic seismic response, to a structured subparallel reflector configuration, increasing in strength and continuity towards the upper boundary of the unit. Point source reflectors occur locally. *Interpretation* This unit gives the same seismic facies response as shown by WBA1. It is suggested that this is a glacial diamicton unit which can be correlated on seismic response with the Wee Bankie Formation.

GEO3

Description This occurs within shallow depressions at the seabed, distributed throughout the area. The upper boundary is the seabed reflector, whilst the lower boundaries of the depressions are third order reflectors representing local unconformities.

The internal structure of the unit ranges from continuous, planar, parallel-bedded, onlapping third order reflectors, of low amplitude, to a uniform chaotic fill. The change in reflection character is gradual.

Interpretation This unit is an onlapping variable energy deposit, including low energy and high energy infill facies. It is suggested that the unit represents either, low to high energy pulsed sediment deposited from along-channel flow, or that the unit forms an infill of fine material, deposited by local settling, but with high energy erosion of the local area occurring, thus providing a nearby source of sediment. Sediment transport is presently occurring, as shown in Fig. 3.15, where unit GEO3 is being overridden by unit GEO4.

It is suggested that unit GEO3 correlates with the Forth Formation, based on the seismic response characteristics.

GEO4

Description This unit occurs as a bifurcating ridge complex, 9m high, in the north-west of the area, and as a mound in the north-east, on the seabed.

The upper reflector is the strong, first order reflector of the seabed, and has a crenulated morphology. The lower boundary is formed by a second or third order reflector, present as a basal unconformity. The internal structure is defined by third order and 'other' reflectors, which form a steeply dipping, downlapping, parallel-bedded unit, onto the unconformity surface. The internal seismic response is medium amplitude, with high continuity.

Interpretation The cross-sectional morphology of this feature, and the internal geometry of the main ridge, would suggest that this unit consists of a sand-dominated lithology, which forms sandwaves. The crenulate upper surface is due to the presence of ripples on the stoss slope of the wave. These indicate pulses of sediment transported across the surface of the ridge.

3.2.1.5 AREA RECONSTRUCTION

The seismic facies analysis confirms that this area represents a palaeo-contact zone between a subglacial diamict and a proglacial glaciomarine, prograding outwash deposit, which fines distally. Seismic facies units GEO3 and GEO4 post-date the glacial sediment units and are not referred to further, with regard to the reconstruction of the ice margin.

The seabed topography is dominated by an upstanding ridge system composed of unit GEO2, which also infills the channel eroded in the bedrock. The ridges and infill are composed of diamicton. Some of the internal reflectors within the diamicton unit may represent glaciotectonic structures, and others outline mounded deposits associated with overriding of earlier structures. They may represent slip-planes for mass movement of unstable diamicton e.g. slumping, or avalanching as the result of pushing of the sediment. Planar, short but high amplitude reflectors within the diamicton may represent boulder pavements, or rafted sediment blocks.

The ridge system is interpreted as a moraine, which formed during the retreat of the glacier from the maximum which existed to the north-northeast of the area, probably within a few

kilometres. If it was possible to trace the channel, and also the primary reflector in the north-northeast, the limit could be found. This follows, given that the first order reflector predates the deposition of the glaciomarine and diamict units, and marks the boundary between the areas of the sediment body which have or have not been affected by the presence of an ice sheet in contact with its bed, as explained in section 3.2.1.3.

The age of the bedrock channel is unknown; it may pre-date the glacial event, but has been subsequently overdeepened by erosion at the base of the ice especially as this area of the bedrock was more susceptible to erosion than the surrounding strata, given the deformed state of the rock, and the location of the fault.

The ice margin remained at this position for sufficient time to deposit and overrun existing ice marginal diamicton accumulations. At this location the ice sheet was still in contact with its bed, as there is no evidence of glaciomarine deposits being incorporated within unit GE02.

The glaciomarine unit is composed of channels associated with an ice proximal prograding outwash fan, which becomes a glaciomarine drape to the east. The channel morphologies, wide and shallow, with a width:depth ratio (F) between 20 and 40 (Schumm 1968) indicate a complex environment of sediment transport and channel behaviour.

Sediment transport would have included both suspended and bedload transport, with erosion and deposition occurring on the banks in the same reach, as indicated by the different internal seismic responses of the channel infill. The channel network (Fig. 3.14) consists of two confluent channels. They exhibit very high F values (~100) suggesting a very active transport regime. The base of the channel network undulates (assuming a uniform response in the overlying sediment). This suggests either channel formation under strong hydrostatic pressure or post depositional deformation. This area does not coincide with the area of high deformation therefore it is associated with hydrostatic pressure. Palaeoflow was from west to east, given the channel network morphology.

The presence of GEO2 overtopping GEO1 shows the expansion phase of the ice in the area, but there is little evidence of the retreat phase. In the north-east of the area, there is an enclosed deep which is 18.5m deep and 150m wide. This is probably a kettlehole, which suggests that some of the sediment was ice-cored, and *in situ* melt-out occurred. However, there is no other evidence to suggest a period of stagnation and downwasting. Thus, it is suggested that ice-retreat was rapid, possibly related to a change in sea level. This would have caused an uncoupling of the ice sheet from the base, and floating off of the ice, resulting in rapid calving and break-up. The lack of a thick cover of glaciomarine sediments, overlying the diamicton, derived from a slowly retreating margin testifies to the speed of break-up. The low gradient of the base of the ice would also have been important, in that a small change in sea level would have had a significant affect on the area of ice that was decoupled from the base.

The ice margin was partly confined by the bedrock channel, suggesting that the margin was possibly an outlet lobe at this point. The incorporation of glaciomarine sediments within the diamicton indicates that it was not always in contact with its base, or there were cyclic advances of the marine based margin.. The presence of a complicated network of channels within the prograding outwash indicates that subglacial meltwater activity was strong, and sediment transport rates were high. The rapid change from the prograded to sub-horizontal seismic reflector patterns, suggests that coarse material was not transported far beyond the margin.

It is suggested that at this location the ice margin was a tidewater margin, calving into a shallow epicontinental sea, with ice rafting, and sediment plumes transported to the east (Powell 1981, 1984 Facies II type margin pp 131).

3.2.2

PETERHEAD (57°-58°N, 0°-2°W)

3.2.2.1 SEISMIC PROFILES

The Peterhead area exhibits extensive glacial and glaciomarine deposits which relate to the late Weichselian glacial episode (Stoker *et al.* 1985). Post depositional reworking by strong seabed currents (Fig. 3.17) has masked/destroyed many of the definitive indicators of the different units and associated reflectors, which would allow unit extents to be mapped out in terms of the seismic facies units defined in the Wee Bankie area. The interpretation of the sedimentary record is also made difficult by the bathymetry of the area, and the lack of lateral stratigraphic continuation within the deeps and over the highs where active sediment transport has removed the evidence. Despite these problems, a composite profile has been constructed for the Peterhead area (Fig. 3.18). This is based on lines taken from BGS projects 70/03 and 72/04.

The profile and area have been divided up into 4 zones; PA, PB, PC and PD, based on the different seismic facies which occur from the coastline to 1°W. The distribution of the zones is shown in Fig. 3.18. Figure 3.19a shows the north-south distribution of seismic facies units.

This work aims to establish the northward extension of the Wee Bankie moraine, and the type of ice margin which existed in the Peterhead area.

Zone PA

This zone is approximately 5km wide, extending from the coastline to a transitional contact with zone PB, but is absent in the north of the area. It occurs in water up to 60m deep. The seabed surface is smooth except where crenulations in the surface reflector indicate bedforms (dunes, ripples) which suggest sediment transport is occurring at the seabed. Rockhead is indicated by a very strong first order reflector, which is smooth

and convex-upwards. The sediment cover is thin, rarely exceeding 15-20m, and forms a sheet drape on rockhead. There is little internal seismic structure within the sediment body which appears to represent a single seismic facies unit (PA1).

PA1

Description This unit displays a chaotic acoustic response. Over much of its distribution there are no internal seismic reflectors within the unit, although near the contact with zone PB there are rare medium amplitude, discontinuous, downlapping, prograding reflectors. Sporadic, randomly located, lensoid inclusions of medium amplitude and continuity seismic response occur near to the prograding internal reflectors, approaching the transition with zone PB.

Interpretation This sediment unit was probably deposited in a variable energy environment. The lensoid features and prograding reflectors may be remnant structures of a fluvio-deltaic sediment body, which has subsequently been reworked giving rise to the chaotic acoustic response. Its proximity to fluvial sediment sources suggest that it is likely to comprise of coarse sediments such as sands and gravels but possibly fining distally. The elongate distribution, paralleling the coast, is probably the result of currents redistributing the sediments, subsequent to the deposition of the delta.

Zone PB

This zone extends from the transitional contact with zone PA, to 15km from the coast, at its maximum extent (Fig. 3.18). It is located in water up to 65m deep. The seabed is a first order slightly uneven reflector, with small upstanding features, and dips gently to the east with a gradient of 1:400. Rockhead is marked by a first order uneven reflector, which becomes more even in the east, where it starts to dip to the northeast with the same order of magnitude of gradient as the seabed surface. The intervening sediment body forms a wedge, which thins from ~15m to

less than 10m from west to east, and represents one seismic facies unit (PB1). Boreholes 72/21 and 72/30 are located in this zone, and are described in detail in section 3.2.2.2. The lithologies associated with this zone are loose sands and gravels with organic material, overlying a diamict.

PB1

Description This unit is acoustically well-bedded, the internal reflections displaying a prograding clinoform pattern. Subparallel reflectors in the west become more sigmoidal eastward, where they downlap onto rockhead, or interdigitate with the sediments of zone PC. The reflectors are typically of high amplitude and are laterally discontinuous in the west, but at the top and base of the unit the reflectors display variable amplitude and continuity, particularly in the east. This unit contains occasional point-source reflectors.

Interpretation The geometry of the unit and its internal acoustic texture resemble a deltaic-like sediment body which, given its location adjacent to the Ythan and other fluvioglacial drainage systems that transported vast quantities of sediment to the sea, is probably composed of outwash material. The clinoform pattern suggests that delta-top, delta-front and pro-delta sediments may be present. These probably consist of sands and silts on the delta-top, becoming more argillaceous, seaward. Larger material is probably present where palaeochannels exist within the deposit and point-source reflectors occur (FIG. 3.18).

The delta is being reworked; sediment transport features exist on the surface, and the structure of the delta is being destroyed by reworking at the eastern limit. Reworking disturbs the internal acoustic response, and can produce a chaotic seismic response indicative of diamictons. In this unit, reworking has not been of sufficient intensity to create the latter response, but it has altered the seismic response at the top and base of the unit, in the east (Fig 3.19b).

Zone PC

This forms a transitional area between zones PB and PD, and may be up to 5km wide (Fig. 3.18). This zone appears to consist of one seismic facies unit, PC1, which forms an uneven blanket deposit, varying in thickness throughout the line, from ~10m to less than 5m, although in the east it is difficult to determine the position of rockhead, and therefore the thickness of sediment overlying it.

The top of the unit, the seabed surface, is highly uneven; it exhibits two discrete sets of waveforms, orientated in opposite directions, and a ridge (Fig. 3.19c). The sediment cover is at its thinnest between these waveforms. The rockhead reflector forms the base of this unit, changing from a first order reflector in the west, to a poorly defined, third order reflector in the east. The poor definition in the east is associated with deformation of the underlying rock, which tends to obscure the reflector (Fig. 3.20).

PC1

Description In the west, seismic facies unit PC1 interdigitates with unit PB1, while in the east there is a transitional contact with unit PD1. The overall acoustic response, however, is chaotic, with rare point-source reflectors, especially in the east, above a possible bedrock depression. Borehole 72/31 is located in this area.

Interpretation This unit is interpreted as a diamict. The sediment is probably a mixture of sands and silts, as suggested by the seismic response, and the available sediment supply. This unit correlates with sediment unit 3, and overlies sediment unit 2, as found in borehole 72/31 (Fig. 3.21), as outlined in section 3.2.2.2. This is currently an area of active sediment reworking and erosion (Total Oil Marine 1973). The sediment at the front of the delta is being reworked, and partly removed, leaving the

sediment cover locally very thin. Two different sets of currents are transporting the sediment, as shown by the two opposing directions in the seabed sediment waves.

Zone PD

This zone extends seaward to 1°00'W, approximately 20km (Fig. 3.18) from the break of slope below 60-70m water depth. The zone consists of two seismic facies units, PD1 and PD2, which overlie an easterly thickening wedge of older, pre-late Weichselian sediments, which are not considered further.

The seabed is a first order reflector, which exhibits waveforms, up to 5m high, and a broad ridge, up to 10m high, near the transition with zone PC, in the west. To the east of the sandwaves, the seabed becomes smooth, with a gentle dip to the north-east, with a gradient of 1:800. The base of the sediments examined in this area is marked by a first order reflector which dips gently to the north-east, but which becomes discontinuous to the east (Fig 3.18). This reflector is locally offset/disturbed by faults which extend from the older sediments upwards into the lower unit studied, but do not disturb the upper unit, suggesting that this unit was deposited on a faulted/offset surface, or that there has been fault reactivation in the older material, possibly as the result of loading during the deposition of the upper unit. This reflector truncates the older sediments deposited beneath it, as well as some of the rockhead in the west, which consists of parallel-bedded Permo-Triassic and Upper Cretaceous strata. The western limit of the reflector is marked by the position of the depression in the bedrock, and associated increase in the deformation structure present in the rockhead. This would suggest that there may have been Quaternary fault movement triggered by loading.

Although two seismic facies units can be clearly distinguished in the east, it is difficult to differentiate

between them near to the western transition area (zone PC) possibly due to poor acoustic responses, or thin to absent cover of the upper unit.

PD1

Description This unit directly overlies the planar, first order reflector, which truncates the older underlying sediments. Although it appears conformable on the surface, there may have been a hiatus between deposition and the event which caused the formation of the reflector. The upper surface of the unit forms an uneven boundary with the overlying unit PD2.

The acoustic texture is characterised by a chaotic, seismic response with occasional point-source reflectors in the west, but internal structure is present to the east, as shown by occasional hummocky, prograding, onlapping and cusped third order reflectors.

Interpretation The cusped reflectors may indicate channel cross-sections, and it would seem likely that the dipping reflectors are along-channel sections. The point-source reflectors indicate the occurrence of oversized clastic material. The clustering of the point-source reflectors to the west suggests that this area may contain an accumulation of coarser material, compared to that in the east. This unit represents sediment deposited in an alternating energy environment, indicated by the different reflectors present; the point-source reflectors indicating the highest energy environments, grading into the lower energy of the prograding reflectors. This is interpreted as a glaciomarine unit.

PD2

Description This is the upper unit. Its surface is marked by the seabed reflector, which in the west, includes some sand waves and also a ridge. The lower boundary of this unit is uneven, and occurs either as a second or third order reflector. The sediment in this unit overlies much of unit PD1 as a conformable drape, although there are areas where it occurs as infill within channels cut into the lower unit. The internal seismic response is chaotic,

with no internal planar reflectors. It gives a low continuity and variable amplitude acoustic response.

Interpretation This is a chaotic sheet deposit. It is probably composed of sands and silts, with occasional more coarse material in the ridged area.

3.2.2.2 CORE ANALYSIS RESULTS

The aim of the sediment work in this area was to establish whether subglacial diamict could be located in an area where it was thought that the icesheet extended offshore in contact with the base. This work was hampered by the paucity of material available for examination, especially to the north-east of Peterhead, on the Peterhead Ridge, where the sediments are subject to strong seabed currents (Fig. 3.17).

Three boreholes BH 72/21, 72/30 and 72/31 have been sampled, as well as vibrocore MF 343 (167), although the latter was for provenance only. The results are shown in Fig. 3.20.

From the limited evidence available, the sequence consists of four units overlain by a veneer of pebbles, which originate from both local and more distant provenance (Fig 3.8). These have been tentatively correlated with the seismic facies units, and the BGS regional stratigraphy (Table 3.3).

Unit 1

Description This unit consists of washed sands and gravel, including angular clasts and cobbles of Devonian sandstone and igneous material. Borehole 72/21 contains sub-angular to rounded pebbles, within a sand matrix consisting of lithics and quartz. The source of the clastic material is from west of the borehole, as well as local rocks.

Interpretation It is suggested that this is a preserved, water-modified and sorted deposit, which incorporates angular material from the rockhead.

Unit 2

Description This unit was found in borehole 72/21 and consists of massive silts and clays, with over 60% of the particles being $<63\mu\text{m}$ (Fig. 3.21), although occasional laminae of micaceous fine sand, and mica are found. A strong red colouration in the laminae originates in the sand fraction, however, within the massive silts and clays the red colour originates in the clay fraction. At the base of the core, green reduction spots are present and the argillites have fractured. Rare clasts occur towards the top of this unit.

Interpretation This unit is either a marl, which has fractured, passing upwards into a waterlain deposit, or an overcompacted and weathered glaciomarine deposit which coarsens upwards, as an ice sheet advances into the area. Clastic material in the upper unit most probably originate from the west, given they are igneous and metamorphics rocks (Fig. 3.8).

Unit 3

Description This unit is a massive diamict with a high silt content, a low basal-restricted shell content, and rare, gravel-sized, sub-angular and subrounded clasts which increase in frequency upward. Again the provenance of these clasts indicate a local source, to the west. There is a transitional boundary between unit 2 and this unit.

Interpretation This unit is suggested to be a late Quaternary glacial deposit based on the seismic facies unit identified in its location, and the clast morphologies within the deposit.

Unit 4

Description This unit consists of loose, washed, sorted sand and gravel, with shell and organic fragments. Given the provenance results from the surface vibrocore, the clastic material is derived from the underlying sediment.

Interpretation This is a sub-littoral sediment.

Macrofaunal analysis of shells found in the boreholes was inconclusive (Graham 1989f). The shell fragments were all poorly preserved and had undergone so much reworking that the majority were unidentifiable beyond bivalve fragments, with the exception of fragments of *Dentalium sp.*, and *Balanus sp.*.

The sequence is tentatively interpreted as follows, unit 4 is a seabed sand, overlying Unit 3, a glacial diamicton, probably basal lodgement till. There is no glaciomarine unit lying between units 3 and 4, suggesting that the seabed sediment may originate from the reworking of unit 3, and that any sediment deposited at the front of a retreating ice mass has been removed, or reworked.

Unit 2 is an ice proximal glaciomarine unit which has been compacted, possibly as the result of ice loading. It represents the increasingly ice-proximal position prior to the deposition of unit 3. Alternately it represents fractured and partially reworked pre-Quaternary strata, which will suggest that this is a marl, or siltstone and that unit 3 is the only Quaternary deposit overlying rockhead. Unit 1 would then appear to be the detritus resulting from weathering of rockhead. However the presence of an igneous cobble casts doubt on this interpretation. Although it may have originated from cavings from the overlying sediments (it was found jamming the bit in borehole 72/21). Its presence suggests that this is a preserved, water-modified deposit. If so, the angular sandstone would then relate to weathering, with the cobble originating within the pre-glacial deposit. The mechanism of weathering is uncertain.

3.2.2.3 AREA RECONSTRUCTION

Figure 3.18 illustrates the composite west to east seismic profile across this area and the distribution of the seismic and lithological units, whilst table 3.3 presents the correlations between the seismic and sedimentary units, coupled to the BGS stratigraphy. Using the evidence summarised in Figure 3.18 and table 3.3, the extent of the ice sheet in this area can be established, and the processes affecting the ice sheet margin can be explored.

Lithological and seismic evidence suggests that this area has been partially covered by an ice sheet which terminated in a glaciomarine environment. The occurrence of the chaotic seismic facies unit, PC1, correlated with unit 3, indicates the presence of a glacial diamict. The sedimentological evidence suggests that this diamict can be interpreted as a subglacial till because the clasts within the unit exhibit evidence of glacial transport. The diamict has been deposited directly onto the uneven rockhead, which may have been modified by erosion at the base of an ice sheet. The presence of channels, such as the Buchan Deep (Fig. 1.5), show that selective high energy erosion has taken place in the area. The shape of the channels suggests that this was by either ice streams, or subglacial meltwater under hydrostatic pressure. Both of which require the presence of ice in contact with its bed.

The occurrence of seismic facies unit PD1, which has been sampled as unit 2, indicates that zone PD consists of a glaciomarine sequence. This consists of laminated sands and silts which fine to the east and contains ice rafted debris, and cold water fauna. This indicates that the ice sheet terminated in a glaciomarine environment because the diamict and glaciomarine units are lateral equivalents.

The glaciomarine unit overlies a first order reflector, which is the northern equivalent of the first order reflector noted in the Wee Bankie area. It can be tied in to the Wee Bankie seismostratigraphy through the north-south lines shown on Fig. 3.1. This would suggest that this reflector relates to the marine transgression suggested by Thomson and Eden (1977). This then makes it possible to locate the maximum position that the ice sheet reached where it was in contact with its bed, as explained in section 3.2.1.3. The maximum position of the ice margin would then be located at the western continuous limit of this reflector, where it was overlain by the seismic facies unit PD1. The reflector should pass into the seismic facies unit PC1, the diamict unit 3, and be destroyed.

Ridges comprised of unit PC1 exist within zone PC. These are ~20m high in the south of the area, but reduce in size to ~15m in the north of the area. The ridges are associated with channels and, as shown in Fig. 3.18, are connected to the Wee Bankie moraine in the south. However, in the north of the area the continuity of the ridges decreases and the morphology changes. The height of the ridges decreases to 15m, gaps occur between the ridges, although it is not possible to quantify the distance between the ridges due to the line coverage. The ridges are asymmetric, having a steeper western side. They are parallel to the coastline and would appear to continue into the Moray Firth, although in this area, they occur as isolated mounds composed of a diamict-type seismic facies unit.

The ridges and mounds are interpreted as moraines, given their seismic and sedimentological composition, linked with occasional dipping and horizontal, planar, high amplitude reflectors which may indicate internal structures, such as push planes, and boulder pavements.

The moraines are not found at the junction between seismic facies units PC1 and PD1. They occur up to 10km to the west of the junction, as shown on Fig. 3.18.

There are three problems which affect the interpretation and reconstruction of the margin position of the ice sheet in this area.

The first problem relates to the northern extent of the first order reflector. It is difficult to trace the reflector in the north and north-west of the area. This is due both to the quality of the data, and the structural geology. This area consists of a series of basins and highs, across which it is difficult to establish any lateral continuity. If the marine transgression of Thomson and Eden (1977) is recorded in the sedimentary succession the lateral continuity found in the Wee Bankie and southern Peterhead area is lost due to the preservation of structural highs, during the transgression. In the other areas both lithified strata and sediments have been planed off. However in this northern area there is a difference in pre-Quaternary geology,

which is more resistant to erosion than the Permo-Trias strata, and the regional planation surface is not present. Therefore, the use of the first order reflector as a marker of the limit of former ice cover becomes invalid, and the available evidence is reduced to seismic facies units and lithological units, in association with glacial erosion.

Seismic facies units PA1 and PB1, and lithological unit 4 relate to a late- and post-glacial depositional landform, which is found in the inshore area, in zones PA and PB. The geometry of the landform as illustrated on the seismic sections by prograding and sigmoidal reflectors, with cusped and occasional point source reflectors, together with the sand and silt lithology, is suggestive of a prograding deltaic structure. This is associated with the River Ythan, and other subsidiary fluvial systems draining into the North Sea. The volume of sediment deposited in the structure is attributed to glaciofluvial activity during the retreat of the last ice sheet. It is unlikely that this volume of sediment would have accumulated from normal alluvium transport. The River Ythan, although possessing a high sediment budget does not transport such a large quantity of sediment at the present time as would be required to construct such a feature.

The deposition of the delta is problematic because it has destroyed the underlying sedimentary sequence associated with the subglacial diamicton unit PC1. For this unit to be found to the east of this location it should be found between the coast and zone PC. It is not present, therefore it is suggested that this unit has been incorporated into the prograding delta by sediment reworking at the delta front, within a higher energy environment than that which existed for the deposition of the well-bedded sections of the delta.

The final problem relates to the reworking of the seabed sediments by present-day seabed current activities. From the current map (Fig. 3.17) it is seen that this area is subject to strong currents. This is also shown by the seabed surface sediment transport features visible on the seismic records, and noted in commercial reports from this area. Areas of rock offshore Rattray

Head have been revealed due to these strong currents (Stoker 1985b). This activity disturbs the sediment succession by post-depositional reworking and removal of sediment, thus damaging the record of sediment deposition in the area.

Despite the problems outlined it is possible to suggest a reconstruction of the ice sheet margin in this area.

From the interpretation of the evidence it is seen that the ice margin was present in the North Sea. However, the maximum extent of the margin is not represented by an upstanding, continuous moraine throughout this area. In the south of the area the moraine is an extension of the Wee Bankie moraine, but this becomes less continuous, and smaller to the north, until it is very difficult to trace the moraine either into the Moray Firth, or to the north of the area.

In the south of the area the moraine represents the maximum position of the ice sheet, however, to the north the maximum position is to the east of the discontinuous series of ridges paralleling the coast. This would suggest that the maximum position was not maintained for long and that the moraine represents a standstill position during the retreat from the maximum.

The size of the morainic ridges suggests that the sediment supply to the margin was less than that in the Wee Bankie area, although this may also relate to reworking and removal of sediment by the strong currents active at the seabed. The size of the eroded channels would suggest that meltwater or ice streaming activity was more efficient than the transportation of sediment. The sediment is of a localised origin, which may also indicate that ice transportation was less efficient than that in the Wee Bankie area (Fig. 3.8).

Little evidence exists at the transitional junction between the subglacial diamict and the glaciomarine unit. Interdigitation may occur, as it does in the Wee Bankie area, for example at the detailed site described in section 3.2.1.4., however it is not as pronounced. This suggests that the ice sheet was static and in contact with the bed at the margin, rather than the dynamic

tidewater ice sheet margin found in the continuous moraine section of the Wee Bankie moraine. It is suggested that the ice sheet became less dynamic towards the north of this area. It may have been cold-based in this area, an alternative explanation for the apparent lack of a moraine of similar dimensions to that of the Wee Bankie, at the maximum position. Drewry (1987) suggests that subglacial erosion and sediment transport are reduced beneath an ice sheet frozen to its bed. However, the ice sheet must have been warm-based initially to deposit the diamicton unit PC1.

No evidence of a retreat sequence of fining-upwards glacial diamict to glaciomarine sediments has been found. It is suggested that the retreat of the ice sheet from this area was fast, although there was a standstill position behind the ^amaximum position, which the ice sheet maintained for sufficient length of time to accumulate morainic ridges, in places. No evidence of downwasting of the ice sheet *in situ* exists either, although this may relate to the removal or destruction of evidence by seabed currents.

3.2.3 MORAY FIRTH (57°45'-58°45'N, 2°-3°30'W)

The evidence presented here has been collected to establish whether the limit of the late Weichselian ice sheet was restricted to the margins of the Moray Firth, or if a more extensive ice sheet was present in this embayment. The results presented do not merely map and describe the Quaternary succession, but test whether ice marginal forms can be found.

Lithological control is provided by the existing BGS lithostratigraphy in the area (Andrews *et al.* 1991). Chesher 1984, Ruckley and Chesher 1987, Stoker *et al.* 1985), although subsequent re-examination of some of the borehole logs suggests that the BGS stratigraphy in this area is open to reinterpretation.

3.2.3.1 SEISMIC STRATIGRAPHY

The BGS seismics shot in the inner Moray Firth are of very poor quality having been collected in 1970 and 1972 using 1KJ 'toothbrush' and 'multispark' systems. However, they provide a rough indicator of the depositional sequence in the area.

Two commercial site investigation projects have been consulted within this area. One centred on the Beatrice oilfield, approximately 35 kilometres east of Helmsdale, carried out by Fugro-Cesco B.V. on behalf of BP, in 1977. The other survey was carried out on behalf of BP by RACAL in 1988. It is centred on the Southern Trench area, 10-15 kilometres north of the Buchan coast, between 1°50'W and 2°15'W.

Due to the complex depositional environment, with several independent basins, it is not possible to construct a composite profile for the whole area. Intrabasin profiles are also difficult to compile due to local structural controls and the poor quality of the old data, hence individual lines have been selected, which provide an indication of the sedimentary succession. These are illustrated on Figs. 3.25* and 3.24a-g. Lines 66 and 24 (Fig. 3.24a and b) trend north-west to south-east across the outer and inner parts of the Moray Firth area, respectively. Lines 22 and 59

illustrate specific features (Fig. 3.24c and d), while the RACAL data (Fig. 3.24e) and lines 1 and 2 (Fig. 3.24f and g) give higher resolution images of some of the features. The BGS profiles across the area from the published maps are shown in Fig. 3.25* (Chesher 1984, Ruckley and Chesher 1987) to indicate the general morphology of the deposit in the area.

Line 66 (Fig. 3.24a).

This line trends from the north-west of the area, south of Wick, to the boundary of the area in the south-east. The thin-to-absent sediment cover is located in water which is between 60 and 70m deep, except in the far south-east where it crosses a linear trough 140m below sea level.

Description The seabed reflector is a second order slightly undulating surface, with variable sized crenulate features in places. Rockhead is poorly defined, and is marked by a third order reflector which is uneven and underlain by strata with disturbed internal structure. Two open channels are cut into rockhead.

Sediment cover is thin to absent, and is up to 20m thick in depressions, although on average it is 10m thick. It thins towards the coast, where it is locally absent. Only one seismic facies unit is represented, MF66-1.

Unit MF66-1

Description This unit is a sheet deposit, with occasional third order reflectors randomly distributed throughout the unit and occasional point-source reflectors. It has a chaotic acoustic character, with variable amplitude and internal continuity. The third order reflectors do not indicate any internal differentiation of the sediment body, except at 'a' (Fig. 3.24a), where a lensoid structure is delineated. This has the same chaotic acoustic response as the rest of the deposit. The upper reflector is the seabed surface and is crenulate. The lower second order reflector is uneven and forms rockhead.

Interpretation This is a sheet deposit emplaced within a highly

variable energy environment. The presence of point-source reflectors, and the chaotic response suggest a diamicton unit. Erosion may have taken place during deposition of the unit, as illustrated by the discrete pocket of acoustically similar material within the sheet. The unit lies directly on eroded bedrock, and has been subject to active sediment transport at the surface, illustrated by the crenulate sediment ripple and wave structures at the surface. This is tentatively correlated with unit 1 of the BGS stratigraphy.

Line 24 (FIG. 3.24b).

This line traverses the inner Moray Firth basin, from offshore Helmsdale, to north of Portsoy, traversing both the South Lossiemouth and Banff basins.

Description The sediment body occurs beneath over 120m of water, as well as an average depth of 60-70m found outwith the basins. The seabed is a second order undulating reflector with occasional crenulations, 6m deep depressions and two ridges (Fig. 3.24b). The first ridge (15m high and oriented parallel to the coast) overlies a shallow basin, it possesses no internal structure and is composed of a chaotic seismic facies unit, however, the other ridge is more complex. The majority of the ridge (10-15m high, oriented parallel to the coast) is formed of the chaotic seismic facies unit, but there is an area of third order structural reflectors (Fig. 3.24b). A gradient of 1:350 causes local differences in sedimentation, as the result of a change in slope. This produces downlapping slope-front third order reflectors.

Rockhead is poorly-defined over most of the line, it is probably the lowest second order reflector, but crops out at the seabed (Fig. 3.24b).

The sediment cover ranges from a maximum of 60m, in the Banff Basin, to absent where rockhead crops out at the seabed but is 10-15m thick on average.

Three distinct acoustic responses occur within the profile but up to 4 units exist. It is difficult to correlate between the

basins on the profile; hence the uncertainty concerning the number of units. The BGS profile based on the lithological units probably indicates the distribution more accurately (Fig 3.25^{*}).

MF24-4

Description This unit occurs as a sheet deposit outwith the basins and channels. It is a thin unit, <15m thick. It exhibits a chaotic variable amplitude internal seismic response with point-source reflectors.

Interpretation This unit is interpreted as a diamicton, and is correlated with MF66-1, on the basis of the seismic response.

MF24-3

Description This is a complex channel infill unit, which is composed of continuous, subparallel-bedded, medium amplitude reflectors. The lateral continuity of the reflectors is broken by the slight vertical displacement of the reflectors. The unit is deposited directly onto rockhead, a second order, uneven reflector. The thickness of the deposit varies, but is seldom greater than 20m. Occasional point-source reflectors are present.

Interpretation These are infill channel deposits which may have originally been deposited as onlapping or draped fill. The energy of the depositional environment alternated between medium and low conditions, resulting in the interbedding of the reflectors. The disturbance of the reflectors is suggested as being post depositional, because it is possible to trace reflectors at a constant offset. This is indicative of disturbance perhaps due to loading. It is likely that these are glaciomarine, or glaciolacustrine deposits, which accumulated in quiescent conditions.

MF24-2

Description This unit forms the upper unit within the more complex infilled Banff Basin. It onlaps onto unit MF24-1 and its upper surface is the seabed first order reflector. Internally it has a complex structure, which includes dipping, prograding third order

reflectors and small cusped reflectors. The seismic response is medium to low amplitude with variable reflector continuity. Within the cusped reflectors the seismic response is more chaotic.

Interpretation This unit is the upper infill sequence, within the Banff Basin, which was partially filled prior to the deposition of this unit, and behaved as a sediment sink. The variability of the infill structures, with reflectors oriented in several directions, was more complex than in unit MF24-1, suggesting a more dynamic depositional environment, with bedload transport rather than suspension sedimentation, as indicated by the cusped reflectors which are interpreted as channel cross sections.

MF24-1

Description This unit is restricted to the infilled basins. Its upper and lower boundaries are uneven, third-order reflectors. The unit gives a chaotic, high energy, structureless response, with rare point-source reflectors. It varies in thickness, but does not exceed 20m.

Interpretation This unit is interpreted as a diamicton-dominated unit, given the acoustic response, however, it is not possible to suggest an origin for the diamict from the evidence available.

LINE 22 (FIG. 3.24c).

This line crosses the Banff Fault and the Banff Basin as it trends in a south-west to north-east direction. The bathymetry of the area is dominated by linear troughs up to 120m deep, parallel to the coast, and partially infilled with sediments. This line crosses lines 1 and 2, from survey 72/15.

Description The seabed surface is a first order uneven reflector, which consists of ridges and shallow channels and depressions (Fig. 3.24c). Rockhead is represented by a highly uneven third order reflector, which crops out at the surface. Sediment cover is less than 10m thick over most of the line. The sediment body would appear to be composed of two seismic facies units; a main unit

which represents most of the sediment body, with a minor unit occurring in isolated depressions both in the seabed, where it is composed of rockhead, and eroded into the main sediment unit.

MF22-2

Description This unit occurs within depressions and channels as a thin, relatively undisturbed, onlapping (and possibly draped) unit. It includes third order parallel-bedded reflectors. It possesses no point-source reflectors. The unit forms a wedge of sediment develops which reaches a maximum thickness of 10m. In the wedge the internal structure is less clear, and the seismic response possesses a slightly higher amplitude, elsewhere the unit possesses a medium amplitude high continuity seismic response.

Interpretation This unit is interpreted as an infill deposit, and as a slope front deposit. It was deposited in quiescent conditions, as indicated by the continuity of the internal structure. This is similar to either units MF24-2 or MF24-3, although it cannot be correlated with certainty, given the problems of lateral continuity of the stratigraphic succession in this area.

MF22-1

Description This unit exhibits a chaotic, structureless acoustic response, which also contains point-source reflectors. The unit occurs along the line and forms the sediment ridges. The ridges are symmetric, with no internal structures.

Interpretation This unit is interpreted as a massive diamicton unit. It is possibly equivalent to unit MF24-4, found in line 24 (Fig. 3.24b).

Line 59 exhibits the same sedimentary units described for line 22. It is included (Fig. 3.24d) to illustrate the deformation structures present in the rockhead. Lines 1 and 2 (Fig. 3.24e and f) illustrate the north-south transects across the Southern Trench, and the Banff Basin, in addition to illustrating the evidence for glacial erosion and deposition in the area.

Line 1 (Fig. 3.24e).

Quaternary sediment cover is thin to absent over most of this profile, except in the north where an infilled basin occurs, containing acoustically chaotic and locally well-bedded units overlying well bedded sedimentary strata. The junction between these units and rockhead is uneven. A rippled seabed surface indicates active sediment transport.

A section across the area of incised topography has been constructed to examine the unexaggerated morphology of the seabed, to deduce the origin of the channels (Fig. 3.26). Four channels exist, with variable sizes and geometry. The two northern examples are steep sided, narrow and slightly asymmetric, with the southern slope being the steepest. These channels have minor terraces associated with them. The third channel is different. It has less steep concave slopes and a more open cross section. It is reminiscent of an open river valley profile. Channel four is the largest. It is ~100m deep and 1.2 kilometres wide. It has steep valley sides and a wide flat bottom. This contains a draped, and partially slumped, infill deposit, also seen on the high resolution DTS seismics, shot by RACAL across the Southern Trench. There is a shallow 'V'-shaped depression cut in the terrace to the south of the channel. The flatish floor and width of the channel resembles the scale and morphology of features associated with glacial erosion, for example, the Strath of Kildonon. The association of the features with a line of structural weakness in the sedimentary substrata, the Banff Fault zone, rather than a wholly glacially-formed feature is also characteristic of glacial erosion.

Line 2 (Fig. 3.24f).

This line exhibits the infill sequence described by Chesher (1984), within an uneven-based bedrock basin. Within the basin, the upper well-structured units indicate prograding deposits, and/or slump deposits on highs which exist on both sides of a wide, shallow channel. There is evidence of a prograding infill sequence, composed of well bedded sediments intercalated with a diamicton-dominated unit. Outwith the infilled basin sediment

cover is thin to absent, with a veneer of seabed sediment, with waves and ripples, indicating active sediment transport in the area.

It is suggested that the channel may have contained a lobe of ice around which ice contact sediment was deposited in terraces/fans which slumped when the ice withdrew. This would explain the slumping and the presence of the intercalated units.

Beatrice

The Sub-Tow Boomer seismics used in the site survey in this area show a simple sediment succession, the upper part of which has been constrained by sedimentological data from vibrocores (Fig. 3.27). There are four units; the lowest is probable reworked Cretaceous rockhead debris, overlying a strong, uneven rockhead. Above this is a layered draped clay unit with a transitional upper boundary. This grades into another unit of layered clays, but with occasional silty layers. This is bounded by a strong reflector (A) which marks a hiatus in sedimentation, or has been suggested to be composed of coarser material or organics. The upper unit is composed of fine sands, which possibly grade to clays. It is bounded at its upper surface by the seabed. This forms a sheet deposit over the underlying basin-infill sediments. The sheet deposits suggest a low energy environment of deposition within the basin. Unfortunately the sediments are not chronologically constrained and it is not possible to correlate them with any confidence with the BGS stratigraphy. From the evidence presented they do not relate to the diamicton units which would be expected from the BGS regional stratigraphy (Ruckley and Chesher 1987). The descriptions of the sediments suggest glacialmarine and marine sediments only. Table 3.4 shows the attempted correlation of the seismic facies units described, with the BGS lithostratigraphy.

3.2.3.2 SEDIMENTARY EVIDENCE: BGS Lithostratigraphy

The existing BGS stratigraphy in this area has been set up from extensive lithological study of several hundred sediment samples. The study indicates that there are seven lithological units within the area, of which two occur throughout the area. The other units are restricted to the Quaternary basins. The chronostratigraphic constraints on the succession are uncertain, given the onshore chronology for supposedly equivalent deposits.

Data obtained from the commercial sources are used to test the interpretations placed on the sedimentary successions in two key areas; the Beatrice field and the Southern Trench. Sediment samples were not available from these sites, but lithological logs of the boreholes and vibrocores were available, as was geotechnical data.

Work by Chesher (1984), and Ruckley and Chesher (1987) divides the Quaternary sediments in the inner Moray Firth, into seven units (Fig. 3.25*). The two lower units are attributed to the middle-Devensian on the basis of a ^{14}C date of 43ka BP on shelly material (Harkness and Wilson 1979). The sedimentary units which relate to the late Devensian (late Weichselian) have been dated to 16ka BP, again using ^{14}C , but on plant material. Two laterally equivalent units occur: a gravelly mud, interpreted as an ablation or ice melt till, and a grey, pebble-free mud and rhythmite unit. The latter is interpreted as being a reworked unit of the lowest, mid-Devensian grey basal till, which was deposited into a low energy aqueous environment. Another till unit is suggested from the sedimentology. This is unit 5, which is composed of brown to grey-brown muddy sands and sandy clays. It occurs above units 3 and 4, and is considered to be the source for unit 6. Unit six is composed of soft red muds which give a radiocarbon date of 12.4ka BP +/- 100, again from shells (thin-walled pelecypods). This implies that unit 5 is post 16ka BP, but pre-dates 12.4ka BP. The top unit is Flandrian.

The above units have only been delineated on the southern coast of the Moray Firth within the infilled Banff and South

Lossiemouth basins. Outwith this area the Quaternary deposits are predominantly unit 1, with occasional pockets of unit 6 overlying it. The western margin, and the northern central area of Moray Firth have very thin to absent sediment cover. The thin cover makes it difficult to isolate specific units outwith the basins.

BEATRICE (FIG. 3.1).

BGS boreholes 71/17, 71/25, 71/27, 72/23 and 74/18 provide the geological framework into which the commercial vibrocore and borings data are fitted. The logs are shown on Fig. 3.28.

Description The BGS boreholes illustrate a sequence composed of silts and clays, diamicts and fine to medium sands. Micropalaeontological evidence from the BGS boreholes suggests that the sediment succession is composed of older material that has undergone significant reworking illustrated by the presence of Cretaceous assemblages of microfossils and microplanktons throughout the cores, in close association with organisms predominantly Flandrian in age (Harland 1971).

Clastic material is found throughout the succession and includes rounded pebbles of quartzitic and gneissic material from the Highland part of the Scottish mainland, as well as fragments of the local sedimentary strata within the sediments immediately above rockhead.

The BP vibrocores show that the subsurface sediment is composed of fine sands with shell fragments, which overlie silt or silty clay, but penetration is limited to the upper 2.5 metres only. The BP borings penetrate up to 85m of the sediment succession and give a complete record of the sediment succession within the basin, and pass into rockhead, at depth. The composite sediment succession can be divided into three broad sections (Fig. 3.28).

Description The lowest, and thickest section (50m maximum) is composed of a series of clay units, up to 5m thick, with varying proportions of silt and sand. The units often contain shell fragments, traces of organic material, clasts and gravels, and

inclusions of fine sand, silt and clay. The units are poorly sorted, and positively skewed within the fine sand and smaller, particle size range. The clay units coarsen upward to the second section.

A diamicton unit is tentatively identified in B12 and 13. There is an increase in the particle size range, to include clastic material, and a decrease in the sorting of the clay so that it is best described as a diamict. Other units, especially interbedded with the clay units may also be diamicts, however it is not possible to classify the sediment in this way from the logs alone.

The second section consists of a silt unit, which contains laminae of clay. In general the strength of the clay laminae increase downcore both above and below a fine to medium sand unit which occurs in B1, 4, 5, 6, 7, and 12. The sand coarsens upward. In B4 and B5 laminae of fine silts and clay exist within the sand. The silt unit is not found in B2 and 4, whilst in B12, the silt unit is laminated. Overlying this is the third lithological section.

Section three contains up to 9m of fine to medium sand. This is divided into two units; a medium to very dense sand unit, overlain by 1.6m of loose sand.

Interpretation The lithological data suggest that the Quaternary succession in this area is far more complicated than is suggested from the BGS Caithness sheet (Ruckley and Chesher, 1987). In their interpretation, only two distinct units are present, a lower till and an upper 'red' unit. These are overlain by a thin covering of sand. In contrast, the logs suggest that the succession records sedimentation within a variable environment of deposition.

The lower units in section one have been overconsolidated and may be pre-Quaternary mudstones. Little structure is found within the clay units of section one. However, they include shell and organic material and may be marine or fluvial in origin. The overlying sand units containing clay laminae also suggest a waterlain origin of variable energy, but without micropalaeontological evidence this cannot be resolved further.

* CONFIDENTIAL DATA
SUPPLIED BY FUGRO-McCLELLAND

Moving up the core there is a return to a lower energy environment of deposition with clay dominated units. Again these are overconsolidated.

It is suggested that the sediments are glacial diamicts. They are poorly sorted, and contain clastic material which has been transported from the Scottish mainland, mixed with local lithologies. The presence of clay laminae and sand units indicate that the energy of the environment changed during deposition. The presence of isolated 'outsized' clasts suggests an ice rafted debris component suggesting that the sediment was deposited in a glaciomarine environment. Variations within the coarseness of the sediments would then represent variations in the relative ice marginal position, with sediments with a larger proportion of fine material illustrative of more ice-distal deposition.

The number of laminated units suggests that sedimentation rates were either low, or bioturbation of the sediment has removed primary structures, or the volume of sediment deposited at any time was constant. Alternately the diamict may represent basal lodgement till, an interpretation consistent with its overconsolidation and lack of structure. Further evidence of pebble shape and micropalaeontological description would allow tighter interpretation. However, given the evidence available it is suggested that the sediment succession represents an extensively reworked glaciomarine sediment. Sediment release from the ice margin could be intermittent due to the hysteresis effects of diurnal and seasonal variation within the closed fluvioglacial system, thus creating units of different lithologies; sands, silts and clays at a point, associated with different energy levels as a function of the relative position of the ice margin. The reworking of the glaciomarine sediment ^{may have} created the diamict, which became overconsolidated because the ice sheet was in contact with the underlying sediment in order to rework it during ice advance. Complete reworking did not take place, and some of the glaciomarine sediments were protected in the basin.

The upper section is probably late or postglacial resulting from large inputs of sediment associated with fluvioglacial and fluvial during deglaciation. The top sand unit is the Holocene seabed sediment veneer.

SOUTHERN TRENCH (Fig 3.1).

Five vibrocores and two gravity cores sample up to 3m of the sediment within the Southern Trench. BGS boreholes 72/17 and 71/23 are shown to indicate the local lithostratigraphy (3.28).

Description The local stratigraphy, outwith the trench, is composed of silty clays with rounded clasts, overlain by fine clays, beneath a thin veneer of fine to medium sands. Within the trench the sediment penetrated by the gravity and vibrocores is predominantly dark grey to olive green silty fine sand, and clays with varying proportions of silt and fine sands. Occasional gravels and clasts occur within the fine sediments, as do rare shells. Some of the vibrocores penetrate strata affected by biogenic gas. The presence of carbon detritus, which increases in concentration downwards, was noted within some of the BGS cored material. This has been used to date some of the sediments using ^{14}C . This produced a series of dates of Late Weichselian to Holocene/Flandrian for the majority of the sediment sequence in the Firth (Chesher and Lawson 1983).

Interpretation The local stratigraphy exhibited in 71/23 and 72/17 is interpreted as an upward fining sequence of glaciomarine sediments laid down in an environment of decreasing energy and overall decreasing coarse sediment input.

Laminae at the base of the sequence may be due to regular inputs of relatively coarser material. Rare rounded pebbles represent an ice-rafted sediment input, and random coarser sediment areas illustrate irregular inputs from sediment plumes. The input of coarse material fluctuates, whether similar fluctuations also occur within the clay fraction is uncertain from the borehole logs.

The laminae are overlain by a marine clay, in the upper 10m of BGS BH 71/23, which contains microfossils and microplankton of Flandrian age. However there are also examples of older microorganisms, indicating that this includes reworked sediment (Chesher and Lawson 1983). The veneer of sand is interpreted as the modern seabed sediment.

The BP vibrocore and gravity cores sample a series of layers of clays and fine sands with varying quantities of shell and organic material. Occasional clasts and coarse inclusions are found in the cores, with chalk being a common constituent of the clastic material. The strengths of the clays vary widely over the area, but decrease with depth.

It is suggested that the sediments within the top 3m of the trench represent recent infill events of differing energy regimes and processes. These include suspension sedimentation and possible downslope mass movement, which have created differences in the geotechnical properties of the clay layers, shown in Fig. 3.28.

3.2.3.3 AREA RECONSTRUCTION

The interpretation of the Quaternary succession in this area is constrained by the quality of the data and the problems of inter-basin correlation of the units within the basins. However, certain generalizations can be made.

A glacial diamicton seismic facies unit occurs across the area. Glaciomarine sediments occur within Quaternary basins in the south of the area, and in depressions in the north-west of the area. However, there are no litho- or seismic facies units which can be confidently interpreted as till. The sediments deposited in the Southern Trench, and at the Beatrice site, do not contain till units. The sediments occur in depressions and would be expected to be protected from the reworking that has affected the sheet deposit outwith the basins. These would be the prime sites for till to be preserved in the sedimentary record. Instead these sites indicate that the area was till-free.

The faunal evidence (Harland 1971, Chesher and Lawson 1983, Lawson in Harkness and Wilson p 33 1979) indicates that the sediment has been reworked. This has resulted in the preservation of late glacial, Cretaceous and Jurassic fauna within the same sediment units. It is not possible to reconstruct Quaternary environmental conditions, or to construct a chronostratigraphy for the sediment succession because of the mixed fossil assemblage.

The glacial modification of the linear deeps, and the morphology of the basins, suggests that ice was present in the basin. In addition the presence of glaciomarine deposits, and overconsolidated silt and clay units would suggest ice was present in the vicinity and had loaded the sediment. There are occasional upstanding ridges composed of the glacial diamict seismic facies unit. However, from the evidence available these cannot be classified as moraines.

The evidence presented suggests that the Moray Firth embayment was affected by an ice sheet, but the absence of a boundary between subglacial and proglacial environments suggests it did not have a fixed terminal position within the Moray Firth. Three possibilities exist for the position of the ice sheet margin from the available evidence.

1. The linear deeps, such as the Southern Trench, and the Quaternary basins, have been affected by ice erosion, or subglacial meltwater activity. These require a cover of active ice, which must have extended to the east of the Moray Firth area because no moraine or subglacial/proglacial boundary exists.

2. The distribution of the glaciomarine sediments in basins occurring in present water depths greater than 40m, would suggest that the ice sheet did not extend beyond the present 40m bathymetry contour, in contact with the bed. Although the ridges in the south of the Moray Firth basin cannot be confirmed as moraines, they occur above the present 40m bathymetry contour, and may represent the position of a grounding line, or pinning point. The ice sheet may have extended further, but was no longer in contact with the base. Cyclicity of particle size within the

sediments, as found in the Beatrice site, would suggest that the ice sheet margin was dynamic, and the glaciomarine environment varied in its location relative to an ice front, from ice-proximal, fining to distal. The presence of a floating ice sheet would permit a dynamic margin without depositing a till.

3. The widespread distribution of a glaciogenic diamict provides another alternative. This proposes that the ice sheet in the Moray Firth advanced into the glaciomarine environment, and reworked the existing glaciomarine sequence, producing a diamict. This would explain the overconsolidation of the sediments, as well as the occurrence of the glacial diamict, and till-free enclaves in the basins. The reworking was efficient, and incorporated material from the underlying, glacially eroded rockhead. This provides a mechanism for the presence of Cretaceous and Jurassic faunal evidence within the sediments.

It is suggested that a restricted ice sheet existed, which was in contact with the base to the present-day 40m bathymetry mark. Glaciomarine conditions existed in front of the ice margin. Ice advanced into the Moray Firth and reworked the sedimentary succession, thus creating the diamict. The margin of the ice sheet became uncoupled from the base as the ice advanced into deeper water. A possible ice margin location would have existed which was constrained by the position of the Southern Trench. This was not crossed by ice in contact with its base. The north-west grounding point of the ice margin could have been the 40m bathymetry mark off the coast of north-east Caithness. The location is not certain, due to the lack of data from the inshore sector of this area, which has been swept clean of sediment by strong currents (Fig. 3.17). The margin position was dynamic and calving, providing ice rafted debris and relative cyclicity in sediment size supplied.

3.2.4

BOSIES' BANK (58-59°N, 0-2°W)

Part of the Quaternary sediment succession in the Bosies' Bank area has been interpreted as a possible tide-water ice sheet limit (Bent 1986) associated with the late Weichselian maximum (Hall and Bent 1990). If this is correct, the ice margin deposits exist as buried, or low relief features, located as shown on Fig. 3.29. This is the opposite of the late Weichselian Wee Bankie moraine. It is thought that the linear deeps (Fig. 1.5) also relate to glacial processes at this time. They have been suggested as being erosional features caused by ice or meltwater processes (Bent 1986, Wingfield 1990).

This section examines the western sector of this area (to 1°W), consisting of possible late Weichselian sediments, in order to establish whether evidence exists which can link the Bosies' Bank moraine to the Wee Bankie moraine, as suggested by Hall and Bent (1990).

3.2.4.1 SEISMIC STRATIGRAPHY

The four seismic line segments presented in Fig 3.30^{a-d}, illustrate the sediments in this area. They are related to the regional framework by reference to the insert in Fig. 3.30^{*}, which shows an isometric diagram of the sedimentary sequence of the Bosies' Bank area as a whole. The lines have been chosen to show the geometry of the moraine, and to tie in with the vibrocores and boreholes which have been used solely for amino acid racemisation relative dating.

Line 1 (Fig. 3.30^a)

Description This shows the distribution of Quaternary sediments from north to south. There is very thin cover within this area, which overlies a highly uneven erosive rockhead reflector. The succession is composed of a thin sheet drape, up to 10m thick, with onlapping characteristics. Towards the middle of the line the sediment cover thickens, and it is possible to identify the BGS

formations mapped in this area (Fig. 1.7). Fixes 57-62 show an infilled eroded basin. The infill is composed of a structureless chaotic seismic facies unit, overlying the uneven rockhead. Overlying this unit is a seismic facies unit comprising parallel-bedded medium amplitude reflectors. Between Fix 67 and the end of the line there is a hummocky surface, with a 'mounded' internal structure, overlying an uneven rockhead. The seismic signature is chaotic with hyperbolics, although in some areas there appears to be no acoustic response. High amplitude, dipping second order reflectors occur within the chaotic units. This may indicate that they represent inclusions of rafted material, or that they represent slip-planes within the chaotic sediment deposits. Gas blanking obscures the response, in places.

Interpretation The chaotic seismic signature is indicative of a diamicton unit. It is possibly a glacial diamicton, given the hummocky internal structure and surface morphology of the unit, however this cannot be confirmed from the seismics in isolation.

Line 2 (Fig. 3.30b)^{*}

Description This line crosses the area in a north-south direction and exhibits similar seismic facies units as in line 1. However, overall it possesses a much more hummocky seabed surface, related to the morphology of the underlying units rather than sediment transport features.

Fixes 6-19 exhibit a partially buried area of hummocky topography. The seismic facies unit response is chaotic with rare point-source reflectors, and patchy inclusions of well-bedded, third order, reflectors. Between fixes 10 and 19, the topography is partially buried by a draped infill. Fixes 19-38 show another area of mounded hummocky topography, with the same internal structure. However this has been subject to deformation, as seen by the vertical displacement of the discontinuous, low amplitude 'patchy' planar-bedded reflectors which occur within the unit. The reflectors would have been displaced by a small amount (2-3m) and the pre-disturbed structure can be reconstructed with little difficulty.

Interpretation The chaotic seismic facies unit is interpreted as a diamicton. The presence of disturbed reflectors within the chaotic units suggests that the unit has been subject to post-depositional deformation, possibly by loading, or overriding of the sediment.

Line 6 (Fig 3.30c*).

Description This line trends west-east across the area. It crosses the proposed moraine (Bent 1986). The sediment cover in the west of this line is very thin and overlies, as a draped veneer, a slightly uneven rockhead. The sediment infills small depressions and channels cut into the rockhead. The moderate continuity and amplitude of the seismic response, and regional stratigraphic position suggest this unit correlates with the Forth Formation.

Large 'V'-shaped, asymmetric channels are present, which are completely infilled with a chaotic seismic response. This is overlain by the veneer unit (Forth Formation). The sediment wedge increases in thickness to the east to include seismic facies units which can be correlated with the Coal Pit and Swatchway formations.

There is an intercalating assemblage of chaotic and multiple-bedded reflectors, over a distance of 0.5-1km, near Fix 23. The reflectors are dipping, and in some cases downlap onto an underlying, uneven erosion surface within the sediment succession. There are some small cusped reflectors within the sequence. These are of the order of ~100-250m wide, and are less than 10m deep.

Interpretation The seismic facies units described are very similar to the assemblage of units found in the Wee Bankie area, near the junction of the Wee Bankie Formation, and the Marr Bank Formation. The chaotic seismic unit is thought to be a diamicton, given the internal seismic response, the presence of point source reflectors, and the hummocky surface topography. Although the geometry of the unit is not as pronounced as that of the Wee Bankie, it comprises a series of planed-off ridges, and some channels, analogous to those in the Wee Bankie area, at the eastern limit of the units distribution.

The unit containing the bedded reflectors, with cusped reflectors and occasional point-source reflectors is tentatively interpreted as an outwash area, probably subaqueous. It is the lateral equivalent of the glacial diamict unit, and is probably a glaciomarine sequence, deposited within an ice-proximal environment at a tidewater ice sheet margin.

Line 8 (Fig 3.30d^{*})

This line is 10km to the north of line 6 and the sediment units have a similar geometry. The main difference is that there is no indication of the subaqueous deposits, or an ice margin.

3.2.4.2 CORE ANALYSIS

The aim of the sediment analysis in this area was to locate shelly material within the succession associated with the proposed late Weichselian, Bosies' Bank moraine (Bent 1986).

A composite log summarising the sediment succession has been compiled from the BGS boreholes BH81/19, and 81/26, the vibrocores 207, 208, 219, and 242, and the stratigraphy defined by Bent (1986), as located on Figs. 3.1 and 3.31, respectively. *Description* The units in the area consist of Bent's Inner and Marginal Facies Associations, with the emphasis on ice-proximal locations. BH81/26 was consulted to recheck that there was a difference between the distal and proximal locations, in terms of the sediment succession, emphasising the fining of the sediments to the east, and associated increase in the structure of the units indicating more quiescent conditions, and differences in sedimentation. This was confirmed, i.e. the sediments in the east are finer, and are highly laminated, with rare coarse clasts present. This borehole is not considered further.

The sediment succession is divided up into four units in the composite log. The base is uncertain from the micropalaeontological evidence, but is marked by a lithological

change around 40m in BH81/19. Unfortunately the vibrocores do not penetrate further than 5m but this is sufficient to augment the borehole information.

Unit 4

This forms the surface unit. It is composed of fine sand and/or coarse silt, with shells and shell fragments, and glauconite in a dominantly quartzitic sand.

Palaeontological analysis of this unit in vibrocore 58-02/242 indicates that the shells present represent a boreal offshore assemblage, with some evidence of reworking. The shell assemblage is interpreted as Holocene (Graham 1990).

Unit 3

This unit is dominantly clay, but also contains a less well sorted range of particles. It is best described as a diamict. The clasts contained within it include weathered chalk. It contains small abraded shell fragments.

Palaeontological examination of the shells forming a drape over this unit (Fig. 3.37) indicated that cold water bivalves were present, *Arctica islandica* and *Macoma calcarea*. These suggest that the shells, which were reworked, were of Pleistocene origin (Graham 1990). This unit is interpreted as a till deposited from a tidewater ice margin (Bent 1986).

Unit 2

Unit 2 is the thickest unit. It is composed of clay with variable proportions of sand and silt, which make up laminae, and lenses and pods within the unit. Internal variations relate to slight changes in sediment supply of the different particle sizes. Within the unit there are occasional to rare small clasts, which are sub-angular to rounded. There are also shell fragments. There is a general coarsening up in the unit, but with an associated decrease in the compaction and strength of the sediment. Glauconite is present, as is sulphide staining, which highlights possible areas of bioturbation or discrete areas of better sorting. Micaceous

laminae also occur. This unit may be conformably overlain by unit 3.

The laminae, sediment sorting and shell fragments indicate that this is a sediment deposited in an aqueous environment. The presence of small 'outsized' clastic material suggests an ice rafted input of sediment, and further suggests a glaciomarine origin for the unit.

Unit 1

Unit 1 is composed of coarse silt to fine sand, with copious shell fragments and complete shells, in a matrix of quartzitic sand, with occasional glauconite.

Interpretation The fine sand units, units 4 and 1, are both interpreted as seabed sediment deposits. The laminae and dropstones in unit 2 suggest that it is glaciomarine in origin. The laminae represent changes in sediment supply, while the dropstones indicate the presence of floating ice. Micropalaeontological evidence suggest shallow water (Bent 1986).

Unit 3 is a massive diamicton, with no internal structure and a coarse particle size distribution. This is probably a glaciogenic diamict. However it is difficult to decide whether it is a till or an ice-proximal, or proglacial glaciomarine deposit. It includes shell fragments which indicate that the shells are reworked rather than *in situ*. This shows that the environment was not suitable for colonisation at this time. This would suggest that it was either close to an area of high energy deposition, for example an ice margin, or that faunal material was not adapted to the environment, for example the water may have been non-saline. The lack of faunal material *in situ* suggests that this was proglacial or subglacial, rather than ice proximal glaciomarine, where *in situ* fauna occur.

Neither unit 2 or 3 are particularly overconsolidated, except at depth, as would be expected if they had been overridden by ice. This suggests that neither unit has been overridden by ice, and

that they represent the last glacial sediments to be deposited in this area. If it is an ice proximal glaciomarine deposit, the lack of structure may be due to rapid sedimentation and the unit may indicate the reworking of sediment at the margin of an icesheet, either in the immediate proglacial environment or in a basal situation, beneath a warm-based, but grounded icesheet. It may represent sediment deposited, or reworked in the retreat phase.

3.2.4.3 RECONSTRUCTION

Bent (1986) proposed that the deposits range from glacial diamict to marine and fluvial deposits. The glacial diamict comprises subglacial till, ice proximal and ice distal glaciomarine sediments. These have been correlated with the BGS formations, as shown in table 3.5.

Bent suggests that these units represent the sediment succession which illustrates the temporal changes of the tidewater margin of a lobe of the north British ice sheet during the maximum stage of the late-Weichselian glacial, and its subsequent retreat, into a shallow glaciomarine sea. In addition to the direct glacial sediment supply and fluvioglacial inputs into the area, the presence of ice rafted debris is also recognised. The margin retreated to the west, towards the British mainland, creating a time-transgressive sediment succession.

Bent proposed that the ice-proximal zone extended 50km in front of the margin, as the result of the effects of strong dense bottom currents.

Provenance studies of the clasts suggest a local source for the majority of the sediments. The volume of material associated with the margin would also suggest that it maintained the maximum position for some time.

Having re-examined the evidence presented by Bent (1986) I would agree that the identification of a glacially derived topography in part of the area, in conjunction with a possible braided outwash area, suggests that the Bosies' Bank area

represents a relict glacial ice sheet margin environment, as proposed by Bent (1986). However, there is no evidence to test whether the sediments represent the maximum eastern margin of the late Weichselian ice sheet or some earlier glaciation.

The lack of a definite link between the glacial features in this area, with the glacial features to the south-west, makes it very difficult to prove or disprove this hypothesis. However shells from the draped intact shell layer overlying the glacial diamict interpreted as till (Bent 1986) have been used to provide a chronological constraint on the moraine (section 3.4).

3.3.1 GEOMORPHOLOGICAL MAPPING

The geomorphological mapping exercise aimed to indicate where glacial modification has been most intense and the dominant directions of ice flow to the margin.

The landscape has been examined at different scales, using aerial photographs and topographic maps, to illustrate any difference which may occur between regional and local ice movements, and to complement the different scales employed to examine the offshore sedimentary succession.

1:50 000 GEOMORPHOLOGICAL MAP

Description The geomorphological map derived from the analysis of the 1:50 000 scale Ordnance Survey Landranger map series is shown in Fig. 3.32*. It extends from Dunnet Head, in the north, to Dunbar in the south, and inland for ~10km and includes inshore islands.

Fig. 3.32* shows three zones of landscape modification. These are: 1) erosional landforms dominate, 2) depositional landforms dominate, and 3) erosional processes are dominant, but indicate different ice movement trends.

The areas where the erosional landforms are dominant are around the inner margins of the Moray Firth, and in the Forth and Tay areas, extending north to Aberdeen. The erosional landforms are aligned perpendicular to the coastline. This is illustrated by the streamlined hills and the directions of ice-scoured bedrock. The main eroded troughs and meltwater channels follow this trend, although minor channels are affected by local topographic controls.

The major erosion at the margins of the Moray Firth indicate an area of converging ice moving into the Moray Firth embayment, with evidence of diverted ice in subsidiary channels at the head of the embayment (Strath Peffer). Diversion of ice is also apparent in the head areas of the Firth of Forth and Firth of Tay.

The altitudes of the coastal hills which exhibit ice modification are presented in table 3.6.

Depositional evidence is dominant in the landscape in the north of Caithness, the southern Margin of the Moray Firth, east of Nairn, and from Buchan Ness to north of Aberdeen. The lowlying land near Fife Ness, Tayside, and Lothian near North Berwick, is also dominated by these depositional landforms. Erosional landforms may occur, but they are buried under outwash, and/or aeolian sand deposits. The patterns produced in the depositional subglacial landforms are discontinuous.

Areas of contradicting ice flow directions occur. These have been looked at in more detail using stereographic aerial photograph interpretation using 1:24 000 and 1:10 000 scale coverage. The results are illustrated in Fig. 3.33A-F, and Fig. 3.34, and are described below.

AERIAL PHOTOGRAPH INTERPRETATION

Area A - Dunbeath

Lineations exist within the area, with features occurring in north to south, west-southwest to east-northeast and west to east orientations. Streamlined hills are found throughout the area which illustrate these orientations. Evidence of meltwater erosion of bedrock is also present; meltwater channels are common in upland areas, often cut into cols and shoulders. Good examples of these channels exist where the Devonian limestones crop out, e.g. near Smirral and the Hill of Yarrows.

Striae are recorded at several locations in the area (Crampton and Carruthers 1914) and indicate a variety of possible ice directions. In the inland part they trend east, whereas at the coast they can vary from north, Beinn nan Coireag (ND 121 254) to, east-southeast at Cnoc Allt na Beithe (ND 040 227).

The structural geology exerts a strong control on the morphology of the area and the lineations within the area, as shown by the north to south lineation near Camster, (ND 261 418),

which is flanked on the east by the Hill of Yarrow, (ND 296 427). This is due to the Camster fault, one of a set of north-south trending faults. Another set of faults trend west-southwest to east-northeast.

The bedded structure of the Devonian strata affects the morphology of the hills, as exhibited by Ben-a-chielt, and near Smerral (ND 169 345), where the beds can be picked out on the aerial photographs. The rock type affects the morphology, as is seen with the Moinian intrusion of Scaraben Quartzite which forms an upstanding ridge, trending west-southwest to east-northeast (ND 066 268). The relative hardness (or resistance to erosion) of the different rock types and stratum within the sedimentary groups has an affect on the degree of glacial erosion which occurred and is preserved in the landscape.

The structural control on the orientation of the erosional evidence is very strong, and has influenced the flow direction of the ice. However, the occurrence of ice moulded landforms in the south of the area which do not follow the structural trends illustrate that all ice flow was not constrained by topography.

Area B - Golspie-Invergordon

The glacial erosional features are presented on Fig. 3.33B. They consist of eroded channels, streamlined features and ice scoured rock.

The streamlined hills indicate ice moved from west-northwest to south-southeast, between Golspie and Dornoch, with a more west-east trend where ice travelled along the Dornoch Firth. Some of the linear features with a north-south orientation are related to dykes. Localised ice erosion associated Orientation in the Dornoch and Invergordon area is south-southwest to north-northeast and is consistent with the structure of the rocks.

Eroded channels are common, they range in size from the glens and firths to small features less than a kilometre long. These are more variable in their orientations and range from linear, west to east trending features on the hill of Nigg, to curved

features on the northern flank of Maolanaidh Mor (NH 725 973) indicating local diversion of younger ice.

Erosion has created bedrock basins, which support small lochs. Scoured bedrock is present near Loch Ruagaidh.

Area C - Fraserburgh to Cruden Bay

From the map (Fig 3.33C) erosional evidence is restricted to lineations within the landscape, and meltwater channels, which may relate to the maximum position. Striae are recorded from cliff-top exposures between Cairnbulg Point (NK 035 657) and Inzie Head (NK 062 628). The striae trend west-northwest to east-southeast, although cross striae from NNW-SSE are also reported (Grant Wilson 1882). The east-southeast orientations relate to the movement of ice from the Moray Firth along the coast.

Area D - Portlethen to Inverbervie

Fig. 3.33D illustrates that the lineations and ice moulded features indicate three directions; west-northwest to east-southeast, west-southwest to east-northeast and south-west to north-east. An area of random erosional and depositional features also occurs. The meltwater channels conform to the directions indicated, except near the coast, where they trend normal to the coastline. An interesting assemblage of possible crossing meltwater channels appears to exist to the north of Stonehaven, near Cowie (NO 872 887).

The directions indicate that at least two ice flows affected the area and were confluent in the area that exhibits random directions and dead ice topography. Ice from the south-west was deflected offshore by the Inland ice flow. Local geology has affected the location of some of the channels, as shown by the crossing channels near Cowie (NO 872 887). The east to west channel occurs on chloritic schist, as opposed to the surrounding schistose grits.

Area E - Dundee

General directional trends in the landscape indicate movement from between west to east, to south-west to north-east, or, in places south-east. Striae are rare in the area, but were noted on the higher ground, trending south-east, by Geikie (1902). However to the east they conform to the general west-east orientation.

Glacial erosive landforms are rare, and consist of meltwater channels, crag-and-tail features and streamlined hills. The meltwater channels trend west-east, except where they are diverted around local highs, or into depressions. The crag-and-tail features are igneous intrusion occurring near the coast. These trend west to east within the Tay valley, but deviate to the east-northeast on the higher land. The streamlined hills have been created by meltwater being deviated around them, than direct moulding by ice, except in the Sidlaw Hills. Here a geological control has also affected the orientation of eroded features.

The dominant ice direction was from west to east. Minor directional changes occur, but relate to local topographic and geological controls. No evidence has been found which disproves current ice direction reconstructions in this area.

Area F - Midlothian

No evidence of pre-Late Devensian glaciations exist in this area. The evidence that exists, striae, meltwater channels, till lithologies and ice moulding, suggest that the area was subject to ice from two sources. These were ice from the Highland area flowing down the Forth valley, and also ice related to the Southern Uplands. Striae and crag-and-tail features indicate movement from the west, as do the lithologies of till found in the Forth valley. Similar evidence which occurs in the valley of the River Esk, and its tributaries suggest ice movement along this axis. Evidence of striae from the Pentl^and Hills, suggest that these were overridden by ice from the west, and would suggest that this was the dominant ice stream at that time.

The evidence of former ice direction consists of meltwater channels, crag-and-tail features, streamlined features, and ice scoured rock. Near the Firth of Forth the landforms used are streamlined and their long axes trend approximately east. The exceptions to this are Corstorphine Hill, which on the basis of its long axis trends approximately north. However field examination of this shows that there are glacial flutes scoured onto its summit which trend eastward. Meltwater channels and / or excavated basins in the lee of Arthur's Seat (Salisbury Crags), Carlton Hill and Blackford Hill, indicate where ice was diverted around the bases of these less erosive igneous intrusions.

An excellent complex of meltwater channels and ice scoured ridges occur on and around the Braid Hills (NT 247 696). The trachyte extrusion has been preferentially eroded into a series of west-east trending ridges, which are complemented by an extensive network of subglacial rock-cut meltwater channels which follow the same directional trend, and which connect with other areas of erosion, e.g. Craiglockhart Hill (NT 232 704) and Blackford Hill (NT 255 707).

Another extensive meltwater system exists in what are now the valleys of the North and South Esk rivers, in the large area of fluvioglacial outwash sands and gravels. These are fed by several smaller meltwater streams which are controlled by the local topography, and are probably related to a younger episode of fluvioglacial erosion when the ice cover was less extensive. This is probably also the case with the meltwater channel now occupied by the Burdiehouse Burn (NT 283 693). Another interesting meltwater channel assemblage occurs near Ormiston (NT 390 688). This trends approximately eastward, and is suggested to relate to the main eastward movement of Highland ice.

The evidence suggests that at the maximum of the glaciation it is suggested that the major ice movement was from west to east along the present Forth valley, from a source in the Highlands. This was sufficiently strong to constrain ice from the Southern Uplands, and to override and erode the Pentland Hills.

Isle of May

The Isle of May lies off the coast of Fife, within one of the main ice drainage routes for an ice sheet. The geomorphic map (Fig. 3.34) was produced from the aerial photographs, and was augmented by evidence collected in the field.

The map shows that the island exhibits lots of ice moulded bedrock, forming 'whaleback' landforms. The dimensions of these landforms range from 0.5m to 10m high, and between 3 to >50m long.

Exploitation of faults and joints by ice have resulted in the formation of meltwater channels, the best example of which occurs across the centre of the island as shown on the map, and in plate ii.

From the map the dominant trend in the ice directions range between west-southwest in the south, to north-northeast at the north end of the island, as shown by the orientations of the bedrock.

The evidence presented suggests that ice present in the Firth of Forth did not move in an easterly direction, but at the mouth of the Firth started to flow in a divergent manner. This was probably due to the change in topography and the removal of topographic constraint on the flow direction of the ice stream.

3.3.2 SUMMARY OF GEOMORPHOLOGIC MAPS

The 1:50 000 geomorphological map shows the ice moved directly from onshore to offshore, except where the lineations indicate an apparent deflection. Ice thickness was sufficient to cover the high land within the coastal strip and to erode the landscape. This also included the erosion of meltwater channels which extend to the present day coastline, and which have been utilised by the subsequent fluvial network. The geomorphological map confirms the general directional trends for the onshore environment, as described by the early workers of the Institute of

Geological Sciences, and outlined in the Memoirs (Sheets 116, 110, 109, 103, 93, 94, 83, 84, 95, 96, 97, 87, 77, 67, 57, 48, 49, 41, 40, 32, and 33), and the reconstruction shown in Fig. 1.1.

The map indicates that there are three zones of glacial modification in the landscape; erosion dominated, deposition dominated, and areas of localised converging ice flow.

3.3.3 SEDIMENTARY ANALYSES

This section presents a summary of the sedimentary evidence from the areas above. The directions of ice movement shown by fabric analysis are described, from within the key site till units (Fig 3.35), as are the sediments collected from the boreholes.

The Quaternary sediment cover within area A, Dunbeath, is thin to absent, except within the valleys and on the cliff-tops. The deposits have been divided into three tills; two inland tills and one originating in the Moray Firth, which relate to a single glaciation (Hall and Whittington 1989). The sequence of events proposed by Hall and Whittington (1989) suggests that an inland ice mass and the Moray Firth ice mass coexisted, with the former deflected by the latter. When the Moray Firth ice mass retreated the inland ice near Berriedale readvanced, depositing the second inland till.

The Quaternary sediments within area B, Golspie to Invergordon, are thought not to predate the late Weichselian glaciation (Read *et al.* 1923). The deposits consist of tills and fluvioglacial deposits, which indicate a two-stage glaciation. The first stage was a main ice sheet which covered the whole area. This was followed by a localised valley glacier stage, which only deposited material within the valleys.

The Quaternary sediments in area C, Fraserburgh to Cruden Bay, consist of three late Devensian tills which overlie older deposits, the oldest of which has been tentatively correlated with the Anglian stage (Kirkhill NK 012 529). The three till deposits are the Inland Series, the Red Series and the Blue Grey Series. These relate to inland, Strathmore and Moray Firth sources,

respectively. The current accepted reconstruction of the sequence of events is shown in Fig. 1.1b (Clapperton and Sugden 1977). The thickness of the till units varies from 2m inland, to 20m at the coast.

Within area D, Portlethen to Inverbervie, the Quaternary deposits consist of two tills, the Inland Series and Red Series. They are confluent in this area along a line which follows the Bervie and Carron Waters. The area exhibits all the geomorphological features indicative of former ice cover; streamlined hills, ice scoured rock, rock-cut meltwater channels and lineations. Fluvioglacial deposits are evident too. The till cover is very thin in places especially on the higher ground.

Area E, Dundee, has been remapped by the British Geological Survey (Armstrong *et al.* 1985). The Quaternary sediment cover is thought to be late Devensian. It ranges in thickness from 2m on the upland area, up to 20m in the carseland, and averages between 2-5m elsewhere. The till consists of one unit which is dominated by local lithologies but also contains erratics from the west.

The last area, F Midlothian, consists of two till units, which relate to the late Devensian glaciation. The till units are differentiated on the lithologies. One unit contains erratics from the west and Highland Series, whilst the other unit contains clasts from the upper reaches of the River Esk. The different ice masses from the Southern Uplands and the Forth Valley dominated the area at different times. The ice from the west crossed over the Pentlands, but was superceded by the ice from the Southern Uplands, which moved down the Esk Valley, and eroded at a lower level, at a later date (Peach *et al.* 1910). No Quaternary sediments exist on the Isle of May.

Outwith these areas, the overall Quaternary sequence is simple, with most of the till deposit being a simple single draped unit over the landscape. Local variations occur where the initial ice sheet till deposits have been reworked by post-maximum valley glaciers. With the exception of Buchan, there are very few areas ^{in east Scotland} where till deposits may relate to pre-late Devensian glaciations.

Fig. 3.36 shows five examples of till sections which have provided the ice directions, as indicated on Fig. 3.33.

Section 1 - Lybster

The section is located in the Quaternary sediments overlooking the harbour. It consists of a light brown massive, matrix supported diamicton. Clasts within the diamicton are of local origin, and include angular to rounded shapes. Less than 15% of the sample of 50 stones were angular. Some exhibited striated surfaces and fractured well-rounded clasts, indicating reworking.

The section is perpendicular to the flow direction, and no fabric was present, or any structures. However, measurements of the orientations of the clasts indicate that the movement of the ice was from onshore to offshore. No shelly material was found in the till, although the 'shelly till' was noted in the area by Hall and Whittington (1989).

Section 2 - Helmsdale

The section is located approximately 3km from Helmsdale, in the Strath of Kildonon. It is a cutting exposed at the base of the valley side. The cutting is parallel to the valley axis, 15m above the river level. It is a diamicton which is both matrix and clast supported. There is a possible discontinuity 1.2m from the surface. Above this there is a coarse clastic diamicton, with iron staining.

The main diamicton is massive, with clast orientations indicating movement parallel to the valley axis. The matrix is sand dominated, and the clasts are dominated by angular to subrounded shapes. There are very few rounded clasts. It is interpreted as subglacial lodgement till.

Section 3 - Strathpeffer

This section is located near Loch Ussie, near to Strathpeffer. It occurs on the side of a dike which has been moulded by ice. The deposit is less than 1m thick, and is composed of a structureless diamict unit. It is dominated by the local

lithology of the dike and pinches out to the east where there is an increase in the gradient of the bedrock. The matrix of the diamict is very poorly sorted, and includes silt and clay, as well as coarser material. The clasts are predominantly angular to subrounded. The orientations of the clasts is the same as that recorded within the ice scouring of the bedrock, i.e. to east northeast to the Moray Firth.

Section 4 - Stonehaven

Few good sections are found in this area. This section is composed of two units. The lower unit is a massive matrix supported, diamict of the Inland Series. This is overlain by fluvioglacial outwash deposits originating from the Red (Strathmore) Series.

The diamicton is poorly sorted and matrix supported, with angular to subrounded clasts. There are occasional faults which are associated with the deposition of the fluvioglacial unit. The clasts within the diamict indicate movement of the ice around the hill, resulting a direction to the north.

Section 5 - Gifford

This section is located in the outlet valley of the Hope Reservoir, near Gifford. It consists of a light brown, matrix supported diamict. There is no internal structure within the unit, and the clasts are randomly scattered throughout the section. The clasts are predominantly angular to subrounded. They are derived locally. The orientation of the clasts is parallel to the valley axis.

The clast orientations in the sections, are all conformable to the localised ice movement in the key sites, as noted in Fig. 3.33. There are no sites where the orientation of the clasts within the sediments disagree with the directions already indicated. However they do add additional evidence to strengthen the arguments about localised ice movements.

The logs shown in Fig. 3.37 illustrate the sediment succession at St. Fergus and Montrose. These are used to

illustrate the changes in the sedimentary environment at the coast. They also provide a comparison with the offshore borehole logs.

The succession within the boreholes at Montrose consists of;
Description rockhead composed of red mudstones, which is overlain by brown clays, which are affected by the red colouration of the mudstone at the base of the unit, in Montrose 1. The clay unit is up to 15m thick, and contains shell fragments. Laminae occur within the unit, with an increase in the proportion of coarse material upward. Overlying the clay unit is a silt unit, again containing shell fragments, increasing sand content upwards, but with a decrease in micaceous particles upward. Two units overlie the silt unit. The first consists of a silty sandy gravel with common rounded cobbles and shells. This fines upwards into the top unit in the succession.; a silty sand, again with numerous shells.
Interpretation This sequence is interpreted as a continuous record of a transgression from marine conditions, through carse into a beach and littoral environment.

The four boreholes at St. Fergus present a more complicated sequence of events;

Description The logs in 3.37 show that the sequence is dominated by silts and clays. However diamicton units are also present.

Borehole 1 penetrates 18m of sediment. It is composed of four units, the lowest of which is a grey, stiff diamicton interpreted as till. This is overlain by two clay units. The lower of unit consists of a fining up, clast supporting red clay, the upper section is laminated. The upper clay unit is a grey silty clay, which coarsens upwards to the top unit. This is a grey silt.

Borehole 2 consists of 5 units overlain by peat. The lowest unit is a grey silty clay. This is overlain by two clastic units. The lower unit is composed of washed angular clasts, whilst the upper unit is a poorly sorted gravel containing subrounded clasts. This is overlain by a grey/brown silty clay, which coarsens upwards, and a grey soft clay.

Borehole 3 penetrates 26m of sediment which is composed of 8 units. The lowest unit is a grey brown/brown stiff diamicton

interpreted as a till unit. A unit of washed, coarse gravel (possibly fluvial) overlies this. Two clay units are next in the succession. The lower unit is a grey laminated clay with dropstones, which is overlain dark grey massive clay, with angular clasts to 6cm long. The first diamict unit overlies this, it is a grey compact sandy clayey diamict. A brown/grey clay unit 1.5m thick splits this from the upper diamict unit, which is composed of the same sediment. The upper unit of the succession is a massive dark grey micaceous clay, which stiffens upward.

Borehole 4 consists of 5 units. The lowest unit is a light brown stiff laminated clay. This is overlain by an olive brown compact diamict with a faint sulphurous odour. A grey compact clay overlies this. In turn this is overlain by a grey clayey silt, which coarsens upwards to a grey/brown micaceous coarse, slightly sandy clayey silt.

Interpretation The units have been correlated in the boreholes, where possible. It is suggested that the sediments represent the different dominant ice streams passing over the area. The grey and red/brown colours relate to ice streams from the Moray Firth and Strathmore, respectively. The sediments sampled in the cores are interpreted as glacial diamictons, probably tills, and glaciomarine deposits associated with the different ice streams. The upper units represent the return to non-glacial conditions and marine deposition.

The presence of washed gravels and clast-dominated deposits indicate fluvial inputs. It is possible that the washed gravels within borehole 3 may be fluvioglacial, given that they occur above a till, and beneath a glaciomarine unit. However, from the borehole logs alone, it is difficult to test this.

AMINO ACID RACEMISATION RATIOS

Fig. 3.38 shows the locations of sample sites for the amino acid racemisation analyses. The results of the analyses are shown in Table 3.7. This correlates the ratios with the aminostratigraphy for NW Europe as set up by Miller and Mangerud (1985), and augmented by Bowen and Sykes (1988), shown in table 3.8.

Two samples were selected from cores 208CS and 219VE in the Bosies' Bank area in order to try and date the Bosies' Bank moraine (Bent 1986) core, whilst BGS borehole 81/32 was sampled from the Wee Bankie moraine for shell material to provide chronological constraint on the deposition of the sediment;

208CS - The shell fragments have been extracted from a shell drape overlying the diamict unit of the Bosies' Bank moraine (unit 3), as shown in Fig. 3.38. The drape consists of unbroken and large fragments of bivalves of arctic fauna. This is in contrast to the shells found in the overlying Holocene sand unit (J.D. Peacock, *pers comm.*) and the highly abraded small fragments found within the diamict unit. The shells of the drape exist as a distinct unit 3cm thick, above the diamict unit.

219VE - The shell fragments have been extracted from beneath a thick unit of shell-rich sand, interpreted as Holocene (J.D. Peacock, *pers comm.*). The underlying unit is a poorly sorted, clast-poor, compact diamicton. The boundary between the two units is transitional rather than a drape, as illustrated in Fig. 3.38.

Borehole 81/32 from the Wee Bankie area was sampled for shelly material. The shell fragments were extracted from within a diamicton unit, thought to be till from the late Weichselian glaciation, again shown in Fig. 3.38.

An *Arctica*? shell fragment from glaciomarine sediments recovered from an onshore borehole, was also tested.

The ratios obtained are presented in table 3.7. These have been correlated with the aminostratigraphy set up by Miller and

Mangerud (1985) and Bowen and Sykes (1988), as illustrated in table 3.8. From this it can be seen that the ratios derived from the Bosies' Bank moraine are correlated with the middle Weichselian high sea level, and would suggest that the material beneath the shells predates the middle Weichselian (>40ka BP). The presence of a younger shell fragment shows that faunal reworking of the sediment has occurred.

The ratios from the Wee Bankie borehole indicate that the shells are middle Weichselian, with younger (late Weichselian) shell fragments incorporated into the upper part of the unit. The ratio obtained for the *Arctica* fragment suggests that the shell is pre-Cromerian in age, and that it has reached equilibrium in the racemisation process. This age is not what would be expected. It is suggested that this is an example of reworking of older deposits because the shell was fragmented, and not *in situ*. However, it serves as an excellent example of the problems caused by sediment reworking, and relying on dates to constrain hypotheses.

The significance of these results is important with regard to the relative ages of the moraines. The presence of mid-Weichselian shells draped over the Bosies' Bank diamict unit indicates that the unit pre-dates the mid-Weichselian, and hence is not related to the late Weichselian glaciation. The incorporation of mid-Weichselian, and late Weichselian shells within the Wee Bankie moraine indicates that this moraine post-dates the mid-Weichselian, in that it has incorporated mid-Weichselian, reworked material into the sediment succession. This must have been deposited prior to the expansion of the ice sheet into this area. This indicates that the ice sheet post-dates the mid-Weichselian, and is inferred to be associated with the last glaciation, during the late Weichselian. This implies that the moraines are not related.

CHAPTER 4

SYNTHESIS OF RESULTS

4.1 INTRODUCTION

This chapter synthesises the results presented in chapter three, in order to present a reconstruction of the whole eastern margin of the last ice sheet to cover North Britain, and to show the eastern margin ice flows for the ice sheet as a whole.

4.2 ICE SHEET EXTENT

4.2.1. Distribution of Glacial Erosional and Depositional Evidence

Figure 4.1 illustrates the distribution of the glacial erosional and depositional evidence from the onshore and offshore areas. The evidence suggests that the onshore area was completely covered by ice, and that the ice extended offshore to a maximum position 50km to the east of Peterhead. To the north of $57^{\circ}40'N$, the position of the ice margin is less certain. However, it extended beyond the present-day coastline and terminated in an aqueous environment. The overall pattern of the evidence shows that the landscape can be divided into four; (1) a landscape dominated by glacial erosion, (2) a landscape dominated by glacial deposition, (3) a landscape where both erosional and depositional evidence occurs and (4) a landscape where erosion has not taken place.

(1) Landscapes dominated by glacial erosion

The distribution and type of erosional evidence is shown on Fig. 4.2. Erosion is concentrated on the higher ground, and on sedimentary strata susceptible to abrasion and plucking. The scale of the erosional features ranges from small striae a few

centimetres long to glacial channels such as the Buchan Deep, over 15km long and over 50m deep. The scale of the eroded channels onshore varies considerably, as do their morphologies, as indicated on Fig. 4.2.

The main areas which exhibit erosion are southern Caithness, Sutherland, the foothills of the Grampians, Strathmore, the Midland Valley, and the rockhead beneath the Wee Bankie Formation and sediment units 1 and 6, in the Moray Firth.

The erosional evidence indicates an onshore to offshore orientation within the inner Moray Firth, Firths of Tay and Forth, and the Aberdeen area. Evidence also indicates that ice has been deflected by the dominant ice streams, for example, to the north of the Tay estuary, here the west to east direction is replaced by a gradual change to a north-east direction, on the coast.

The glacial basins and channels in the southern part of the Moray Firth Basin, trend west to east, paralleling the coastline. The channels in the Wee Bankie and Peterhead areas trend south-west to north-east, whilst those in the Bosies' Bank area trend either north to south or west to east. The west to east channels within the Moray Firth are perpendicular to the onshore erosional evidence, which suggests north-west to south-east flow on the northern margin. The Quaternary basins within the inner Moray Firth relate to the caledonoid trend evident in the Great Glen area.

Comparison of the erosional features with the structural (Fig. 1.3) and pre-Quaternary geology (Fig. 1.4) of the study shows that both the lithology and structure of the underlying strata affect the distribution of the erosional landforms. This is best seen in the inner Moray Firth where the features are aligned parallel to the Great Glen Fault. The location of the Southern Trench, parallel to the Moray coast would also appear to be a function of the structure, occurring along the Banff Fault. The preservation and scale of the erosional features is a function of the susceptibility of the pre-Quaternary strata to erosion, as well as the efficiency of the basal ice sheet processes. This is best illustrated where igneous dykes occur within sedimentary

strata. The lineations of the dykes dominate the orientation of the features which have been subsequently affected by glacial erosion, for example Costorphine Hill (Fig. 3.33f). However, in Caithness, the arcuate trend noted by Peach and Horne (1881) and referred to by Crampton and Carruthers (1914) does not relate to a geological control in the Devonian strata.

The topography has affected the potential for erosion, with pre-existing drainage patterns channelling ice along pre-defined pathways, such as the Firths of Tay and Forth, and the Beaully Firth. These corridors are intensely eroded. In areas where there are major changes in relief this has affected the movement of ice, for example, the line of the Highland Boundary Fault, in Strathmore has been a barrier causing ice to be channeled along the fault, for example at the coastline. Changes in relief affect the erosional potential of the ice sheet, and will restrict the ice movement.

The overall distribution of the erosional landforms indicates that ice in southern Caithness and the inner Moray Firth converged on the Moray Firth Basin, and flowed onto the shelf where it eroded rockhead (Fig. 3.24). However, given the lithostratigraphy and the chronological constraints (Fig. 3.23), it is unlikely that they have been eroded in the late Weichselian glaciation; the basal till (Ruckley and Chesher 1984 and Chesher 1987) found within the basins pre-dates this glaciation.

Ice flow along the Midland Valley was dominated by a west to east direction. The Forth valley was the dominant ice stream in central Scotland, as illustrated by the orientation of the landforms as far east as Dunbar. The lineations on the north shore of the Firth of Tay show that the ice stream flowing along the Tay valley was deflected to the north-east.

Interpretation of the ice flow patterns recorded in the rest of zone 1 is more difficult because they illustrate a more complicated erosional environment, especially in northern Caithness and along the east coast, in the Mearns and near Aberdeen. The different orientations of the erosional landforms also suggest multiphase erosion.

The north-east of Caithness is blanketed in peat, with a high density of small water bodies (lochans), in an area of thin sediment cover, over rock. These lochans indicate a surface subject to areal scouring, as described by Linton (1964). The strong arcuate pattern in the landscape reflects the movement of an active ice sheet across the area, from south-southeast, to north-northwest. The erosional evidence suggests ice movement from the Moray Firth Basin, onto the Caithness plateau. This is at odds with the onshore to offshore direction of movement found in southern Caithness, and the inner Moray Firth basin.

The parallel and perpendicular patterns of erosion (Fig. 4.2) which converge in the vicinity of the Mearns and Aberdeen, have been suggested as indicating multiple episodes of glaciation (Jamieson 1865, 1886). This concept was expanded and applied to north-east Scotland and led to the suggestions that the area had undergone several episodes of glaciation (Bremner 1932).

An alternative explanation is that the changing ice directions indicate the relative strengths of the main ice streams from Strathmore and the Grampians, during the course of a glaciation. The west to east pattern was eroded by the ice issuing directly from the eastern highlands. The south-west to north-east pattern was eroded by the Strathmore ice. Where these occur together they indicate the fluctuations in the relative ice stream dominance.

The multiple glaciation of Buchan has been similarly resolved into a complex series of fluctuations reflecting the relative dominance of three ice masses (Clapperton and Sugden 1977, Munro 1986), although this has not been universally accepted (Price 1983, Hall 1984). At various times Buchan was covered by local ice or affected by north-east flowing Strathmore ice or south-east flowing Moray Firth ice. The ice masses originate in the Moray Firth, the Grampian Massif and from the south, Strathmore.

No erosional evidence exists to suggest that ice moved onshore, for example to the north of Aberdeen, due to the deflection of Strathmore ice by ice lying offshore, as suggested by Hoppe (1974). The offshore evidence (Stoker *et al.* 1985,

Cameron *et al.* 1986 and Sejrup *et al.* 1987) indicates that the Scandinavian and Scottish ice sheets did not coalesce in the North Sea, during the last glaciation.

Differences between the regional and local erosional evidence are apparent at the local scale. The detailed survey of the Helmsdale area, for example, showed that there were two phases of erosion. One was associated with regional movement of an extensive ice sheet (discussed above), followed by a restricted, valley glacier event. The distribution of the regional indicators (striae, polished bedrock, plucked surfaces) is restricted to the top of the high ground, and the saddle of the hill behind Helmsdale, Creag Bun-Ullidh (ND030 157). Beneath 100m the geomorphology is affected only by the localised ice movement of the valley glacier. This has removed any evidence of the regional movement which suggests that the restricted phase post-dates the regional event. This multi-phase erosional pattern is also found in the Midland Valley, and near Aberdeen, where the regional evidence of flow towards the east, exhibited at Tyrebagger, near Aberdeen, has been slightly modified by subsequent local movement down the Dee and Don valleys. To the south of Aberdeen a second phase of erosion is present, with more localised movement within depressions and valleys, at a later stage, as shown in the meltwater channels to the west of Stonehaven.

The pattern of the erosional evidence can be usefully compared with that of Clayton (1974) (Fig. 4.3), and that described in the memoirs of the Geological Survey; Grant Wilson and Hinxman (1890), Armstrong *et al.* (1985), Peach *et al.* (1910, 1912), Howell *et al.* (1866), Greig (1988), Davies *et al.* (1986), Geikie (1863, 1902), Grant Wilson (1882, 1886), Read (1923, 1931), Read *et al.* (1925), Francis *et al.* (1970), Horne (1923), Peacock *et al.* (1968), and the numerous reviews of the glacial erosional geomorphology of this area (Sissons 1976, Price 1983, Hall 1984, Sutherland 1984, Sibrava *et al.* 1986, Hall and Whittington 1989, Auton *et al.* 1990), giving good agreement.

Clayton (1974) outlines five zones of different intensity of glacial erosion for the late Weichselian glaciation of Britain

(Fig. 4.2). The study area spans four of the zones ranging from no glacial erosion over Buchan to the second highest zone of intensity of erosion along the Great Glen. Clayton does not attempt to classify the offshore erosion intensities, but these are shown in Fig. 4.1. They form offshore continuations of the onshore zones.

The memoirs describe the location and orientations of the main erosional landforms as mapped by the Geological Survey, and these have been compared to the erosional landforms taken from the aerial photographs.

There is good agreement both with the zones of intensity of erosion, outlined by Clayton (1974), and with the orientation of the landforms described in the memoirs. Figure 4.2 is a synopsis of all the erosional evidence.

(2) Landscapes dominated by depositional evidence

The depositional evidence falls into two types; subglacial and proglacial. Subglacial deposits consist of till or glacial diamict (material deposited in a glacial environment, which has been reworked, and lost primary structure, but is likely to be glacial in origin). Subglacial fluvioglacial deposits occur near the margin. Proglacial deposits are found to the east of the margin and consist of fluvioglacial, glaciolacustrine or glaciomarine material, with reworked sediments, and ice rafted debris.

Subglacial Deposits

i). Till

Till blankets the onshore area, except where it is restricted to valley bottoms and sides, or is buried by younger deposits. The main till units attributed to the Late Devensian ice sheet have been identified in the onshore sites. Diamicton interpreted as till has been identified offshore along the east coast as the Wee Bankie Formation (Stoker *et al.* 1985) and its northern

continuation, and tentatively, within Quaternary basins in the Inner Moray Firth Basin (Chesher 1984) (Figs. 1.6 and 1.7).

Within the Moray Firth basin till-free enclaves exist. This indicates that a large part of this area was not covered by ice in contact with its bed, or that any till unit has been entirely reworked. The presence of a massive glaciomarine unit within the Beatrice basin at a site where a till unit would be expected to have been preserved is particularly important. Micropalaeontological evidence of macrofauna (Harland and Gregory, unpublished BGS data) suggests that the sediment has been totally reworked beneath the post-glacial sediments because the fauna recovered from the deposit include Jurassic and Cretaceous organisms, as well as Quaternary material. There is no evidence onshore to suggest that till-free enclaves existed.

Ice flow was from onshore to offshore, as indicated by fabric analysis of tills at the onshore sections (Fig. 3.35). However, depositional evidence of an offshore to onshore flow direction occurs in Caithness. 'Shelly till' (Peach and Horne 1881, Jamieson 1886), and a sandstone raft reported at Leavad (Carruthers and Crampton, 1914), suggest basal ice-rafting of material from the Moray Firth basin over a distance of 15-20km. The occurrence of short (40m), high amplitude dipping third-order reflectors, found within the diamict seismic facies, may indicate similar rafts of local strata offshore.

Hall and Whittington (1989) suggest that the glaciation of southern Caithness was a single event with three distinct ice movement phases. They suggest that this can be extended to include north-east Caithness. Depositional evidence suggest contemporaneity between the ice masses acting in different directions, with striae on the high ground suggesting that the interior ice expanded onto the plain of Caithness, after the Moray Firth ice mass withdrew.

The onshore and offshore till units are not attributed to a single glacial event. There is evidence from Buchan (Hall 1984) that at least three glaciations and intervening interglacials are recorded in the onshore sediments. For example, the onshore

boreholes (Fig. 3.36) illustrate that more than one subglacial till has been deposited at St. Fergus. A glaciomarine deposit occurs between the tills, and the colour of the tills would suggest that they were transported by ice from different source areas.

ii). Subglacial fluvioglacial deposits

Onshore, ice-marginal fluvioglacial deposits exist on all the low-lying topography, with the exception of the Holocene emergent shorelines, carselands and coastal sand accretions, for example Firth (1989). Deposits also occur within valleys, even in the uplands. The area with the greatest coverage of fluvioglacial forms occurs between the coast and the foothills of the Grampians between Strathmore and the Spey. There is an irregular pattern to the distribution of the fluvioglacial deposits, complicated by the sequence of deglaciation landforms.

The offshore fluvioglacial sediments mark the position of the ice sheet margin. The coarse sediments entrained within the subglacial fluvioglacial system are deposited at the ice margin location as it passed from the enclosed, high energy meltwater system, to the lower energy glaciomarine environment, as the margin decoupled from the grounding line, or the sediment was debouched at the conduit exit.

The low-level onshore deposits may also relate to subglacial fluvioglacial activity near a retreating ice margin (or possibly the topographic location). The fluvioglacial deposits within the valleys relate to valley glaciers which post-dated the maximum position of the ice sheet. The deposits relate to standstill positions of the glaciers, shown by the presence of moraines or hummocky topography, as shown in the field sites (Appendix 3b).

iii). Derived glacial diamict deposits

Where sediment has undergone post-depositional reworking it is possible to identify features which can indicate the processes of reworking, such as push structures and other glaciotectonic indicators (Aber 1985,1988, Aber and Aarseth 1988, Lawson 1982 and Saettem 1990) although the primary structures may have been lost. Evidence of glaciotectonism is not easily accessible on land, and was not detected in any of the till deposits.

Offshore, possible push structures have been identified on seismic records from the North Sea basin, where Coal Pit Formation sediments have been pushed by the overlying Wee Bankie Formation diamicton, 35 km east of Cruden Bay (Stoker 1985). If so, this indicates that the ice margin was once located in the vicinity of this position.

Proglacial Deposits

i). Proglacial fluvioglacial deposits

Subaerial proglacial fluvioglacial deposits occur as deglaciation landforms, overlying till. They are composed of outwash sands and gravels, consisting of sand and gravel-bedded, prograding channel systems, of anastomising wide, shallow, ephemeral braided streams. The sediment is laterally and vertically sorted as a function of the distance from the sediment source at the ice margin. Good examples occur in the Don and Ythan valleys.

Offshore, proglacial fluvioglacial landforms occur within the glaciomarine deposits, but have been tentatively identified only at the GEOTEAM site and in the deltaic body near Peterhead. The depositional environment is different to the subaerial example and is described in detail below;

ii). Glaciomarine deposits

The glaciomarine deposits are derived from three sources; sediment supplied from fluvioglacial inputs, meltout at the ice terminus, and ice rafted debris. The distribution of the glaciomarine deposits is shown in Fig. 4.4. Note that the western margin of the deposits is diachronous, and extends onto the present onshore area.

The major source of sediment is supplied from the meltwater streams as indicated by the areal extent and volume of the proglacial glaciomarine deposits. The sediment particle size and shape, and the entrainment potential of the meltwater containing the sediment plume is important with regard to the transport distance. The higher the velocity of the plume the further material can be transported away from the margin (Powell and Alley *in press*).

Figure 4.4. shows that the distribution of the glaciomarine deposits covers the offshore area, and helps to delineate the eastern position of the margin. The glaciomarine deposits are of two types; those which have undergone syn- and/or post-depositional change, and those which remain undisturbed. The disturbed sediments are found within the Moray Firth Basin, on the Peterhead Ridge, and at the margin. Undisturbed sediments form the extensive well-structured deposit in the central North Sea, which extends into the northern North Sea.

The well-bedded formation (Marr Bank Formation) can be split into relative ice distal and ice proximal environments, on the basis of the particle size and internal sedimentary structure. Due to the lack of sediment control from cores between $1^{\circ}30'$ and $0^{\circ}30'W$, it is not possible to define a transitional zone between the two environments. However, there is a distal fining, as shown by the PSA results (Fig. 3.7). The ice proximal deposits are dominated by massive deposits of coarse clastic material, whilst the ice distal deposits consist of muds and silts. This is illustrated very well by comparing the PSA results of BH81/27 and BH81/33. Note that it is possible to get some units of fine

material at the margin. These occur as rhythmites, the result of tidal drawdown, for example (Smith *et al.* 1990), and diurnal or seasonal meltwater fluctuations. Mass movement, and turbidites can also result in similar fine grained facies (Mackiewicz *et al.* 1984, McCabe 1986, McCabe *et al.* 1988 and Rust 1988). The source of the sediment rich meltwater is important with regard to the forms of the deposits produced, and the sediments present. Differences occur in the morphology of material deposited from subglacial and englacial conduits (Powell 1981, 1983, Syvitski and Praeg 1989, Powell and Alley *in press*, Carlson 1989, Cowan and Powell 1990 and Josenthal *et al.* 1988). Surficial sources of sediment also create different morphologies. The mixing of the non-saline meltwater and the glaciomarine water also affect the settling rates of the particles in suspension. Clastic material transported entrained within ice (ranging from bergs to sea ice) is a minor source of sediment, but is a generic indicator of a glacially influenced aqueous environment. This was found within the well-bedded formation, both as indicated as point-source reflectors on the seismics, and confirmed by the PSA analysis of the cores.

(3) Erosional and depositional landforms

This is a transition zone which is characterised by a complex pattern of both erosional and depositional subglacial landforms, with neither set being dominant. Figure 4.1 shows the location of this zone. It occurs between the zones of dominantly erosional or depositional landforms. The landforms in the transitional zone have a random pattern and there is no dominant direction. However there are two orientations within the landforms which conform to the directions of the landforms in the zones bordering this zone. The area has been covered by an ice sheet, but the evidence does not indicate that the ice sheet was dominantly erosional or depositional. It is suggested that this area represents a zone of changing ice flow directions and basal processes. The location of the areas would suggest that the landforms represent the glacial

modification found at the base of an ice sheet where the dominant basal processes were changing from erosional to depositional, and *vice versa*. The complex pattern would suggest that this area was very sensitive to changes which influenced the basal processes of the ice sheet.

(4) Erosion-free areas

There is evidence of erosion-free areas offshore. Stoker and Graham (1985) note the presence of planar platforms in the rockhead, which they interpret as pre-late Weichselian marine erosion surfaces. These can be traced 10km to the east of Stonehaven. The adjacent onshore area is glacially modified, indicating that erosion was occurring at the base of the ice sheet, and glacial erosion of the rockhead is present elsewhere in the inshore areas. The lack of erosion of the rock platform suggests a change in the basal processes, possibly related to change in the gradient at the base of the ice sheet.

Erosion-free areas exist onshore in Buchan. These are examined in detail in Hall (1984) who reviews the evidence which shows that pre-glacial remnants occur in Buchan.

4.3 ICE MARGIN LOCATION

The main evidence used to establish the location of the margin (Fig. 4.6) is based on the seismic interpretation of the sedimentary sequence, with lithological control provided by the core evidence. The margin has been located by tracing the relative position of the subglacial and glaciomarine facies units. The presence, or absence, of the first order reflector at the base of the glaciomarine facies unit has also been used as an important marker because it is used to locate the eastern maximum marginal position of the ice sheet. The western section of the sediment succession which does not exhibit this reflector has been overridden by grounded ice.

The margin is characterised by three morphological and sedimentary associations; 1) an upstanding diamicton ridge (moraine), 2) a series of small ridges at or near the boundary with glaciomarine sediments overlying the planar first-order reflector, and 3) a discontinuous ridge on the margin of an area of reworked sediment with till-free enclaves.

i). Continuous Ridge

The continuous ridge*, and associated channels is located between 56°N and 57°N, and is formed from an arcuate series of mounds. (Fig. 4.6) It is located 30-50 km from the present coast. The ridge, and the associated sheet-form sediment sequence to the west, is composed of subglacial till and derived glacial diamicton. The ridge contains some steeply inclined, strong, but short reflectors, and overlies a depression in the underlying rockhead. The depression beneath the ridge may be a submarginal area of active erosion.

The presence of the first order reflector at the base of the glaciomarine facies unit is important with regard to the maximum extent of the ice sheet. This is based on the premise that the first order reflector represents a transgression which pre-dates the deposition of the glacial sediments. The expansion of ice from the land onto the basin margin removed the reflector, or disturbed the reflector so that its continuity was destroyed. This is best seen where the reflector is linked with a ridge, where it only occurs outside the ridge.

The coincidence of the ridge with the western limit of the reflector suggests that in these locations the ridge represents the maximum position, at the regional scale. This confirms the interpretation placed on this feature proposed by the initial workers in the area (Holmes 1977, Thomson and Eden 1977, Stoker 1985, Stoker *et al.* 1985). To the north of 57°N, the ridge becomes discontinuous and untraceable, and the sediment sequence becomes disturbed.

Another possible indicator of icesheet extent is provided by the areal extent of the deformation of the rockhead. This could be related to the presence of an icesheet which loaded the underlying material, or deformed it by the presence of freshwater in the vicinity of halide-rich strata, causing salt solution. In confirmation of this idea, Figs. 3.12 and 3.15 would suggest that there is a close relationship between the proposed location and the presence of rockhead deformation.

ii). Discrete Ridges and Seismic Facies Unit Boundary

The maximum position in the Peterhead area is found where the western limit of the planar, first order reflector and the boundary between the subglacial and glaciomarine seismic facies units occur. The geometry of the relationship between these features shows that the diamict seismic facies unit only occurs in the west, overlying an uneven rockhead, while the glaciomarine seismic facies unit overlies the planar first order reflector and occurs to the east of the diamict unit. The boundary between the units is transitional, with the glaciomarine prograding seismic facies unit overlying the maximum position. This is the same geometry as is found at the margin in the Wee Bankie area, but without the morainic ridge.

Upstanding mounds composed of the diamicton occur to the west of the maximum position. Presumably these represent stillstands during the retreat phase of the ice sheet from the area.

Evidence from the north and east of the margin does not provide alternate positions. However the data set to the north is poor, and the extension of the margin to the Bosies' Bank moraine to the north, as suggested by Bent (1986), cannot be discounted.

iii). Isolated Ridges and Till-Free Enclaves

The final form of the margin occurs within the Moray Firth basin. The margin is proposed on the distribution of till-free enclaves, the bathymetry of the basin, and the occasional presence

of diamicton ridges. Controversy exists in the area about the interpretation of the sediments, and the age of the sediments. Chesher and Lawson (1983) suggest that some of the units present are till, whereas in this study it is suggested that these are glaciomarine.

Till, dated as mid to late Weichselian has been found within the basins in the southern part of the Moray Firth (Chesher and Lawson 1983). However the till has also been suggested as pre-mid-Weichselian (Lawson in Harkness and Wilson, p 244, 1979). However re-examination of core logs in this project interpret the sediment described as till is extensively reworked glaciomarine material (Figs. 3.27 and 3.28). This significantly affects the reconstruction of the ice sheet margin in this area. The presence of till would indicate that the ice sheet was in contact with its bed and was warm-based. A glaciomarine interpretation does not dispute the presence of ice, but suggests that the ice sheet was either restricted to the margins of the Moray Firth Basin or that it was floating. Whatever the interpretation, it is apparent that there is no continuous ridge which can be interpreted as a moraine.

In the south of the basin, there is no evidence that ice expanded north of the Southern Trench. There are no diamicton ridges and survey of the Southern Trench suggests that it is composed of a glaciomarine and marine draped mud infill (RACAL 1988). The trench appears to have acted as a northern limit to ice expansion from Buchan, although it may have channeled the flow of ice along the coastline, during some earlier glaciation.

The lack of a terminal ridge within the Moray Firth Basin is puzzling, given the volume of sediment available. One possibility is that the margin of the ice sheet was a floating, ice shelf, possibly grounded as far as the present-day 40m bathymetry line (Figs. 1.5 and 4.6). The sediment accumulated in present-day depths greater than 40m are diamictons interpreted as reworked glaciomarine sediments. There are no till units deposited in the sediments, even preserved in the Quaternary succession in the basins. All the sediments within the basins are glaciomarine.

The reworking of the sediments in the Moray Firth as a whole, and the erosion of the rockhead are suggested to be the result of post depositional reworking by an ice sheet advancing along the Moray Firth, to the north-east, in contact with the sediment body. The ice sheet became decoupled from the bed as a function of the buoyancy of the ice, and the depth of the water related to the glacio-isostatic depression at the margin. The ice shelf then retreated by rapid calving, creating glaciomarine sediments. The marginal positions proposed suggest a minimum scenario, based on a grounding line at the 40m bathymetry line and a maximum position where the extent of the ice margin is constrained by the Southern Trench, in the east. Hulton (1990) suggests that cyclic calving and readvance is characteristic of this type of dynamic margin, creating a lack of moraines within a highly reworked glaciomarine embayment.

An alternative location for the margin has been suggested by Bent (1986) and Hall and Bent (1990) (Fig. 4.6). This connects the Wee Bankie moraine, with the Bosies' Bank moraine of Bent (1986), over a distance of ~75km, of which 30km is unconstrained by useful seismic or core evidence. The Bosies' Bank moraine described by Bent, is up to 40m thick but is normally 20m thick, ca. 5km wide and ca. 90km long. Hence it is a significant ice terminus.

The moraine is partially buried by younger marine sediment, although diamict crops out at the surface in places where it is slightly planed off. The morphology is different to that of the Wee Bankie moraine, which is a more continuous upstanding feature, although both deposits exhibit the small scale hummocky topography indicative of glacial material (Stewart and Stoker 1990). The facies units are similar, with the exception of the origin of clasts, and the hardness of the deposit (Bent 1986). The seismic facies units from both moraines give the same chaotic, patchy response, with variable amplitude. Both units contain point-source reflectors, and strong but short randomly orientated planar reflectors.

The diamict of the Wee Bankie moraine, and the associated subglacial lodgement till is both harder and less well sorted than that of the Bosies' Bank moraine. Bent suggests that this is due to the composition of the sediment source for the Bosies' Bank moraine, which is more restricted than in the Wee Bankie Formation till, being derived from local sources only. The relative softness of the Bosies' Bank till could relate to deposition in an area of high pore-water pressure within the subglacial sediments, thus negating any compaction of the material by the overlying mass of ice (Bent 1986).

Bent suggests that the material deposited to the west of the moraine is a thin (3m maximum) deposit of the subglacial till (lodgement?) found at the margin. This has not been sampled because of poor seismic and borehole and vibrocore coverage in the area. However, Bent implies that it would continue into the Moray Firth. It is possible that the moraine does represent a maximum position. If so the amount of sediment that was deposited as the result of this event suggests a long lasting position, rather than a transitory event.

An attempt to establish whether the moraines were contemporaneous and associated with a common sea level was made by investigating the the current bathymetry to the moraines, given an average thickness of the moraines of 20m (Bosies' Bank moraine) and 25-30m (Wee Bankie moraine). Fig. 1.5 shows that the depth varies from between 80-100m in the Bosies' Bank area, and 40-80m along the line of the Wee Bankie moraine, excluding incised deeps. The depth to the top of the associated glaciomarine units, to the east of each moraine is ~100m in the northern case, and 60m in the case of the Wee Bankie. These present-day depths are significantly different. However, when allowance is made for isostatic compensation the reconstructed depths are less. The glacio-isostatic depression at the margin has been worked out for points on each reconstruction (FIG. 3-39). The bathymetric difference is not as extreme as present-day differences, which suggests that with isostatic compensation, the moraines may be part of the same margin.

The preferred location of the ice margin in the Moray Firth is of a restricted ice sheet with floating ice shelf. However the alternate position proposed by Bent (1986) and Bent and Hall (1990) cannot be discounted out of hand as some evidence would support this reconstruction. One possibility is that the Bosies' Bank moraine relates to an earlier, more extensive ice sheet, which covered the area pre-43 ka BP. This is supported by the amino acid ratios. Relict landforms of a glacial origin have been described from the Scottish west coast continental shelf (Stoker 1989, 1990, Stewart and Stoker 1990). Examples have also been described on the Norwegian Shelf (King *et al.* 1987, Nesje and Sejrup 1988, Holtedahl 1989 and Vorren *et al.* 1984) and the North American shelves (Josenhans and Fader 1989, Oldale 1985, Sharpe 1988 and Syvitski and Praeg 1989). It would not be unexpected for such features to be preserved in the North Sea; for example Jansen *et al.* (1979) suggested that the "southwestern ridge" of the 'Hills Deposits' was a Saalian moraine.

4.4 BASAL THERMAL REGIME

Glacial erosional and depositional landforms are the result of different processes acting at the base, or in front, of an ice mass. An important variable is basal temperature and particularly whether the ice mass is cold or warm-based (i.e. at the Pressure Melting Point-PMP). Cold-based ice masses, i.e. those frozen to the ice bed, move by deformation of the ice, and erosion is inhibited. In warm-based ice masses, sliding is a significant process which leads to active erosion of the bed, be it unlithified or solid. Deformation of the bed is also affected by the temperature of the ice mass, in that it is powered by high pore water pressure in the sediment (Boulton and Jones 1979). Subglacial meltwater is also an important agent of erosion and deposition beneath warm-based ice.

The basal thermodynamic regime can be linked to the pattern of erosion and deposition. Erosional processes are dominant at the base of an ice sheet where the temperature gradient conducts heat

to the basal layers, melting and basal sliding take place. Depositional landforms occur where the basal temperature of the ice is sufficient to allow melting, and release of debris, but is associated with a slow moving ice mass which is not capable of eroding the bed, as occurs with diverging ice flow.

Figure 4.5 equates the distribution of landforms to possible basal temperatures, and whether or not the ice sheet was warm-based. This implies that the ice sheet was warm-based in southern Caithness, the inner Moray Firth, and south of Aberdeen. Within these areas the most intense areas of erosion are in the inner Moray Firth and the Midland Valley, where converging ice flow dominated. A relationship of intense erosion with areas of ice convergence in uplands has been recognised (Sugden 1978). It is suggested the evidence indicates that these were major ice streams, which carried large sediment loads. This explains the volume of sediment associated with the Wee Bankie moraine complex, in the Tay-Forth approaches.

The main areas of cold-based ice is the southern margin of the Moray Firth Basin continuing southward onshore to $\sim 57^{\circ}20'N$. It is possible that northern Caithness may also have been covered by cold-based ice, if the 'shelly till' and the erosional features relate to an earlier glacial episode (Hall and Whittington 1989, Bowen and Sykes 1988) and have survived a subsequent glaciation. The lack of continuous upstanding ridges and significant thicknesses of glacial diamict immediately offshore may relate to the reduced sediment supply from the ice sheet in these areas. Preglacial surfaces exist in Buchan which have not been modified by the last ice sheet (Hall 1984). Pre-glacial rock platforms also exist offshore which have not been significantly affected by the last ice sheet (Stoker and Graham 1985), although these occur, in part, in the warm-based ice sheet area.

4.5 TYPE OF MARGIN

The calculated glacio-isostatic depression at the margin (Fig. 3.39) indicates that the entire margin was marine-based, and ended in water depths ranging from 66 to 120m. Models of maritime-influenced ice sheet margins terminating in a mid-latitude, shallow, epicontinental, marine basin have been reviewed from the numerous models that exist for ice sheet margins, these include; Bent (1986), Boulton (1986), Drewry & Cooper (1981), Elverhoi (1984), Elverhoi *et al.* (1989), Eyles (1987), King and Fader (1986), King *et al.* (1987), Molnia (1983), Powell (1981, 1983, 1984), Powell & Alley (*in press*), Powell & Molnia (1989), Stoker & Bent (1985), Syvitski and Praeg (1989), Vorren *et al.* (1989) and Prichonnet (1988).

The models conclude that there are seven important factors regarding the nature of the margin, which have to be considered, these are;

1. Location
 - shelf edge/slope break (Elverhoi 1984, Eyles 1987, Eyles and Lagoe 1990, King and Fader 1986, King *et al.* 1987, Stoker 1990, Vorren *et al.* 1989).
 - intracontinental sea (Stoker and Bent 1985, Eyles and McCabe 1989, Syvitski and Praeg 1989).
 - fjords (Powell 1981, 1983, Syvitski and Praeg 1989).
2. Latitude
 - High (Anderson *et al.* 1984, Karl 1989) to mid-latitude (Stoker and Bent 1985, Eyles and McCabe 1989).
3. Margin
 - Fjord glacier (Syvitski and Praeg 1989).
 - ice shelf (Orheim and Elverhoi 1981).
 - ice sheet (Powell 1981, 1983, 1984, Molnia 1983).

4. Basal - cold-based or warm-based (Drewry and Cooper Temperature 1981).
5. Terminal - subaerial or subaqueous (Powell 1981, 1983, Environment Boulton 1986, Eyles *et al* 1989).
6. Processes - Calving
 - Fluvio-glacial-sources - supraglacial
 - englacial
 - subglacial
 - mixing
 - Ice Rafting of Debris
7. Tectonic - Active to passive margins, intracratonic.
Setting

The factors act together to produce the different ice marginal sedimentation environments outlined in table 4.1. The lithofacies identified in the sedimentary succession are used to reconstruct the most likely depositional environment.

The most important conclusion reached in recent ice margin studies is that the crucial factor governing the stability of mid-latitude, warm-based-margined, ice sheets is the link between the glacio-isostatic downwarping in front of the margin and the relative eustatic level at the margin, i.e. whether the ice margin is in contact with the base, or whether it is decoupled ('free-floating') (Hughes *et al.* 1977). This is considered to be of more importance than climatic control on the mass balance of this type of ice sheet (Eyles and McCabe, 1989).

During the late Weichselian, the North Sea was a shallow intracontinental marine basin (Thomson and Eden 1977), with subaerial exposure to the south (Cameron *et al.* 1986), and an opening into the North Atlantic gyre, via the Norwegian Sea to the north (Kellogg 1977, Sejrup *et al.* 1989, Stoker *et al.* 1985).

In this study the models have been applied to the

interpretation of the seismic sections from the sediment ridge in the North Sea. They also provide a framework with which to constrain the type of margin and the processes acting at the margin in the Moray Firth.

4.6 ICE SHEET MARGIN IN THE NORTH SEA BASIN

The evidence extracted from the BGS regional survey and the applicable ice margin models, suggest that the upstanding margin in the Wee Bankie and Peterhead areas, was a stable, grounded tidewater margin (Powell, 1981, 1983, 1984), which was subject to partial decoupling from its bed, due to fluctuations in sea-level (Hughes *et al.* 1977). This is in marked contrast to the dynamic, calving ice margin (Powell 1981) proposed for the marine embayment of the Moray Firth.

Figures 4.7-4.9 illustrate the ice margin in the three areas identified; 1) the upstanding ridge (Wee Bankie/Peterhead), 2) the discontinuous ridge and seismic facies boundary (Peterhead), and 3) the Moray Firth. The main characteristics are summarised below;

1) Wee Bankie/Peterhead

Fig. 4.7 illustrates the margin in this area. It is an adaptation of the models of Powell (1981, 1983, 1984), Powell and Alley (*in press*), and Stoker and Bent (1985) and Bent (1986). This section of the margin, is interpreted as an active (warm-based), low surface-angled, tidewater margin, calving into a shallow glaciomarine environment.

The presence of a former calving, grounded tidewater ice margin is indicated by the geometry of the facies, and the types of facies represented. There are two main assemblages; a subglacial diamicton (till unit), and a diamicton deposited in a glaciomarine environment. The former ^{seismic} facies is chaotic, and this and the ^{lithology} confirm it is a till. The provenance and morphology of the clasts indicate a local origin, derived from the

Scottish mainland and the adjacent offshore zone. The subglacial meltwater channels, rockhead erosion and till are consistent with a warm-based ice sheet. The large volume of sediment in this section of the margin supports this interpretation.

The junction between the subglacial and proglacial sedimentary units is an upstanding ridge, or bank, which overlies a depression which has been created by sustained subglacial erosion at the margin. Interdigitation of the two sedimentary units also occurs. Little structure is present, but it is suggested that this is a function of the lithology due to the high degree of reworking that has occurred at the margin. Some of the short, high amplitude reflectors may relate to loading structures or push structures within the moraine. Alternately they may relate to thin beds of fine sediment deposited as rhythmites at the margin, indicating episodes of decoupling of the ice sheet by slight changes in the relationship between the depth of water and the buoyancy of the thin ice mass.

The ice-proximal environment is chaotic, with numerous point-source reflectors indicating the presence of coarse clastic material. Occasional drape and prograding wedge units exist, which may represent subaqueous flowage of fine material at the margin.

The glaciomarine environment outside the morainic ridge can be split into an ice-proximal and an ice-distal zone. The proximal zone, extending up to 25km from the ridge, consists of coarse prograding subaqueous outwash, which was probably supplied with sediment from subglacial sources. It was also the area where the majority of material derived from calving at the margin was deposited, the ice rafted component (Gilbert 1990) within the glaciomarine facies is less than 1%. The water was shallow (66-120m deep) and would have produced small growlers and bergy bits rather than large icebergs. These would deposit material as a sediment rain and roll over process, as well as by meltout as they circulated in the marine embayment. Most debris was dumped close to the margin.

Interdigitation of seismic facies units at the margin indicates that the ice periodically decoupled from the sediment

bank at the margin, either because there was a change in sea level, or because ice thinning increased its buoyancy.

Some of the boreholes examined exhibit coarsening upward sequences, suggestive of ice advance or change in sediment supply, subsequently followed by fining upward sediments.

The environment of deposition decreases in energy away from the margin. Fines dominate the glaciomarine facies, having been transported by plumes of sediment released at the base of the margin. Not only is the input from calving, and sediment transport via meltwater reduced as a function of mixing and distance, but the sorting by wave action is also reduced.

Basal meltwater channels occur within the diamict seismic facies interpreted as till, and are linked to ridges interpreted as moraines. This shows that the ice sheet was warm based with a dynamic meltwater system transporting sediment to the ridge area, and beyond.

The junction between the subglacial till and the proglacial glaciomarine deposits differs; there are two geometrical associations between the two units. One is a simple, but transitional, contact between the two units. This is suggestive of an area where there is a high energy environment, with reworking of the sediment brought into the area. There are occasional steeply dipping high amplitude reflectors, which may indicate overriding, or pushing of sediment (Boulton 1986). This also suggests that proglacial deposition in this area creates a diamicton similar to the subglacial till, with a poorly sorted particle distribution, ranging from coarse clastic material to a significant fines component. This would suggest that the predominant source of the material is from melt-out at the base of the ice front, as occurs at the margin of a grounded tidewater ice sheet, which is either stationary or retreating slowly (Powell 1983).

The second type of margin incorporates a distinct waterlain unit immediately to the rear of the margin. This is either an area of advance where the ice lobe has overridden the proglacial glaciomarine sediments, without deforming them, or it represents

an area where the base of the ice has become decoupled from the base and has been floating. Deposition of sediment in the latter scenario would be by basal melt-out into an aqueous environment. The continuation of the till unit beyond this area indicates that the ice grounded beyond this point, and was actively depositing or, more probably, reworking the sediment at the margin.

2) Peterhead

Fig. 4.8 illustrates the model of the ice margin proposed for this area. It is again derived mainly from Powell (1981, 1983), Stoker *et al.* (1985), and Bent (1986). However, it differs from the margin to the south, in that the position of the marker reflector and lateral changes within the sediment succession provide more information than the surface morphology of sea bed.

The proposed margin is interpreted as a grounded, tidewater ice sheet, which was initially warm-based during expansion of the ice sheet, but became cold-based after it reached its maximum position. It was more extensive than would be suggested from the seabed morphological evidence alone. The ice sheet extends 10-15km further east than the discontinuous ridges would imply. This is shown by the lateral relationship between the subglacial till, the glaciomarine seismic facies unit, and the position of the first order reflector. This relationship is the same as that used to establish the maximum position of the moraine in the Wee Bankie area, with the exception that a moraine does not exist at the maximum position, and the maximum position is overtopped by a thin glaciomarine unit. Erosion was inefficient at the base of the ice sheet, as illustrated by the reduced intensity of the erosional landforms to the west of the margin.

A standstill position during retreat is indicated by a discrete series of small mounds, indicating that the distribution of the subglacial sediment transport was uneven along the margin. The volume of sediment deposited is less than that found in the

Wee Bankie moraine to the south. This suggests less efficient sediment transport to the margin, perhaps due to diverging ice flow over Buchan and different basal thermal conditions.

3) Moray Firth

The location of the ice margin in the Moray Firth is open to question, with less definitive evidence than available elsewhere. Fig. 4.9 illustrates the proposed marginal model.

The onshore evidence indicates that part of the margins of the Moray Firth basin are heavily eroded. Ice flow was directly offshore, and a major ice stream flowed from the Great Glen. Other ice flow directions are indicated in Caithness, which include contradicting directions and a flow to the north-west.

The onshore area is covered by lodgement till. Dates in the area suggest both a late Devensian assemblage of tills (Hall and Whittington 1989, Auton *et al.* 1990) as well as pre-late Weichselian tills (Bowen and Sykes 1988, Hall and Whittington 1989). The offshore sediments have been variously interpreted as tills and glaciomarine sediments, ranging in age from <16 ka BP, to >43ka BP (Chesher and Lawson 1983, Andrews *et al.* 1991). In chapter 3 it is argued that the tills are restricted to the Quaternary basins and in the nearshore area, where water depths are less than 40m. The sediment covering the Moray Firth Basin is reworked glaciomarine material. If so then the pattern is most easily explained if there was an ice shelf in the inner Moray Firth floating beyond the position of the 40m bathymetric contour.

The ice shelf must have been grounded from time to time in order to rework the underlying sediment so effectively such that no structure exists within the deposits, except in the protected basins. It is possible that the ice shelf advanced and retreated cyclically, as indicated by the cyclicity within the lowest glaciomarine units in the Moray Firth. The ice shelf was maintained by the ice stream entering from the Great Glen. The phase of advance or retreat was dependent upon the relationship between glacio-isostatic loading, and the depth of water as a

function of crustal depression at the margin, and relative eustatic sea level. When the balance between these parameters allowed the ice to advance, the grounded ice flowing into the embayment from the north-west was deflected so that it moved normal to the margin. This implies an overall movement towards the north-east. When the ice shelf was present, this ice was no longer deflected and produced the north-west to south-east flow patterns on the northern coast of the Moray Firth. This provides an explanation for the conflicting ice flow directions around the Moray Firth embayment within a single glaciation. When an ice shelf existed in the inner Moray Firth, the ice around the margins of the basin converged on the embayment creating strong onshore to offshore erosional patterns in the landscape. When ice thickened and grounded ice flow produced the landforms paralleling the coast.

There are two possible mechanisms which could explain a cyclic variation from an ice shelf to grounded ice sheet within a glaciation.

One involves isostatic depression beneath grounded ice which in the case of a glacier advancing into deep water, triggers off calving. This in turn can cause downdraw and further thinning of grounded ice, leading to more calving. The process is discussed in detail in relation to the possible collapse of the west Antarctic Ice Sheet, by van der Veen (1987). Isostatic recovery can then cause a shallowing of the water and thus enable the grounded ice to extend offshore once more. Such isostatically induced cyclic fluctuations have been modelled by Hulton for the Greenland Ice Sheet (Hulton 1990). Interestingly such behaviour is restricted to areas of West Greenland where there are no clear moraine ridges. Presumably one would expect reworked glaciomarine and sub-glacial deposits, as occur in the Moray Firth.

A second possible explanation of cyclic behaviour could relate to sediment supply. A glacier may extend into deeper water with the aid of a morainic shoal which restricts calving. This shoal advances with the ice margin into deeper water until a phase of calving is triggered and causes retreat of the margin.

Subsequent advances depend on building up the shoal once more. Such cyclic behaviour has been described in Alaska by Mann (1986) and in South Georgia, by Clapperton *et al.* (1989). This process would also account for reworked glaciomarine sediments and till and explain the lack of clear morainic ridges.

The calculated isostatic depression at the margin suggests that such a scenario is possible with water depths at the margin of up to 80m (few glaciers calve into water greater than 100m), given an assumed glacio-eustatic depression of 121m +/-5m (Fairbanks 1989). This is insufficient to allow large icebergs to calve and float off to be incorporated into the gyre in the Norwegian Sea (Kellogg 1977). However, it is sufficient to enable bergy bits to calve, and ablation by calving would be efficient. The calved ice would be dispersed to the north-east, or east exploiting the deeper water in the Southern Trench. Shallow water would exist over the Smith Bank, although it is unlikely (given the calculated crustal depression) that this would be subaerial at any time.

The controls affecting the location of the calving ice margin are threefold; the position of pinning points (Hughes *et al.* 1977) depth of water (Powell 1984) as a function of the glacio-isostatic downwarping of the crust, and the mass of ice flowing into the embayment. Together they allowed the ice to extend into the Moray Firth, as an active, grounded, advancing tidewater margin. However on reaching a critical point the three variables acted in such a way that the ice sheet decoupled, became marine-based, and was unable to maintain its position, thus retreating quickly by high calving rates at the margin. Isostatic depression triggers calving when the relative depth of the water at the margin increases to the point that the ice floats off the basal sediments. The depression increases due to the increase in the mass of ice in the Moray Firth, as the ice advances. Calving causes the margin to retreat until the ice shelf becomes grounded again. There may be some local isostatic recovery which also affects the position at which the ice shelf becomes grounded again. The ice sheet can then readvance into the marine embayment, reworking the glaciomarine

sediments deposited at the retreating margin. The cycle of isostatic depression would then be triggered again and calving would occur. The environment was one of very high energy. Calving ice margins of this nature are characterised by the lack of material deposited at the margin (Powell 1981, Hulton *pers comm*) which would explain the scarcity of depositional evidence within the basin. The 'downdraw effect' (Hughes *et al.* 1977, Ruddiman and McIntyre 1981) continued until the net loss of ice from the area was such that isostatic compensation for the depression occurred, the relative sea depth decreased, and the ice margin became partially, or completely grounded, and the ice stream was able to stabilise, and readvance. At the same time as this was occurring the onshore ice was changing flow direction, making this a very dynamic area.

The extent to which the ice advanced in a north-easterly direction is unclear. A possible restriction to ice extent is presented by the Southern Trench, which is up to 200m deep. There is no evidence to suggest that this was crossed by ice in contact with the bed. There is no evidence of widespread till deposits below the 40m bathymetry contour. If ice extended over the Southern Trench it must have been as a floating ice shelf. Only glaciomarine sediments occur within the Trench. It may have acted as a calving point due to its depth, although there is no seismic unit apparent on the profiles which would suggest a concentration of coarse debris, which would be expected at a calving margin, associated with rain-out of clasts on calving. Calved ice could also be trapped within the deeper water, and grounded on the margins of the enclosed deep. Grounding features which could be attributed to this were not found. However, if the calving ice was small the shallowing of the water would not affect the mobility of the ice. The sediment released on calving would be less and would be dispersed more evenly.

It may be that the Bosies' Bank moraine is related to the maximum advance of the ice on several occasions. This would explain the large volume of sediment associated with this moraine.

It is proposed that northern Caithness may have been covered by inactive, cold-based ice. Although the area exhibits erosional evidence it is suggested that this relates to a previous glacial episode. There is no evidence to suggest that the late Weichselian (Hall and Whittington 1989) 'shelly till', located to the south of the area does not extend as a continuous drape into this area, having been deposited when the ice margin within the Moray Firth was at a maximum position, and the area was slightly depressed. It is unlikely that the local ice in the area was capable of eroding the features. This is also supported by the presence of erratics and megablocks, as well as the shelly material, from the Moray Firth basin. The erosion, and megablock deposition may relate to a more extensive, earlier glacial, which deposited the Leavad block as it expanded from the Moray Firth onto the northern Caithness headland, and across to the north-west having been slightly deflected by inland ice, and possibly maintained by an increase in the gradient of the bed into the channel existing between the west Orkney shelf, and the Stormy Bank. This is a tentative proposal, but may relate to the 'Warthe' restricted, northern glaciation of Bowen and Sykes (1988).

4.7 CHRONOLOGY

The amino acid ratios suggest that the subglacial lodgement till found in the Wee Bankie area, as shown in Fig. 4.11, incorporates reworked shell fragments of middle Weichselian age. If so the ice sheet post-dates the mid-Weichselian, and was late Weichselian, which confirms the existing chronology. The moraine identified by Bent (1986), which has been implied as being contemporaneous with the Wee Bankie moraine is different, it is draped by a shell-rich unit of middle Weichselian D/L ratio (0.085 +/- 0.002) age. The shell drape lies unconformably over the diamict unit. The drape has been deposited after the diamict unit. It is unlikely to be a reworked deposit from the diamict unit since the shells are bigger and more complete than those in the underlying glacial diamict, which, although containing shelly

material, does not contain large fragments, and complete shells as found in the drape. This means that the diamict pre-dates the deposition of the shell drape and it is older than the shells. Dating suggests that the glacial diamict is older than 40,000 years BP. This leads to the conclusion that this feature relates to an earlier more extensive glaciation. This could relate to the early till unit identified by Chesher (1984) in the Moray Firth, and the earlier glaciation proposed by Bowen and Sykes (1988).

4.8 POSSIBLE MECHANISMS OF RETREAT

This section discusses a possible retreat mechanism in order to complete the reconstruction.

The ice sheet terminated in a marine environment along the entire margin. Given the controlling parameters of the 'catastrophic drawdown' hypothesis of Ruddiman and McIntyre (1981) of depth of water, and thickness and buoyancy of a marine-based ice sheet margin, the initial trigger for the retreat of the late Weichselian ice sheet in northern Britain could have been a relative rise in sea level. If so the Moray Firth embayment, with its floating ice shelf, could have been a particularly unstable trigger for the initial destruction of the ice sheet.

Dated samples (Figure 4.11) show that retreat from the marine-based margin was rapid, but once the ice sheet became land-based the retreat rate reduced. There are two lines of evidence supporting a view of rapid retreat offshore. First, the rate of retreat of the margin was faster than the rate of glacio-isostatic recovery of the crust allowing a glaciomarine transgression to take place (Jardine 1982). This would explain the presence of glaciomarine sediments found onshore today in the boreholes from St. Fergus and Montrose. Second, the lack of a complete retreat assemblage of sediments within the offshore boreholes, above the till units also suggests rapid retreat, since there was insufficient time to deposit a glaciomarine unit fining upwards in to a marine unit.

4.9 CONCLUSION-RECONSTRUCTION

Fig. 4.12 summarises the proposed reconstruction of the late Weichselian maximum marginal conditions for the eastern margin of the last Scottish ice sheet. The significant conclusions are;

1. Ice cover at the maximum was complete onshore; there were no ice-free enclaves.
2. The entire margin of the ice sheet terminated in a glaciomarine environment. It consisted of a dynamic calving ice bay in the Moray Firth, the position of which was a function of the glacio-isostatic depression and the calving rate. The Wee Bankie moraine was a relatively stable partially-grounded, tidewater margin linked to the area of active erosion.
3. The ice sheet was composed of distinct zones of active, warm-based ice, where subglacial erosion was the dominant process. Such zones are common in lowlands and embayments. Zones of cold-based ice may also have occurred in the peripheral areas of the ice sheet, i.e. north-east Caithness, and north-east Buchan.
4. The last ice sheet did not erode the Caithness plain. The anomalous onshore ice flow represents a previous glacial episode.
5. The last ice sheet may have not extended as far east as the Bosies' Bank moraine (Bent 1986). Preliminary dating suggests that this is a pre-late Weichselian feature. But without better data control in the Peterhead area it is not possible to test this idea, although a substantial amount of evidence exists.
6. A tentative model of retreat is proposed suggesting a rapid initial break-up and retreat of the offshore component of the ice sheet, followed by a slower retreat of the land margin, dependent upon the depth of water at the ice margin (Hughes *et al.* 1977, Ruddiman and McIntyre 1981).

CHAPTER 5

IMPLICATIONS OF THE RECONSTRUCTION

5.1 INTRODUCTION

The reconstruction presented in chapter 4 is the preferred reconstruction of the late Weichselian ice sheet margin from the evidence available. However the alternate model proposed by Bent (1986) cannot be discounted because of the inadequacy of the seismic and core data north of $57^{\circ}40'N$.

Theoretical ice sheet profiles have been constructed in order to compare the empirical evidence with theory. This chapter explores both maximum and minimum ice sheet scenarios, and suggests that the late Weichselian ice sheet in northern Britain is represented by the minimum reconstruction, whilst the maximum reconstruction relates to an earlier event. The Moray Firth Basin is shown to be a key area of the ice sheet, and may have been crucial in maintaining the stability of the ice sheet as a whole.

The final section of this chapter considers the implications of the reconstructions with regard to future research.

5.2 THEORETICAL RECONSTRUCTIONS

5.2.1 Theoretical ice sheet profile

Ice sheet profiles from the alternative proposed ice margins in the North Sea have been constructed using Nye's ice surface profile equation (Nye 1952);

$$\delta H = \frac{h_0}{h} \cdot \delta_s$$

δH increase in absolute
 height of ice surface
 δ_s distance along a line
 of flow, opposite to the
 ice flow direction.
 h ice thickness
 $h_0 \tau/pg = 5.5$

On the basis of ice sheet reconstructions which agree with erosional evidence in the Eastern Highlands, Glasser (*pers comm* 1990) suggests that the shear stress (τ) active on the bed should be taken as 0.5 bar. The integral distance was 5Km and the datum used was relative to the bathymetry at the reconstructed margin.

The glacio-isostatic depression at the margin was calculated using the assumptions and method outlined in Walcott (1970), which takes into account the flexural behaviour of the earth's crust. The depression at the margin is taken as $H/11.5$, where H is the elevation in the centre of the ice sheet. This relationship has been derived from a Weertman (1961) profile applied to the Canadian ice sheet (Walcott 1970), rather than the Nye profile.

The Nye profiles (Fig. 5.1) have been used to contour the ice sheet, and ice flow directions normal to the contours have been applied. The maps produced (Figs 5.2 and 5.3) are reconstructions of the ice flow for the maximum and minimum scenarios.

The Nye (1952) theoretical model of ice sheet thicknesses is very simple. However, it provides a simple theoretical model with which to compare the empirical evidence. The comparison between the theoretical and empirical profiles highlights the areas where the theoretical and real ice sheet behaviour differ.

The theoretical ice sheet profiles make several important assumptions. These are:

1. The ice acts as a perfect plastic.

2. The ice sheet profile is calculated for steady state conditions.
3. The ice sheet is approximately circular.
4. The ice sheet profile is parabolic.
5. The ice gradient at the margin is steep.
6. The bed is horizontal ($\pm 200\text{m}$).
7. The bed is not deformable.
8. The ice sheet is land-based.

The glacio-isostatic calculations of the crustal depression at the margin are constrained by the following assumptions:

1. Ice loading and crustal depression are in equilibrium.
2. The land has fully recovered from the glacio-isostatic loading of the last ice sheet.
3. The effects of the Fennoscandian ice sheet did not affect the British ice sheet.
4. No non-glacial tectonism has occurred, or is taking place today.
5. The maximum lowering of sea level was coincident with the maximum extent of the late Weichselian ice sheet advance in Scotland, and maximum crustal depression.
6. Eustatic lowering was $-121\text{m} \pm 5\text{m}$ O.D. (Fairbanks 1989).

5.2.2 Basal thermal regime

The distribution of glacial erosion and deposition is the result of changes in the basal regime of the ice sheet in time and space. This reflects differences in the main parameters, ice thickness, climate and geothermal heat flux, which control the basal processes (Chorley *et al.* 1984).

Where the ice sheet extends into an aqueous environment, the thermal interaction between the ice sheet and the aqueous body dictates whether the basal ice will melt, or whether freezing will occur. This affects the supply of sediment from the basal ice to the glaciomarine environment.

The factors affecting the thermodynamic regime are the ice thickness, the geothermal flux, the specific heat capacity of ice, the shear stress and shear strain within the ice mass, the basal sliding velocity, the areal fluctuation in the mass balance, and the heat transfer within the ice mass as well as surface temperature and long term climatic change (Drewry 1986).

The heat sources which affect the thermodynamic regime can be quantified as follows;

Geothermal $\Lambda_g = -K_r (dT/dh)_r$ K_r thermal conductivity of rock
 dT/dh temperature gradient

Internal shear $\Lambda_H = \epsilon_{xy} \cdot \tau_{xy} / J \cdot p_i \cdot c_i$ ϵ_{xy} shear strain in ice
 τ_{xy} shear stress in ice
 J mechanical heat equivalent
 c_i specific heat capacity of ice
 p_i density of ice

Friction of sliding $\Lambda_s = \tau_b \cdot U_s / J \cdot p_i \cdot c_i$ τ_b basal shear stress
 U_s basal sliding velocity

When considered in conjunction with each other, it is possible to identify three boundary conditions which illustrate the relationship between the ice mass thermodynamic regime, and the ability of the mass to move (Weertman 1964, Boulton 1972);

$$1. \quad \Lambda_s + \Lambda_g > K_i (dT/dh)_{i*}$$

$$2. \quad \Lambda_s + \Lambda_g \sim K_i (dT/dh)_{i*}$$

$$3. \quad \Lambda_s + \Lambda_g < K_i (dT/dh)_{i*} \quad (dT/dh)_{i*} \text{ lower most layers of ice}$$

In the first equation the temperature gradient conducts the heat away from the base, and the ice-rock interface remains as a heat sink, thus it remains frozen, and any water in the basal zone will freeze and erosion will cease.

The second equation indicates that the heat transfer is approximately equal between melting and freezing. This becomes an area where regelation takes place, and the ice mass will slide on the base.

The final equation shows the scenario where active basal melting occurs, and the ice mass will slide. Erosion occurs at the bed and a net excess of meltwater is produced, although regelation still occurs. The meltwater may be stored, or released either as thin laminar flow at the base, or as discrete turbulent flow within conduits maintained either, at the base of the ice mass, or eroded into the bed. This depends on the hydrostatic force, the relative ease of erosion of the bed, and the sediment transport capacity of the meltwater above the energy required to maintain the open conduit. This is related to the comparative pressure of the water (ρ_w) and the ice (ρ_i). Where $\rho_i > \rho_w$, the conduit will be closed, and vice versa, to a pressure threshold above which the ice will prevent further expansion of the conduit. In extreme circumstances the pressure of water is such that the conduit expands to the point of collapse, as may occur during jokulhlaups.

Where the pressure of the ice and water is approximately equal, water either flows as a very thin layer at the base (which is highly susceptible to regelation), or is stored/flows under the force of gravity in the interstitial spaces in the ice-lattice. This forms the piezometric head, which is important in sustaining the hydrostatic force at the base of the ice. The water may also flow through the sediment (Boulton and Jones 1979).

The boundary conditions outlined for basal sliding, and also the transfer of meltwater through the system, are not mutually exclusive in either space or time, within the ice mass. The spatial and temporal changes become more complicated at the margin of an ice sheet, as it fluctuates in response to local and regional environmental changes.

The thermal regime for a flow line from the ice divide to the margin in the North Sea has been calculated by Glasser (*pers comm* 1990) as shown in Fig. 5.4. This indicates that the basal thermal regime changes from cold-based, over the Cairngorm Massif, to warm-based at the ice margin. This is important because the basal thermal regime indicates whether basal erosion will occur, given that there is a strong relationship between areas of glacial erosion and ice sheets with basal ice at the pressure melting point (Sugden 1978, Gordon 1979). The flow line illustrated is the 'typical' line produced by Glasser (*pers comm* 1990), showing the change in the thermal regime, perpendicular to the ice margin. If the ice margin of the ice sheet were straight, then the thermal regime of the basal ice for the ice sheet profile would be simple, as shown in Fig. 5.5. However, the empirical evidence shown in chapter 4 suggests that the margin was not straight, and that areas of converging and diverging flow existed. Convergent flow generally increases velocities within ice sheets, and thereby raises basal temperatures through heat produced by friction. Divergent flow decreases velocities and can reduce the basal temperature to below the pressure melting point. The relative small temperatures differences in Scotland are sufficient to cause divergent flow zones to be cold-based (Glasser *pers comm* 1990).

The basal thermal regime for an ice margin with embayments, and therefore diverging and converging flows can be predicted from Fig. 5.2, and is shown in Fig. 5.5.

5.3 MINIMUM AND MAXIMUM RECONSTRUCTIONS: theoretical and empirical comparisons

5.3.1 Minimum

The minimum theoretical and empirical reconstructions of the ice sheet extent and dominant flow directions are shown in Fig. 5.6. Chapter 4 outlines the empirical evidence and arguments which shows that the ice sheet margin is within 50km of the present day coastline.

The empirical evidence suggests that the margin of the ice sheet terminated in water and in a floating ice shelf within the Moray Firth, beyond the present-day 40m bathymetric line. Ice flow directions are onshore to offshore, with areas of convergence in the inner Moray Firth and Tay and Forth approaches, and divergence in Buchan and possibly northern Caithness. Conflicting ice flow directions occur paralleling the coast, in the inner Moray Firth, and in the Mearns.

The theoretical marginal depression (Walcott 1970) indicates that the ice sheet terminated in an aqueous environment, assuming a sea level of $-121 \pm 5\text{m}$, as outlined by Fairbanks (1989). The theoretical ice flow indicates that, with the exception of Buchan and northern Caithness, ice movement was from onshore to offshore. Ice converges in the inner Moray Firth, whilst flow is divergent over Buchan.

The likely basal thermodynamic regime would be warm-based in the areas of convergent flow, with the cold-based ice occurring in the areas of divergent flow. This is presented on Fig. 5.7. This implies that erosion would be intense in the inner Moray Firth, and that Buchan would be covered by cold-based ice, with little erosional modification of the landscape. This is the case with the erosional evidence in the inner Moray Firth, which indicates flow

from onshore to offshore, and shows that ice streams were present due to the high intensity of glacial erosion. Areas of Buchan also exhibit evidence of preserved landscapes (Hall 1984), as well as glacial landforms, which suggest that the area has been covered by cold-based ice.

Some evidence does not support this reconstruction, it is the west to east oriented Quaternary basins and incised deeps and troughs, located within the Moray Firth Basin, as shown in Fig. 4.2. Till(?) at the base of the sediment succession within the Quaternary basins in the south of the Moray Firth has been dated as >40ka BP.

The erosional evidence which occurs near Buchan Ness, striae and glacial rock pavements at the coastline, indicate ice movement from the Moray Firth was deflected to the south-east. This movement is supported by the presence of a grey-black glacial diamicton, interpreted as till, which contains clasts of a Moray Firth origin, found to the south-east of Buchan Ness (Fig. 1.7). Figure 4.10 indicates that this diamict has been dated as early late-Weichselian.

5.3.2 Maximum

Figure 5.3 illustrates the theoretical maximum margin reconstruction, using Hall and Bent's limit (1990). The margin is approximately linear, and is not affected by the outline of the coastline. The computed depression at the margin, caused by the British ice sheet alone, indicates that the ice sheet margin would terminate in water.

The predicted ice flow directions are from onshore to offshore, with slight convergence of flow in the Forth and Tay approaches. The rest of the flow lines are approximately parallel and indicate east to west flow to the ice margin (Fig. 5.6). Because there is an absence of divergent and convergent ice flow along the margin, the basal thermal regime is unlikely to vary. From Glasser's work (Fig. 5.4), the thermal regime would produce a warm-based ice zone at the margin (Fig. 5.5).

The empirical evidence which reflects this west to east flow direction, with warm-based ice at the margin, is restricted to the area south of $57^{\circ}00'N$, and the west to east trending features in the Moray Firth basin. The apparent deflections of ice around Buchan Ness are not produced by the flow of ice in this reconstruction, nor does it produce the erosional evidence on the margins of the inner Moray Firth.

This reconstruction would explain the lack of important erosional landforms in Buchan, with a west to east directional trend. This is due to the presence of cold-based ice to the west of the warm-based zone at the margin, which, given the relative positions of the margin and Buchan, would suggest that cold-based ice should occur over Buchan. The reconstruction does not provide any explanation for the origin of the complex pattern of landforms on the Buchan coast, in northern Caithness, or in the Mearns. The ice movement producing the erosional evidence converging on the Moray Firth is difficult to envisage with this scenario. The apparent lack of subglacial depositional evidence to the west of the moraine in the Bosies' Bank area also casts doubt over the feasibility of this reconstruction, although the presence of cold-based ice in the area, after the ice sheet has advanced to the maximum position shown may explain this. Retreat would involve warm-based ice which could produce erosional features, albeit of a small scale, and over a short time period.

5.4 EXISTING RECONSTRUCTIONS

Both the maximum and minimum reconstructions differ from the existing reconstructions presented in Fig. 1.1, especially to the north of $57^{\circ}30'N$. The differences to the existing reconstructions relate to the position and type of margin. The main differences found in this work are, the sub-aqueous terminus, the lack of ice-free enclaves on land (except perhaps nunataks on the Moray Firth coast), the position of, and the mechanism affecting the ice sheet margin in the Moray Firth. South of this latitude, there is general agreement in the extent of the ice, although the flow

directions disagree where historically the effects of a Scandinavian ice mass have been inferred.

The reconstructions advocating complete or near complete, ice cover of the North Sea basin within the study area during the late Weichselian glaciation (Fig. 1.1a) can be rejected. These are the models of Flinn (1967), Boulton *et al.* (1979), Andersen (1981), Denton and Hughes (1981) and Price (1983). The following reconstructions of the ice margin location present evidence which indicate conclusively that the north British ice margin was not affected by Scandinavian ice during the last glaciation (Thomson and Eden 1977, Holmes 1977, Stoker *et al.* 1985, Stoker and Bent 1985, Bent 1986, Cameron *et al.* 1987, Sejrup *et al.* 1989). This effectively negates the mathematical models used to reconstruct ice cover at the maximum of the late Weichselian in which it is proposed that the North Sea was entirely covered by an ice mass.

The mathematical models incorporate a variety of assumptions, of which the most important relate to the shape of the profile, the nature of the bed and whether the ice sheet has achieved steady-state conditions. The basic assumptions listed in section 5.1 indicate the problems associated with a simple Nye (1952) reconstructed ice profile. As the models become more complex, the assumptions inherent within them become more complicated and more removed from the observed detailed behaviour of ice sheets. For example Ballantyne (1990) would suggest that the profile of the last ice sheet was not parabolic, and steady-state may never have been achieved (Nesje and Sejrup 1988).

Work on the Norwegian ice sheet suggests that the ice sheet was restricted in extent during the last glacial (Nesje and Sejrup 1988). Although Anundsen (1990) suggests that a coastal ice dome existed in south-west Norway. Nesje and Sejrup (1988) suggest that the Norwegian ice sheet did not reach steady-state; it was a low-angled restricted cold-based ice sheet, where it was not actively eroding. The ice sheet terminated in a marine location as a result of crustal downwarping due to glacial loading. It would seem unlikely that the Norwegian and North British ice sheets would

behave in a markedly different manner given that they are influenced by similar climatic and locational controls associated with the North Atlantic and the North Sea. This would provide further support for a limited ice sheet extent during the late Weichselian glacial.

The main areas of difference in both the maximum and minimum ice sheet reconstructions compared to those presented previously relate to Buchan, northern Caithness and the inner Moray Firth basin (Fig.1.1b).

Previous reconstructions question the maximum reconstruction in the north of Caithness, as would the apparent lack of erosional evidence to support the flow directions. Sutherland (1984), Shotton 1986, Bowen and Sykes (1988), Wingfield (1990), Cameron *et al.* (1986) and Sejrup *et al.* (1987) all favour an ice-free enclave in northern Caithness, although Jansen *et al.* (1979) and Andrews *et al.* (1991) agree with the maximum reconstruction. The latter explain the flow directions over northern Caithness as the result of an ice transgression onto the mainland from the Moray Firth. This reconstruction also implies that the ice sheet was more extensive to the north of the mainland than can be confirmed given current evidence. Orkney would be covered by the ice sheet, an idea supported by Flinn (1967), Jansen *et al.* (1979), Hall and Bent (1990) and Andrews *et al.* (1991), on the evidence of a north-west glacial modification in the landscape, similar to that of northern Caithness. However, the chronological control on this is poor.

Buchan and the Moray Firth are the other main areas where the pre-existing reconstructions differ. This is a function of contradicting evidence onshore, and insufficient evidence available offshore. This has led to conflicting ideas about the position of the ice sheet, although with the exception of Clapperton and Sugden (1975), Jansen *et al.* (1979), Bent (1986), Hall and Bent (1990) and Andrews *et al.* (1991) the models reviewed place the ice margin to the west of Buchan, even though there is no evidence of a margin, and Buchan is covered in subglacial till. The concept of a cold-based ice sheet protecting this area from

erosion as the result of diverging ice has not been widely accepted, and as recently as 1984 it was proposed that Buchan was an ice-free enclave during the last glaciation (Hall 1984).

An interesting model is presented by Wingfield (1990), Ehlers 1990 and Wingfield and Ehlers (*in press*). This suggests that the maximum of the ice sheet lay to the east of a series of glacially derived 'deeps' in the central North Sea basin. This theory resurrects that of Flinn (1967). The proposed location of the margin is placed to the east of these features. This would suggest that the ice sheet was much more extensive and that both proposed margin positions represent significant standstill positions, rather than the maximum. However, from the evidence available it is difficult to reconcile this model with the seismostratigraphy. The mechanism suggested for the formation of the features would require the storage of large quantities of water, which would then debouch catastrophically into the proglacial environment, creating the deeply incised channels. Some of these were infilled as a function of this process. There is no evidence of large scale ponding of water. It would also require that the basal contact was impermeable to allow water to accumulate. This implies a cold-based ice margin, which disagrees with the theoretical evidence. It has also been suggested that to extend any distance offshore, the ice sheet margin would have to surge over a deforming bed. This would not be conducive to creating and maintaining an impermeable environment. This would, however, provide a mechanism for allowing the ice to extend over a large area without leaving any till, and to create a planar seabed surface. However it would be expected that such a process would leave extensive evidence of glaciotectonism (Aber 1988, Sharp 1984). This is rarely recognised within the sedimentary sequence (Stoker 1985).

Sutherland (1984), Bowen *et al.* (1986) and Bowen and Sykes (1988) propose reconstructions of the late Weichselian ice sheet which rely heavily on chronological evidence to constrain areas of uncertainty. However, this approach encounters problems where the stratigraphic position of the shells is uncertain, as has been the case in the Moray Firth. Dates have been shown to be open to

question (Sissons 1981), and may have prolonged the acceptance of 'ice-free' Buchan and Caithness, which has in turn hampered the interpretation of the empirical evidence.

The use of the offshore data in conjunction with onshore data has also highlighted a flaw in the previous reconstructions in that the assumption seems to have been made that the ice sheet did not extend offshore, or that the limit would not be preserved. The location of the north-western late Weichselian ice sheet margin on the shelf and the north Scottish shelf, should help to constrain the reconstructions proposed for Caithness, for example.

5.5 IMPLICATIONS

There are several implications inherent in presenting both the maximum and minimum scenarios for the reconstruction of the ice sheet. The two reconstructions imply three possible explanations: (1) the reconstructions are unrelated and are two different ages, with different equilibria, (2) the reconstructions represent two equilibria positions within the same system, and (3) a stepped development to the maximum reconstruction position.

(1) Different glacial events

The maximum reconstruction would represent an earlier glacial ice sheet position, ^{pre-late Weichselian (mid-Weichselian?)}. The theoretical flow directions of the ice would be from west to east, this is supported by the west to east orientation of the major ice outlets in the Forth and Tay valleys, and the eroded basins and deeps in the Moray Firth. This is also supported by the dates obtained for the Bosies' Bank moraine. The basal thermal conditions would be approximately similar along the margin, and would produce a zone of warm-based ice near the margin, with cold-based ice to the west.

The minimum reconstruction would be younger and represents the last glacial ^{maximum}. It is governed more by local topographic control than the maximum. It has a ^{more} variable basal thermal regime at the margin, than the maximum reconstruction, with zones where the

empirical and theoretical evidence suggest a system which switched from warm-based ice to cold-based ice as the minimum reconstruction ^{oscillated} between stages 1 and 2₁ ^(Fig. 5.5) as ice flow patterns changed from converging to linear flow. This would not be expected to occur at the margin of an ice sheet which had reached a steady-state. The minimum reconstruction implies that there were areas of cold-based ice on the peninsulas of north-east Caithness and north-east Buchan. The maximum reconstruction suggests that these areas were no different from the rest of the ice sheet.

Neither reconstruction suggests that ice-free areas existed in north Britain, although in the minimum, stage 1 scenario it is possible that nunataks could have existed on the north-west margin of the Moray Firth, within the zone of intense erosion. Likely hills to be affected would be Creag Thoraraidh (ND 041 186), and Creag Riasgain (NC 956 127).

(2) Equilibrium position fluctuations

This scenario implies that the reconstructions represent two equilibrium positions within a complicated ice sheet system. The system fluctuates between the maximum and minimum positions, but remains at each equilibrium position for sufficient time to establish an erosional pattern and depositional pattern specific to that position. The evidence associated with each position would be the same as that outlined in (1). However the dates derived from organic material at the maximum position would be similar to that derived from organic material located within the boundary of the ice sheet. This is not the case. This scenario would imply that the late Weichselian glaciation in north Britain was more extensive than had previously been thought. This implies different climatic values than previous work suggests in order to build up and maintain a larger ice mass. There is no evidence to suggest that these conditions occurred.

(3) Stepped development to the maximum reconstruction

The final explanation of the minimum and maximum reconstructions is that they represent steps in the development of an ice sheet. This implies that the minimum stage with the grounded ice was the first stage of expansion, which then developed by advancing into the Moray Firth embayment, altering the ice flow and pattern of erosion. This then advanced to the maximum condition and the ice flow patterns changed again to create the erosional evidence within the warm-based ice zone associated with the maximum reconstruction.

The preferred scenario is number 1, but, as outlined in chapter 4, it is not possible to discount the second mechanism because of the quality of the data. The third alternate model may be a stepped development from the minimum reconstruction to the maximum reconstruction. However this would require some mechanism to protect the initial steps from subsequent erosion during the advance to the maximum, or that the withdrawal of the ice from the area followed the same steps as the advance and that the evidence left reflects both the advance and retreat stages. This is highly unlikely. It also does not explain the reworked nature of the sediment succession found in the Moray Firth Basin, nor the preservation of the different erosional evidence. It is unlikely that the initial erosion pattern of the minimum reconstruction would not be affected by a strong west to east orientation of erosion associated with the maximum reconstruction, unless it was all covered by cold-based ice, and the Great Glen ice stream was inactive once the maximum position was achieved, or was diverted to a west to east flow along the northern Buchan coast. However, there is no evidence to support a deflection of flow, or an obstacle which would have caused this change of flow. Hence this explanation and the implications associated with it are discounted.

5.6 APPLICATIONS

The work presented in this thesis is applicable to future offshore investigations, both academic and industrial.

Academically, it attempts to correlate onshore and offshore data to formulate a unified reconstruction of the regional extent of the last north British ice sheet. It has highlighted the problems associated with working with data collected onshore and offshore, but shows that it is possible to tie the two areas together once the intrinsic problems and assumptions in each data collection method are realised.

This work has commercial applications in that it emphasises the need for good quality seismics, shot over small areas, which tie into the regional framework. The detailed site surveys illustrate that the variability of the offshore glacial environment is as great as that encountered onshore. This is not unexpected as the present offshore environment in the North Sea was subject to the same glacial processes as affected the onshore environment; they were both subject to subglacial processes. However the offshore environment provides interesting glaciomarine sedimentation and tidewater margin structures which are different to the features found onshore in northern Britain, and are far more extensive. The problems involved in collecting representative samples from such an environment have also been highlighted by this work. The high variability of the environment, over short distances, is very important for hazard analysis for engineering structural sites. The short distance of change requires that a high density survey should be undertaken, especially near possible ice marginal sites.

This study has shown the dynamic nature of the mid-latitude ice sheet margin which terminates in a marine environment, and its sensitivity to the effects of eustasy and glacio-isostasy on the stability of the margin. The effects of these processes on the ice sheet are important considerations for any long term exploitation or resource management of the continental shelf.

The possibility of future glacial events and the behaviour of the ice sheet over the present-day margin of the North Sea implies that care should be taken in the disposal of long-term waste on, or within, the offshore sediment. The Moray Firth provides an excellent example of the reworking capabilities of a dynamic ice shelf, whilst the subglacial erosion of the rockhead to the margin indicates the erosive power of ice sheets. Any material deposited in such an environment would be disturbed very quickly. The reconstructions relate to a restricted ice sheet and are not adept at predicting the likely areas of intense erosion, as seen when comparing the empirical evidence with the computed evidence. More sophisticated models may be developed in the future to deal with such problems but caution should be exercised in any long term engineering project which may be constructed in this environment.

The scale between the datasets and the information available highlights the need for high quality surveys prior to any utilisation of the resource potential of the offshore sediment succession.

5.7 FUTURE WORK

In conclusion, it is suggested that several avenues exist for future research following on from this work. These all relate to problems which have been encountered in this study:

1. Offshore Database

The offshore database could be improved by shooting better quality seismics with increased resolution, penetration and coverage of the North Sea basin in order to provide more information for both regional and local scale study. A greater number of cores which penetrate the Quaternary succession, with high percentage recovery would help to provide better lithological control for the seismics, and further scope for sedimentological analyses of the material recovered, adding to the breadth of evidence available for reconstructing the palaeoenvironments, such as the multidiscipline approach of Sejrup *et al.* 1987.

2. Glacigenic Sedimentation Models

The problems associated with trying to apply land-derived glacial sedimentation models to seismic and cored data suggest that models need to be developed for this environment specifically for use with these data sources. The resolution constraints of seismic systems make it very difficult to apply models which rely on the presence of small features as the generic indicators of glaciomarine sedimentation, for example. Rhythmites are not visible on seismic sections, but are important for identifying cyclicity and depositional processes. Emphasis should be placed on the geometry of the deposits, and the likely seismic facies units present, along with their acoustic responses and internal configurations. Similarly attempts should be made to try and find generic indicators within the sedimentary succession, which are small enough to be picked up in a core, yet are specific to glacigenic deposits only. One of the problems associated with this is that the glacial models are derived from subaerial sections, for example the Yakataga formation in Alaska (Eyles 1987). There is no restriction of access to these sites at any scale, unlike those examined using seismic surveying.

3. Dating

There is a need for a greater number of dates to be obtained both onshore and offshore, to constrain the available glacigenic evidence. With a greater number of dated sedimentary units and landforms it will be far easier to assess the validity of obtained dates, and reconstructions of palaeoenvironments. A greater recognition of the mechanisms for reworking organic material is required. This is especially the case in the offshore environment where material is continually reworked.

4. Moray Firth Basin

With regards to the reconstruction of the late Weichselian ice sheet in north Britain, it is suggested that the key site for further work is the Moray Firth Basin. It is a key site within the

preferred reconstruction, and a thorough examination of the seismic and sedimentology evidence should provide the evidence required to establish the ice sheet behaviour and extent in this controversial area. This can only be improved by the acquisition of better seismic data either by consulting commercially shot data, or by undertaking a detailed survey of this area, and that which covers the proposed link between the Bosies' Bank moraine and the Wee Bankie moraine (Bent 1986). An interesting extension of this would be further investigation of the dynamic, fluctuating terminus. What effects would this have on the ice sheet as a whole, and what controlling factors brought about the final fluctuation which initialised the destruction of the ice sheet through 'downdraw', or some other process which may have triggered the collapse of the ice sheet?

5. Caithness

Northern Caithness and the offshore area to the north-west is the other area which can provide more information about the late Weichselian ice sheet, its behaviour and effects on the landscape. In addition the speculation about an earlier more extensive ice sheet in this area could also be tested. This could be coupled with a comprehensive dating programme to establish the chronology of the ice modifications to the landscape, and whether the sediment has been reworked within the Moray Firth prior to deposition, and thus contains reworked, older shelly material, or whether it relates to an older glacial episode, as suggested in this work (maximum reconstruction).

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