Keele UNIVERSITY

THE QUATERNARY SEDIMENTS OF THE SHETLAND PLATFORM AND ADJACENT CONTINENTAL SHELF MARGIN.

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2 Volumes.

Submitted for the degree of Ph D.

University of Keele.

1987.

VOLUME .1. TEXT.

This work is dedicated to

My Mother and Father

For all their sacrifices.

ACKNOWLEDGEMENTS.

The following people have given invaluable assistance to me during the completion of the present study.

Firstly I would like to thank the technical staff in the Geography Department at Keele for their assistance during the laboratory work for this study and during the production of material for the final work. Mr D Morris produced the seismic and x-ray photographs and plates in volume .2., and Mr M Edge copied the large dyeline diagrams for chapter three. The technical staff in the Geology Department produced the x-ray diffraction traces of clay minerals used in chapters two and six.

Secondly I would like to thank all the members of the Marine Geology Unit (North) of the British Geological Survey, Edinburgh. The laboratory staff, particularly Mr G Tulloch, gave assistance without which the core material in this study could not have been obtained. I would also like to thank all the scientific staff for their comments during the course of the present study, both on- and off-shore.

I also acknowledge the assistance of Lucas Girling Limited for the use of facilities in producing the final copy of this thesis.

Finally I would like to thank my supervisors. Dr N G T Fannin gave guidance and valuble critical comment during the early stages of this study and on early drafts of the final work. Dr A J Parsons also gave critical comment on the final text without which the study could not have been completed.

The work for this thesis was undertaken whilst in receipt of a NERC (CASE) research studentship, number GT4/83/GS/34.

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ABSTRACT.

Borehole material obtained from the continental shelf and shelf margin around the Shetland Islands has made possible a reconsideration of the glacial history of the archipelago. Analysis of British Geological Survey boreholes, from the areas between 0 and 4°W and 60 to 61°N, and 3 and 4°W and 59 to 60°N, has revealed an uneven distribution of Quaternary sediments. The Shetland Islands are surrounded by a relatively flat basement platform, beyond which unconsolidated sediments thicken eastwards into the North Sea and westwards across the continental margin. Maximum thicknesses range up to 200 metres, in the vicinity of the modern shelfbreak.

Micropalaeontological and sedimentological evidence indicates that these sediments probably date back to the Late Saal. The major part of the sequence relates to the Upper Pleistocene Eemian interglacial, Devensian and Holocene. Environmental reconstructions for these periods indicate that the Shetland Islands were probably ice-free during the Eemian. Subsequently, ice reached its maximum westerly extent during the Early Devensian. The margins of this ice lay to the east and west of the islands, just beyond the margins of the modern basement platform. This indicates a local ice mass debouching from the islands' central watershed. No indigeneous ice appears to have existed during the Late Devensian or the preceding interstadial. During these periods intense periglacial activity occurred.

Most of the existing literature describing the glacial history of the Shetland Islands is incompatible with this new evidence. The present study indicates more restricted ice activity in this area than these earlier works suggested, with a much greater emphasis on periglacial activity, particularly during the Late Devensian.

PREFACE.

From what might be called its inception, with the works of Agassiz, Quaternary science has, to a greater or lesser extent been concerned with the identification and description of former environments of the past two million years. In the case of northwestern Europe work has for a long time focused on the delimitation and causes of the various ice advances which have affected the region. The most commonly used evidence for this kind of study has been information obtained from sediments. Owing to this, and the nature of ice action, research has concentrated on the last one or two glacial advance stages. Despite the amount of research effort that has been expended there is still relatively little unequivocal evidence on the outer limits of these glacial advances.

In northwestern Europe this has to a large extent been the result of geography. Much of the area over which ice is thought to have advanced, and where the margins of the ice at its maximum extent are thought to have lain, exist below present sea level on the continental shelf margin and in the North Sea. As a consequence it is only during the past fifteen to twenty years, with the advent of effective offshore drilling technologies, that geological information has become available at all from these areas. Investigations in marine geology have already cast doubt on many of the assumptions made, on the nature and extent of ice activity, before this evidence was available. Much more analysis is required before the full implications of the offshore record to the Quaternary history of northwest Europe can be appreciated. The present study was initiated within this context, to take advantage of this opportunity in one limited area.

The area chosen is centred around the Shetland Islands. It is just over a century since the first study of the glacial history of the Shetland Islands was made by Peach and Horne (1879). Subsequent work has been relatively limited compared to other areas in the British Isles, due, in part at least, to the geographic inaccessibility of the area. An absence of research is surprising considering the important marginal location of the islands, which lie north of British and west of Scandanavian ice centres, and relatively close to the continental shelf margin. The work that has already been published on the area has also been restricted by the limited information available in the form of onshore evidence. The availability of a new source of information, in the form of offshore material, makes possible a reassessment of these existing works on the glacial history of the Shetland Islands. Such an investigation can also be combined with a reconnaissance study of the Quaternary sediment record, and its palaeoenvironmental implications, in the important physiographic setting of the continental shelf margin.

The scope of the present study was limited by the time period available, and the existence and quality of Quaternary borehole material. It was necessary to base the divisions of the study area on British Geological Survey (BGS) survey areas which consist of latitudinal and longitudinal divisions of the seabed. This compatability is essential because the BGS interrelate geophysical and sedimentological sampling within each of these areas, and it is this evidence which forms the basis for the present study.

The primary area (see fig P.1) lies between 2 and 4 degrees West and 60 and 61 degrees North, and constitutes the Foula map area, west of Shetland. This area contains the thickest and most complete Quaternary sequences within the entire study area. Its boundaries incorporated the important physiographic division of the shelfbreak. The second area lies south of the Foula area, between 2 and 4 degrees West and 59 and 60 degrees North. This comprises the Orkney map area.

Large tracts of this area, including virtually the whole easterly half, consists of a Devonian platform devoid of Quaternary sediments. These areas were not analysed in any detail. The third area constitutes the Shetland map area, ranging from 0 to 2 degrees West and 60 to 61 degrees North (i.e. east of the Foula map area). This area was studied towards the end of the present study, to gain an insight into the geographic relationship between the offshore sediments analysed, and the onshore evidence used as the basis for former interpretations of the glacial history of the Shetland Islands.

The aims of the present study are, of necessity, influenced by the evidence used and the study area chosen. Primarily it is hoped that an analysis of marine sediments will enable a reassessment of the existing theories for the glaciation of Shetland, and a resolution of ambiguities within them, from the new perspective which this new material will produce. If these theories are found to be lacking, the reasons for these shortcomings must be identified, and a new synthesis produced to account for the glacial history of the Shetland Islands, based on the findings of the present study. The wider implications of these conclusions, to the existing understanding of the Quaternary history of northwest Europe, must also be considered. It is also hoped that a basic understanding of the Quaternary record on the continental shelf margin will be produced where existing knowledge is still so limited. Such a pioneer assessment should, at the very least, produce a framework to which future investigations can be compared.

The approach taken to realise these aims was also largely determined by the available evidence. However, with cooperation with the Geological Survey being an integral part of the present study, it is essential to carry out the investigation in a way that is of operational use to the BGS Marine Geology Unit, as well as one of academic importance through the aims expressed above. For this reason, the main evidence used in the present study is sedimentological, resting on the laboratory analysis of BGS borehole material. The aim of this analysis is to produce divisions of the sedimentological record into distinct sections with similar physical characteristics. The division of the Quaternary record into "units" will give a stratigraphic bias to the present study, which can then be of direct use to the BGS in their production of reconnaissance facies maps for these offshore areas, as this process replicates, in essence, their own investigative procedures. As the borehole material represents a limited two-dimensional sampling frame, geophysical evidence will also be used, to build up a three-dimensional impression of the spatial variations in sedimentary characteristics throughout the study area.

To proceed further, and produce an analysis that will be capable of determining the palaeoenvironmental conditions at the time these sediments were deposited, will require the acceptance of assumptions which will take the present study beyond the semi-objective division of the rock record on the basis of its physical characteristics or acoustic response. The most important of these assumptions is uniformitarianism. Under this assumption analogues from past and present arctic environments can be employed comparatively, assuming throughout that the relationship between physical properties and formative environment, deduced from these analogues, can be applied directly to similar physical characteristics in the sediments analysed in the present study area. Another implicit assumption made in this form of analysis is that sedimentological changes are themselves a consequence of environmental variations influencing the depositional regimes which then lay down the sediments.

With this in mind, the present study is structured so that the most objective evidence will appear first. Progressing through the work the discussion will become increasingly subjective as more assumptions have to be made. The most reliable information (the sedimentological and, to a lesser extent, the seismic evidence) on which the remainder of the present study is based is consequently given first, in chapters two and three. Following chapters deal with the genetic interpretation and palaeoenvironmental reconstructions for these sediments. Throughout these later chapters the existing literature on the glacial history of the Shetland Islands, and the research questions for this study, will be reconsidered together in the light of the information provided at each successive stage of the investigation. The final two chapters will develop a chronology for the offshore material analysed, and assess its bearing on the existing understanding of ice activity in northwestern Europe, and particularly northern Britain, during the Pleistocene.

CHAPTER .1.

BACKGROUND AND QUESTIONS

1.1. ICE ORIGIN AND EXTENT.

This first section will discuss the origin of ice masses that are thought to have affected the Shetland Islands during the Pleistocene. Theories that have been forwarded to date have focused on three major source areas. These areas will be discussed individually. However, several of these theories invoke more than one of these source areas at different times and in different orders of occurrence.

1.1.1. SCANDANAVIAN ICE.

In the first study undertaken on the glacial history of the Shetland Islands, Peach and Horne (1879) defined a "main" and a "later" glacial phase. The main glaciation was thought to have been the more severe. It was suggested that the dominant ice movement originated in the North Sea, crossing the Shetland Islands from east to west. This ice was believed to come from a Scandanavian ice mass that had crossed the northern North Sea and flowed in a south-southwesterly or southwesterly direction (see fig 1.1.1.). In Unst, Fetlar, Whalsey, Bressay, Yell, the Outskerries and on eastern Mainland a uniform west-southwesterly to south-southwesterly striae orientation was taken as indicative of this flow. Moreover, this direction, particularly in the Outskerries and on Whalsey, was cited as confirmatory evidence that the ice responsible could not have been of local origin (ibid., 792).

Further south, in western Yell, western Bressay and western Mainland, as well as in Muckle Roe, Papa Stour and on Foula, a change in the striae orientation occurred. This indicated a change in the dominant flow direction towards the northwest or north-northwest. This was believed to be a consequence of the local topography deflecting the flow of ice to the east as it overtopped the island's watershed (ibid., 809). To the west of the watersheds of the other islands ice flow produced the overdeepening of the voes characteristic of the archipelago.

In a subsequent and much later work, a localised study in Shetland nearly a century later appeared to confirm Peach and Horne's observations. Chapelhow (1965) also used striae evidence to define an ice flow from the northeast, in North Roe on Mainland. This was thought to coincide with the east-west flow of Scandanavian ice which Peach and Horne had attributed to their main glaciation (Chapelhow, ibid., 63).

In another later work Hoppe (1974), using striae observations on the east coast of Mainland, visualised an early glacial stage during which the Shetland Islands were similarly overriden by ice approaching from the east. Although uncertain, he suggested that this ice must have been of Scandanavian origin, and that it must have been grounded (ibid., 206). The northerly extent of the ice was unknown; it was assumed that it must have covered both Unst and the Outskerries, despite the fact that no easterly-trending striae could be observed in these localities.

A more restricted influence for Scandanavian ice was envisaged by Mykura (1976), on the basis of erratic trails on Whalsey, Fetlar and the Outskerries, which indicated a change in ice flow direction from easterly to northeasterly. This was attributed to the resistance imposed on Mainland (local) ice by a proximal Scandanavian ice mass which was able to flow westwards over northern Unst and Bressay, and over the south of Mainland (Quarff). His reconstructed ice flow pattern is shown in figure 1.1.2.

Flinn (1964) similarly assumed that the Scandanavian ice mass that was present in the area was fairly restricted, with its front lying in the northern North Sea to the east of Shetland. Much of the surrounding sea floor was thought to have been subaerially exposed during this "last glacial maximum" (ibid., 338). As an alternative, he suggested that Shetland could have been completely overrun by Scandanavian ice during this period. However, later work on Foula led him to reject the influence of Scandanavian ice to this degree (Flinn, 1978).

For the preceding glacial maximum Flinn accepted Peach and Horne's (1879) theory that the archipelago had been completely covered by ice from Scandanavia, at least during the early part of this period. In a later work, however, he suggested that even during this earlier glacial maximum the ice may only have overriden the southern parts of Mainland (Flinn, op. cit., 118). At a later stage this ice retreated eastwards to lie in the northern North Sea, isolated from the Shetland Islands altogether, much as it was thought to have done in the subsequent "last" glacial maximum.

As support for this view he went on to discuss a belt of submarine deeps in the North Sea (Flinn, 1967). He proposed that these features marked the terminal limits of Scandanavian ice in the north, and a Scottish ice sheet (see section 1.1.2.) to the south (see fig 1.1.3.). Under this proposal Scandanavian ice may only have overrun the northern and southern extremities of the archipelago (ibid., 1154) as it flowed around a local ice cap (see fig 1.1.3.). In a further study, he went on to suggest that in a lateglacial phase this reduced Scandanavian ice mass expanded to the south to overrun Fair Isle from the west (see fig 1.1.3.), although this was thought to have been a relatively insignificant event. In the "last" glaciation as a whole, the extent of Scandanavian ice was thought to have been so restricted that it did not cross the Norwegian Channel (Flinn, 1981, 177).

1.1.2. SCOTTISH ICE.

Support for the existence of Scottish ice over the Shetland Islands has been more limited. Peach and Horne (1879) suggested that the northwesterly swing in the flow direction of Scandanavian ice overtopping the islands' watersheds, during the main glaciation, resulted from a Scottish ice mass abutting the Scandanavian ice in an area south of the islands.

In a subsequent study they deduced that this Scottish ice was itself deflected by the Scandanavian ice to overrun the Orkney Islands to the south (Peach & Horne, 1880). This ice originated in northeast Scotland, flowing out from Caithness and across the Moray Firth, until it abutted the Scandanavian ice. At this point it took the path of least resistance northwestwards over Orkney (ibid., 657). Their original proposal for the iceflow pattern is shown in figure 1.1.4.

Robertson (1935) and Mykura (1976) accepted this ice mass configuration, with Scottish ice being deflected over Orkney, and being prevented from penetrating as far north as Shetland by a Scandanavian ice mass in that area. Mykura even suggested that this flow over Orkney may have occurred several times, with distinct intervening phases during which the Orkney Islands were ice-free (ibid., 114).

In his early works, Flinn (1967) envisaged an even more restricted Scottish ice mass (see fig 1.1.3.) which may only have overriden Caithness and the most southerly areas of Orkney. However, in a later work (Flinn, 1981) he stated that during the last glaciation of the Shetland Islands a local ice cap (see section 1.1.3.) abutted an expanded, but probably stagnant and by then downwasting, Scottish ice mass that had flowed out from Caithness in a northeasterly direction to cover Orkney (see fig 1.1.5.).

1.1.3. LOCAL ICE.

All of the theories discussed in the two preceding sections also invoke the presence of a local, indigeneous, Shetland ice mass at some stage. In their study Peach and Horne (1879, 806) envisaged a local ice cap during their later glacial phase. This period was characterised by much smaller glaciers on Mainland, flowing radially outwards from the central high ground. The ice gradually retreated, producing successively more restricted moraine belts on the slopes flanking the central watershed on Mainland, as the climate ameliorated. At their greatest extent these glaciers were not thought to have advanced far beyond the limit of the modern coastline (ibid., 791), and Unst, Yell, the Outskerries, Whalsey and Bressay were presumed to have developed their own glaciers. On Bressay, striae orientations indicated that Mainland ice did reach the north and west of this island, but that local glaciers dominated the eastern seaboard. In the coastal areas around Lerwick this later ice activity was thought to have been so severe that striae from the main glaciation were "well-nigh effaced" (ibid., 793) by it. In other areas, however, tills from the main glaciation were thought to have protected bedrock surfaces from the imposition of this later striae pattern. The major facets of this later stage are reconstructed in figure 1.1.6.

Chapelhow (1965, 69), similarly, proposed a later local ice mass centred on Ronas Hill, from which ice flowed out in a northwesterly direction under topographic control. This is presumed to correlate with the onset of Peach and Horne's later glacial phase. At a later stage still, Chapelhow invoked the presence of immature cirque glaciers which deposited plateau moraine. This would seem to correlate with the end of Peach and Horne's (1879) later phase. In contrast to these authors, however, Chapelhow (op. cit.) suggests that there may have been an interstadial between these two periods.

In contrast to both of these works, Hoppe (1974, 207) envisaged a continuous transition from the Scandanavian ice phase to a local ice cap. This change occurred during a single deglacial episode and not over two separate stadials. In the field this transition is represented by a progressive shift in striae orientation. The ice cap had its divide in the vicinity of the modern watershed on Mainland (see fig 1.1.7.), from which ice flowed out to the east and west, approximately normal to the present coastline. In the vicinity of the coast the ice calved into open water (ibid., 201).

In the course of his investigation Hoppe was also able to reassess some of Peach and Horne's (1879) original observations. Unst, Yell and Bressay, for example, were now thought to have been covered by the Mainland ice cap, in contrast to Peach and Horne's supposition that these islands had only supported local glaciers (compare figs 1.1.6. and 1.1.7.).

Mykura (1976) suggested that during the "maximum" stage of glaciation in Peach and Horne's (op. cit.) theory, their supposition that Scandanavian ice had overriden the Shetland Islands remained insubstantiated. The only evidence for westward-flowing ice came from the extreme north in Unst and North Roe, and in the south on Bressay and in Quarff. Elsewhere erratic provenance studies pointed to the existence of a local ice sheet at that time. To the west of the islands' watersheds movement was predominantly westwards, although local variations were evident. In North Roe the flow was northwestward, west to west-northwesterly in Northmaven and Muckle Roe, almost radially outwards from the Walls peninsula, and southwestwards in the Scalloway-Burra Isle region. In the eastern parts of Mainland striae orientation changed from east-southeasterly to easterly in northern Tingwall, Nesting, Laxo and Soth Whalsey. In Lunnasting, central and northern Whalsey and the Outskerries the orientation even changed to north-northeasterly.

From this evidence Mykura (1976) came to a similar conclusion as an earlier unpublished study by Robertson (1935), in suggesting that a local ice cap had lain over central Mainland, flowing both east and west from a central divide in the vicinity of Pettadale and Weisdale Hill in the centre of the island (see fig 1.1.2.). At a later stage, as the Scandanavian ice to the east began to break up, the local ice cap became isolated with its eastern margin no longer abutting this ice mass. As a consequence, local ice was able to expand to produce a radial outflow throughout the Shetland Islands which gradually removed the evidence of the earlier westward flow in the extreme north and south of the archipelago. In the western parts of Mainland this later stage was, therefore, indecipherable from the earlier flow, as there was no change in the dominant flow direction (Mykura, op. cit., 109). This later ice flow could not be positively identified on Unst, Yell and Bressay because there was no supporting evidence in the form of striae. Around Foula local glaciers probably developed at this time flowing in an easterly direction towards Mainland.

During a final stage, as the Shetland ice cap gradually downwasted, a small number of immature corrie glaciers and snow patches were left on the higher areas of Mainland, and on Foula to the west. These smaller ice masses produced the morainic mounds and ridges first identified by Peach and Horne (1879). The absence of glaciofluvial deposits on Mainland from this period was attributed to a postglacial submergence of the coastal areas in which these deposits were originally laid down (Mykura, op. cit., 9).

In his earliest work on Shetland, Flinn (1964) implied that the islands were covered either by a local ice cap or by Scandanavian ice (see section 1.1.1.). In a later work on Fair Isle (Flinn, 1970) he appears to have decided that the former in fact occurred. On the basis of striae orientations and till particle analyses, he proposed a subsidiary dispersal centre for the local ice cap in the Foula area. This had deflected westward-flowing Shetland ice towards the southeast, and this Shetland ice had then engulfed Fair Isle producing the predominantly northwesterly-orientated striae pattern (ibid., 275).

In a later investigation on Foula, Flinn (1978) further altered some of his original ideas. Using till particle-size and clast analyses, he now suggested that Foula was affected by ice flowing out from the southwestern parts of Mainland. This ice, presumably grounded, approached the islands from the southeast and was deflected towards the north and east around the highland mass which forms the core of Foula (ibid., 115). This ice configuration seems to imply that he had by this time rejected the idea of a dispersal centre in the vicinity of Foula.

At a later stage, during the last glaciation of the Shetland Islands, the local ice cap was thought to have pushed out in all directions and reached so far south that it abutted an expanded, but stagnant, Scottish ice mass (see fig 1.1.5.). It was at that time that easterly-flowing local ice had covered the northern North Sea.

In his most recent work, Flinn (1983) completed his observations in the northernmost islands of Yell and Unst. In these areas he discovered what he thought to be "misfit" dry watercourses, flat-bottomed gorges with only marginal drainage in them, and deep narrow channels which cut across the watershed areas of the modern topography (ibid., 312). Flinn concluded that these features must have been meltwater channels during some previous glacial period, and, that because these areas appeared to be devoid of striae, and in some cases had current-sorted glaciofluvial deposits (e.g. on Yell) and no tills, in contrast to the rest of the islands, they must have been ice-free (ibid., 319). The local ice front was assumed to have reached a maximum "halt" position just south of these channels, offshore from north Yell and across northern Unst. This led Flinn to modify slightly his previous reconstruction of the ice flow of the last Shetland ice cap to avoid these ice-free areas (see fig 1.1.8.). Recent offshore evidence of terminal ice features appears to support this reconstruction (Long & Skinner, 1985).

1.1.4. WESTERLY EXTENT.

One important factor which the present study will consider is the limit of any ice masses, west of the Shetland Islands on the continental shelf margin. None of the studies mentioned above specifically adressed this problem.

In their study Peach and Horne (1879, 806) gave no direct indication of the westerly limit of their main glacial Scandanavian ice, although the observation of striae on Foula, said to relate to this period, make it probable that ice reached at least this far west. In a subsequent study on Orkney (1880) they appear to believe that this Scandanavian ice, together with Scottish ice to the south which overran Orkney, reached as far west as the shelfbreak (see fig 1.1.4.), although this is probably an idea they acquired from Croll, whose influence on their work they clearly acknowledged (1879, 779).

Hoppe (1974) was also uncertain of the westerly extent of Scandanavian ice during this early phase. He cited striae evidence from Foula to suggest that the island had been at least partially affected by ice from the direction of Mainland, although he remained uncertain whether this evidence in fact related to the later local ice cap. In an accompanying diagram (see fig 1.1.9.) he appeared to favour the Scandanavian ice phase. In his later local ice phase, the ice front was assumed to have lain in the vicinity of the present shoreline (see fig 1.1.7.)., leaving Foula to the west, and possibly Fetlar to the east, ice-free.

During the maximum extent of his local ice cap Mykura (1976, 112) indicated that ice carried at least as far west as Foula, where local corrie glaciers flowing eastwards were deflected towards the north and south. During the later stage, as Scandanavian ice over the North Sea began to retreat, he appears to have drawn the implicit conclusion that, as Hoppe (op. cit.) had proposed, the western margin of the local ice cap lay in the vicinity of the modern shoreline of Mainland. Beyond this the ice calved into open sea, producing a topographically-influenced marginal flow pattern normal to this coastline (Mykura, op. cit., 110).

Flinn made no reference to westerly ice limits in most of his work. In one of his later papers he did, however, appear to suggest that during the last glaciation of the Shetland Islands a local ice cap did penetrate towards the shelfbreak, overrunning at least Foula (see fig 1.1.5.).

1.2. METHODOLOGICAL CRITICISMS.

The evidence used to derive the theories detailed in the previous sections is based on the relict features left by active ice, in the form of striations and in the movement of erratics. There is nothing inherently wrong with these techniques provided their limitations are recognized. The use of these methods to interpret the glacial history of the Shetland Islands fails to take into account certain variables which have a marked influence on the reliability of the conclusions that are then produced.

1.2.1. STRIAE ANALYSIS.

Five important factors will be discussed here, which have an important influence on the acceptibility of the theories detailed in the preceding sections which draw their evidence from striae analysis. These factors include the formation, sense, and scale of the striations together with the ice mass producing them, and the local topography in which they were created.

Striae are deciphered with reference to their orientation. As they are usually linear this indicates two potential (and dipolar) origins for the abrading agent which produced them. For this reason the sense of direction is determined from the associated phenomena of stoss- and lee- (or proximal- and distal-) side abrasions on striated rock surfaces and, at a macro scale, on roches moutonnées.

It is not doubted that striae are formed by entrained material, in the basal debris zones of active ice, abrading the underlying bedrock. The circumstances of their formation, and their post-formational histories, can however lead to their misinterpretation. According to local conditions, the preservation of striae, and other glacial phenomena such as tills and erratics, can vary widely. For example, Peach and Horne (1879, 803) suggested the absence of striae in the Delting area, was a result of a till cover protecting the underlying bedrock surfaces from erosion. In essence, therefore, it is logical to assume that no two striae, whether they have similar or dissimilar orientations, need be attributed to an identical period of genesis.

With active ice as a formative agent, it might be expected that the only features to be preserved would be those relating to the most recent erosional episode. Peach and Horne (ibid., 793), for example, suggested that in Quarff (southern Mainland) and around Lerwick, their later local ice phase "well-nigh effaced" the striae pattern relating to the previous phase of Scandanavian ice, and Hoppe (1974, 199) stated that striae produced below high water mark by calving ice were more likely to be recessional (deglacial) features. A statement in one of Flinn's later works (1978, 122) is equally applicable to all of the other theories mentioned here, and to all relict glacigenic features :-

" In each area the features described are the last visible effects produced by the ice in those areas but there is no direct evidence that any or all the sets of features were produced contemporaneously."

Local topography can have a marked influence on any mass of ice flowing over it. Adjacent striae in the field, with similar vectors, may not have been produced contemporaneously because the local relief could have forced ice masses in different periods, or from different origins, to follow a similar path. This problem cannot be resolved as striae cannot be dated using present techniques. For this reason, Peach and Horne's (1879, 791-2) supposition that differences in striae orientation on Mainland and the Outskerries indicated the preservation of two separate ice flow directions, and hence two periods of glacial activity, need not hold. Similarly, Hoppe's (1974, fig.6.) identification of a temporal sequence on the basis of changes in striae orientation need not be accurate, for in the same way topographic effects could produce striae with varying orientations that were contemporary. Topographic influence of this kind is most likely when ice masses are relatively thin. This occurs most often during downwasting periods, in lateglacial and deglacial phases, when the majority of striae that are preserved are likely to have been formed (see above). In comparison, during periods of maximum ice extent and thickness, shearing in higher levels of the ice (particularly with cold-based conditions) could effectively isolate the influence of the local relief on the predominant ice flow direction. Peach and Horne (ibid.), for example, identified a "main" and a "lower level" ice flow direction near Fethaland Point on the east coast of Mainland.

Even without topographic forcing, variations in striae vectors can still occur. Hoppe (1974, 199-200), in the introduction to his work on Shetland, discussed the ice flow conditions at calving margins. Below high water mark he suggested that the rapid break up of an ice mass would produce concentrated erosion, and the formation of striations, parallel to the unstable calving margin. Marginal instability would also produce frequent changes in the form of the ice front. As striae would be formed normal to this ice front, their orientation would also change frequently. This would eventually leave a collection of striations with several vectors which were, in geological terms, effectively contemporary. Above the high-water mark, the ice margin (during the gradual recession of the calving front back onto land) would change from a lobate calving bay form (concave) to a terrestrial tongue form (convex). With ice flow vectors and, therefore, erosion perpendicular to both of these margins (cf Boulton et al., 1985, 448), striae trends would differ above and below the high-water mark. Differences in striae orientations may not, therefore, represent actual palaeoenvironmental differences in terms of time, or large scale ice flow directions.

Observation is slightly more rigorous where sense is taken into account. Peach and Horne (1879, 790) claimed to have used roches moutonnées to define sense, and Flinn (1970, 275) used micro- stoss- and lee-side features to determine the ice flow direction on Fair Isle. Even this information is prone to misinterpretation if post-formational history is not taken into account. The possibility that these features could be protected under a till "blanket" has already been mentioned. This would leave a "fossilised" sense of ice movement, which may be completely unrelated to the period in which the overlying till body was produced. In addition, during recessional and deglacial phases, the stripping-off of till covers by meltwater action, leaving the earlier features exposed, would then leave no record at all of the last ice activity in an area. The identification of the "last" ice movement on the basis of these features can, therefore, be incorrect.

A final problem, rarely considered with striae, is their scale. Most of the literature mentioned in the earlier sections of this chapter makes no reference to striae dimensions at all. The diagrams produced to illustrate this information (see figs 1.1.2. & 1.1.8.), are purely schematic, as the striations shown bear no relation to their true ground scale. Only Chapelhow (1965, 63) mentions size, and these examples are very small (rarely over 15 cm long and 3 mm wide). The potential influence of topography on ice flow has already been discussed. With striations that are as small as this it appears certain that local bedrock relief would have some influence on flow and, therefore, produce striae vectors at variance with any overall regional flow direction. For this reason, any extrapolation of flow direction should have only local significance. Statements such as that of Peach and Horne (1879, 809) :-

" The land ice which glaciated Shetland could only have come from Scandanavia, as the striated surfaces clearly point in that direction."

are unreliable, as the scale of inference employed is beyond that which the evidence can support with any degree of accuracy.

The observation of a large number of striae, and their associated phenomena, may help to counteract these local influences and enable a regional trend to be deciphered. Sample sizes in the studies mentioned earlier are rarely large enough to validate this approach. Peach and Horne (ibid., 794) considered only 320 striations and roches moutonnées, and even the most detailed work on Shetland (Flinn, 1977, 139) produced only about 1000 striae observations. Notably this larger sample size produced an interpretation different from that proposed by Peach and Horne.

1.2.2. ERRATIC ANALYSIS.

Criticisms of erratic provenance studies can also be made. Even assuming the origin of an erratic can be accurately defined (see below), its history prior to arrival at the location where it is now observed can only be guessed at. Ice flows and, therefore, erratic trajectories can be very complex, especially if the timescale under consideration is extended to include several glacial-interglacial cycles (Hoppe, 1974, 197) when different ice masses and flow directions may have affected the erratic.

A problem particularly evident in the present study area is the accurate definition of erratic origin. Vast tracts of uncharted bedrock lie below sea level around the Shetland Islands. For this reason the assignment of erratics, such as the tonsbergite erratic, to similar rock types in Norway is unwarranted, as a basement core with similar rock types may run below the North Sea between the two areas. The tonsbergite erratic, now in southern Mainland (see fig 1.1.2.) could, therefore, have come from a basement facies just off the Shetland coast as easily as it could from Scandanavia. Flinn (1978, 113) can be criticized in the same way for inferring an ice flow direction, from Mainland to Foula, on the basis of erratics on the latter resembling "but not exactly matching" outcrops on Mainland. The realisation of this potential error is essential if, as Flinn (1977, 139) suggests, the only direct evidence he could see for the presence of Scandanavian ice over the Shetland Islands is from erratics.

A final problem is the implicit tendency of researchers to consider erratic histories in terms of glacial maxima alone. This ignores the potential movement rock may undergo during deglacial or interglacial periods. Apart from active ice, the commonest process which could move large erratics is gravity. Periglacial activity may be very widespread before, and after, an ice advance in any given area. Chapelhow (1965, 69), for example, mentioned the occurrence of block disintegration (felsenmeer) features on the Ronas Hill granite in northern Mainland, which she attributed to periglacial activity post-dating the main glaciation of the area. Solifluction and other creep processes can be very efficient agents in the downslope movement of surface materials of any size when they are in an unconsolidated condition. Such downslope "post-ice" movement might be expected to be common, for the reasons given above, in many formerly glaciated regions. As early as 1880, in a critique of Peach and Horne's (1879) original treatise, Home alluded to this possibility :-

" I confess that I have never been able to understand, how boulders carried on the surface of either a glacier or a mer de glace could be left perched on the ridges, much less on 'the tops of the highest hills'."

(Home, ibid., 360).

An appreciation of this factor is particularly important in the case of the Shetland Islands. Peach and Horne (op. cit., 806-7), for example, suggested that their theory of a two-stage glacial history for the archipelago was placed beyond doubt with a study of erratic trajectories. In another instance, Flinn's suggested reconstruction of the flow of the last local ice cap over Shetland (see fig 1.1.8), away from the central watershed, could be attributed to periglacial weathering instead of ice action, as both processes would produce the same downslope movement of material.

In the light of the potential misinterpretation of the evidence used to support the theories so far proposed to account for the glacial history of the Shetland Islands, it is not surprising that such a variety of views has been produced, from what is effectively identical evidence. It is not surprising either that Flinn (1978, 122) has commented :-

" The evidence presented is apparently self-contradictory, and all the reconstructions offered so far have been based on only a selection of the available evidence."

Additional information relevant to an accurate appreciation of Shetland's glacial history will now be considered. This is required so that the research aims and questions for the present study can be produced, and critically examined, in the light of the more general existing understanding of the Quaternary palaeoenvironment in this area of the Northern Hemisphere. The following section will discuss palaeoclimatic and related ice expansion theories. Section 1.4 will consider evidence from other areas offshore from mainland Scotland and in the northern North Sea. Section 1.5 will then consider this information from a chronological perspective.

1.3. ATMOSPHERIC PATTERNS AND ICE GROWTH.

In an early paper on palaeoclimatology, Lamb and Woodroffe (1970) reconstructed the ice limits of the last (Weichselian) ice advance stage in Europe. The apparent rapidity of ice expansion which they derived was attributed to a southward expansion of the circumpolar vortex. This produced a highly meridional circulation pattern over the northern temperate latitudes with an accompanying predominance of northerly surface winds. The southerly movement of the upper cold trough, in conjunction with the polar anticyclone, then blocked the west-east and southwest-northeast tracks of depressions across the eastern Atlantic (ibid., 49). The diversion of these depressions further south then produced precipitation over the European ice centres in Scandanavia and northern Russia, throughout the year. In effect, it was the distribution of these depression tracks which governed the timing and rate of ice expansion in the Northern Hemisphere.

Linked with the track of depressions, later workers illustrated an accompanying movement in the oceanic polar-subpolar water convergence zone. Ruddiman et al.,(1980, 52) concluded that over 50 per cent of ice expansion after 75,000 years BP occurred prior to oceanic cooling between 40 and 45 degrees North in the Atlantic. The inference that can be drawn from this is that the warmer southerly water masses would provide increased amounts of moisture to the depression tracks as they moved south, thereby increasing precipitation and ice growth during the early part of a stadial. As the polar-subpolar water convergence also began to move southwards, the North Atlantic ocean currents were also pushed south. This caused a drop in ocean temperatures, and pack ice could form at more southerly latitudes. With the accompanying southerly movement of the depression tracks, glaciers in the high Arctic and northern Russia then began to decay, as those in more temperate latitudes expanded (Boulton, 1979, 386). The southerly movement of cyclonic activity, in effect, produced a drop in the moisture flux to the Arctic and as a result, during glacial maxima at lower latitudes, this area may only have been covered by pack ice (ibid., 389). In essence, all of these reconstructions suggest that if ice growth was governed by the availability of precipitation and, therefore, the track of cyclonic activity, the high and temperate latitudes of the Northern Hemisphere could not have had ice maxima simultaneously. This would seriously question "maximalist" ice sheet reconstructions such as those of Grosswald (1980) and Andersen (1981).

At a regional scale, if glacial features relating to the last Scottish ice masses are considered, a similar pattern can be seen. Maps of the inferred equilibrium line altitude (the theoretical point on a glacier where net accumulation in the upper reaches directly balances the net ablation towards the snout: from here on shortened to ELA), for glaciers of the Loch Lomond Stadial, show a marked rise in altitude, from south to north, and inland from the western seaboard (Sissons, 1980, 33). The only variable which Sissons considered could produce this pattern was to invoke heavier snowfall on the southern and western sides of the upland areas, with a precipitation deficit to the east reducing ice expansion.

This snowfall pattern in turn suggests that the dominant precipitation-bearing winds were southerlies, associated with Atlantic depression tracks following more southerly courses than they do at the present day. This would be a result of the southerly movement of the atmospheric and oceanic convergence zones mentioned earlier. Sissons went further to suggest that the southward extension of the depression tracks, and the Arctic pack ice limit, produced increased anticyclonic activity in the east and northeast of the Scottish mainland. These conditions would be ideal for increased periglacial activity in the areas not actually covered by ice, as these northerly areas would be left effectively arid (Sissons, ibid., 42). Through time, therefore, ice would expand, first in the far north of Scotland, and then these areas would experience an increasing precipitation deficit as the polar fronts moved southwards, and the more southerly ice masses expanded. Under these conditions the northerly ice masses would begin to retreat. Sissons showed that much of the Late Weichselian ice mass of northern Britain must have decayed while these areas were surrounded by the cold polar waters associated with anticyclonic activity (1981, 10-15), and so it was a snowfall deficit, and not increased temperature, that caused ice retreat.

The implications of this work are similar to those quoted earlier for the whole Northern Hemisphere. Ice expansion would probably have been diachronous over Britain as a whole, in association with the advance and retreat of the hemispheric circulation of atmosphere and ocean. As the most northerly point of Britain, therefore, the Shetland Islands may have had a very different glacial history to areas on the mainland. For example, Sissons (ibid., 15) noted that confirmatory evidence that marginal areas such as Shetland, Orkney and northeast Scotland (particularly Caithness) were covered by ice, during the Weichselian maximum further south, was not available. Moreover, as during this period the polar front probably lay much further south than it did during the Loch Lomond Stadial, on which his suppositions were based, the Shetland Islands were probably even more isolated from precipitation in that earlier period. As no evidence of ice has been found in these northern regions for the Loch Lomond Stadial, it seems unlikely that they could have supported ice during the Weichselian maximum (ibid., 12). By contrast, these areas may have undergone intense periglacial activity. To date, consideration of this latter possibility, by the study of periglacial phenomena, has only been carried out on the mainland (ibid., 7).

1.4. OFFSHORE EVIDENCE.

Many of the problems associated with the reconstruction of ice limits relating to the Late Weichselian in northwestern Europe stem from the fact that vast inaccessible areas lie beneath the North Sea and on the continental margin. These areas may contain information of critical importance but, to date, relatively little research has been carried out. Sissons (1981, 7), for example, states that no terminal end moraines have so far been found which mark the limit of the Late Weichselian ice advance above modern sea level. The implication must be that these features exist beneath the sea. There is, however, information available which has relevance for the present study. This comes from the islands off northern Scotland, and from borehole material from the northern North Sea.

1.4.1. ISLAND EVIDENCE.

Glacial deposits on the continental margin will have a particular importance to the present study. As was stated earlier, no accurate definition of westerly ice extent has been provided in any of the existing literature on the glaciation of the Shetland Islands, so the outer shelf, and the islands on it, are areas that potentially contain important evidence.

In the Hebrides, Sissons suggested that the western margin of the last ice mass in the area must have lain amongst the inner Hebrides (Ballantyne & Gray, 1984, 267). Sutherland and Walker (1984, 703) illustrated how a presumed Late Weichselian ice limit lay across northern Lewis, leaving the north of the island ice-free. They concluded that this ice front was of local origin, and for this reason, that mainland Scottish ice may only have spread some 100 kilometres from the major icesheds (ibid.). The implication of these findings is that the continental shelf margin, west of the Hebrides and north of Caithness and Sutherland, was not extensively glaciated during the Late Weichselian.

Even further west, in a study of the glacigenic features on Hirta, in the St. Kilda archipelago, Sutherland et al. (1984) concluded that during the Late Weichselian St. Kilda was affected by intense periglacial activity. The only ice that developed formed local glaciers in the southeasterly-facing areas backing Village Bay. Here also, therefore, the presence of any mainland Scottish ice could not be attributed to the Late Weichselian. This adds weight to the idea of a restricted mainland ice mass west of Britain, and an ice-free continental margin.

Taking this evidence a step farther, similarities between Hirta and Mainland in Shetland are marked, despite their latitudinal separation. As Sutherland (1984a, 441) noted, the presence of a subsea rock platform about 40 metres below modern sea level around St. Kilda, is similar to that at about 64 metres around Orkney (Flinn, 1969) and 82 metres around the Shetland Islands (Flinn, 1977). Both areas also have steep and precipitous backing cliffs along the coast, which drop vertically to these erosion surfaces. Shetland also lies at a similar distance from the shelfbreak as does St. Kilda further south. Considering the possibility of diachronous ice expansion outlined in section 1.3., it could be argued that conditions on St. Kilda during the Late Weichselian maximum mirrored those over the Shetland Islands at an earlier stage, when the polar fronts lay further north. Shetland may, therefore, have been subjected to only minor ice activity during the Late Weichselian but have undergone intense periglacial conditions. The Shetland and Orkney Islands do have evidence of these conditions which, although they have been recently active, cannot be explained away in terms of lateglacial or postglacial activity alone (Ball & Goodier, 1974; Goodier & Ball, 1975).

1.4.2. NORTH SEA BOREHOLES.

Recent evidence has become available from the northern North Sea, as a result of the BGS shallow borehole programme being carried out on the continental shelf. Detailed analysis has still to be completed on the majority of the material recovered. Some of the information presented in this section is, therefore, conjectural and should be seen as a first approximation of the probable results.

The discussion in section 1.1.1. illustrated that several researchers believed that Scandanavian ice reached the Shetland Islands at some stage during its glacial history. Early investigations in marine geology appeared to confirm this belief (Eden et al., 1978, 5). More recent BGS boreholes, have been sunk in the direct path that this Scandanavian ice would have had to have taken to reach Shetland, in order that this supposition could be re-examined. Five boreholes will be mentioned here. To date only the first one has been studied in any detail.

Borehole 81/26 was drilled through the Quaternary sequence in the Bosies Bank area (see fig 1.4.1.). Detailed sedimentological and biostratigraphical analysis of this core has been carried out by the Department of Geology, Bergen University, and by the BGS (A. Bent, pers comm.). The results suggest that only one zone, between 62 and 104 metres below the seabed, can be classified as a potential terrestrial till (Sejrup et al., 1984), with a second zone tentatively identified at 150 metres (Ellingsen et al., 1984). The remainder of the core is composed of marine or glaciomarine deposits, with evidence of ice-rafted clastics (ibid.). Amino acid dating on mollusc fragments suggests that the tills were deposited between 300,000 and 100,000 years BP. This would presumably correlate with the period prior to the last (Eemian) interglacial, during the Saalian ice advance. This led Sejrup et al. (op. cit.) to conclude that during the subsequent Weichselian, Scandanavian ice never crossed the 1 degree east meridian between 58 and 59 degrees North.

North of the Bosies Bank area knowledge of the westerly limit of any Weichselian ice mass is even more limited. However, three boreholes have been drilled by the BGS in the Halibut Bank area, immediatley east of the Shetland Islands. These boreholes (81/15, 81/16 & 81/18: see fig 1.4.1.) have not yet been analysed sedimentologically, but shipboard logs are available (Jobson & Fannin, 1981). These indicate that the cores are composed of sands, interlaminated silts and clays, and clays often with clastic and bioclastic inclusions. This kind of sequence is interpreted here as a glaciomarine succession, with the clastic inclusions representing ice-rafted debris. Shipboard logging limitations tend to produce the over-identification of tills (ice-rafted pebbles in clays are often so described), hence, as no tills were identified at any depth on the logs for these boreholes, it can be surmised that they are probably not extant. The one till that was logged, taking this kind of error into account, is interpreted here as a glaciomarine sequence. None of the cores, therefore, shows any evidence of the passage of grounded ice.

Palaeomagnetic dating of one of the cores (81/18) suggests that the core recovered in each borehole may date back to at least the Blake Event, between 117,000 and 104,000 years BP (Stoker et al., 1983, 333, fig .3.). All of the cores probably have a complete

Weichselian record (as no major unconformities in the upper palaeomagnetic record were noted by the above authors), hence, it can be stated for this area too that there is no evidence for the presence of grounded ice during this period. If this interpretaion is correct, the location of these boreholes means no Scandanavian ice could have crossed the northern North Sea to overrun, or encroach on, the eastern coast of the Shetland Islands. This would cast doubt upon the acceptibility of several of the theories outlined in section 1.1.1. which require this sequence of events.

The final borehole to be mentioned occurs on the extreme northern tip of the continental shelf in the Cormorant area (see fig 1.4.1.). Borehole 78/09 has been analysed geotechnically, palaeomagnetically and biostratigraphically by the BGS (Skinner & Gregory, 1983), and is now undergoing sedimentological investigation (M. J. Edge, pers comm.). The palaeomagnetic evidence appears to show that only the top 15 metres of the core relates to the Weichselian (Skinner & Gregory, op. cit., fig .3.). This zone is composed of sandy gravels and silty clays with sand layers. The facies are also overconsolidated, though the common association of this property with ice loading need not be correct. Many other factors can leave a sediment in an overconsolidated condition. For example, the growth of segregated ground ice under periglacial conditions in subaerially-exposed marine sediments (ibid., 146). This kind of environment may have been extensive considering sea level fluctuations during ice expansion and retreat phases. Depositional regime is another factor which could be invoked to explain certain properties, particularly rapid variations in the degree of consolidation over very small vertical distances (Milling, 1975, 313). Diagenetic change could also be important. Microfabric investigations of North Sea sediments have revealed features which may be halite cements in unconsolidated facies (M. A. Love, pers comm.). None of these possibilities has, as yet, received sufficient consideration.

Potential till deposits have been identified at lower levels in the borehole (M. J. Edge, pers comm.), but these probably relate to the passage of Saalian or Elsterian, and not Weichselian, ice (Skinner & Gregory, op. cit., 152). In essence, therefore, this core appears to preserve a similar sedimentological record to that found in the Halibut Bank boreholes further south.

In their entirety, these cores seem to suggest that Scandanavian ice could not have crossed the northern North Sea in the direction of the Shetland Islands, during the Weichselian at least. The only evidence for this chain of events is, therefore, the unreliable information derived from erratic provenance studies (see section 1.2.2.). This has serious implications for the theories discussed in section 1.1.1. which require this kind of ice activity.

1.5. CHRONOLOGY.

Much of the preceding discussion has concentrated, either explicitly or implicitly, on the last major ice advance stage in northwestern Europe (the Late Weichselian/Devensian). A consideration of timing is critical to the appreciation of all this information. If the theories outlined in section 1.1.1., for example, require the presence of grounded Scandanavian ice during the Late Weichselian, they could be rejected on the strength of the borehole evidence discussed in section 1.4.2. However, this same evidence would not preclude the existence of such an ice mass during an earlier (e.g. Saalian) stadial. Similarly, the possibility of latitudinally-diachronous ice expansion (section 1.3.) suggests that the designation of time limits to Shetland, which correlate with glacial phases from mainland ice stages, may be erroneous. Chronology is, therefore, a critical variable in the accurate appreciation of the glacial history of the present study area.

There is very little attention given to the timing of events in the theories outlined in section 1.1. The earliest works were written before the modern appreciation of glacial history, in the form of glacial-interglacial and stadial-interstadial cycles, was achieved. Peach and Horne's (1879) reference to "main" or "primary" and "later" glacial phases is a reflection of this. All that can be assumed today, with regard to their theory, is that these phases represent two periods of ice advance, separated by one, or several, interglacials or interstadials. They could also relate to a single stadial with a sufficiently extended timescale for both flow patterns to have developed.

Later researchers are equally vague. Hoppe (1974) is an exception, in that he does appear to attribute his local Shetland ice cap (see section 1.1.3.) to the Late Weichselian (after 35,000 years BP: ibid., 208). The presence of Scandanavian ice at an earlier stage is given no fixed time setting. The presentation of his findings seems to suggest that Hoppe thought this ice also existed during the last glacial (the Weichselian as a whole), although this is not unequivocally stated.

Chapelhow (1965) placed her Scandanavian ice phase in an "older" glaciation, prior to the Late Weichselian development of a local ice cap, but implied that the two stages were all part of a single ice advance (ibid., 68-9, table .4.). In this case both stages could be either Weichselian or, specifically, Late Weichselian.

Flinn's more extensive literature contains a variety of chronological terms which can be misinterpreted depending on the individual's understanding of his evidence. He often uses the term "end of the last glaciation" (e.g. 1977, 139) for the Shetland ice cap stage, which would appear to indicate the Late Weichselian. However, the use of terms such as "last glacial maximum" (e.g. 1970,275; 1983, 320) and "last major glaciation" (e.g. 1983, 311) need not refer to this period. In the former case, the discussion in section 1.3. suggested that the Shetland Islands may not have been covered by ice during the Late Weichselian maximum at lower latitudes. In the second case, as the influence and extent of ice advance stages prior to the Late Weichselian cannot be easily quantified, the identification of the last "major" glaciation in the area may be impossible. In relative terms, the local ice cap at this time could have been the "least" extensive glaciation of the islands during the Pleistocene as a whole.

The application of absolute dating techniques has only been employed relatively recently. All that results suggest so far is that the glacial deposits on Shetland today postdate the pre-Late Weichselian (Lowe, 1984, 407), and those to the south on Orkney probably predate the Late Weichselian (Rae, 1976, 225). These radiocarbon dates can only be taken as approximate indicators, owing to the possibility of contamination, and the fact that in these cases the technique is being pushed to the limits of its present accuracy. With this in mind, where no specific statement is made to the contrary, it is assumed that all of the theories discussed so far in this chapter relate to the Late Weichselian, because it is probable that most of the glacial features on which these theories are based relate to this last ice advance period.

1.6. RESEARCH QUESTIONS.

In the light of the preceding discussion, it is felt that all the theories that have been forwarded to describe the glacial history of the Shetland Islands appear to be deficient in some form. Firstly, the techniques researchers have employed are not very reliable or capable of reproducibility. Secondly, the evidence available for observation is very restricted. Thirdly, the interpretations made of this information have not been sufficiently rigorous to discount other possibilities. A number of theories exist, none of which may be indicative of the true sequence of events, and none of which can be supported or rejected to the exclusion of all the other possibilities. This suggests that the approaches adopted so far, and the techniques and evidence employed, are probably incapable of producing a solution that can be satisfactorily tested in terms of the original hypothesis. In essence, none of the theories that exist to date can be rejected by the observation of contrary evidence. A new approach would, therefore, appear to be needed.

Another point that must be considered is the absence of information for the offshore glacial record. There is no knowledge of terminal limits for mainland Scottish ice in the pre- or Late Weichselian, which may have influenced both Shetland, and Orkney to the south. Reconnaissance borehole evidence from the North Sea (section 1.4.) does suggest that the view that Scandanavian ice crossed the northern North Sea, and the Shetland Islands during the Late Weichselian, may be incorrect. There is also no positive evidence to indicate the westerly limit of any ice that crossed Shetland, at any time during the Pleistocene, towards the continental shelf margin. Marine geologic information would, therefore, appear to be needed.

Finally, the glacial history of the present study area has not been set within a rigorous chronological framework. This, in turn, has added to the problems of any reassessment of the theories proposed so far. If diachronous ice expansion was a reality, a completely new time sequence may be necessary, as this problem has not been addressed by researchers so far.

The approach taken in the formulation of the research aims for the present study had to take these factors into account. It was important to try to produce simple questions, which could be substantiated or rejected on the strength of the evidence which could subsequently be collected. The questions produced were not, therefore, designed to critically examine the existing theories, presented in section 1.1., in their entirety, but merely to focus on some of the anomalies which have already been highlighted in the preceding discussion. The first stage of the present study concentrated on the continental margin west of the Shetland Islands. Three primary research questions formed the basis for the investigation.

1.6.1. QUESTION ONE.

Did active ice ever cross the continental shelf to the west of the Shetland Islands ?

The absence of any information on the terminal limits of any ice mass on the continental margin meant that this kind of information was thought to be essential to any course the ensuing study might take. It also has important bearings on several of the existing theories for the glacial history of the Shetland Islands, which require local, Scottish or Scandanavian ice on the West Shetland Platform. Similarly, this kind of information has relevance to the proposed presence of ice over the region given in ice sheet reconstructions (e.g. Grosswald, 1980, fig .1.; Boulton et al., 1985, figs .10. & .22.). Marine geologic evidence should be capable of answering this kind of question. The presence of "till-like" diamictons in boreholes, or ice marginal features like moraine ridges, if they can be positively identified as such, should indicate the presence or close proximity of grounded ice. At the other extreme, the absence of these features would show that no active ice had been extant, assuming there was no evidence of post-depositional erosion. The borehole evidence from the northern North Sea (section 1.4.2.) suggests any borehole record will cover the Weichselian at least, so this question can be assessed over at least this time span.

1.6.2. QUESTION TWO.

If present, what areal and physical form did this ice take ?

Ice, if it is found that it did occur, should have definable limits on the basis of the proximal facies it would subsequently leave behind it. Terminal ice limits should, therefore, be represented by areal changes in facies composition (this point is taken up in section 4.2.2.). Assuming "till-like" diamictons, a grounded ice mass would be expected. However, active ice could also have been extant in the form of a floating ice shelf, as a pack ice cover, or as isolated icebergs, attributable to active ice in other areas. All of these ice morphologies should produce sufficiently different facies types and associations to enable them to be distinguished from each other.

1.6.3. QUESTION THREE.

If present, what was the probable origin of this ice ?

This question was posed very tentatively. It was felt that it could probably not be answered with any degree of certainty. As was stated earlier, the use of erratic provenance to define origin and ice flow direction (see section 1.2.2.) is very prone to inaccuracies. As a similar approach would have to be adopted here, based on the analysis of rock fragments found in boreholes, similar misinterpretations would be possible, especially when the large areas of uncharted bedrock beneath the sea around the Shetland Islands are taken into account. However, facies morphology on a regional scale (e.g. a consistent directional dip in facies boundaries) may indicate the dominant transportational and depositional trends in the area, and hence the likely origin of the material that had been deposited.

CHAPTER .2.

SEDIMENTOLOGY

2.1.1. APPROACH / OFFSHORE SAMPLING.

Several potential approaches could have been adopted in the present study. Sedimentological material was available from the BGS in two forms, which allowed two approaches to data analysis, though time limitations meant that only one could be utilized in the present study. A detailed two-dimensional pattern of information could have been procured from an analysis of shallow surface (and seabed) samples (shipek grab, gravity core and vibrocore data) covering the upper six metres of the Quaternary sediments. A great number of these cores have already been collected by the BGS. This approach was rejected, primarily because it would give a very limited impression of the vertical variation in facies type. It is this vertical succession which is most likely to preserve the records of change through time, so an understanding of the sediment sequence in this dimension was considered to be of more importance for the present study. For this reason the sedimentological analysis was based on shallow boreholes.

Using this data source the impression of spatial facies variation would be more limited. The sense of this variation was, therefore, achieved by correlating facies boundaries between borehole sites using seismic survey analysis. The implicit assumption made in this instance was that noted lithological changes within boreholes (see section 2.1.3.) were represented by reflection terminations on the seismic records. The seismic evidence is presented and discussed in detail in chapter three. Therefore although the seismic and sedimentological evidence is discussed separately, it was analysed simultaneously.

Certain factors must be taken into account when analysing borehole material. These factors relate to drilling procedures and the subsampling techniques employed. The BGS shallow boreholes are drilled using standard offshore techniques with a Christensen wireline recovery system. This can retrieve core "runs" of up to 5 metres in length, to an effective sub-bottom depth of 300 metres. All the drilled depths quoted in the present study relate to sub-bottom depth (and not from Kelly height as is common in exploration operations). In the recovery diagrams used in this chapter (and chapter six), recovery is drawn to scale from the seabed. Samples taken for later sedimentological analysis in the present study are also identified by a sub-bottom depth relating to the top of the sampled section. Samples were anything from 5 to 25 centimetres in length, dependent upon the physical properties of the core in that particular section. All of the samples are vertically-split half-core sections. The laboratory techniques employed to produce the parameters used in unit definition (see section 2.1.3.) are detailed in Appendix .1.

All borehole positions are fixed using a Main Chain Decca sateillite-navigation system. These positions are also included in this chapter.

2.1.2. BOREHOLE QUALITY.

The major problem in analysing boreholes, of relatively unconsolidated Quaternary sediments, is that the core recovered rarely represents the entire drilled depth. Preferential recovery, non-recovery and drill-induced disturbance are often the norm. This can produce a bias in initial logging if care is not taken. For each run (drilled section) the actual amount of sediment recovered is always logged from the base of the run. Incomplete recovery means that although sediment is logged in this way, it could have originated from any depth within the run length. For this reason, where poor recovery is experienced run length is reduced to increase the accuracy of depth assessment.

Incomplete recovery can result from a number of causes. These are largely a function of the physical characteristics of the sediment. Very soft unconsolidated clays often run out of the recovery barrel during retrieval, and very large cobbles can jam in the barrel mouth preventing further sediment from being recovered. Sands and other finer sediments may also be disturbed, or have the fine content washed out, under the rotary action of the drill head and the consistency of the mud being used. Sands can also be washed out during retrieval. As a consequence of this, sediments with these kinds of characteristics tend to make up a smaller proportion of the undamaged material recovered, whatever their abundance in reality. The level of detail given in the borehole descriptions in this chapter often varies for this reason.

2.1.3. UNIT DEFINITION.

As was stated in the preface to the present study the aim of laboratory analysis was to produce parameters to enable the division of the sedimentological record of each borehole into distinct sections, exhibiting similar physical characteristics. These sections will be termed "units". The method of defining these units centred on the identification of marked changes in various sedimentological and acoustic properties (chapter three) over very short vertical distances. These rapid vertical changes, in contrast to surrounding zones exhibiting relatively homogeneous sedimentological/acoustic properties, are assumed to correlate with lithological changes which mark unit boundaries.

The accuracy with which these boundaries could be delineated varied, dependent upon the level and condition of recovery and consequently the frequency of samples that could be taken for analysis. It also depended on the sedimentological contrasts between units. Where differences were very slight, or the transition gradual, the definition of unit boundaries became more subjective as the differences between the sedimentological parameters on each side of the divide was much less clear-cut. Moreover, with only gradual physical changes seismic evidence (chapter three) gave no clear indication of the unit boundaries either. In these cases boundaries were placed where any one of a number of parameters showed a change in average value over the vertical range where the unit boundary was thought to exist. In the absence of even slight changes divisions were based on the extrapolated regional trends of seismic terminations (chapter three).

This method of unit division is, therefore, essentially qualitative, although it is based on the analysis of quantitative laboratory tests. For the reasons detailed earlier, for example poor or preferential core recovery and the lack of distinct facies changes, a statistical approach to unit division was impossible, and unjustified. The large size of the study area, and the small number of borehole sites, meant that the samples that were analysed could not be construed to have any statistical significance in the representation of the entire study area. Using seismic evidence to interpolate between these sites would, however, enable a projection across the whole region, so that a qualitative impression of facies variation could be constructed.

2.1.4. NOMENCLATURE.

The nomenclature used for these units was numeric, to avoid any implication of age or formative origin at this stage, and being based solely on the relationship of each unit to those around it. This is particularly important in the present study where the possibility of several environments being represented in the sedimentological record for any given unit is high, because of the extent of the area involved. This holds despite the relatively small number of sampling points (boreholes) analysed.

The numeric nomenclature was based around the first core analysed. In the analysis of borehole 82/10 (section 2.2.) the units identified were numbered from the seabed down to the rockhead transition in ascending order, from one to five. Subsequent borehole analyses led to the extension of this range, according to the stratigraphic position of units in relation to those in 82/10 (largely interpreted from the seismic evidence given in the next chapter). Units overlying those in 82/10 were given successively lower numeric values (0 to -2). Unit 5 was kept throughout as the identifier for the transition to the pre-Quaternary lag deposit overlying bedrock. Where a definite stratigraphic position could not be identified, the unit in question was given a floating classification (X or T; see also chapter six). In the borehole descriptions in the rest of this chapter the units present are discussed sequentially from the seabed down to the base of the recovered section. The location of all the cores analysed in the rest of this chapter is given in figure 2.1.1.

2.2. BOREHOLE 82/10.

LOCATION: 60°10.00'N 03°40.01'W | **MAP AREA: Foula**

DEPTH DRILLED: 105 metres | **WATER DEPTH: 139.60 metres**

ROCKHEAD: 104.50 metres | **PERCENTAGE RECOVERY: 23.8%**

Borehole 82/10 was the first core analysed for several reasons. Primarily it showed marked facies changes at certain depths which produced accurate definitions of unit boundaries. There was also good seismic evidence from this area which enabled an accurate correlation of termination geometry (chapter three) with the sedimentological changes discussed in the following section.

2.2.1. UNIT 1. Seabed to 27 metres.

FABRIC.

This unit was predominantly an earth brown, unconsolidated, silty sediment. A slight variation in colour downcore was apparent (7.5 YR 4/2 to 10 YR 3/2). The original shipboard log described this unit as being dark grey to greyish-brown. It is thought that the present colouration is a result of oxidation since the core was originally drilled. This unit can be further subdivided into two zones.

The first zone runs from the seabed to 14 metres. At the top of this section the matrix is composed of a massive grey-brown material. Small clastic and bioclastic fragments are common. Between 3.90 and 8.00 metres, a region of sand occurs which is thought to be a result of the washing out of the fine fraction during drilling. Below 13.60 metres the massive matrix is replaced by a laminated region, perpendicular to the core axis. Clastic material is present throughout this zone. Clastic material ranges from about 4 centimetres (all clast dimensions are "b"-axis diameters) at 8.00 metres to 5 centimetres at the base of the zone.

The second zone comprised the rest of the unit. The fabric in this section was laminated throughout. Clastic debris was also present at all depths. Clast dimensions tend to be greater than in the first zone, ranging between 2 and 7 centimetres. At 18.00 metres the remains of a very large (gneissic) clast were recovered. Bioclastic debris is also common, and can be seen on x-ray plates of this zone lying at varying angles to the lamination (plate 2.2.1.).

COMPOSITION.

This unit was characterized by bimodally distributed sediments. The proportions of a sample in the sand fraction remained fairly constant, whilst variations in the gravel and fine fractions determined the degree of bimodality. Gravel concentrations were largely a function of the large clastic debris mentioned above. Gravel percentages ranged between 4 and 30%, sand between 42 and 60%, and fines from 30 to 50%. Considering only the matrix of the samples, these values recalculated to 42 to 60% sand, 20 to 36% silt and 18 to 28% clay (see figs 2.2.1. and 2.2.2.). The description of these plots, and their use in unit definition, is given in appendix 2.4.

MINERALOGY.

X-ray diffraction analysis of the clay fraction indicated little variation in the clay mineralogy in this unit. Iron-rich chlorites, identified on the strength of the 7.10 and 3.55 Å peaks, and illite (mica) dominate. The exact species of mica cannot be positively identified. The absence of a peak at 3.90 Å might suggest that the 1M polytype is present. The commonest minerals in this group are biotite and phlogopite (Brindley & Brown, 1980, 50). A peak around 3.00 Å also indicates the presence of the 2M1 polytype of which muscovite is the commonest form (op. cit.). A characteristic diffraction trace for this unit is given in figure 2.2.3.(The key with this diagram also relates to all further XRD traces presented in this study). Peaks at 2.28, 1.87 and 1.91 Å also show the presence of calcite.

2.2.2. UNIT 2. 27 to 49 metres.

FABRIC.

This unit bears many similarities to unit 1. It is composed of a dark brown (10 YR 3/1) silty-clay matrix. Lamination, perpendicular to the core axis, becomes very noticeable below 28.00 metres. Intercalated with this lamination are two features not observed in unit 1. Firstly sand layers (often of varying colours) occur at certain levels. They are often isolated, but commonly appear to be associated with similarly coloured clasts (plate 2.2.2.). Their predominant orientation is parallel to the lamination and they range in thickness from 3 to 4 millimetres up to 1 centimetre. The fact that these features do not disrupt the lamination indicates that they are not a function of drilling disturbance. Black bands also occur in this unit below 32.00 metres. These features parallel the lamination and are up to 4 millimetres thick. They occur rhythmically every 2 centimetres. These features are thought to be sulphide bands (plate 2.2.3.). From approximately 41.00 metres, the matrix becomes more sandy and the lamination disappears to be replaced by a massive matrix, grading into sand at the base of the unit. The colour of the matrix also changes to a light red-brown (5 YR 3/2).

Clastic material is supported within the matrix throughout this unit. Clasts range in size up to 8 centimetres in diameter. Three major clastic subzones could be identified. Between 27.50 and 28.00 metres the first subzone is characterised by a downcore increase in clast size and abundance (plate 2.2.4.). All of the clasts are rounded to subangular. This increase must be endemic as there is no evidence of drill-induced disturbance on x-ray prints (plate 2.2.5.).

In the second subzone, down to 31.70 metres, there is a single elongated clast perpendicular to the sulphide banding. At the edges of this clast the matrix laminae have been bent downwards (plate 2.2.6.).

In the third subzone, to 42.50 metres, a similar downcore increase in clast size and abundance occurs to that in the first subzone.

One final feature of note in this unit is a matrix aggregate (at 32.80 metres) within the core. This inclusion is roughly spherical in form, with a diameter of approximately 6 centimetres. The colour of this aggregate is noticeably different from the surrounding matrix, being more reddy-brown (7.5 YR 3/2). This inclusion also contains several clastic fragments (plate 2.2.7.) within its matrix. Below the inclusion there is also evidence for the depression of the laminae in the main core (plate 2.2.8.). No other features of this kind were observed elsewhere in the unit, though the disaggregated sand layers described earlier (see plate 2.2.2.) may represent the broken down remains of smaller examples of this phenomenon.

COMPOSITION.

Among the samples in this unit particle size composition varies markedly, as a function of the presence or absence, and abundance, of clastic material and sand layers. Overall the unit exhibits a similar composition to unit 1, but with a greater variation in the end-member gravel and fine populations. The average composition lies between 0 to 16% gravel, 20 to 44% sand and 50 to 80% fines (see fig 2.2.1.). When the matrix is considered in isolation these values recalculate to 20 to 50% sand, 22 to 50% silt and 22 to 40% clay (see fig 2.2.2.).

The aggregate inclusion plotted outside the boundaries for both unit 1 and 2 sediments (Second sample at 32.80 metres on figs 2.2.1. and 2.2.2., marked "inclusion").

MINERALOGY.

Clay mineralogy resembles unit 1. All of the samples are dominated by iron-rich chlorites and illites. The illites may have mixed layer structures containing at least the 1M and 2M1 polytypes. This layering may be quite common in detrital illites (Carroll, 1970, 19). One notable difference in this unit is a broadened 14.00 Å peak for chlorite, together with secondary peaks at 12.30, 13.80 or 15.00 Å (one example is given in figure 2.2.4.). On glycolation these peaks are replaced by a single peak at 17.00 Å. This response is typical of smectites. Smectites were evident below 31.00 metres, and are also present in the aggregate inclusion.

2.2.3. UNIT 3 49 to 96.6 metres.

FABRIC.

This is the largest unit in core 82/10. It also had the poorest recovery, much of it being drill-washed thixotropic sand. The most notable damage to the fabric occurs between 57.00 and 84.50 metres, and from 90.00 to 95.00 metres. Two samples were taken from these regions (at 72.30 and 75.30 metres), and the severe sorting produced by this disturbance led to their elimination from subsequent analysis. This left only five samples on which to base the description of this unit. The description is, therefore, selective, and the internal consistency of the unit had to be assessed from the gamma log response.

The unit is dominated by a dark grey (10 YR 3/1 to 3/2) sandy material. Overall, this matrix appears to be massive, although a few areas of lighter coloured sand towards the base of the unit suggest that it may be crudely laminated in this region. Elsewhere, any banding observed was attributed to drill damage.

Small angular to subangular bioclastic fragments occur throughout the unit, being predominantly orientated perpendicular to the core axis (plate 2.2.9.). Large clastic debris is much less common than in umits 1 and 2, and where present, clasts are more rounded than in those units (plate 2.2.9.). At one point (approximately 88.00 metres) a large rock-drilled sandstone clast suggests that some very large clastic material does exist in the unit.

COMPOSITION.

The particle size distribution of this unit is dominated by the sand component. Total composition ranges between 0 to 15% gravel, 55 to 80% sand and 30 to 40% fines (see fig 2.2.1.). The matrix alone, contains 58 to 92% sand, 5 to 35% silt and 0 to 15% clay (see fig 2.2.2.). The two drill damaged samples mentioned earlier are omitted from this plot.

MINERALOGY.

Clay mineralogy resembles that of the overlying units. Iron-rich chlorites and mixed-layered illites again dominate, with subsidiary amounts of smectites (peaks at 11.20 and 19.00 Å on dry traces). Minor peaks at 4.23, 2.84 and 2.27 Å also indicated the presence of feldspars, quartz and calcite respectively. There was effectively no variation in the mineralogy throughout the unit.

2.2.4. UNIT 4. 96.6 to 97.8 metres.

FABRIC.

The fourth unit identified in this core is very thin and its limits were primarily identified on the basis of a slight increase in gamma log signature, compared to the adjacent units. Only one sample could be taken for analysis.

The material available indicates a dark earth-brown matrix, clay rich and laminated. Cutting across the core are several areas which are black, or lighter red to reddy-brown in colour compared to the general matrix colour (plate 2.2.10.). These areas also tend to be more sandy than the surrounding matrix. Lower down in the unit, thicker and more pronounced bands occur which often have a higher sand content than the surrounding matrix (plate 2.2.11.), but these regions are thought to be a result of drill-disturbance.

Clast inclusions are present in the unit, but are much less abundant than those in units 1 and 2. Long axes range up to a maximum of 1 centimetre. A few small bioclastic fragments are also evenly distributed throughout the matrix.

COMPOSITION.

The composition of the one sample from this unit is identical to that for unit 2 sediments. The sample plots in the middle of the unit

2 area on both total (see fig 2.2.1.) and matrix (see fig 2.2.2.) composition plots.

MINERALOGY.

The clay mineralogy for this unit also resembles the overlying units. Iron-rich chlorites and illite dominate, with lesser amounts of smectite, and traces of halite and calcite.

2.2.5. UNIT 5. 97.8 to 104.5 metres.

FABRIC.

This unit represents the transition into the underlying bedrock at this particular site. Above the bedrock level the core shows many similarities to unit 3.

This unit is composed predominantly of a dark grey sandy material that is massive. Below 100.00 metres a hint of lamination is apparent, intercalated with blackened bands of sulphide. Below this the sand grades into a grey-green sand, with rhythmic layers of a higher silt content which look much greener (plate 2.2.12.). These features are a result of differential washing-out of the fine component to these lighter areas.

Small bioclastic and clastic fragments are present in the upper part of this unit, but the clastic debris is absent below the transition into the grey-green matrix. This grey-green material is thought to represent the lag deposit overlying the Tertiary bedrock at this site.

COMPOSITION.

The composition of this unit also resembles unit 3. The absence of a significant gravel fraction results in plots along the 0% gravel axis for total composition (see fig 2.2.1.). In the matrix, values varied between 66 to 78% sand, 10 to 26% silt and 8 to 10% clay (see fig 2.2.2.).

MINERALOGY.

Clay mineralogy also resembles the overlying units. Chlorites, mixed-layered illites and smectites were identified. However, towards the base of the unit below 103.00 metres, smectites and chlorites are absent. Mineralogy in the grey-green material is dominated by mixed-layered illites. Subsidiary peaks at 4.17 Å indicate potential feldspars, and at 2.70 and 2.44 Å indicate biotite (see fig 2.2.5.).

SUMMARY.

As was stated earlier, this borehole is believed to have penetrated the entire Quaternary sequence at its location. The low recovery level (23.8%) is not thought to be too unrepresentative, on the basis of the gamma log record between unit boundaries (see fig 2.2.6.). A summary of the lithology, stratigraphic sequence and recovery is given in figure 2.2.6.

2.3. BOREHOLE 82/01.

LOCATION: 59°55.18'N 03°31.14'W | **MAP AREA: Orkney**

DEPTH DRILLED: 74.55 metres | **WATER DEPTH: 128.00 metres**

ROCKHEAD: Not reached | **PERCENTAGE RECOVERY: 30.5%**

Borehole 82/01 is located to the south of core 82/10 (see fig 2.1.1.). A total of 27 samples were taken for analysis, on the basis of which two units could be identified. As no seismic lines ran directly over the core location , and no gamma log was taken, only the sedimentological data could be used for unit definition. Adjacent boreholes (e.g. 77/09: not analysed in this study) indicated a rockhead level approximately 50.00 metres below the seabed, with a unit change around 30.00 metres below the seabed. A similar division is evident in this core although the rockhead level must be at a greater depth. The comparatively high recovery level for this borehole was the main reason it was analysed in preference to these other sites.

2.3.1. UNIT 1. Seabed to 58.6 metres.

FABRIC.

This unit is thought to correlate with unit 1 in core 82/10. It is characterized by a massive, silty-clay matrix. Externally the core showed a "rust" brown colour (5 YR 4/4) which was thought to be the result of oxidation since the core was drilled, as internally the colour was dark grey to black (5 YR 3/1) (plate 2.3.1a.). Below the blackened zone, this colour is dispersed into distinct sulphide bands. They are generally less than 2 millimetres in thickness but are often found in very close proximity to each other (plate 2.3.1b.). This banding indicates that the matrix is laminated. In other parts of this unit the sulphide bands are more disjointed and contorted, or they form localised irregularly shaped "blotches" orientated in both the horizontal and vertical planes (plates 2.3.2. and 2.3.3. respectively).

Below 49.00 metres sulphides disappear and a reddy-brown clay dominates the matrix. Differently coloured sand layers can also be identified in this region (plate 2.3.4.) parallel to the lamination.

Clastic and bioclastic debris occurs throughout the unit. In the upper reaches, clasts are large, with long axes of up to 9 centimetres. The number of smaller clastic fragments (subrounded to angular in form) increases below 15.00 metres. All of the clastic material is orientated in no preferred direction. The bioclastic fragments, ranging up to 1 centimetre in diameter, also increase with the increase in the proportion of smaller clastic debris, and can be clearly seen in x-ray sections (plate 2.3.5.). Large clastic debris dominates again below 49.00 metres.

COMPOSITION.

Unit 1 in this core has a finer average composition than the same unit in 82/10. Complete particle size plots showed ranges of 0 to 15% gravel, 28 to 43% sand and 48 to 61% fines (see fig 2.3.1.). Matrix plots showed an average composition of 32 to 48% sand, 30 to 50% silt and 16 to 30% clay (see fig 2.3.2.). The sample analysed from 31.80 metres plotted outside the limits of both the units defined in this core. This wide discrepancy was thought to be indicative of damage during drilling, so this sample was not utilised further in the present study.

MINERALOGY.

Clay mineralogy in this unit is dominated by iron-rich chlorites and mixed-layered illites. Subsidiary minerals included potassium-rich feldspars (peaks at 4.23, 3.23 and 2.88 Å), calcite, halite and quartz. Hematite was tentatively identified on the strength of weak peaks in some samples at 2.71 and 2.49 Å below 58.40 metres.

Smectite is also a component of the clay minerals in this unit but in smaller proportions than illite and chlorite. On air-dried mounts smectite appears commonly as a double broad peak with chlorite at 14.00+ Å. In some cases secondary peaks also appear at 11.20 Å. On glycolation the distinctive smectite peak at 16.80 Å appeared (see fig 2.3.3.), and the 11.20 Å peak decayed to one at 10.50 Å (see fig 2.3.4.). This may be indicative of a mixed-layered mica-smectite (Brindley & Brown, 1980, fig 5.1, 325).

2.3.2. UNIT 2. 58.6 to 74.55+ metres.

FABRIC.

As no positive identification of bedrock was made in this core, the depth drilled did not penetrate to the base of this unit. It is assumed that this unit overlay the bedrock directly, on the basis of the seismic evidence from adjacent areas (chapter three). It is thought that this unit correlates with unit 2 in borehole 82/10.

This unit is characterized by a dark grey to greyish-brown (5 YR 4/1 to 4/2) silty-clay matrix, which is poorly laminated. Clastic inclusions are common at all depths. The largest clasts range up to 4 centimetres in diameter and are subrounded to angular in form. Rock types include granites, gneisses and other highly metamorphosed fragments. Smaller clastic inclusions, with diameters of up to 1 centimetre, are more profuse. None of these clasts show any preferred orientation relative to the matrix lamination, although the largest do show a tendency towards lying parallel with this lamination (plate 2.3.6.).

One notable component of the clastic debris in this unit is a light grey semi-consolidated clay, which shows evidence of being laminated itself (plate 2.3.6b.). This material is very brittle and can be easily broken down, which suggests that the profusion of this clast type below 60.00 metres (plate 2.3.7.) indicates the proximity of their source as they could not have been carried far without being broken down. The larger examples are rounded indicating at least some comminution (plate 2.3.8.). Below 63.00 metres this material dominates the clastic component, and probably accounts for the colour change of the matrix to a slate grey (10 YR 5/2: plate 2.3.9.).

It is thought that this grey clay may be a lag deposit resulting from the erosion of the underlying bedrock. Micropalaeontological analysis indicates, on the basis of benthonic foraminifera, a species change below 59.00 metres to a zone where planktonic species of Tertiary or Late Cretaceous age are present (Gregory, 1983a). Dinoflagellate cysts also suggest the presence of reworked Tertiary/Late Cretaceous bedrock. This contamination correlates with the appearance of the grey material observed during the present study, and does, therefore, seem to indicate that this debris is representative of the underlying solid geology.

COMPOSITION.

This unit is finer than the overlying unit 1 sediments when the total composition is taken into account (see fig 2.3.1.). This appears to be a result of the lower sand content in unit 2, with larger proportions in the fine fractions. Average composition lies between 0 and 10% gravel, 8 to 23% sand and 68 to 93% fines. These values recalculate to 8 to 25% sand, 32 to 44% silt and 33 to 50% clay when the matrix composition is considered (see fig 2.3.2.).

MINERALOGY.

Both iron-rich chlorites and illites are present in the clay fraction of this unit. Smectite was, however dominant. Additional smectite peaks to those not already seen in other units occur at 11.35 and 12.45 Å, both of which disappear on glycolation. On two samples an additional peak was also noted at 8.90 Å, which changed to a broad peak at 8.50 Å on glycolation (see fig 2.3.5.). These peaks probably represent other forms of smectite, in terms of varying inter-layer cations, and their hydration condition. The specific identification of the exact inter-layer structure is complex and time consuming and was not undertaken in the present study. This was because the exact identification of the clay lattice structure was thought to be of minor importance for genetic interpretation, compared to fabric and particle size characteristics of the sediment.

SUMMARY.

A summary of this borehole is given in figure 2.3.6. As was stated earlier, although not positively identified, it is thought that the bedrock transition does not lie far below the drilled depth of 74.55 metres.

2.4. BOREHOLE 84/02.

LOCATION: 60°08.48'N 03°10.06'W | MAP AREA: Foula

DEPTH DRILLED: 33.4 metres | WATER DEPTH: 170 metres

ROCKHEAD: 33.3 metres | PERCENTAGE RECOVERY: 35.2%

This borehole is located to the northeast of the boreholes described so far (see fig 2.1.1.). No gamma log was taken at this site, and the high sand content made the utilization of x-rays impossible. One complete run was thought to have undergone drill damage (5.80 to 10.80 metres). The core was divided into three main units, correlating with those found in 82/10.

2.4.1. UNIT 2. Seabed to 5.3 metres.

FABRIC.

The top 50 centimetres of this core is characterized by a very sandy horizon with numerous bioclastic fragments, and often entire shell valves. The matrix is dark greyish-brown in colour (10 YR 4/2) and is highly consolidated.

Below this horizon a gradation occurs into a massive silty clay with a much darker colour (10 YR 3/2). This material contains bioclastic and clastic fragments in a structureless matrix. Sulphide banding, similar to that in 82/01 is also apparent. Clasts show no preferred orientation, but the unconsolidated matrix prevented further analysis as modification of internal structure during drilling was highly probable.

COMPOSITION.

Only two samples could be taken from this unit. Although this prevented an accurate division or definition of the limits of this unit, the two samples were sufficiently different to the underlying sediments to justify their separation. Total composition plots show a direct comparability with unit 2 deposits in 82/10. The samples contained between 7 and 9% gravel, 30 to 36% sand and 57 to 61% fines (see fig 2.4.1.). Matrix components varied between 32 to 38% sand, 31 to 36% silt and 30 to 32% clay (see fig 2.4.2.).

MINERALOGY.

Clay minerals are similar to those described earlier, being dominated by iron-rich chlorites and illites, with subsidiary amounts of smectite, and minor amounts of feldspar. Notable feature are peaks at 7.50 and 22.00+ Å on glycolated mounts (see fig 2.4.3.) which could indicate the presence of a mixed-layered chlorite-smectite.

2.4.2. UNIT 3. 5.3 to 24.5 metres.

FABRIC.

This unit dominated the core. Where drill damage has not occurred it appears to be made up of a dark grey (2.5 YR 3/4) laminated sand. In certain areas a higher fine content is present which gives the matrix a redder (10 YR 4/2) colour. Clastic and bioclastic fragments occur throughout the unit. Clast long axes are commonly less than 2 centimetres, but in a few cases range up to 4 centimetres. Elongated clastic and bioclastic material does show some preference for alignment parallel to the matrix lamination.

Below 15.50 metres the matrix colour changes to a dark greyish-green (5 Y 3/1), otherwise the core is identical to the section already described.

COMPOSITION.

This unit shows a wider range in compositional values than unit 3 in core 82/10. This is, in part, a function of the higher gravel percentages in this core between 5.80 and 10.00 metres. It could also be a result of the selective washing-out of the fine fraction during drilling or retrieval. On total composition plots (see fig 2.4.1.) average values range between 0 to 11% gravel, 64 to 83% sand and 14 to 25% fines. The matrix values recalculated to range between 54 and 88% sand, 4 to 24% silt and 8 to 21% clay (see fig 2.4.2.).

MINERALOGY.

Mineralogy resembles the overlying unit. The only additional minerals identified were potassium- or sodium-feldspars (peaks at 4.23 Å).

2.4.3. UNIT 5. 24.5 to 33.3 metres.

FABRIC.

This unit is similar to unit 5 in borehole 82/10. It has a directly comparable grain size signature to the overlying unit (unit 3), but is characterized by the increasingly grey-green colour of the matrix towards the base. It is fairly consolidated and shows no signs of lamination. Small grey-green clasts, up to 3 millimetres in diameter, were observed in the matrix near the base of the unit and these probably represent the underlying Tertiary bedrock. This rock is composed of a consolidated, fissile, presumably Neogene clay which contains no clastic debris. Drilling was halted on entering this material at 33.3 metres.

COMPOSITION.

Only one sample could be analysed from this unit. This showed a total and matrix composition plot similar to the overlying unit (3) (see figs 2.4.1. and 2.4.2. respectively).

MINERALOGY.

This sample is dominated by smectites, characterized by broad peaks around 14.50, 11.20 and 10.00 Å. The first peak may represent the presence of a mixed-layered chlorite-smectite. On glycolation these peaks were replaced by a peak at 16.70 Å. The preservation of the 11.20 Å peak on glycolation may indicate the presence of a mixed-layered mica-smectite as well. Chlorite and illite were identified in lesser amounts, together with some feldspar and quartz (see fig 2.4.4.). The predominance of smectite is probably derived from the underlying Neogene bedrock, which is dominated by smectite with only minor amounts of chlorite and illite (see fig 2.4.5.).

SUMMARY.

The summary log for this core is given in figure 2.4.6. No evidence was found in this borehole to suggest that unit 4 deposits existed as they did in 82/10.

2.5. BOREHOLE 82/11.

LOCATION: 60°15.06'N 03°52.16'W **MAP AREA: Foula**

DEPTH DRILLED: 46.15 metres **WATER DEPTH: 175 metres**

ROCKHEAD: Not reached **PERCENTAGE RECOVERY: 23.8%**

This borehole is located close to the shelfbreak, west of Foula, and northwest of the Orkney Islands (see fig 2.1.1.). It is composed of two units which, on the basis of seismic analysis, are not thought to have been sampled in any of the cores described so far. It appeared that they directly follow the deposition of unit 1, and so are termed units 0 and -1 respectively. A total of 13 samples were taken for analysis. Again no gamma log record was available.

2.5.1. UNIT -1. Seabed to 25 metres.

FABRIC.

This unit is composed of a dark grey silty-clay which, where it has not been damaged during recovery, shows evidence of lamination perpendicular to the core axis. This lamination is present throughout the unit, below the uppermost 3.00 metres. The silty consistency of the matrix means that the lamination is not always immediatley apparent. The upper 3.00 metres is comprised of softer material which is massive and contains minor sulphide banding.

Clastic and bioclastic fragments are present in the core. The clastic debris is aspatially distributed. It is composed of generally small angular to subrounded clasts (up to 2 centimetres in diameter). The more elongated clasts tend to be aligned parallel, or at 45 degrees to, the lamination (plates 2.5.1. and 2.5.2. respectively). At certain depths there are marked increases in clast size for distances of up to 20 centimetres downcore. Four such zones were seen, starting from 6.80, 9.90, 17.40 and 19.60 metres respectively. The upper zone is shown in plate 2.5.3. At the base of these zones large rock-drilled rock fragments are often seen which indicates that very large clasts must exist in these areas.

COMPOSITION.

This unit is dissimilar to those units described so far. Overall the total composition plot shows average values ranging between 1 and 21% gravel, 26 to 44% sand and 44 to 72% fines (see fig 2.5.1.). The matrix values range from 28 to 49% sand, 27 to 42% silt and 20 to 31% clay (see fig 2.5.2.). The reason for the first sample, at 2.80 metres, plotting so far away from the rest of the unit could be a result of two factors. Firstly, it could be the result of drill modification or the "dropping-out" of the coarser particle size fractions during retrieval. Alternatively, it could represent a post-depositional influx of finer material overlying the unit proper.

MINERALOGY.

The clay mineralogy of this unit shows little difference from the units described in other cores. Chlorites and illites occur in all of the samples, with potassium-feldspars in minor amounts below 15.00 metres. Smectite showed a double peak with chlorite at 14.00+ Å, with additional peaks at 11.30 and 11.60 Å. All of the smectite peaks rationalised to a single peak around 16.70 A on glycolation.

2.5.2. UNIT 0. 25 to 46+ metres.

FABRIC.

It was evident from the seismic analysis that the depth drilled at this particular site did not penetrate to the base of unit 0. The following description is, for this reason, only representative of the upper levels of this unit.

The unit is characterized by a dark grey (10 YR 3/1), massive sandy sediment. No bedding or lamination could be seen at any depth (plate 2.5.4. for example). Drill-damaged thixotropic sand composed a significant proportion of the material recovered. This sediment was not sampled where it could be discerned.

Inclusions again include clastic and bioclastic debris. Clasts were up to 4 centimetres in diameter at the top of the unit, and rock -drilled fragments occur at several depths indicating that much larger clasts are present. Bioclastic debris tends to be more common than in unit -1 (plate 2.5.5.), and in one zone, between 28.00 and 30.00 metres, entire valves are evident. Valves and elongated bioclastic material tend to align perpendicular to the core axis, suggesting that some form of crude bedding is present.

COMPOSITION.

Unit 0 has a higher sand content than unit -1. The deepest sample, from 46.00 metres, was thought to have been drill-modified as it plotted in the area of unit -1, whereas the rest of the unit 0 sediments plotted in a fairly tight group. Total composition plots gave average values of between 2 to 13% gravel, 55 to 70% sand and 26 to 38% fines (see fig 2.5.1.). Considering only the matrix these values recalculated to 59 to 74% sand, 16 to 24% silt and 8 to 18% clay (see fig 2.5.2.).

MINERALOGY.

This unit is again dominated by iron-rich chlorites, with illite and some smectite. A notable smectite peak between 11.30 and 11.85 Å rationalised on glycolation (see fig 2.5.3.) to a peak around 17 Å, whilst still maintaining the dry peaks. This may indicate the presence of a mixed-layered mica-smectite. In some samples calcite and feldspar could also be identified.

SUMMARY.

The summary log for borehole 82/11 is given in figure 2.5.4.

2.6. BOREHOLE 84/04.

LOCATION: 60°45.03'N 02°16.21'W **MAP AREA: Foula**

DEPTH DRILLED: 154 metres **WATER DEPTH: 134 metres**

ROCKHEAD: Not reached **PERCENTAGE RECOVERY: 8.9%**

Borehole 84/04 was the deepest and longest core analysed in the present study. However, the very poor recovery means that samples are widely spaced so that the description of units, and the definition of unit boundaries, was often very difficult. A total of 23 samples were analysed, at least one of which was thought to have been modified under drilling. A total of six units were identified.

2.6.1. UNIT -1. Seabed to 10 metres.

FABRIC.

No samples were available from this unit. Its limits were identified on the basis of the different gamma log signature in the upper 10.00 metres of the core, compared to the underlying unit (see fig 2.6.1.). The marked jump in the gamma signature at 10.00 metres was taken as the lower limit of this unit (see fig 2.6.1.). Seismic definition of this boundary was also impossible because of the masking effect of the primary seabed multiple. Some sediment was recovered from this unit but this was insufficient to allow sampling.

This material was characteristically a massive, unconsolidated, brown (10 YR 5/3) calcareous sand. Below the upper metre of the core, odd pieces of recovered core indicate that the rest of the unit is composed of a massive dark grey (10 YR 3/1) silty clay. No evidence of bioclastic material is seen at any depth, though rounded to subangular clasts occur at all levels. A large gneissic fragment, with a long axis of 8 centimetres, was recovered at 7.00 metres.

2.6.2. UNIT 0. 10 to 40 metres.

FABRIC.

This unit was identified by its slightly higher gamma signature compared to the surrounding units (see fig 2.6.1.). Two samples were taken from this unit.

Like the overlying unit, unit O is composed of a dark grey (10 YR 3/1) silty clay which shows evidence of lamination in some sections. Between approximately 20.00 and 35.00 metres the matrix becomes black in colour (10 YR 2/1) indicating the presence of sulphides. No lamination is apparent in this zone and the matrix is massive.

Bioclastic and clastic fragments are present. At the top of the unit clasts are subrounded to angular in form, with long axes of up to 6 centimetres. Below 13.00 metres the maximum clast size is reduced to around 2 centimetres (plate 2.6.1.), although the odd clast up to 3 centimetres in diameter can be found. Large clastic fragments, up to 8 centimetres in length, occur more commonly below 17.00 metres. There follows a further progressive decrease in size towards the base of the unit. All of the clastic debris shows no preferred orientation (plate 2.6.1.). In the top of the sulphide zone clastic and bioclastic material is much smaller in size, with fragments rarely exceeding 3 millimetres in length. In the rest of the unit angular bioclastic debris can be up to 7 millimetres in length. None of this debris shows any preferred orientation.

COMPOSITION.

The two samples analysed from this unit indicate that the total composition lies between 8 and 18% gravel, 38 to 45% sand and 37 to 56% fines (see fig 2.6.2.). The matrix composition ranges between 40 to 55% sand, 21 to 42% silt and 18 to 24% clay (see fig 2.6.3.).

MINERALOGY.

The clay mineral fraction is similar to that of samples already described. Iron-rich chlorites and mixed-layered illites are significant components, but in this unit smectites are dominant.

Subsidiary minerals identified are potassium- and sodium- feldspars, and some halite.

2.6.3. UNIT 1. 40 to 60 metres.

FABRIC.

The fabric in this unit is dominated by a very dark grey (10 YR 3/2) to reddy-brown (7.5 YR 5/2) sandy-silt. Most of the samples recovered are consolidated and massive.

Small bioclastic fragments occur throughout this unit. They are generally angular and rarely exceed 3 millimetres in diameter, showing no preferred orientation. Clastic debris resembles that in unit 0. Large subangular clasts occur below 47.00 metres. Long axes range up to 9 centimetres, and drop progressively to around 4 centimetres at 54.00 metres. Smaller clasts are profuse throughout the unit. No preferred orientation was noted in any of the clastic material.

COMPOSITION.

The two samples from this unit are coarser than those from unit 1, in boreholes 82/10 and 82/01. Total composition ranges between 20 to 34% gravel, 37 to 42% sand and 29 to 38% fines (see fig 2.6.2.). The matrix values lie between 54 and 56% sand, 28 to 29% silt and 18 to 20% clay (see fig 2.6.3.).

MINERALOGY.

Clay mineralogy for this unit is identical to unit 0, except that in this unit iron-rich chlorites and mixed-layered illites predominate over the smectites.

2.6.4. UNIT 2. 60 to 120 metres.

FABRIC.

This is the largest unit recovered in 84/04. It was divided into four zones on the basis of its fabric characteristics. The division between the third and fourth zones, at around 100.00 metres below the seabed, can also be seen as a rise in the gamma log signature (see fig 2.6.1.). These zones will be described in sequence from the top of the unit.

The first zone runs from 60.00 to approximately 77.00 metres. It is characterized by a massive dark grey-brown (10 YR 3/2) silty-sand. A clay layer occurred at 73.30 metres, running for 10 centimetres and showing signs of lamination. Clay bands also occur around 64.00 metres. Clastic fragments occur throughout this zone. They are subrounded to angular in form, the largest examples ranging up to 4 centimetres in diameter. No preferred orientation is seen, though in some cases a-axes do tend to align perpendicular to the core axis (plate 2.6.2.). Bioclastic material is very much smaller and is evenly distributed throughout the matrix. Fragments range up to 6 millimetres in diameter.

The second zone runs from 77.00 to 91.00 metres. This section is composed of a dark grey-brown (10 YR 4/2) silty matrix which is predominantly massive. Signs of lamination were seen around 82.00 metres. Clastic material is profuse in this zone (plate 2.6.3.) and is commonly subangular to subrounded in form. Sizes range up to long axis dimensions of 5 centimetres, though size is more commonly between 1 and 2 centimetres. In many cases recovery in this section was restricted to drill washings comprising only the clastic material from the sediment with no matrix. Clast sizes are similar to those described, suggesting the sample taken (plate 2.6.3.) was representative of the zone as a whole. None of the clastic debris recovered in matrix material showed any evidence of preferred orientation, except in the clay-rich zone around 82.00 metres, where the clasts are aligned parallel to the lamination.

The third zone runs from 91.00 to approximately 100.00 metres. It is composed of a dark grey (10 YR 3/2) massive, and slightly consolidated, sandy material. Apart from this, the zone has clastic and bioclastic inclusions similar to the overlying zone, though some larger shell fragments were noted in this section.

The fourth zone constitutes the remainder of the unit down to 120.00 metres. It is dominated by a massive, dark grey-brown (10 YR 3/2) silty material. At the top of this zone clastic debris is less abundant than in other zones (plate 2.6.4.), but below 107.00 metres the number of clasts under 2 centimetres long increases markedly again. In other aspects this zone resembles the overlying zones.

COMPOSITION.

Within, and between, the zones in this unit there is a great range in particle size characteristics. The ranges given here are, therefore, of less diagnostic use than the parameters quoted for other units earlier in this chapter. In general this unit appears to be coarser than unit 2 deposits in boreholes 82/10 and 82/01. Total composition ranges between 4 and 44% gravel, 36 to 70% sand and 17 to 44% fines (see fig 2.6.2.). The matrix values recalculate to 49 to 78% sand, 12 to 28% silt and 3 to 30% clay (see fig 2.6.3.).

MINERALOGY.

This unit shows some variation in clay mineralogy. From the top of the unit to a depth of about 82.00 metres, clay mineralogy resembles that of the overlying units discussed earlier, being dominated by smectites, chlorites and illites. Mixed-layered mica-smectites may also be present (see fig 2.6.4.), together with minor amounts of feldspar and halite.

From 82.00 to 90.00 metres glycolated traces suggest that no smectites are present in the clay. Mineralogy here appears to be dominated by mixed-layered illites and chlorites, with subsidiary amounts of halite, feldspar and calcite.

Below 90.00 metres smectites reappear, and traces resemble those of the first section down to 82.00 metres. The final sample, from 115.80 metres, has a different mineralogy to the rest of the unit. No evidence of smectites could be seen, and the mineralogy here is dominated by iron-rich chlorites, illite and a small amount of potassium feldspar and calcite (see fig 2.6.5.).

2.6.5. UNIT 3. 120 to 148 metres.

FABRIC.

This unit is dominated by an unconsolidated, dark grey-brown (2.5 Y 3/2), massive silty sand (plate 2.6.5a.). Around 135.00 metres the colour changes to a dark grey (5 Y 4/1) for a depth of 5.00 metres. The sandy consistency of this material means that much of the recovered sediment from this unit had been damaged during drilling.

Clastic and bioclastic material, in contrast to the other units at this site, are relatively scarce and small (generally under 5 millimetres in length), or completely absent (plate 2.6.5b.). A large rock-drilled clast at 148.00 metres was taken as the junction with the underlying unit.

COMPOSITION.

The composition of the four samples from this unit resemble those for unit 3 in borehole 82/10, but are slightly finer than the unit 3 deposits from 84/02. Total composition covers a very narrow range between 0 and 7% gravel, 59 to 70% sand and 25 to 60% fines (see fig 2.6.2.) The matrix values range between 59 to 72% sand, 10 to 23% silt and 12 to 18% clay (see fig 2.6.3.).

MINERALOGY.

The clay minerals in this unit resemble those in the overlying units. Chlorites, illites and smectites dominate, and mica-smectite was again tentatively identified. Subsidiary minerals include potassium-feldspar, calcite and halite.

2.6.6. UNIT 4. 148 to 154+ metres.

FABRIC.

This unit did not terminate in the recovered core section at this site. On the seismic lines (see chapter three) the depth drilled already penetrated below the seismic multiple, so the base of this unit could not be discerned using geophysical evidence either.

The unit is composed of a dark grey-brown (10 YR 3/1) silty clay. At the top of the unit the matrix is massive, although lamination becomes apparent close to the base of the drilled section (plate

2.6.6.). Clastic and bioclastic inclusions are present. At the top of the unit they are generally up to 8 centimetres in diameter, but in the rest of the recovered section they are more widely dispersed and less than 1 centimetre in length (plate 2.6.7.). None of the clastic material shows a preferred orientation. The bioclastic fragments do not exceed 5 millimetres in length and are sparsely distributed through the matrix. In certain areas a horizontal colour variation can be seen (plate 2.6.8.) accompanied by a change in composition. This is thought to be a result of drill-induced disturbance.

COMPOSITION.

This unit has a similar grain size distribution to unit 4 sediments in borehole 82/10. Total composition ranged between 0 and 9% gravel, 29 to 50% sand and 41 to 60% fines (see fig 2.6.2.). The matrix values vary between 31 and 53% sand, 25 to 38% silt and 20 to 32% clay (see fig 2.6.3.).

MINERALOGY.

Mixed-layered illites, chlorites and smectites dominate the traces from the top of this unit down to 153.00 metres. The samples from 154.00 metres indicate the presence of only iron-rich chlorite, illite and smectite, without the subsidiary minerals (halite and feldspar) found above this depth.

SUMMARY.

Although the recovery and, therefore, the descriptive accuracy in this core is very selective it is thought that the descriptions given in the preceding section do reflect conditions in the core as a whole.

For interpretative purposes, however, more weight will be placed on the descriptions from other cores, where possible, in later sections of the present study. The summary log for this borehole is given in figure 2.6.1.

2.7. BOREHOLE 84/03.

LOCATION: 60°29.58'N 02°12.11'W **MAP AREA: Foula**

DEPTH DRILLED: 18 metres **WATER DEPTH: 151 metres**

ROCKHEAD: 18 metres **PERCENTAGE RECOVERY: 30.3%**

2.7.1. UNIT X. Seabed to 18 metres.

FABRIC.

Very little information could be gathered from this borehole. It is composed of a single unit comprising a highly unconsolidated, thixotropic, olive grey (5 Y 4/2) clay. This material was so soft that any structure it had was destroyed during drilling and recovery. Much of the sediment simply "ran out" of the barrel during retrieval. No clastic debris was seen, except just above rockhead where a few angular fragments were recovered.

COMPOSITION.

Two samples were taken from this core. Both show a nearly identical particle size signature. As the core contained no gravel, only matrix composition is given here. Values range between 16 to 18%

sand, around 54% silt and 28 to 30% clay (see fig 2.7.1.).

MINERALOGY.

The two samples taken indicate a clay mineralogy with similar elements to the other units described previously. Chlorites, illites and smectites are present with minor amounts of potassium-feldspar.

SUMMARY.

The correlation of this unit with one of the units described in the boreholes discussed so far was problematical, on the basis of the geometric association between these units (see chapter three). It may correlate with units 0 and -1 in 82/11, but this cannot be stated with any degree of certainty. Further discussion is left until chapter three. For this reason the unit was given a floating classification (as unit X) at this stage of the present study. The summary log for this site is given in figure 2.7.2., and the location is shown in figure 2.1.1.

2.8. BOREHOLE 80/09.

LOCATION: 60°32.00'N 01°55.50'W **MAP AREA: Shetland**

DEPTH DRILLED: 37.5 metres **WATER DEPTH: 117 metres**

ROCKHEAD: 34 metres **PERCENTAGE RECOVERY: 12.1%**

This was the last core analysed in the first stage of the present study. Recovery at this site was not particularly good, and was largely composed of rock-drilled clastic fragments. The small amount of matrix material available enabled two units to be tentatively identified, largely on the basis of the seismic analysis (chapter three).

2.8.1. UNIT X. Seabed to 8 metres.

FABRIC.

This unit was thought to correlate with the sediments in borehole 84/03 to the west of this site (see fig 2.2.1.). No matrix was recovered from this unit to enable an accurate description of the sediments which comprise it. Drill bit samples seem to suggest that it consists of a very soft dark grey clay like that described in 84/03. Apart from this recovery was restricted to a few clastic fragments. Sanstone, gneissic, metaquartzitic and dark volcanic lithologies were identified.

2.8.2. UNIT 4. 8 to 34 metres.

FABRIC.

The matrix of this unit is composed of a dark reddy-brown (7.5 YR 4/2 to 5 YR 5/3) massive clay. Internally the core shows evidence of profuse sulphide banding perpendicular to the core axis. Clastic material occurs throughout the unit. At the top of the section, clasts with long dimensions of up to 1 centimetre are found, and this size gradually increases down-core to about 9 centimetres at 19.00 metres. There is then a further decrease to around 6 centimetres at 21.00 metres, and a further increase to about 12 centimetres at 25.00

metres. Clastic fragments are predominantly subrounded to subangular, and the dominant lithology (a leucocratically banded, medium grey, gneiss with an augenitic tecture and pink granitic veining) is thought to reflect the underlying Lewisian solid geology.

COMPOSITION.

The material in this unit is coarser than that in the other cores. This is largely a result of the higher clastic component in the overall sample composition. Ranges in this unit are from 10 to 34% gravel, 11 to 45% sand and 40 to 69% fines (see fig 2.8.1.). When the gravel component is removed the matrix values recalculate to 15 to 50% sand, 33 to 53% silt and 18 to 33% clay (see fig 2.8.2.).

MINERALOGY.

Clay mineralogy shows some variation in this unit. In the upper portions the unit contains mixed-layered illite, iron-rich chlorites and smectites. Mica-smectite was again tentatively identified by an 11.20 Å peak which remained on glycolation . In the middle portion of the unit this form of smectite disappears, and below 25.00 metres smectites disappear from the clay fraction altogether and chlorite and illite become dominant (see fig 2.8.3.). Subsidiary amounts of potassium-feldspar, calcite and halite are also present.

SUMMARY.

Both of the units identified in this core are derived from the seismic survey analysis given in the following chapter. The unit X definition was thought to be fairly reliable, but the unit 4 deposits could, on fabric and compositional grounds, equally well to attributed to unit 2. The summary log for this final core is given in figure 2.8.4.

2.9. CONCLUSION.

This completes the description of the boreholes used for the initial phase of the present study. A summary of the overall inter-core unit relationship is given schematically in figure 2.9.1. The following chapter will present the seismic analysis, which was used in conjunction with the sedimentological evidence given in this chapter to define these unit inter-relationships.

CHAPTER .3.

SEISMIC ANALYSIS

3.1. INTRODUCTION.

The first section of this chapter deals with the theory behind any interpretation of seismic data. This is followed by a consideration of the specific features noted during the present study, particularly in the locality of the boreholes described in chapter two. As the same unit division is used in this chapter the same numeric coding to chapter two is also employed.

The description of the specific seismic features extant in the present study area is given to try to define the precise chronostratigraphic relationship between the units defined in chapter two. This analysis will aim to assess whether the boundaries between units represent unconformities or stratal surfaces. Once this is achieved the genetic interpretation of the sediments can be made in chapter four.

In contrast to practice in the oil industry, the investigation of unconsolidated Quaternary sediments means that standard deep seismic techniques can be abandoned and more accurate high resolution methods can be employed. It is this kind of technique that the Marine Geophysics Unit of the British Geological Survey (BGS) used to produce the records discussed in the rest of this chapter.

3.2.1. INTERPRETATION TECHNIQUES.

The high resolution seismic data used in the present study (see figures later in this chapter for examples) illustrates two major attributes. Firstly, there is a pictorial representation of the seismic response of the rock/sediment sequence penetrated. Secondly, at certain depths, there are distinct changes in this response over relatively short distances. Records can be interpreted accurately to the depth where the seabed multiple overlies the primary record (see for example fig 3.4.).

The commonest approach to analysis can be broken down into three stages. Firstly, it is necessary to identify the important reflector types and reflection terminations. Secondly, these features can be grouped into zones of geometrically similar reflection patterns and, thirdly, these sequences can be interpreted in genetic terms. There are, however, a number of important factors which need to be taken into account in utilizing this procedure.

The first stage, involving the identification of reflection patterns and terminations, represents the delineation of acoustic interfaces within the sediment column. These interfaces result from the elastic properties, velocity and density contrasts between sediments on opposite sides of what is, acoustically, a physical surface. As a result only "surfaces" having these kind of material contrasts between sediments will influence the seismic record produced. At each of these interfaces the amount of energy that continues to penetrate the sediment column is reduced by the amount reflected back to the surface and the receiving equipment. The degree of contrast across any given series of interfaces therefore governs the depth of penetration for the sound source being used. The graphical presentation of these interfaces, as a function of the time taken by the energy pulse to travel from source, to an interface, and back to the receiving equipment (two-way time), is what comprises any seismic record.

The rate of travel of the energy pulse, like the contrasts across interfaces, is largely dependent on the physical properties of the sediments being penetrated. In general terms, the velocity increases with an accompanying increase in the density of the sediments. Hard, rigid rocks have relatively high velocities compared to soft unconsolidated ones. Akal (1972) suggested that porosity was the most important sedimentary parameter influencing the velocity of seismic waves and the strength of reflectors at interfaces, and Gregory (1977) stated that in unconsolidated sediments this porosity was predominantly a function of the sediment's grain size distribution and clay content. This suggests that the infinite variety of possible grain size signatures often seen in Quaternary sediment sequences will produce complex variations in sound wave velocity. For this reason the depth scale on any seismic record cannot be considered as truly linear (Sieck & Self, 1977, 355). In the present study this problem was considered to be of minor importance. Whilst studying glacial Quaternary sequences in the Bering and Chukchi Seas, for example, Moore (1964, 327) concluded that corrections for velocity changes were unnecessary for the interpretation of seismic profiles with a reasonable degree of accuracy.

At the time of deposition of any sedimentary sequence, two kinds of reflection generating surface (interface or termination) can occur between facies. These are unconformities and/or stratal surfaces (bedding planes). In the latter case the reflection geometry consequently reflects the depositional geometry. In the former case, an unspecified amount of time, or sequence of events, will have occurred between the deposition of the two facies on each side of the termination. In both cases it is common to find the terminations corresponding with lithological changes, but this need not always be the case. Terminations are identified on the basis of acoustic changes, which need not reflect marked physical or compositional changes in the sediment column. For this reason, and invoking the Law of Superposition, it is evident that, strictly speaking, reflection terminations only have chronostratigraphic significance. This is because stratal surfaces and unconformities will, in the areas over which they can be traced, be synchronous events (geologically speaking). Although small-scale structural variations can commonly occur along bedding planes, the accompanying chronostratigraphic break is insignificant and the surface can still be taken as being geologically continuous. In the case of unconformities, however, once the termination has been identified the sediments on each side of it should not be assigned to an arbitrary lithological unit because it will probably transgress several physically different facies.

The second stage of analysis, accepting the potential for misinterpretation of the terminations mentioned above, is to define seismic sequences. A depositional sequence is a stratigraphic unit consisting of a succession of relatively conformable and genetically related strata (as was defined in section 2.1.3.). A seismic sequence is a relatively conformable succession of reflections on a record, bounded at the top and base by terminations. These sequences, once defined, can then be interpreted as a series of temporally related strata. The definition of a series of such units therefore enables the construction of a parastratigraphy (Boulton et al., 1981, 47) for any area based on these acoustic subdivisions of the rock record. From this an appreciation of the spatial extent and overall regional succession of the seismic units can be used to genetically interpret the depositional history. This approach was used in the present study, in tandem with the sedimentological analysis given in chapter two.

The final stage of analysis, often called facies prediction, involves the delineation and explanation of reflection geometry in terms of physiographic factors. The seismic sequence provides a logical framework within which palaeoenvironmental factors can be set. As was stated earlier, seismic facies need not necessarily correlate with lithological facies, but in existing studies of Quaternary sediments the use of seismic facies for palaeoenvironmental interpretation has been used as a tool in subdividing the vertical rock record in the other two dimensions.

Once this spatial element is appreciated, the sediments falling into any one seismic facies can be interpreted in three dimensions. This particular stage is considered in detail in chapter four. The remainder of the present chapter is concerned with the first two stages of the analysis.

In the present study, analysis was based on three main projects (regional offshore surveys) carried out by the Marine Geophysics Unit of the British Geological Survey between 1974 and 1979. These surveys (74/04, 77/07 & 79/14) are usually constructed in grids composed of a series of traverse lines placed approximately 5 kilometres apart. Fix positions are taken using a sateillite navigation system, with integrated doppler sonar and Main Chain Decca and/or Hi-Fix systems. A suite of equipment is employed, dependent upon conditions, including magnetometer, gravimeter, precision depth recorder, side-scan sonar and high-resolution profiling (1.0, 2.25, 3.25 to 3.75 kilojoule sparkers, boomer and airgun) systems. In the present study attention was limited to the sparker and side-scan profiles, because initial assessment showed that these records produced the best resolution of the reflection terminations present in the sediments. The location of the traverse lines is given in figure 3.1.

In the rest of this chapter selected localities will be illustrated, particularly those around the sites of the boreholes described in chapter two. The estimates of depth for the reflection terminations was based on an average two-way travel time of 1600 to 1800 metres per second because, as was stated earlier, exact estimates of velocity are unnecessary for this kind of interpretation. Scale accuracy for individual fixes was, therefore, estimated using the distinct marker of the seabed multiple and relating this proportionally to a depth equivalent to the known water depth at that particular site. In most cases, terminations could be placed within a 20 to 40 metre range depending on the resolution on a given line. Where reflectors were very clear on profiles, accuracy increased to less than 10 metres. Definition within 10 to 20 metres of the seabed was always conjectural because of the masking effect of the initial seabed surface response.

3.2.2. INTERPRETATIONAL APPROACH.

As well as the initial seabed surface response, several problems became apparent at an early stage of the analysis. The resolution of the seismic records available was very poor, and the positive identification of terminations and internal geometry was very difficult. The definition of seismic facies on the basis of internal reflector geometry was consequently impossible throughout the study area (see, for example, fig 3.9.) and the following analysis had to be based entirely on the identification of reflection terminations. In many cases, the two-way signal also died out above what was thought to be the bedrock transition zone, or the lower reaches of the profile was obscured by the seabed multiple (see, for example, fig 3.10.). The former factor was a function of the high signal absorbtion of the upper zones in the sediment column. Variable gain recorders can now obviate this problem to a great degree, but this type of equipment was not available when the lines for the present study were taken (C. Brett, pers. comm.). The lack of penetration was not always accompanied by better termination definition at higher levels. Signal decay with depth did not, therefore, appear to be a function of high reflectance from the near-surface interfaces. The higher-powered sparkers consequently gave the best resolution because of the greater initial signal strength.

The poor quality of much of the data means that the diagrams produced (see figs 3.2a to 3.3b: inside back cover, volume 2) are tentative interpretations. In the following discussion, and on these diagrams, three levels of assessment could be made. Where reflection terminations could be positively identified they are represented as solid lines (see, for example, figs 3.6. & 3.7.). In other instances reflectors could be tentatively identified, or clear reflectors could be extended. These lines are represented on the diagrams as wide-dashed lines (see, for example, fig 3.5.). In many cases, however, reflection terminations were virtually indistinguishable from the background signal on the profiles (see, for example, fig 3.10.). In these situations a subjective assessment was made of the most probable reflection geometry, based on the adjacent facies geometry on other lines, or on apparent regional trends. This variation accounts for the ranges over which terminations could be identified detailed in section 3.2.1. This level of analysis is represented on the diagrams as narrow-dashed lines.

3.3.1. DATA INTERPRETATION.

The most notable facet of the spatial distribution of the sediments in the present study area is their relatively restricted occurrence on the pre-Quaternary (undifferentiated here, but composed primarily of Lewisian Basement and Old Red Sandstone) basement platform west of Shetland, and north of the Orkney Islands. The Quaternary deposits appear to be underlain by what are thought to be Tertiary sediments, to the west of this basement platform (see figs 3.2a to 3.3b: Fannin, 1980, 5). Using the termination patterns a number of different geometric associations could be identified.

On the inner continental shelf, in areas directly bordering the basement platform, a sequence of horizontal terminations could be observed. These terminations correlate with units 1 to 4 , found in boreholes 82/01, 82/10 and 84/02. In the extreme south of the study area only units 1 and 2 were present on the basement platform, in the vicinity of borehole 82/01. To the north of this area the transition to unit 3 can be seen underlying units 1 and 2 (see fig 3.4.). Farther north unit 4 sediments also appear above the bedrock level, and north of 60 degrees north, units 1 to 4 appear in near horizontal succession. Unit 4 increases in thickness as it is traced farther northwards (areas marked "a" on figs 3.2a to 3.3b). Around borehole 82/10 the sedimentological changes noted in chapter two are reflected by weak terminations (see fig 3.5.). The thinness of unit 4 in this core meant that it was indistinguishable on the seismic profile and only the unit 5/bedrock boundary could be seen. To the south of 82/10 the best delineation of the unit terminations could be seen on line 27, where an undulating, irregular, reflector occurred between units 1/2 and 2/3 (see fig 3.6.). The transition to the underlying bedrock was also very clear on this line. Finally in this zone, borehole 84/02, to the east of the other cores (see fig 3.2b), also had sediments from units 2 and 3. Units 1 and 4 appeared to be absent in this area, and units 2 and 3 dip in a northerly direction (see fig 3.7.) towards a zone where the other two units outcrop (fig 3.2b, line 30, section marked "a").

To the north and east of these inner shelf areas, closer to the modern shelfbreak, these four units begin to dip towards the north and west. The inclination is accompanied by a "pinching-out" of units 2 to 4 (areas marked "b" on figs 3.2a and 3.2b) in an offshore direction west and north of the Shetland Islands. Beyond the break of slope in the surface of the Tertiary bedrock (beyond the shelfbreak) usually only unit 1 remains, continuing for an unknown distance down the continental slope. Within this general pattern it also appears that the thicknesses of units 1 to 4, and their easterly encroachment, is greater the farther north their outcrop/subcrop is traced. For example, the estimated thickness of unit 3 is around 50 to 60 metres on line 33, compared to about 45 metres farther south near borehole 82/10 (see fig 3.2a). The assumption that the lower portion of borehole 80/09 belongs to unit 4 was based on the dip of the overlying unit (3/4) termination farther west (see line 24, fig 3.2b) and north (see line 33, fig 3.2a) of this core.

In the vicinity of the modern shelfbreak, unit 1 is overlain by unit 0. Two overlap geometries can be identified. In some cases unit 0 overlies units 1 to 4 in the shelf zones where they constitute a horizontal succession (see, for example, lines 22, 32, 34 & 35 on fig 3.2a and lines 16 & 31 on fig 3.2b). The succeeding unit (-1 and possibly -2) show a similar pattern farther west beyond the modern shelfbreak (areas marked "c" in figs 3.2a & 3.2b). Generally the thickest part of each of these units lies between their inshore limit and the onlap of the subsequent unit. Estimated thicknesses can range up to 100 metres in these areas.

The outer limits of these units cannot be definitely determined beyond the modern shelfbreak, because of the mass of closely spaced reflectors and the lack of borehole data from these areas. The continuation, and division of these units is, therefore, highly conjectural in this area. It is thought that the balance of the evidence indicates the termination pattern given in figures 3.2a and 3.2b (see fig 3.8a), but they could also lense out down the continental slope to be overlain by further, unidentified units (see fig 3.8b). No unit -2 sediments were analysed in the present study, so the definition of this, and any other units in these areas, is arbitrary.

Two boreholes penetrated inshore portions of these outer shelf units. Borehole 82/11 was situated approximately 10 kilometres northwest of core 82/10, just beyond the point where units 2 and 3 lense out over the bedrock surface (line 32, fig 3.2a). The lower part of this core penetrated the upper reaches of unit 0, but did not reach its base (see fig 3.9.). Unit 1 deposits probably occurred at this site below 100 metres, judging from the dip of the adjacent unit 0/1 reflection termination (see fig 3.9.). No positive reflector could be identified at this site to indicate the change to the underlying Tertiary bedrock. Adjacent lines suggest that it lies approximately 140 metres below the seabed (see fig 3.2a). The upper unit 0/-1 was very clearly defined (see fig 3.9.) and correlated almost exactly with the sedimentological division derived in section 2.5.

Borehole 84/04 to the northeast appears to be situated where the Quaternary sediments in the present study area reach their maximum thicknesses on the continental shelf (see fig 3.2a). The interpretation of the seismic sequence at this site is complicated by the fact that sediment was still being recovered, during drilling operations,below the primary seabed multiple at 134 metres (see section 2.6.). The definition of terminations below this level was, therefore, impossible. The assumed bedrock transition at this site, of around 170 metres below seabed, is at best a working estimate. The major terminations, correlating with the sedimentological data, that could be tentatively identified were the 0/1 termination at 40 metres, the 1/2 termination at 60 metres, and the 2/3 termination at 120 metres, just above the seabed multiple (see fig 3.10.). The presence of the seabed multiple meant that the unit 3/4 termination could only be estimated using the sedimentological data discussed in section 2.6.

In the eastern shelf areas it became apparent that the seismic structure west and northwest of Shetland was more complex than it was in the southwest of the present study area, around boreholes 82/10 and 82/01. The shoreward dip of the main shelf units (1 to 4) was broken by a further unit which was enclosed in an area in, and northwest of, St Magnus Bay. This unit (unit X) unconformably overlay all of the other units, possibly including unit 0 in the far north (see figs 3.2a, 3.2b & 3.11.). Areas covered by this unit are marked "x" in figures 3.2a and 3.2b. The outcrop pattern of unit X meant that, chronostratigraphically, it could correlate with the outer shelf units described earlier (units -1 and -2). It could also represent an inshore thickening of unit 0, if the tentative division between these two units on lines 63, 47 (see fig 3.2b) and 38 (see fig 3.2a) is incorrect. Unit X could also postdate all of the units so far described. It was for these reasons that unit X was given a floating chronostratigraphic designation at this stage of the present study. Two boreholes penetrated this unit.

Borehole 84/03 is situated towards the southern end of the "basin-like" outcrop. The seismic structure around the site clearly shows the transition to the underlying basement (see fig 3.12.). The bedrock high at this site is thought to be the reason why no unit 4 deposits were recovered because they are thought to occur to the east. This assumption is based on the further assumption that the deposits recovered in borehole 80/09, about 10 kilometres to the east (see lines 24 & 39, fig 3.2a) relate to unit 4. At the site of 80/09 the bedrock transition could again be clearly identified, though the unit 4/X transition was less clear (see fig 3.13.).

All of the seismic lines discussed so far were also analysed using side-scan sonographs. A notable feature of these traces are elongated troughs which appear to indicate scouring of the modern seabed on the upper continental slope and shelf. These scours vary from less than 10 metres in length, to very elongated and randomly orientated furrows, which can extend for distances of up to 10 kilometres (Stoker & Fannin, 1984, 10). Widths vary from a few to 300 centimetres, and depths from 2 to 10, and exceptionally 15, metres (ibid.). The margins of these furrows are often marked by ploughed back ridges of material. Most of the scours are thought to be the result of the movement of grounded icebergs (see fig 3.14.). The regional trends of the largest of these furrows have been reproduced in the present study, together with the derived seabed surface outcrop pattern of the units described so far (see fig 3.15: inside back cover, volume 2). The general trend of these features appear to parallel the trend of the modern shelfbreak (Fannin, unpubl. working maps). The estimated thickness of the Quaternary deposits over the shelf is given in figure 3.16., and the regional bathymetry in figure 3.17.(both inside back cover, volume 2).

3.4.1. CHRONOSTRATIGRAPHIC SIGNIFICANCE.

The basic sequence of units identified in chapter two could be constructed by invoking the Law of Superposition, and by relating units identified in any given borehole to the other cores using the regional trend of the seismic terminations. In tandem these methods were used to produce the numeric unit coding used throughout this, and the previous, chapter and described in section 2.1.4. The sequence is reproduced in the key for figure 3.2a.

Having identified these major terminations, the next section will discuss their overall morphology with particular reference to the likely chronostratigraphic significance of each. As was stated earlier terminations can be viewed in two ways, either as unconformities representing unspecified breaks in sedimentation, or as stratal surfaces. In the former case an unquantifiable sedimentary and/or erosive phase occurred between the deposition of the two units bordering the termination. In this case the units represent separate "glimpses" of sedimentary conditions through time. Alternately, if the terminations are bedding surfaces they could still represent a break in sedimentation because a change in environmental conditions would be required to produce changes in sedimentation. However, if this change occurred relatively rapidly (in geological terms), the record in this type of sequence would carry a continuous record of deposition covering the entire time period represented by the rocks on each side of the termination. The difference between these two types of sequence must be identified, therefore, before an accurate interpretation of palaeoenvironmental conditions can be made.

3.4.2. TERMINATION MORPHOLOGY.

At the most general level the regional trend of the terminations can be used initially to assess the relative sea level changes and average shelf energy conditions during the period for which the entire sedimentary sequence is representative. This will have a marked influence on the likelihood of depositional or erosive phases having existed in the area during the deposition of the units identified earlier. From east to west, and south to north, the overall series illustrates a prograded morphology. Similar patterns have been observed in shelf to slope transition areas on other mid-latitude shelf areas, such as the margin of the Rockall Trough (Bailey et al., 1974, 59). Studies elsewhere suggest that this type of prograded sequence is symptomatic of continental margins with relatively high sedimentation rates and high energy fields (Field et al., 1983, 307). Moreover, these conditions only form where any shelfedge barriers, like submerged ridges or valleys, are absent. In the present study area the Tertiary bedrock on which most of the Quaternary is deposited shows no such obstructions on its upper surface (see figs 3.2a & 3.2b).

As well as being prograded the lower units (1 to 4) also show a tendency towards onlapping (see fig 3.18.) of the underlying units. For example, unit 0 appears to onlap units 1 to 4 east of borehole 82/11 (see line 32, fig 3.2a). Similar associations are apparent farther north around borehole 84/03, and borehole 84/04 farther north (see, for example, line 34, fig 3.2a), and on most of the north-south lines (see fig 3.2b). Vail et al. (1977, 65) suggest that this type of "coastal" onlap is indicative of a relative rise in sea level through time.

On a number of lines, close to or beyond the modern shelfbreak, terminations (especially the unit 0/1) show localised inflections. These take the form of concave surfaces cutting the general convex surface of the prograded reflectors (see fig 3.19.). Field et al.

(1983, 308) identified this type of morphology as indicative of cut-and-fill deposits. Environmentally this kind of sedimentation is considered to be a result of higher than average rates of erosion in shelfedge areas, during times of oscillating sea level. Terminations showing these inflections therefore represent at least minor erosional unconformities (ibid.).

With an understanding of these morphologies an initial appreciation of the temporal significance of the terminations can be made. With prograded sequences deposition is thought to be episodic and minor reworking may be common (ibid., 307). This suggests that, with the entire sedimentary sequence from unit 4 upwards apparently prograded, even if the terminations are stratal surfaces, the rock record preserved may not represent continuous deposition, the terminations being the result of the periodic pauses in sedimentation.

In the case of the onlapping morphology, however, the sequence from unit 4 to unit 0 may represent continuous deposition. The depositional record would be complete because in these circumstances no relative drop in sea level would have occurred which could have produced large scale, regional, erosion at a reduced base level.

When the cut-and-fill morphology is taken into account as well, the balance of the evidence does, however, appear to suggest that the seismic sequence is not completely continuous. The outer shelf units (0 to -2) suggest that the terminations represent at least minor breaks in deposition, as these units also show a downward shift in the clinoform pattern of the terminations towards, and beyond, the shelfbreak (see, for example, lines 28 & 30, fig 3.2b). This morphology is attributed to a gradual fall in sea level, in contrast to the indications of the onlapping morphology. Slight reductions in extant base level of this kind would increase the possibility of at least minor re-erosion of seabed sediments.

On a smaller scale than these features, the presence of irregular terminations, with minor "u" shaped inflections, may indicate the existence of small channel-like features which would support the idea of minor erosion along terminations. This kind of morphology was seen on the unit 0/1 and 1/2 terminations in the southwest of the study area (see fig 3.6.), and in the north on the 0/1 and 2/3 terminations (see line 15, fig 3.2b). The identification of unit 2 sediments in borehole 84/02 also necessitates a dip in the unit 2/3 termination, again indicative of at least minor erosion prior to the deposition of the overlying unit.

Overall the evidence from termination morphology is ambiguous with respect to the determination of whether they represent either stratal surfaces or unconformities. The balance of the evidence presented above appears to suggest that the latter alternative is more likely, although the evidence of erosion is relatively minor and does not suggest that these erosive episodes had major regional significance.

3.4.3. TECTONISM.

One complicating factor that must be taken into account is tectonism. From submerged peat beds, for example, it is known that Shetland is still sinking isostatically today (Hoppe, 1965). Tectonism could have been influential during the deposition of the Quaternary units identified in the present study and, at a regional scale, if a gradual submergence of the north of the area is envisaged, could account for the greater easterly encroachment of individual units as they are traced farther north. In the far north, for example, unit 0 can be seen much closer to the present coastline of Shetland than it can in the south (see fig 3.2a). The gradual sinking of the north of the present study area through time, would enable greater deposition in these areas, for any given unit. In contrast to the south, with much less submergence or even relative emergence, these units could, at one time, have extended farther inshore but have been subsequently planed-off during periods of reduced base level and increased erosion, as indicated by the morphological features on several of the terminations discussed earlier. The clinoform pattern, for example, in the south of the present study area would be compatible with such erosional phases, leaving the prograded morphologies farther north where continuous tectonic depression produced more constant depositional conditions. Isostatic recovery could also be invoked, producing a reduced base level, to account for the absence of units 1 to 3 on the basement platform (see figs 3.2a & 3.16.).

3.4.4. UNIT X.

There is evidence that at least one termination is a major unconformity rather than a stratal surface. At a macro-scale, the geometric association of unit X to the other units (see figs 3.2a & 3.2b) means that its lower surface must be an unconformity. This is emphasized in the north of its outcrop area where it crosses the regional trends of the other terminations for all the units down to unit 4 (see, for example, line 10, fig 3.2b). This indicates that a relative base level below that present for the deposition of all of these units must have interceded before the deposition of unit X. This reduced base level could also be invoked to account for the stripping of units 1 to 4 from the basement platform mentioned at the end of the previous section if, as the remaining outcrops of unit 4 and the regional trends of the other units suggest, these deposits did at one time cover these nearshore basement areas. In the south of the present study area, for example, there is a direct correlation, below present sea level, between the surface dip of the basement platform and the upper (seabed) surface of unit 1 (see all lines, fig 3.2a), suggesting that both these surfaces relate to an erosional episode postdating the deposition of unit 1, and possibly units 0 and -1. The base level preceding the deposition of unit X is, however, even lower than this.

The existence of this second, lower, base level can also be seen in the area just west of the basement platform in the south of the present study area. On a number of lines a broad, open "u" shaped, elongated trough occurs (see areas marked "v" in figs 3.2a & 3.2b, plus figs 3.5 & 3.6.). This feature gives the impression of an open valley running from south to north, approximately following the basement/Tertiary contact zone (see figs 3.2a & 3.2b). The vertical distance between the base of this feature, and the seabed surface, is between 50 and 70 metres. This correlates with the thickness of unit X where it outcrops to the northeast. These two physiographic depressions would, therefore, appear to be related to the same phase of reduced base level and consequently to the same erosive chronostratigraphic phase. In terms of the entire sedimentary sequence identified in the present study, this phase would appear to postdate the formation of the general seabed planation surface which, as was stated earlier, itself probably postdates the deposition of units -1 and possibly -2.

Another possibility is that the deposition of unit X predates the creation of the general seabed planation surface, in which case the erosive phase preceding its deposition would have to postdate all of the sediments described earlier. In this case as well, the submerged valley feature in the southwest of the present study area would need to be isolated in some way from the agents depositing unit X on the shelf just to the west of Shetland.

The only other alternative is to invoke two erosive phases for the formation of this feature. Preferential erosion in the southern area does not appear to have been restricted to one period of time. The unit 3/4 termination clearly indicates an erosional unconformity here prior to the deposition of unit 3 (see fig 3.6.). Moreover, to the south of this depression, near borehole 82/01, a similar feature occurs within the unit 2 deposits, which has been subsequently infilled by unit 1 (see unit 2 outcrops, fig 3.4.). All of these features indicate erosive phases in this area predating the creation of the present trough, so a two-stage erosion of the present feature could be invoked. In this case unit X could have been deposited in this depression, as well as those immediatley to the west of the Shetland Islands, but in this more distal area the deposits were subsequently re-eroded away.

3.5. SUMMARY.

The evidence presented in the present chapter does not unequivocally indicate that the unit terminations identified in the present study are stratal surfaces or unconformities. However, the greater part of this evidence, relating to several different terminations at varying localities, seems to indicate that the latter possibility is widely represented in the form of minor, local, erosional phases, although major intervening erosive episodes appear to be restricted to those periods preceding, and possibly postdating, the deposition of unit X. The exact relationship of unit X to the other deposits is difficult to delineate, but the balance of the evidence seems to suggest that it postdates the deposition of unit 0, and that it might also postdate the deposition of units -1 and/or -2. A summary of this information is given in figure 3.20.

The possibility that all of the terminations represented at least minor breaks in sedimentation necessitated the genetic interpretation of these units individually, rather than as a continuous sequence. The following chapter is structured in this way.

As stated at the start of this chapter, much of the seismic interpretation presented here is conjectural, especially beyond the modern shelfbreak where no borehole data is available for cross-correlation. It is thought that the interpretation given does represent reality at the regional scale, and as the subsequent interpretation is set at this level, the information available can be taken as satisfactory for the remainder of the present study.

CHAPTER .4.

GENETIC INTERPRETATION

4.1.1. INTRODUCTION: DATA QUALITY.

The following chapter contains the synthesis and interpretation of the information described in the two preceding chapters. The purpose of the present chapter is to derive an understanding of the genetic origin of these sediments. To this end the same units used in the previous chapters are analysed individually here.

The approach taken to interpretation was designed so that the maximum use could be made of the quantitative and semi-quantitative data produced during the sedimentological analysis. This includes the information on particle size distributions, constituent end-member proportions, x-ray diffraction analysis and organic and carbonate content. In addition, particle size statistics were calculated at this stage to produce graphic plots which could be interpreted in terms of hydrodynamic conditions at the time of deposition. The two techniques used were those of Sly et al. (1983b) and Pelletier (1973). Discussion of these techniques, and the computer programs used to produce the graphic plots is given in appendixes 2.2 and 2.3 respectively.

When as much information as possible has been used from these semi-quantitative sources, additional information was incorporated, consisting of the qualitative data from the visual description, plus micropalaeontological data provided by the BGS. This information was analysed by D Gregory and R Harland of the Micropalaeontology Unit, BGS Keyworth, as part of the BGS programme to date and characterize Quaternary marine sediments from the continental shelf. The data is reproduced here with the permission of the BGS. As this analysis was not related to the present study the sampling points for the micropalaeontological analysis differ from the sample depths for the present study. The use of this information could, therefore, only be included at this stage when unit boundaries had been defined from the sedimentological data.

4.2.1. APPROACH TO DATA INTERPRETATION.

The analysis of the data discussed in preceding chapters was carried out in three stages, for each of the units defined in chapters two and three. The quantitative and semi-quantitative information was considered first to enable an objective idea of the physical characteristics and likely hydraulic conditions prevalent during the deposition of any one unit. The optimum use of this information would ensure that the final interpretation of the unit was as objectively based as possible.

This information was then combined with the more qualitative information to build up a more detailed impression of a unit's sedimentary history. From this point, modern or Quaternary analogues from other areas were introduced for comparison.

Thirdly, invoking uniformitarianism, it was assumed that environmental characteristics which could be related to a sediment's features (accounting for any differences associated with different geological and physiographic conditions) for regions outside the present study area, indicated that, for similar physical features, a similar environment had existed in the present study area during the deposition of any given unit. The elements of interpretation are outlined below :-

1. PHYSICAL CHARACTERISTICS (Quantitative data).

Particle size constituent proportions

Particle size curves

Statistical parameters

Hydrodynamic interpretation

Carbonate content

Organic content

AIM: Definition of sediment type.

2. SEDIMENTARY HISTORY (Qualitative data).

Physical description

Fabric

X-rays

Micropalaeontology: Benthonic foraminifera

Dinoflagellate cysts

AIM: Definition of sediment formation

3. ENVIRONMENTAL INTERPRETATION.

Specific environmental analogues

AIM: Inference of environment at time of deposition.

This list is very simplified, and could not be rigorously followed in every case. For example, it was not always possible to give a positive identification of sediment type on the basis of the quantitative data alone, and the descriptive information often had to be incorporated before a decision could be made.

4.2.2. APPROACH TO ANSWERING RESEARCH QUESTIONS.

The procedural framework outlined in section 4.2.1. acted as a base around which to order the available information to define a unit's genetic origin. This process was carried out, however, within a further framework designed more specifically to aid in answering the research questions oulined in section 1.6. As was stated there, division should be possible between directly derived glacial deposits ("till-like diamictons"), and material which had undergone subsequent modification by other transportational mediums, or had had a completely non-glacial origin. On the assumption that the physiographic setting of the present study area would support either grounded, or floating marine, ice, if such ice had ever been present, five major types of sediment could possibly occur. The aim of the first two stages of unit analysis was to produce a designation consistent with one of these sediment types. They are :-

1) TILLS

Directly attributable to the presence of active ice i.e. a diamict carried at the sole of a moving and grounded ice mass. Generally polymodal and unsorted, dependent upon the contributing source rocks.

2) ORTHOTILLS

First defined by Harland _et al._ (1966) as produced by immediate release from ice by basal melt-out or ablation. This deposit is consequently difficult to differentiate from true till on particle size characteristics, unless modification occurs during melt-out owing to subaqeous/subaerial currents, or differential settling through a deep water column.

3) PARATILLS

First defined by Harland _et al._ (_ibid._) as deposits derived from ice rafting and laid down in a marine or lacustrine environment. Anderson _et al._ (1980) made a further subdivision of these deposits which is used here :-

3A) RESIDUAL PARATILL

These reflect the ice rafting of glacially-derived material coupled with active bottom and traction current activity in the area of deposition. This produces winnowing of the resulting sediment by the removal of the fine (silt & clay) content (Chriss & Frakes, 1972; Type 3 sediments of Anderson _et al._, _op. cit._).

3B) COMPOUND PARATILL

These deposits (Type 2 sediments of Anderson _et al._, _ibid._) occur in areas beyond the reach of active bottom and traction currents in which the winnowed fine content from the resdiual paratill zones is deposited.

4) MARINE/LACUSTRINE

Derived directly from marine or lacustrine processes with little, if any, evidence of the influence of glacial conditions.

The main features used to distinguish between these five different sediment types are summarised in table 4.2.1. This table is synthesized from previous works (mentioned above) with the addition of criteria used specifically in the present study. The approach taken to the definition of any facies as one of these sediment types is presented schematically in figure 4.2.1. The aim throughout was to compare the characteristics of a given unit to the features in table 4.2.1. to enable the rejection, if possible, of all but one of these sediment types. This was essential if the primary research question was to be answered. The observation of other features within these sediments would also help to answer the secondary research question, as to the physical form of any ice present in the following ways :-

The presence of till would clearly indicate the presence of active grounded ice at a particular borehole site at the time of deposition of the unit under scrutiny. In the case of a marine ice mass it could be assumed that tills would occur inland of the grounding line (Anderson et al., 1980, 406), and that partially modified tills (orthotills) would be produced in the locality of the grounding line with deposition through some form of water column, and elements of subglacial circulation or tidal forcing.

The division between orthotills and paratills would indicate a transition between any grounding line, or floating-off point, as the presence of paratills indicates a clear marine influence on sedimentation. In their study, Anderson et al. (ibid.) termed these sediments as glaciomarine, indicating that they were derived, at least partially, from floating ice. Studies beneath the Antarctic ice shelves and other iceberg-covered high latitude seas indicate that residual paratills occur inshore of compound facies, the latter being enriched with the material winnowed out of the former (see above). The boundary between these two sediment types therefore represents an oceanographic division between a high energy hydrodynamic zone of current activity and a low energy zone with deposition primarily from a hydraulic suspension (ibid., 413).

Beyond the paratill zones processes normal to marine or lacustrine deposition would exist. The location "offshore" where these sediments occur may be a function of distance from an ice mass or physiographic factors could also be important, for example, marine barriers and the location of the shelfbreak.

A summary of these zones and their geograpic relationship is given in figure 4.2.2. This kind of pattern should be represented by changes in sediment type between the borehole sites where any given unit is recovered, in relation to their relative distance from the sediment source (see section 4.2.3.). In this way, if none of these sediment types can be positively identified at any particular site, an appreciation of the physical changes between the other sites will enable this pattern of association to be less rigorously employed to define genetic origin. The use of a more detailed model of association was considered to be inappropriate at this stage, as there is no existing evidence of complex ice movements or patterns of deposition in the present study area for the Quaternary. Despite this, it should be possible to make a distinction between glacioterrestrial and glaciomarine palaeogeographic settings, so that an assessment of the likely configuration of land and sea can be made. This information by itself would add substantially to the existing understanding of the present study area's glacial history.

4.2.3. QUALIFICATIONS.

The differentiation of these sediment types depends upon the acceptance of certain implicit assumptions. Firstly, to differentiate tills from orthotills and paratills, it had to be assumed that the original particle size signature of the ice rafted sediments resembled that of any till-like diamictons that might be found. This was necessary if the presence of bimodality and sorting was to be used as an indicator of water-borne transport and deposition in non-terrestrial conditions. In the absence of any till deposits it was assumed that if present they would show similar characteristics to tills identified elsewhere (see table 4.2.1.).

Secondly it was assumed that the present terrestrial land masses of Shetland, and to a lesser extent Orkney, represented the core of any land masses that existed during the Quaternary and that they, therefore, represented the main sediment sources for the deposits identified in the present study. The regional geometry of the units, identified from the seismic terminations in chapter three, would appear to support this view. The dominant trend of all the units was from the south and east, towards the north and west (see figs 3.2a & 3.2b) which, assuming no marked isostatic changes since, would indicate deposition from source areas around the Orkney and Shetland archipelagos.

Throughout the remainder of this chapter (and later in chapter six) units are discussed individually, with all the deposits relating to any given unit from different borehole sites considered together. In certain cases units have been divided into "subgroups", which have similar characteristics across several cores, although in many cases subgroups are synonymous with the deposits from a single borehole. In some cases also, notably for unit 2, the deposits from a unit are subdivided within a single core into "subsets" (for example, borehole

84/04).

The particle size curves used in the description of these units are selected examples, representative of a subgroup, subset or other specified division of a unit, all of which have approximately similar particle size signatures. As these curves are characteristic of a sample's particle size distribution, they are also indicative of the relative proportions of gravel, sand, silt and clay to be found in any sample group. Consequently the groupings discussed in this chapter will correlate with the cluster of sample points, within any borehole:unit, illustrated on the ternary composition plots in chapter two. The greater the plotted concentration of sample points for any given unit in chapter two, therefore, the smaller the particle size variations and the fewer the representative sample curves which will need to be considered in this chapter.

UNIT 4.

4.3.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

Unit 4 sediments were identified in three boreholes; numbers 80/09, 82/10 and 84/04. On the basis of cumulative particle size curves these deposits were divided into two subgroups.

The first subgroup was composed of the deposits from 80/09. These sediments showed an evenly distributed particle size signature spread across all the end-member groups (see fig 4.3.1.: The computer program written to produce these plots is given in appendix 2.1a). This distribution was clearly polymodal, and with the absence of sorting meant that a marine origin for the sediment could be rejected. The absence of any significant degree of bimodality also enabled the rejection of a compound paratill origin.

Organic content in this first subgroup was very low, ranging between 0.2 and 1.2%.

The second subgroup consisted of the deposits from the other two cores (82/10 & 84/04). Particle size distribution curves for these sediments showed a more uneven distribution than the first subgroup, with a high fine and sand content but a relatively low gravel component (see fig 4.3.2.). The absence of polymodality enabled the rejection of a till or orthotill origin. The absence of a marked fine distribution and the presence of a significant sand component with some gravel also enabled the rejection of a marine or lacustrine origin for this subgroup.

Organic content was low in this subgroup ranging between 0.10 and 0.74%. Carbonate content throughout unit 4 was fairly uniform ranging between 8 and 12%.

HYDRODYNAMIC INTERPRETATION.

All of the samples from the first subgroup plot on high energy regime graphs (see fig 4.3.3.). The clustering of points inside the outer boundary curve (zones Eh & Fh) indicated samples that were not in hydrodynamic equilibrium owing to the presence of "anomalous" amounts of coarse clastic debris. Sly et al. (1983a) suggested that sediments in these zones were characteristic of environments with fluctuating velocity conditions in the depositional/transportational medium.

In contrast, the samples from the second subgroup were split between high and low energy regime plots. The lowermost samples from

84/04 plotted on the high energy regime plot in zones Gh and Hh, indicating similar hydrodynamic conditions to those in the first subgroup but deposition farther offshore (see fig 4.3.4.). The rest of the samples from this subgroup plotted on low energy regime graphs (see fig 4.3.5.) in zones Al and El. This also indicates deposition relatively close inshore but under more quiescent hydrodynamic conditions, associated with the selectively finer deposition of material from a suspension.

Plots of silt:clay ratio against phi mean diameter (see fig 4.3.6.) show a marked horizontal, but relatively little vertical, dispersion. This pattern is taken to indicate that the entire unit was deposited under approximately similar water depths. The variation in phi mean diameter may be indicative of two things. Firstly, it could be the result of a fluctuating shoreline, creating changing relative distances to these depositional sites and, therefore, the particle size characteristics of the sediments. Alternatively, taking into account the evidence for velocity fluctuations from the energy regime plots, this could be a function of varying competence in the transportational medium at these sites through time. With the evidence from the energy regime plots this is seen as a more plausible interpretation, and the idea of a fluctuating shoreline during the deposition of unit 4 is rejected.

Plots of raw silt:clay percentage for this unit all show points plotting above a 1:1 axis level (see fig 4.3.7.) which is considered to be characteristic of sediments deposited fairly close to a shoreline and, consequently, in relatively shallow water depths. This supports the idea that unit 4 sediments are not deep water marine facies.

4.3.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The visual description of unit 4 showed variation between a massive and a laminated matrix. The clastic and bioclastic content in the cores, and the lack of any preferred orientation parallel to the lamination (plate 2.6.7.), together with heterogeneous matrix indicates that these sediments are of glaciomarine origin.

In this case the high energy regime plots, large clast size and poorly sorted particle size range for the first subgroup suggest that these deposits are residual paratills. A compound paratill origin was consequently rejected for this subgroup. The low fine content (fig 4.3.1.), fluctuating velocity and high energy conditions would then be indicative of the traction and bottom current activity in the residual paratill zone winnowing out the finer material from the settling sediments.

These deposits can be separated from those in the second subgroup as the latter have a more bimodal distribution and a smaller ice rafted component, deposited in a low energy regime indicative of compound paratills.

MICROPALAEONTOLOGY.

Micropalaeontological data was only available at two of the sites, from 149 metres in 84/04 and from 97.25 metres in 82/10 (the methods used for analysing the raw BGS data for interpretation are given in appendix 2.5). This information is summarized in table 4.3.1. The most striking feature of these assemblages is their domination by marine species, primarily Elphidium excavatum (Terquem) forma clavata Cushman (from here on shortened to Elphidium clavatum) and _Cassidulina laevigata_ (d'Orbigny). Both of these species are indicative of shallow shelf conditions associated with water depths in the order of 20 to 50 metres (Gregory, 1985), although since the end of the Pleistocene _Cassidulina laevigata_ has been found on the continental slope down to depths of 250 metres (Ostby & Nagy, 1982, 64). This correlates with the relatively shallow water depths inferred from the silt:clay and phi mean diameter plots. _Elphidium clavatum_ is a common arctic species today, but during the Weichselian at least, appears to have formed a dominant proportion of benthonic communities in shallow brackish water conditions (Nagy, 1984, 330), in the vicinity of marine ice fronts (Osterman, 1984, 472). This supports the assumption that unit 4 sediments are paratills.

Cassidulina laevigata, on the other hand, is today associated with the influx of warm Atlantic waters from lower latitudes (Ostby & Nagy, _op. cit._, 83) which would suggest some form of oceanic amelioration during the deposition of unit 4 (Gregory, 1985). The fact that only two samples were available from this unit precludes a mnore detailed interpretation as they may be unrepresentative of the unit as a whole. For example, the more proximal assemblage from the residual paratill in 84/04 contains a greater proportion of the ameliorative species _Cassidulina laevigata_ and a lower proportion of the proximal species _Elphidium clavatum_, compared to the more distal compound paratill deposits represented by the assemblage in 82/10.

Faunal diversities do indicate fairly severe oceanic conditions. Low diversities are usually attributable to extreme or variable oceanic temperatures, commonly associated with high turbidity (Elverhoi _et al._, 1980, 51-2; Vorren _et al._, 1984, 252). The diversities seen in this unit (see table 4.3.1.) are not as low as extreme ice- proximal assemblages which commonly have values ranging down to between two and zero (Nagy, _op. cit._, 321; Osterman, _op. cit._, 474). For this reason the values seen here are interpreted as indicating the presence of ice masses, but presumably lying on the "landward" side of the sites from which unit 4 assemblages were recovered.

4.3.3. ENVIRONMENTAL INTERPRETATION.

The evidence discussed so far indicates that unit 4 sediments represent glaciomarine deposition, from an ice mass debouching into a shallow marine sea. The variation between high and low energy regime conditions at the site of 84/04 also indicates either that sediment supply and energy conditions were variable through time or, that energy conditions were constant through time but the margin of the ice mass varied in space. Assessing the probable location of this ice and its physical form is more difficult because of the limited information available for this unit.

It is possible that marine ice shelves deposit most of their basally-rafted material close to the grounding line, in the orthotill facies zone (Drewry & Cooper, 1981, 119). If this is correct any ice rafted, berg-derived, material farther offshore would be derived from outlet glaciers (<u>ibid.</u>, 120), on coastlines free of ice shelves (Orheim & Elverhoi, 1981, 126). This kind of "total" melt out may continue for 60 to 70 kilometres from the grounding line (<u>ibid.</u>, 123-4). If an ice shelf was present during the deposition of unit 4 it can be assumed that the rafted debris in the paratills would correlate with the outer reaches of this melt out zone, where the microfauna indicate marine processes were more influential. This supposition would, however, not account for the presence of distinct residual and compound paratill facies. Moreover, the shallow water depths indicated by the benthonic foraminifera prevents the assumption of a thick floating ice shelf. Water depths of 20 to 50 metres would suggest maximal floating ice thicknesses of 30 to 75 metres. If the ice was any thicker it would have grounded under these conditions and evidence of reworking, or characteristic basal tills, would be expected. These types of sediment were not observed, which suggests that ice thicknesses must have been substantially lower. If this were so, a continuous floating ice mass of shelf proportions seems improbable.

Alternatively the more restricted ice coverage associated with outlet glaciers on a semi-glaciated coastline could be invoked. This would enable a more economical interpretation of the available information. For example, the profuse sulphide banding noted in 80/09 could be attributed to an origin similar to that producing features observed in a proximal location in front of a glaciated fjord (Elverhoi et al., 1983, 138), where it was taken to indicate the spring "bloom" in microfaunal species. Although there is still uncertainty as to the likelihood of microfaunal assemblages surviving beneath ice shelves (Lipps et al., 1977), the ice thicknesses and spatial coverage would make oceanographic conditions more severe and consistent throughout the year. The presence of spring blooms and ameliorative species would, in this case, be improbable compared to a situation where a more variable ice cover existed, both in space and time, on a semi-glaciated coastline.

Taking this analogue further, layered and laminated sediments can be experienced within 500 metres of the ice front (Elverhoi et al., op. cit., 137), produced by near surface sediment plumes, outwash, bottom current reworking and temporal (seasonal) variations in sediment input. This would mean an ice front could have existed in the locality of 80/09 at the time for which sediment is preserved.

The thinner ice masses associated with this scenario, and the more rapid and profuse existence of ice rafting and calving would also provide a more plausible reason for the observation of ice rafted clastic material at all the borehole sites. A discontinuous, or only seasonally extended ice cover of the shelf in these circumstances would also help to explain the presence of ameliorative benthonic foraminifera so far east (in 84/04).

This idea of a semi-glaciated coastline therefore appears to be the most feasible interpretation of the environment that existed during the deposition of unit 4, and makes a more economical interpretation of the available information than is possible invoking an ice shelf. The facies belts that can be derived from this interpretation are shown in figure 4.3.8.(The facies types relate directly to those shown in fig 4.2.2.).

UNIT 3.

4.4.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

Sediments preserved from unit 3 are more extensive than those from unit 4. Material was recovered in cores 82/10, 84/02 and 84/04.

Two subgroups were identified on the basis of particle size curves. All of the samples from 82/10 and 84/04, and those below 10 metres in 84/02, showed a unimodal, well sorted sandy particle size distribution (see fig 4.4.1.). Variation between the samples in this subgroup was very slight, although the upper section of this unit in 82/10 did have a higher gravel content (see fig 4.4.2.). The very well sorted matrix enabled the rejection of a till and an orthotill origin for this subgroup. The coarse skew of the distribution also enabled the rejection of a marine/lacustrine origin.

The second subgroup, consisting of the samples in 84/02 above 10 metres, was more polymodal than the first subgroup (see fig 4.4.3.) and had a higher gravel content. The absence of a fine component, poor sorting, lack of stratification and the coarse skew of the matrix enabled the rejection of a marine/lacustrine and a compound paratill origin.

Organic content was low for this unit ranging between 0.06 and 0.80%. Carbonate content ranged between 10 and 20%.

HYDRODYNAMIC INTERPRETATION.

All of the samples from 84/02, from both subgroups, plotted on high energy regime graphs (see fig 4.4.4.). This also applied to the three samples from the top of 82/10, and one from 84/04. The positive skewness values for all these samples suggests deposition in a relatively nearshore environment (Damiani & Thomas, 1974). Many of the samples also plot in zones Eh and Fh, indicating modification of the sediment by velocity fluctuations in the transportational medium. The overall location of points suggests that this material may be a lag deposit. The fact that the sediments had a high energy regime signature also made it unlikely they were marine or compound paratills.

The remaining samples from 84/04 and 82/10 plotted with low energy regime signatures across zones Al, El and Hl. This indicates modified sediments with anomalous amounts of coarse debris, associated with lag deposits or ice rafted sediments (see fig 4.4.5.).

The plot of silt:clay ratio against phi mean diameter shows a much greater vertical spread than was seen in unit 4. This is probably a function of the more unimodal matrix and coarser particle size (see appendix 2.3.). The horizontal (phi mean) spread may also be indicative of the fluctuating energy conditions suggested by the energy regime plots. The approximately similar location of the points on the horizontal axis (see fig 4.4.6.) suggests deposition of all the sediments under roughly similar water depths.

Raw silt:clay graphs (see fig 4.4.7.) show unit 3 samples plotting closer to, and around, the 1:1 reference line than unit 4 which suggests that unit 3 was deposited in deeper water, or farther offshore than unit 4. However, plotting all of the units from any given core on this type of graph also shows unit 3 positioned consistently closest to the origin. One example, from 82/10, is given in figure 4.4.8. This is taken to indicate that unit 3 was the unit deposited closest to a terrestrial shoreline.

4.4.2. SEDIMENTARY HISTORY.

DESCRIPTION.

Unit 3 sediments were visually very similar in all of the cores. The generally massive, sandy charcteristics (plate 2.6.5a), and the absence of coarse clastic debris characteristic of paratills (plate 2.6.5b) was notable. Where present clastic material appeared to be much more rounded than fragments associated with ice action. This, together with the parallel alignment of bioclastic fragments (plate 2.2.9.) suggested some form of depositional stratification. This enabled the rejection of a till or orthotill origin for the unit. Clastic debris also enabled the rejection of a marine/lacustrine origin. The paucity of clastic material, absence of penetration structures and prominant lamination, and the well sorted sandy matrix were taken to indicate that neither subgroup was a residual paratill either. For the same reasons a compound paratill origin was rejected.

At this stage, therefore, it became apparent that neither of the unit 3 subgroups adequately fitted the definitional criteria of any of the facies types defined in table 4.2.1. This meant that a different genetic origin for these sediments had to be proposed (see fig 4.2.1.).

MICROPALAEONTOLOGY.

Both benthonic foraminifera and dinoflagellate cysts were recovered from the cores which contained this unit.

The foraminiferal analysis (for 82/10 and 84/04) showed assemblages (see table 4.4.1.) dominated at various depths by Elphidium clavatum, indicating arctic conditions and Cibicides lobatulus, indicating high energy shelf conditions (Ostby & Nagy, 1982) with distinct current activity and a high sediment input (Vorren et al., 1984, 247). Cassidulina reniforme (Norvang) is another species indicating arctic shelf conditions. From this, Gregory (1983b) inferred shelf conditions with cold water and depths of about 20 metres. The presence of boreal species, such as Trifarina angulosa (Williamson), and to a lesser extent Bulimina marginata would appear to indicate the possibility of some oceanic warming, although assemblages with similar dominants to those mentioned above have been attributed to areas directly affected by ice sheets in the Barents Sea during the Weichselian (Ostby & Nagy, op. cit., 75).

Assessing the proximity of any ice mass to these assemblages is consequently difficult. The presence of brackish (Protelphidium orbiculare (Brady)) and arctic brackish (Elphidium clavatum) species would suggest the proximity of ice to provide the necessary input of freshwater to support these assemblages. Osterman (1984) produced a succession model in which Cassidulina reniforme would predominate over Elphidium clavatum in extreme proximal locations. The higher faunal diversities seen in this unit (see table 4.4.1.), compared to extreme proximal values of one or two, also suggests a more distal location for the unit 3 assemblages. In her model, for example, Osterman (ibid.) places Islandiella helenae as a dominant species in extreme distal locations. If this comparison holds, the absence of this species in unit 3 assemblages precludes an extreme distal origin.

The possibility that the assemblages might be reworked or modified, especially in such a coarse, sorted sediment (Nagy, op. cit., 330) with a high energy regime signature, cannot be discounted. Any more detailed interpretation of these assemblages is, therefore, unwarranted.

Dinoflagellate cyst analysis was available from boreholes 84/02 and 84/04. The best assemblage was recovered from the middle of the 84/04 section at 129.80 metres (Harland, 1985a). This information is reproduced in table 4.4.2. The presence of a cyst assemblage at all indicates that the deposition of unit 3 was not characterized by continuous turbidity, because of the very low settling velocity of these microfauna. The assemblage in table 4.4.2. indicates deposition in a severe cold environment (Harland, ibid.) with indications of the neritic to marine (Harland, 1985b, 1). Two of the dominant species found still exist on the British continental shelf today. Bitectatodinium tepikiense occurs between Shetland and Iceland and appears to be associated with the North Atlantic Current, in oceanic to outer neritic locations (Harland, 1983c). This species may, therefore, indicate a degree of oceanic amelioration. Spiniferites spp. indet is another group of species found around Britain today which is taken to be indicative of neritic environments in the past.

Finally, the presence of Operculodinium centrocarpum contrasts with the first two dominants as it is usually seen as a pioneer species in north temperate to arctic environments, thereby indicating cold glacigenic conditions. Although this seems at variance with the species mentioned earlier, this may be a consequence of preferential post mortem removal of other species (Harland, 1983, 379) over-emphasizing the relative importance of this latter group.

4.4.3. ENVIRONMENTAL INTERPRETATION.

The evidence discussed so far indicates that unit 3 does not fit into the glacial to marine facies sequence proposed at the start of this chapter (see fig 4.2.2.). One solution to this problem would be to attribute the sediments to localised features associated with one of these facies types. For example, one possibility would be that unit 3 represents glaciofluvial outwash from the orthotill or residual paratill zones. This interpretation was rejected for three reasons :-

1) On the basis of the seismic analysis (chapter three) it was apparent that this unit had a large areal extent, and thicknesses incompatible with localised outwash fans.

2) The unit did not show marked areal changes in composition between borehole sites. As outwash fans are usually concentrated close to meltwater emergence points, and rapid falls in hydrodynamic velocity would be expected beyond this point, the consistency in particle size characteristics, seen here over wide areas, is incompatible with this kind of activity.

3) The indigeneous microfauna, even taking into account the possibility of substantial reworking, indicate deposition of this

unit in a cold, but open, shelf environment. If these deposits represented proximal outwash facies a lower faunal diversity would be expected because of the more turbid conditions, and no microfaunal assemblages would be more probable.

The other alternative was to find a modern analogue which could satisfactorily account for the major features discussed so far, without the need to resort to complex qualifications or elaborate reconstructions, which the quality of the data could not support. The best analogue that could be found was that of the modern Yukon delta - Norton Sound area in the northwestern Bering Sea. This analogy was chosen for the following reasons, based on the explanation of unit 3 by reference to the physiographic features of the Yukon delta :-

1) The broad, microtidal, delta-front platform, up to 25 kilometres wide (Dupre, 1982, 66), and the prodelta extending up to 100 kilometres offshore (Nelson, 1982a, 537), is on a scale more compatible with the dimensions of unit 3 than the invocation of localised outwash fans.

2) The prodelta of the Yukon is characterized by tidal flats, distributary mouth bars, and channel outwash deposits of moderately to poorly sorted unimodal sands. Such a large area of sand would account for the consistency in composition between recovery sites for unit 3, and the fact that the sediments are composed of sorted sands.

3) Another reason for the widely distributed sands being so similar in composition could be the presence of active reworking of the prodelta by waves, tides, wind, and oceanically-induced currents which are operative on the Yukon prodelta today. These processes tend to winnow out the fine content and resort the sediments to a more widespread and uniform level (Dupre, op. cit., 63). The fact that many of the unit 3 sediment samples have a high energy signature (see

fig 4.4.4.), indicative of velocity fluctuations or reworking in a nearshore environment, supports this view. Moreover, the interpretation of the samples containing a significant gravel content as lag deposits would also be consistent with this analogue, as the gravel would be the material left by preferential reworking of the sand component. The samples from low energy regime plots, representing deposition from a hydraulic suspension, could then correlate with the redeposition of material in the aftermath of this reworking.

4) The presence of distributaries beyond the shoreline and across the tidal delta front as "sub-ice" channels could provide relatively coarse sandy sediments farther offshore than might be expected under normal, open marine, deltaic sedimentation. Moreover, the presence of these channels could be invoked to explain the valley-like feature seen during the seismic analysis north of Orkney (sections marked "v": see chapter three). The apparent erosion in these areas prior to, and postdating, the deposition of unit 3, indicated by the seismic terminations around borehole 84/02 (see fig 3.7.), could represent periods when the "v" feature was an area of concentrated "sub-ice" channel formation on the delta front, removing material from areas to the south.

5) The inference taken from the micropalaeontological data of an open, high energy, current-affected shelf with water depths in the vicinity of 20 metres would mirror the physiographic conditions in Norton Sound almost exactly. If this is so, the presence of arctic species could be related to a winter cover of sea ice over the prodelta, whilst the more ameliorative species would relate to the summer break up of this ice over the prodelta, and the increased turbidity associated with storm-induced current activity and the seasonal outwash of material through the "sub-ice" channels. The brackish species could then correlate with the higher freshwater

provision associated with the outwash emergence points.

6) The absence of ice rafted material in Norton Sound would correlate with the absence of this kind of coarse clastic debris in unit 3. Ice in Norton Sound is almost entirely debris-free sea ice formed during the winter by direct freezing, and containing no debris from terrestrial glacial sources. As was stated earlier, the clastic material that is present is associated with the reworking of the prodelta sands and the concentration of clastic debris as a lag deposit.

One feature of the Yukon prodelta area which is at variance with unit 3 is the relatively thin outcrop of the former (Nelson, 1982b, 17). In the Yukon delta area, however, rates of sedimentation are greater than the rates of tectonic subsidence (Dupre, op. cit., 69) so that sediment thickness is limited by the depth to which currents and wave activity resuspend material during periods of increased turbidity. The simplest solution to this difference is to invoke tectonic subsidence (see section 3.4.3.) in the present study area equal to, or in excess of, the rate of deposition of unit 3. If this were the case, although surface reworking could still occur there would be a net increase over time in the thickness of sediment left undisturbed.

The use of this kind of analogue to explain the features associated with unit 3 clearly indicates a reduced glacial influence compared to unit 4. Glacial activity in the area of the Yukon delta today is very limited, although the paucity of organic material in the unit 3 sediments (even accounting for the probable decomposition of any such debris since unit 3 was deposited), compared to the organic-rich Yukon sediments, does suggest that terrestrial conditions during the deposition of unit 3 were more severe than they are in the Yukon delta area today. A summary of the facies association for this unit is given in figure 4.4.9.

UNIT .2.

4.5.1. PHYSICAL CHARACTERISTICS.

Unit 2 sediments were the most extensively recovered of all those analysed in the present study, both in terms of total core and number of sites. Samples were taken from 82/01, 82/10, 84/02 and 84/04. Three subgroups were defined on the basis of the data presented in chapter two.

PARTICLE SIZE DISTRIBUTION.

The first subgroup of this unit comprises all of the samples from 82/10 and 84/02. This subgroup is characterized by multimodal particle size distributions, with approximately similar percentages of the sand, silt and clay end-members (see fig 4.5.1.). The main variation from this comes in samples which have a significant gravel component (ranging up to 16%). An example of this kind of particle size curve is given in figure 4.5.2. The absence of a markedly fine-dominated matrix, the presence of clastic debris in some of the cores, and the textural heterogeneity of this subgroup enabled the rejection of a marine/lacustrine origin for these sediments. In the same way the absence of a predominantly coarse-skewed matrix, variable clastic component, lack of textural homogeneity and relatively unconsolidated matrix enabled the rejection of a till origin.

The second subgroup comprised the sediments from borehole 82/01.

This set of samples had a much higher fine content than the first subgroup and a lower sand content. The overall distribution was polymodal but with a slightly fine-skewed mode which produced consistently low to negative skewness values (see fig 4.5.3.). Despite the fine skew, the textural heterogeneity and the gravel content of this subgroup enabled the rejection of a marine/lacustrine origin for these sediments. The absence of a coarse skew and consolidation, and the heterogeneous matrix also enabled a till origin to be discounted.

The third subgroup was made up of the samples from 84/04. From the sedimentary analysis (chapter two) it was evident that there was a great textural variation within the deposits at this site (figs 2.6.2. & 2.6.3.). For this reason the deposits in 84/04 were further subdivided into three subsets, according to their particle size signatures :-

1) Polymodal samples with a significantly coarse-skewed matrix (see fig 4.5.4.). This kind of distribution clearly precluded a marine or lacustrine origin. The coarse-skewed matrix and the absence of a significant fine mode also enabled the rejection of a compound paratill designation.

2) The second subset showed a predominantly unimodal matrix, concentrated in the sand fraction (see fig 4.5.5.) with a minor gravel and fine component. These samples were not thought to be of marine or lacustrine origin for the same reasons as the first subset. A compound paratill origin was also rejected because of the paucity of fines and the absence of any marked bimodality in the particle size curve. The relatively minor gravel component compared to some of the other samples in this unit, and the absence of polymodality, also enabled the rejection of a till origin.

3) The third subset was similar to the second, except that in this case the sediments had a significant proportion of gravel (see

fig 4.5.6.). The absence of a pronounced fine mode in these sediments again allowed the rejection of a marine/lacustrine or compound paratill origin. The absence of consolidation or a polymodal distribution also enabled the rejection of a till origin.

Organic content throughout the unit 2 sediments is fairly consistent around 0.5%. Localised increases were seen in 82/10 between 32 and 33 metres where values rose to approximately 1.2%, and in 82/01 to 0.8 to 0.9% between 59 and 60 metres. Values in 84/04 were lower, varying between 0.16 and 0.65%. Carbonate content was also uniform in 82/10 and 84/04, ranging between 5 and 15%. In 82/01, however, unit 2 is characterized by very high carbonate contents ranging between 10 and 33.25%.

HYDRODYNAMIC INTERPRETATION.

The first subgroup, from 82/10 and 84/02, plotted on both high and low energy regime graphs. The samples on the low energy regime plots represented the matrix-dominated zones, compared to those with a significant gravel content which tended to plot on high energy regime graphs. Low energy regime sample points were restricted to zone Al, indicative of sediments settling out from a hydraulic suspension (see fig 4.5.7.). The high energy regime plots concentrated in area Ah, but the anomalous gravel component tended to make the majority plot inside the outer boundary curve in areas Eh and Fh (see fig 4.5.8.). This indicates deposition in a fluctuating hydrodynamic environment, with the coarse debris probably indicating ice rafting.

The second subgroup (82/01) also plots on high and low energy regime graphs, in similar areas to the first subgroup. The one notable difference was the tendency for some samples to plot in zone B, as well as in zones E, F and H (see fig 4.5.9.). This indicates similar hydrodynamic conditions to the first subgroup, but deposition farther offshore.

Graphs from the third subgroup (84/04) showed that most of the samples plotted on the high energy regime graph. The exception came from the second subset from 101.00 metres. This sample plotted on the low energy regime graph in area A1, indicating deposition by settling out from a hydraulic suspension. The other sample in this subset plotted in a similar location but on the high energy regime graph (see fig 4.5.10.) indicating similar depositional conditions but with the presence of incipient hydraulic motion.

The polymodal samples from the first subset plotted in zones Eh and Fh, indicating that they might contain ice-drop debris, or be reworked samples resulting from fluctuations in the velocity of the depositional medium.

The samples from the third subset plotted in zones Eh and Gh. This signature makes it probable that these deposits were laid down under similar conditions to the first subset. The spread into the latter (Gh) zone, however, suggests that the deposition of this subset occurred at a greater distance offshore.

The predominance of the samples from the third subgroup on high energy regime plots would support the rejection of a low energy (depositionally-dominated), compound paratill, origin for these sediments.

Plots of silt:clay ratio against phi mean diameter produced a broad horizontal spread (see fig 4.5.11.), but relatively small variations in the silt:clay ratio. The consistent vertical plot of the sample parameters was taken as an indicator of deposition of the entire unit in approximately similar water depths. In this case the horizontal dispersion of points, in terms of decreasing phi mean diameter, from 84/04, through 82/10 and 84/02, to 82/01, is taken to indicate deposition at increasing distances from the shoreline. The large range in the values for 84/04 mirrors the variation in particle size distributions identified within the subsets of this core. Another important feature of this plot was that the matrix "pellet" inclusion seen in 82/10 (plates 2.2.7. & 2.2.8.) plotted outside the zone of 82/10, and in the region of the 84/04 samples (see fig 4.5.11.). This was taken to indicate that this material had originated in the more proximal zone represented by 84/04 and had been carried, unmodified, and deposited again, in the 82/10 zone. The only process which could be invoked to produce this outcome was ice rafting. The fact that the 82/01 deposits plotted farthest to the right indicated that they represent the most distal unit 2 deposits.

4.5.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The first subgroup identified above was clearly laminated (plate 2.2.2.) and showed evidence of sulphide banding (plate 2.2.3.). Clastic inclusions in this subgroup ranged from rounded clasts lying parallel to the lamination (plate 2.2.4.), to elongated clasts penetrating the laminae vertically (plate 2.2.6.). This, with the textural heterogeneity of the unit, was taken as evidence of ice rafting. This enabled the rejection of an orthotill origin for this subgroup. The energy regime plots appeared to indicate fluctuations between a high (residual) and a low (compound) energy paratill setting. If the high energy regime samples are produced by the biasing affect of the coarse gravel component, a compound paratill origin would be more appropriate. The laminated matrix can, for example, be attributed to ice melting and debris release in a cold environment at a considerable distance from an ice source (Frakes, 1985, 349). However, the presence of friable matrix pellets (plate 2.2.7.) would suggest deposition fairly close to an ice source in quiescent hydrodynamic conditions, to prevent the break up of this inclusion during settling out. The areas around some of the clastic inclusions suggest precisely this may have happened in other instances (see plate 2.2.2., around reddish clast). For these reasons only a glaciomarine designation could be given to this subgroup at this stage.

The second subgroup also showed a poor matrix lamination, with numerous clastic inclusions crudely aligned parallel to the laminae (plate 2.3.6.). This was taken as evidence of a paratill origin, so the orthotill designation was rejected for this subgroup. For the same reasons as the first subgroup, the exact paratill type could not be defined on the visual data alone. However, hydrodynamic regime and silt:clay plots (figs 4.5.9. & 4.5.11.) indicated that these deposits were laid down farther offshore than those in 82/10. This increases the likelihood that they are distal, compound paratills. The dark grey clasts in this core (plate 2.3.6.), by contrast, suggest that this material cannot have been carried very far, or that it was entrained under very low levels of erosive competence. This may indicate a more proximal paratill setting.

The whole of unit 2 in 84/04 (third subgroup) was composed of a predominantly massive matrix with only localised zones that appeared laminated, in areas where the clay content was higher. A high content of clastic debris (plate 2.6.2.) was also characteristic, with some evidence of orientation perpendicular to the core axis. Within the subsets of this core, the sediments also showed a marked textural homogeneity. Together with the consolidation at certain depths, and a lack of evidence for ice rafting (no laminae penetration structures or deformation, and textural heterogeneity) or a silt mode, a compound paratill origin was rejected for all the sediments from this subgroup. The lack of stratification and textural homogeneity also made it improbable that these sediments represented true residual paratills. The high energy signature of most of the sediments, and the silt:clay plots indicating these deposits were the most proximal deposits of the whole of unit 2, supported the possibility that they might represent tills or orthotills.

MICROPALAEONTOLOGY.

Benthonic foraminiferal analyses were available for all the cores except 84/02, although the samples from 82/10 and 82/01 are probably too small (two in each case) to be taken as truly representative indicators of average assemblage constituents at their respective sites.

All of the assemblages were dominated by Elphidium clavatum (see table 4.5.1.) indicating arctic shelf conditions with brackish waters around 20 metres in depth (Gregory, 1983a). The second dominant species in 82/10 and 84/04 is Cassidulina reniforme, another arctic shelf species. The presence of Cibicides lobatulus as a third dominant also indicated some importance for strong current activity and high suspended sediment inputs (Vorren et al., 1984, 247). This applies particularly to 84/04 and 82/01, and its absence in 82/10 would, therefore, suggest more quiescent hydrodynamic conditions at the latter site.

The presence of Elphidium clavatum and Cassidulina reniforme could indicate the relative proximity of an ice mass (see micropalaeontology section; section 4.4.2.). The brackish water species Protelphidium orbiculare would also seem to indicate an input of freshwater from a potential ice source at the sites of 82/01 and 84/04. Faunal diversities ranging up to thirteen clearly suggest less severe conditions than would occur in the immediate vicinity of an ice mass. Moreover, the diversities in 82/01 are much higher than in the other cores, which is indicative of a more distal origin. This would confirm the interpretation of the silt:clay ratio plots, placing this core in the most distal location for unit 2 as a whole.

The absence of Cassidulina laevigata, taken as indicative of influxes of ameliorative temperate North Atlantic water (Ostby & Nagy, 1982, 82) in all of the samples except one in 82/01, suggests a continued period of cold conditions during the deposition of unit 2. The occurrence of this species in 82/01 again suggests that this site was the farthest offshore and was consequently the first site affected by the onset of an ameliorative oceanic phase.

Placing the hydrodynamic and micropalaeontological evidence together, therefore, the indications are that unit 2 sediments in 82/01 were deposited at a substantial distance offshore from any terrestrial ice mass. For this reason a residual paratill origin was rejected for this (second) subgroup. This left a compound paratill origin for these deposits.

The central part of unit 2 in 84/04 contained no benthonic foraminifera (Gregory, 1985). With Elphidium clavatum indicating ice proximity, and diversities of one or two being observed today in the vicinity of ice masses in Spitsbergen (Nagy, 1984, 321), the absence of any species could represent an extreme proximal environment, or a locality beneath an ice shelf. The three samples from this zone that were analysed sedimentologically plot towards the left on silt:clay ratio against phi mean diameter plots of the entire 84/04 sequence, which would support the supposition that they represent the period of maximum ice extent in relation to this site. With the level of uncertainty as to whether microbiota can survive uncer Quaternary ice masses (Lipps et al., 1977), it is also possible that the absence of a fauna represents a continuous floating ice cover.

Microfaunas were recovered from sediments in the first two subsets of 84/04 sediments. The presence of assemblages in these cases is unlikely to have been a consequence of reworking. This enabled the rejection of a till origin for the first (polymodal) subset. However, the absence of any fauna in part of the second subset, clearly suggested they had a proximal origin. The unimodal sandy matrix of these two subsets, plus the massive matrix, was thought to be uncharacteristic of orthotills. This origin was rejected for both of these subsets, leaving some form of residual paratill designation as the most probable origin.

4.5.3. ENVIRONMENTAL INTERPRETATION.

The 82/10 and 84/02 samples were believed to be of glaciomarine origin. On plots of silt:clay ratio against phi mean diameter (see fig 4.5.11.) a distal location seems to be indicated as some of the samples overplotted the 82/01 samples which were designated as compound paratills. However, at the other extreme, they also overplotted the 84/04 samples classified as residual paratills. A medial location would seem to be indicated, so these sediments from the first subgroup were classed as residual (to slightly compound) paratills.

The polymodal samples from 84/04 had particle size curves consistent with tills but the micropalaeontological analysis indicated that they were deposited in a marine setting. The lack of sorting compared to the deposits classed as residual paratills in the other subsets would suggest that this subset was an orthotill.

Overall the deposits from unit 2 can now be viewed as representing an offshore progression of the facies model given in figure 4.2.2., from orthotills (first subset: 84/04), through residual paratills (second & third subsets: 84/04) and a transition to compound paratills (82/10 & 84/02), to distinctly compound paratills (82/01). As with unit 4 the assessment of the location, and physical form, of any associated ice mass was problematical. Considering first an ice shelf (presumably located above or immediatley east of 84/04), Elverhoi and Roaldset (1983, 19) identified several features characteristic of the Weddell Sea ice shelf which would appear to correlate with the features associated with unit 2 :-

1) Sediments are mainly supplied by ice rafting. This is clearly illustrated by the zones of clastic debris in 82/10 which show many of the features characteristic of ice-drop structures (Thomas & Connell, 1985) in the compound paratill zone. Deposition was also apparently slow, as the presence of sulphide banding (plate 2.2.3.) and the microfauna indicate a flourishing organic component on the shelf. This would not be present in areas with a high or continuous suspended sediment input.

2) Winnowing out of the fine grades. This is evident in the proximal deposits from 84/04, with the second and third subsets showing sand and/or gravel-dominated matrixes characteristic of residual paratills.

3) Bioclastic debris may be significant. The presence of a consistent 5 to 15% carbonate content, and the presence of shell fragments suggest erosion and comminution of bioclastic material. The very high carbonate content in 82/01, without the presence of valve fragments, may indicate greater comminution of this material and, therefore, a larger concentration in the fine grade.

4) The presence of orthotills in 84/04 could indicate the

existence of a nearby grounding line during at least some period of the deposition of unit 2.

There are, however, problems in invoking this analogue :-

1) With a large ice shelf more temporal stability in sedimentary conditions might be expected, beyond the grounding line, than the range of particle size signatures in 84/04 suggests occurred.

2) The Weddell Sea ice shelf produces icebergs with keel depths of up to 300 metres, beyond the calving line (Elverhoi, 1984, 61). On a shelf where microfaunal analyses indicate that water depths varied around 20 metres, bergs of this size could never reach the paratill zones in 84/02, 82/10 and 82/01. The consistent lamination of the sediments in 82/10 also indicates that the surficial sediments were not extensively reworked by deep iceberg keels. Relatively thin ice must, therefore, have provided most of the rafted debris to these more distal sites which would be inconsistent with ice derived from a calving ice shelf, although the production of ice rafted debris from this kind of ice mass may be very small compared to alternative sources anyway (Orheim & Elverhoi, 1981, 125).

Another possibility is, therefore, to envisage a more restricted ice source. One example would be to suggest tidewater (or fjord) outlet glaciers or lobes emerging from a semi-glaciated coastline like that of western and northern Spitsbergen today. Using the analogy of gradually retreating glaciers under these conditions (Powell, 1981, 131), several features seen in unit 2 can be interpreted in support of this environmental setting :-

1) Outlet glaciers are known to calve rapidly and produce debris-laden icebergs (Drewry & Cooper, 1981, 117) in greater amounts

than ice shelves. This would provide a better qualitative reason for the frequent occurrence of ice rafted clastic debris in all of the cores except 82/01. The thinner rafted ice produced by this type of ice mass also makes ice dispersal more probable in the shallow seas indicated by the microfaunal analysis. Some authors (Elverhoi et al., 1983) have argued that the ice rafted output from this kind of coastline might be minor, and comparable to that of ice shelves. If this were the case the concentration of ice rafted detritus could be attributed to the influx of ice from outside the present study area. Such activity was, however, thought to be of minor importance as most of the clastic material was of high grade metamorphic or sandstone origin compatible with the Cambrian and Devonian lithologies of the present study area.

2) The presence of sulphide banding can be attributed to the annual spring faunal "bloom" associated with the break up of winter sea ice in front of the calving margin of the glaciers. The absence of sulphides in the proximal zone represented by 84/04 would then be a consequence of the high turbidity preventing deposition of organic debris, or any microfaunal assemblages, in these areas (Elverhoi & Roaldset, 1983, 19).

3) Underflows and subglacial meltwater streams introduce material subaqueously at the ice front of tidewater glaciers (Mode et al., 1983, 500). These deposits are predominantly composed of sand and gravel. This analogue can produce a more economical interpretation of the facies changes noted in 84/04. The second subset (unimodal sands with minor gravel and fine components) would represent the outwash delta products of this kind of subglacial channel. The third subset could be similarly explained, except that the larger gravel content would suggest either more coarse debris in the sediment, or a location nearer the outflow point.

In the light of all this evidence it was thought that this latter scenario represented a more economical interpretation of unit 2 sediments that that of an ice shelf. A summary of the facies associations for this unit is given in figure 4.5.12.

UNIT .1.

4.6.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

Unit 1 sediments were recovered in 82/01, 82/10 and 84/04. Two subgroups could be identified.

The first subgroup comprised all of the samples from 82/10 and the two samples from 84/04. The particle size curves showed a coarse skew with modes in the sand and silt end-members (see fig 4.6.1.). In some samples a gravel mode was more pronounced at the expense of the fine content (see fig 4.6.2.). The majority of the samples in this subgroup plotted between these two extremes. The coarse skew enabled the rejection of a marine or lacustrine origin for these sediments. The variable gravel content, lack of a polymodal distribution or an overconsolidated matrix, and the textural homogeneity also enabled the rejection of a till origin.

The second subgroup consisted of all the samples from 82/01. These sediments showed a dominant fine sand to coarse silt mode with minor amounts of gravel (see fig 4.6.3.). Overall this subgroup had a higher fine content than the first. The presence of gravel again enabled the rejection of a marine/lacustrine origin. The predominance of fines, relative paucity of gravel, absence of consolidation and textural homogeneity also enabled the rejection of a till origin. The well sorted matrix and non-massive structure also enabled the rejection of an orthotill origin.

Organic content in unit 1 was low, varying between 0.09 and 0.56%. Samples from 82/01 showed the highest values. The carbonate content was consistent between cores, varying between 6 and 15%, and averaging 11%.

HYDRODYNAMIC INTERPRETATION.

All of the samples from the first subgroup plotted on high energy regime graphs inside the outer boundary curve (see fig 4.6.4.) in zones Eh, Fh and Gh. This is indicative of deposition in a relatively nearshore location. The fact that the 82/10 samples plotted to the right indicates that they were most proximal. These zones are also characteristic of sediments laid down in conditions of reworking, and of sediments with anomalous coarse debris associated here with ice rafting. This high energy regime signature was used to reject a compound paratill origin for these sediments.

The samples from the second subgroup plotted on high and low energy regime graphs (see fig 4.6.5.). The high energy regime samples plotted in the same sectors as the first subgroup, suggesting a similar interpretation. The existence of low energy regime samples in zones Al and El indicate ice rafting but also the selective deposition of finer particles from suspension in more quiescent periods.

Plots of silt:clay ratio against phi mean diameter (see fig 4.6.6.) appear to support the assumption that 82/01 deposits were laid down farther offshore than the first subgroup, as they plotted farther to the right. The narrow vertical spread of points is again thought to indicate deposition of the entire unit under approximately similar water depths.

4.6.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The first subgroup was predominantly unconsolidated and had areas of lamination which tended to predominate over more massive sections. No apparent clastic/bioclastic alignment was seen (plate 2.2.1.). The 84/04 samples showed a predominantly massive matrix. The profusion of clastic debris with a coarse-skewed distribution suggested that this subgroup was more likely to be a residual paratill deposit. The orthotill origin was consequently rejected for the first subgroup.

The second subgroup was apparently massive but the profusion of sulphide banding (plate 2.3.1.) suggested lamination was present. The concentration of sulphide features (plates 2.3.2. & 2.3.4.) clearly indicate a relatively high organic productivity, which might not be expected in the turbid conditions of the residual paratill zone. The profusion of small clastic and bioclastic fragments (plate 2.3.5.), with the odd larger clast showing laminae distortion (plate 2.3.1a) clearly indicated ice rafting, but the specific glaciomarine setting could not be delineated at this stage.

MICROPALAEONTOLOGY.

Benthonic foraminiferal analyses were available from all of the cores in this unit. As in other unit assemblages unit 1 is dominated by the arctic shelf species Elphidium clavatum (see table 4.6.1.), which together with Protelphidium orbiculare indicated brackish water conditions. The second dominant, Cassidulina reniforme, also indictes arctic shelf conditions, whilst the third dominant, Cibicides lobatulus, indicates at least periodically high suspended sediment inputs to the shelf with moderately active oceanic and bottom currents. Gregory (1983a) interpreted this assemblage as a typical "late" Quaternary cold environment fauna, indicative of water depths in the order of 20 metres, or varying around that depth (Gregory, 1983b).

This type of assemblage has been attributed to areas directly affected by glaciers or ice sheets during the Weichselian (Ostby & Nagy, 1982, 75), although the proportions here would suggest a transitional assemblage to open shelf conditions, possibly involving only the presence of icebergs. Some authors have interpreted the presence of Cibicides lobatulus, for example, with high sediment inputs to ice-free environments (Vorren et al., 1984, 247). In her dominance facies model Osterman (1984) also placed this type of assemblage in a distal location.

The faunal diversities would support this interpretation. In 84/04 and 82/10 they range between three and six (see table 4.6.1.) which is not indicative of an extreme proximal environment as seen in other units. This evidence is used to reject an orthotill origin for the first subgroup. In this case the only remaining designation for these sediments would be as a residual paratill.

There is a notable increase in faunal diversity in the second subgroup. This would appear to indicate more quiescent (rather than turbid) conditions, and the profusion of fauna would also correlate with the intense sulphide banding observed in this subgroup. Where the sulphide banding disappears (below 49.00 metres), sand layers can be seen similar to those in unit 2, indicating an increased level of turbidity and, hence, less biological productivity. The zone of increased productivity in the upper part of this subgroup is associated with a slightly increased presence of the boreal species Bulimina marginata, and Osterman's (1984) extreme distal dominant Islandiella helenae. In conjunction with the silt:clay ratio plots (see fig 4.6.6.), suggesting deposition farther offshore than the residual paratills of the first subgroup, this information was taken to reject a residual paratill origin for this subgroup. The second subgroup was, therefore, categorized as a compound paratill.

4.6.3. ENVIRONMENTAL INTERPRETATION.

Unit 1 sediments, whatever their environmental setting, have a relatively consistent particle size signature throughout the unit. This suggests that conditions were relatively stable during the sedimentation of the deposits recovered during the present study.

With the relatively shallow water depths indicated by the microfauna, the same problems exist in interpreting any ice mass as an ice shelf during the deposition of this unit, as existed for unit 2 (see section 4.5.3.). Additional reasons can be given in the case of unit 1 for assuming that any ice present did not originate from an ice shelf :-

1) The intense sulphide banding and mottling of the sediments in 82/01, and the larger faunal diversities in this core, suggest a more ameliorative environment than occurred in distal locations during the deposition of unit 2 (also identified at this site).

2) No orthotill deposits were identified at any site for unit 1. This indicates a more restricted ice cover in the present study area compared to the period represented by unit 2, when proximal deposits

were identified at the site of 84/04.

3) Where present, ice rafted detritus is smaller and less profuse than it was in unit 2. This would indicate less available material at each site. This could be a result of changes in sediment source or resistance to erosion. However, the relative consistency in clast size in all the other units indicates that this factor did not have a great influence on sediment supply at other times. The alternative is to suggest that the smaller clast size represents deposition farther from the original sediment source and, consequently, a more restricted ice cover than occurred during the deposition of unit 2. This could be interpreted the other way, if it is accepted that ice sheets might not produce much ice rafted debris beyond the calving line (Orheim & Elverhoi, 1981, 125), but the factors mentioned earlier (section 4.5.3.) make it improbable that a substantial ice sheet could have been supported in the conditions indicated by the sedimentological and micropalaeontological analyses.

4) In the foraminiferal assemblages the greater observed percentages of Cibicides lobatulus, compared to unit 2, may indicate a more extensive area of ice-free shelf during the deposition of this unit (Vorren et al., op. cit.).

Taking all of these factors into account it was concluded that unit 1 was deposited under similar, but less severe, conditions to those inferred for unit 2. A summary of the facies associations for this unit is given in figure 4.6.7.

UNIT .0.

4.7.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

This unit was only recovered in two cores (84/04 & 82/11). Only two samples were recovered in 84/04, and 82/11 did not penetrate the full depth of the unit at its site (see fig 3.9.). Particle size curves were dominated by the sand end-member with subsidiary amounts of silt (see fig 4.7.1.). In two cases, there was a notable gravel content (see fig 4.7.2.), with an accompanying decrease in the sand fraction. In both cases the reduced fine fraction gave the overall distribution a coarse skew. This, with the gravel content, was used to reject the marine/lacustrine origin for these sediments.

Organic content was again very low, ranging between 0.53 and 0.30%. No significant variation was seen between samples from the two different sites. Carbonate content did vary. The two samples from 84/04 had values from 10 to 12%. In 82/11, however, the values ranged between 15 and 20%.

HYDRODYNAMIC INTERPRETATION.

The sediments in this unit divided between high and low energy regime plots (see fig 4.7.3.). The majority of the samples plotted inside the outer boundary curve in zones Eh and Hh on high energy regime plots. This indicates near to offshore deposition under fluctuating velocity conditions, with an input of coarse ice rafted clastic material.

The two samples on the low energy regime plot (see fig 4.7.3.) indicated deposition by selective fall out from a hydraulic suspension in a nearshore setting. This suggests at least minor periods of fairly subdued hydrodynamic activity during the deposition of this unit. The high energy regime samples could also, however, indicate deposition under conditions of incipient hydraulic motion as a result of reworking.

The plot of silt:clay ratio against phi mean diameter emphasizes this point, with the two low energy regime samples plotting above the asymptotic curve (see fig 4.7.4.). The remaining samples show a very narrow horizontal dispersion, interpreted as being indicative of deposition in approximately similar water depths and distances offshore for both sites. The high silt:clay ratio for the two low energy regime samples is a function of their higher overall fine content. The location of all the samples towards the centre of the phi mean diameter axis also suggests deposition at some distance from any terrestrial sediment source, though the plot of sample points above a 1:1 reference line suggests this was in fairly shallow water depths(See fig 4.7.5.).

4.7.2. SEDIMENTARY HISTORY.

DESCRIPTION.

Apart from the zones of finer material, this unit was predominantly massive with a profusion of clastic and bioclastic fragments (plate 2.5.4.) which showed no apparent alignment (plate 2.6.1.). The fact that these deposits did not have a marked silt mode, a laminated matrix or clear dropstone structures, plus the dominantly high energy regime signature of the samples, enabled the rejection of a compound paratill origin for this unit.

In borehole 84/04 the black colour of the matrix, indicating the presence of sulphides, also argues against a terrestrial origin (where anaerobic sedimentation would be more unlikely). With the profusion of bioclastic fragments this was taken as evidence to reject a till designation for this unit.

MICROPALAEONTOLOGY.

Benthonic foraminiferal analyses were only available for 84/04. Dinoflagellate cyst analysis was carried out on 82/11 but produced assemblages too poor to warrant any attempt at environmental interpretation (Harland, 1983d). The foraminiferal data is summarised in table 4.7.1.

The assemblages are again dominated by the arctic shelf species Elphidium clavatum and Cassidulina reniforme, indicating shallow shelf conditions and water depths between 20 and 50 metres. The presence of Protelphidium orbiculare with Elphidium clavatum also indicates brackish water conditions. The poor representation of Cibicides lobatulus in this unit would seem to indicate that current activity and turbidity was less pronounced than in some of the other units.

The most notable feature of unit 0 is the increased proportion of southern boreal species indicating oceanic amelioration. The most important of these are Bulimina marginata and Trifarina angulosa (Williamson). The appearance of Nonion barleeanum (Williamson) may also be indicative of gradually increasing water depths (Ostby & Nagy, 1982, 64).

Using Osterman's (1984) succession model, it would appear that the presence of Islandiella helenae with significant proportions of Cassidulina reniforme, indicates a more distal location in respect of any potential ice mass. This supposition would be supported by the relatively high faunal diversities (see table 4.7.1.) which, with the presence of cold-sensitive species, would suggest ice had little influence on conditions at the site of 84/04. This enabled the rejection of an orthotill origin for unit 0.

4.7.3. ENVIRONMENTAL INTERPRETATION.

The wide separation between the two recovery sites (see fig 4.7.6.) for this unit, and the lack of micropalaeontological data for 82/11 clearly make the resolution of the environment extant during the deposition of this unit very difficult.

If a residual paratill origin is inferred, unit 0 shows marked differences to deposits classed as residual paratills in other units. The fine content is noticeably lower than in unit 2, and the sand mode is more pronounced. Bioclastic debris is also more common in unit 0 as witnessed by the higher carbonate content. Evidence of lamination is also less obvious than in the other residual paratills and, together with the more boreal microfauna in this unit, a different environmental setting to these other units would seem to be indicated.

Compositionally, and with regard to fabric, unit 0 deposits are very similar to proximal glaciomarine facies from the central North Sea. In these sediments the coarse sand-dominated matrix was attributed to meltwater deposition in front of a grounded ice mass that was gradually retreating (Stoker & Bent, 1985). This possibility was rejected for unit 0 for the following reasons :-

1) The relatively low percentages of Cibicides lobatulus in the microfauna suggest that highly variable and turbid conditions with high sediment inputs, characteristic of a proximal meltwater environment, were not present during the deposition of unit 0. Faunal diversities also suggest a more distal location than this type of

glaciofluvial setting.

2) The close compositional similarity between the two sites where sediments were recovered suggests a more widespread process than meltwater efflux was involved in their formation.

3) The presence of a significant bioclastic element, including complete but brittle valves, suggests an open marine environment. The preservation of these valves, intact, indicates that the material must have undergone some post mortem reworking, but not to a degree consistent with the passage of active ice.

4) The presence of sulphide staining in 84/04 also suggests an open marine shelf, with non-turbid conditions predominating, in which biological productivity would be higher than in areas close to a meltwater outflow point.

At the other extreme, these deposits could represent a period of reworking of the surficial sediments over the whole shelf during an interglacial period. This would help to account for the compositional consistency between the recovery sites. Wave-induced reworking and the removal of fines on an open shelf could also be invoked to explain the profusion of bioclastic material, as an indigeneous seabed fauna incorporated into the reworked sediment. The high energy regime plots, indicating reworking under velocity fluctuations, would also support this supposition. The presence of arctic species in the microfauna, however, indicates cold but ameliorating conditions compatible with the presence of some restricted ice activity, but clearly not indicative of interglacial conditions.

In comparison with the other units identified in the present study, the particle size characteristics of unit 0 show a closer resemblance to those of unit 3, as opposed to the other residual paratills. Other characteristics are common to both, including the comparatively high carbonate content and the presence of boreal microfauna (particularly Trifarina angulosa). This led to the conclusion that unit 0 deposits were not residual paratills. For the reasons given above, plus those discussed in the interpretation of unit 3 (see section 4.4.3.) this unit is attributed to a similar environmental setting as unit 3. The microfaunal analysis does suggest, however, that conditions during the deposition of unit 0 were more temperate than those associated with the formation of unit 3, with less oceanic turbidity. A summary of the facies pattern for this unit is given in figure 4.7.6.

UNIT .-1.

4.8.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

Only six samples were available from this unit, all from the site of borehole 82/11. Apart from the uppermost sample at 2.80 metres, the particle size curves of these sediments were fairly consistent with polymodal distributions and a slight predominance of the sand end-member (see fig 4.8.1.). Most of the curves also showed a fairly even distribution between the coarse and fine grades. The absence of a predominanlty fine matrix enabled the rejection of a marine or lacustrine origin for this unit.

The sample from 2.80 metres had a notably fine-skewed distribution that contained very little coarse sand and gravel (see fig 4.8.2.). This well sorted matrix was used to reject the till, orthotill and residual paratill categories for this sample.

Organic content was consistent with the other units defined in this study, ranging between 0.31 and 0.56%. The sample from 2.80 metres showed a higher value of around 0.71%. Carbonate content varied between 9 and 15%.

HYDRODYNAMIC INTERPRETATION.

A division was apparent on energy regime plots. The sample from 2.80 metres plotted on the low energy regime graph in area A1, indicating deposition by the settling out of progressively finer grades from a hydraulic suspension. All of the other samples plotted on the high energy regime graph (see fig 4.8.3.) inside the outer boundary curve. These samples were restricted to zones Eh and Fh, indicative of either a lag deposit or a sediment produced under fluctuating velocity conditions with "anomalous" amounts of coarse debris probably brought in by ice rafting. This high energy signature, the lack of a marked silt mode and absence of bimodality was used to reject a compound paratill origin for this unit.

On plots of silt:clay ratio against phi mean diameter the sample from 2.80 metres plotted farthest to the right (see fig 4.8.4.) indicating that it was deposited in deeper water than the rest of the unit. The silt:clay ratio range is again taken as an indication of deposition of the unit in approximately similar water depths, and the horizontal spread of points suggests deposition at some distance offshore.

4.8.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The sediments in this unit show evidence of lamination, and the alignment of clastic and bioclastic fragments parallel to this lamination (plate 2.5.1.). With the textural heterogeneity of the unit, and the presence of ice rafted pebbles and bioclastic fragments, irregularly orientated in other locations, this was taken as evidence for rejecting a till or orthotill origin for this unit. This left only a residual paratill designation.

The sample from 2.80 metres was, by contrast, massive and unconsolidated with minor sulphide banding and ice rafted pebbles. Lamination was probably present in the sediment when it was in situ, but the coring of this unconsolidated zone had erased any evidence of this, except where the sulphide bands could be seen. The homogeneity of this sample would seem to suggest that it is not a compound paratill. This leaves only a marine origin for this sample.

MICROPALAEONTOLOGY.

Only dinoflagellate cyst analysis has been carried out on this unit. Only four samples contained sufficient specimens to warrant any interpretation. These included two samples, from 1.90 and 2.90 metres, representative of the sample from 2.80 metres.

Assemblages (see table 4.8.1.) are dominated by Bitectatodinium tepikiense which suggests the possible influence of the North Atlantic current in an outer neritic location. The additional presence of Operculodinium centrocarpum suggests a semi-arctic environment, though it might also be a pioneer species in north temperate to arctic conditions (Harland, 1983c, 379) where its relative importance can be overstressed as a result of post mortem removal of other species. The third dominant species is Spiniferites spp. indet. which also indicates neritic conditions. Overall, therefore, these assemblages are taken to indicate a cold temperate neritic environment, with some signs of the onset of oceanic amelioration in the more productive samples (Harland, 1983d). Water depths for this kind of assemblage would be around 40 metres.

4.8.3. ENVIRONMENTAL INTERPRETATION.

The evidence assessed so far indicates that unit -1 represents a proximal glaciomarine deposit with a marine component at the surface.

One important factor in interpreting this unit is its physiographic setting beyond the modern shelfbreak. If it is assumed that no erosion of this unit has taken place since its formation, the presence of residual paratills in this locality would require a nearby ice mass, presumably encroaching on the shelfbreak from the east and/or south. The alternative is for these sediments to have been deposited from floating ice which originated outside the present study area. The shelfbreak location for the unit would then indicate the maximum inshore transgression of these bergs before they grounded and began to melt, depositing their debris.

If post-depositional erosion is assumed, conditions reminiscent of proximal glaciomarine deposition discussed for other units could be applicable, as it could be suggested that the sediments once covered larger areas of the shelf, to the east of the modern shelfbreak, but were subsequently planed off.

It was thought that any further discussion of specific environmental conditions extant during the deposition of unit -1 was unwarranted because of the paucity of available data. The facies succession for this unit is given in figure 4.8.5.

UNIT .X.

4.9.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

The fact that only two samples were available from this unit, both from borehole 84/03, meant that any interpretation would be highly subjective. Only a general examination is given here for this reason. A more detailed interpretation is presented in section 6.4.3.

The two samples indicated a sediment with a fine-skewed matrix and virtually no coarse material (see fig 4.9.1.). The matrix was highly unconsolidated and texturally homogeneous. The absence of a coarse fraction and the lack of consolidation enabled the rejection of a till or orthotill origin. The absence of bimodality or any ice rafted clastic debris also enabled the rejection of both paratill origins. This left a marine or a lacustrine origin.

HYDRODYNAMIC INTERPRETATION.

Both samples plotted on low energy regime graphs in zone A1, indicating deposition by the selective settling out of material from a hydraulic suspension (see fig 4.9.2.). This would suggest, hydrodynamically, very quiescent and current-free conditions. This seems a more logical interpretation than attributing these sediments to reworking as this should produce a wider range of particle sizes than was observed, with less marked sorting.

These two samples locate on plots of raw silt:clay percentages around the 1:1 reference axis, indicating deposition in intermediate water depths (see fig 4.9.3.). Plots of silt:clay ratio against phi mean diameter, however, plot well to the right (see fig 4.9.4.), indicating deposition in deep water at a considerable distance from any sediment source.

4.9.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The highly unconsolidated matrix that was recovered may have had a structure in situ, but coring had destroyed any visible features. For this reason no more detail could be added to that gained from the particle size analysis.

MICROPALAEONTOLOGY.

Neither benthonic foraminiferal, or dinoflagellate cyst analyses had been carried out on this unit.

4.9.3. ENVIRONMENTAL INTERPRETATION.

The paucity of data at this stage of the present study meant that further discussion was delayed. The detailed environmental interpretation of this unit is given in section 6.4.3.

4.10. CLAY MINERALOGY.

Although the analysis of clay mineralogy was undertaken for all of the units described in the preceding sections, this data has not been used in assessing their depositional environment. This stemmed from the fact that the sedimentological analysis (chapter two) had shown that there was virtually no variation in the clay fraction between the units identified using other criteria.

The dominant minerals identified in all of the units were iron-rich chlorites, illites and smectites. These minerals are known to be widely distributed in the Arctic (Clark et al., 1980; Markussen et al., 1985, 274) and the Ross Sea in Antarctica (Anderson et al., 1980, fig .5.). They therefore appear to be characteristic of shelf and deeper oceanic localities influenced by glacial activity. Their presence is commonly attributed to the reworking of sediments which have been mildly to intensively leached in an exposed terrain (ibid., 407), and under low temperatures (Carroll, 1970, 819). Together with the detrital minerals such as potassium- and sodium-feldspars, quartz, biotite and calcite, they are taken here to indicate prolonged erosion of the basement bedrock, which characterizes the present study area, under glacial action.

4.11. SUMMARY.

The sedimentary interpretation of the units, based on the facies model presented at the start of this chapter (table 4.2.1. & fig 4.2.2.) is given in figure 4.11.1. The information compiled in this chapter will now be used in the following chapter to reassess the research questions highlighted at the end of chapter one.

CHAPTER .5.

RECONSIDERATION

5.1. INTRODUCTION.

This chapter is divided into three major sections dealing, in turn, with each of the research questions formulated in chapter one. Each of these questions will be reconsidered in the light of the evidence presented in the preceding chapters. This will, in turn, enable a reconsideration of various aspects of previously forwarded scenarios for the glacial history of the Shetland Islands.

5.2. QUESTION ONE.

Did active ice ever cross the continental shelf to the west of the Shetland Islands ?

5.2.1. RECONSIDERATION.

The genetic interpretation of the units identified in the preceding chapters illustrated that no tills could be identified in any of the boreholes analysed (see fig 4.11.1.). For that period of the Quaternary represented by these units, therefore, it can be stated that there is no evidence that active ice crossed the continental shelf, or the shelf edge, west of Shetland and north of Orkney, in a grounded form. For this to be supported tills should have been identified at one, or several, of these sites.

The most proximal deposits that were identified were the orthotills seen in unit 2 of borehole 84/04 (first subset: see section 4.5.1. & fig 4.5.4.). This suggests that active ice did occur in the immediate vicinity of this site during the deposition of unit 2. The geographic location of this core (see fig 2.1.1.) also suggests that this ice would have come from the southeast off northern Shetland. No tills were seen at sites closer inshore than 84/04 because unit 2 deposits have not been preserved in these areas (sites of 84/03 & 80/09: see chapter 3).

The borehole sites utilised in the present study also means that this conclusion can only be reliably applied to the area between 2 and 4 degrees west and 60 to 61 degrees north (Foula area), and to those areas where sedimentary evidence is available north and west of the basement platform (see fig 3.16.). No evidence is available from the areas on the basement platform, between the onshore areas of Orkney and Shetland and the boreholes beyond the basement margin.

The possibility that there was active floating ice is more difficult to discount, as the majority of the sediment types identified in the boreholes are paratills. This implies that floating ice had a major influence on sedimentary conditions. A distinction has been made in the present study between total ice cover, as would be found under an ice shelf inshore of the calving line, and partial ice cover, associated with fragmenting icebergs beyond the calving line (see fig 4.2.2.). Using this succession model, compound paratills would be found beyond the calving line, so the presence of these deposits is taken to indicate sedimentation from rafted icebergs beyond the margin of a continuous ice cover. None of the sites with compound paratills are taken to indicate the presence of a floating ice shelf for this reason, added to the reasons given in chapter four for rejecting the presence of an extensive floating ice shelf on physiographic grounds.

The assumption that paratills will be found predominantly beyond the calving line of ice shelves is supported by studies of modern arctic marine sediments. Anderson et al. (1980, 411) suggested that the transition from tills to paratills occurred at the grounding point. However, their study made no provision for the identification of slightly modified tills as orthotills (Drewry & Cooper, 1981, 119: see section 4.2.2.). It is this type of sediment which would occur immediatley seaward of the grounding line where slight modifications could be induced by settling through a water column, and the periodic occurrence of traction and density currents or meltwater efflux. Moreover, the change from orthotill to residual paratill (Anderson et al., op. cit., 415) can be taken to represent the change which will occur where a predominantly solid ice cover (ice shelf) begins to breaks up and marine currents and surface waves have more influence on sedimentary conditions (i.e. beyond the calving line: see fig 4.2.2.).

Other authors have suggested that both types of paratill would be found beneath a continuous ice cover (Drewry & Cooper, op. cit., fig .4.). This would mean the entire study area between 2 and 4 degrees west would have been covered by an ice shelf during the deposition of units 1, 2 and 4 at least. This assumes that conditions were amenable for ice shelf expansion to this degree. As was argued in chapter four, several features of the paratills recovered from various units, dictate environmental parameters which are at variance with this scenario. Most notably, the uniform occurrence of microfaunal assemblages indicating water depths as shallow as 20 to 50 metres is almost an order of magnitude smaller than the water depths in the Weddell Sea area today (Elverhoi & Roaldset, 1983, 1) where an extensive, continental margin, ice shelf exists. Moreover, as enhanced melt of the ice base is likely closer to the calving line (Drewry & Cooper, op. cit., 119), it will thicken inshore of this point. With water depths of around 50 metres (assuming a 1:2 above:below sealevel to ice ratio), and the absence of ice thick enough to produce significant bottom reworking, the maximum ice thicknesses that could be supported on the shelf would be around 60 metres (see section 4.3.3.). It is improbable that an ice mass of this thickness in the compound paratill zones identified, would maintain this thickness through the residual paratill zone. It would, in fact, thicken and ground-out before the basement platform was reached. The evidence presented would, in this case, be supplemented by the presence of tills and orthotills to the west of the basement platform. These sediments were not found. The available evidence, therefore, prevents the invocation of a floating ice shelf as the origin for both the compound and the residual paratills identified in the present study. A continuous ice cover cannot be supposed in the areas where paratills were deposited.

The identification of residual paratills at sites distant from the basement margin, without the presence of tills or orthotills (from the same unit) in more proximal locations, also indicates that an ice shelf originating on the Orkney-Shetland Platform could not have been responsible for their deposition. This applies to units which can be traced off the basement platform, as no assessment of sedimentary conditions on this platform is possible in the absence of any preserved material.

To summarize, in the areas from which sedimentary material has been recovered it is evident that, for the periods represented by this material, no active grounded ice existed west of Shetland and north of Orkney, off the basement platform. On the basis of other evidence collected in the present study, it also seems improbable that an extensive floating ice shelf existed in the area.

5.2.2. IMPLICATIONS.

These conclusions have relevance to the acceptibility of several works refering to the present study area, most notably to the large scale ice sheet reconstructions, and model reconstructions, of former ice masses. Those reconstructions requiring the passage of a continuous active ice mass to the shelf edge are all incompatible with the evidence obtained in the present study. This supposition dates back to the very early works, such as that of Peach and Horne (1880: see fig 1.1.4.), and is still seen in more recent reconstructions such as those of Boulton et al.(1977), Boulton (1979a, fig .1.) and Boulton et al. (1985, figs 10, 11 & 22). The reason that this misconception has persisted so long is due, in part at least, to the former lack of sedimentological information from the shelf margin, which is provided in the present study.

Other studies which claim to produce supporting evidence for these scenarios must now be viewed sceptically. Grosswald (1980, fig .1.) produced previously unpublished CLIMAP data indicating end moraines and seabed ridges west of Shetland, which were taken to represent the passage of (presumably) grounded ice towards the shelf edge. No evidence of these kinds of features were noted at any time during the analysis of the seismic lines or boreholes in the present study area. This reconstruction is, therefore, rejected as wholly unsupportable within the boundaries of the present study area at least, and for those time periods from which sediment is preserved. The sedimentary evidence discussed in section 5.2.1. also prevents these reconstructions being attributed to floating, rather than grounded, ice under similar conditions.

With reference to the theories specifically concerned with the glacial history of the Shetland Islands, it has already been shown the Peach and Horne's suggestion that Scandanavian ice reached the shelf edge can be rejected. Flinn's supposition that a local ice mass flowed out towards the shelf edge (see fig 1.1.5.) can be rejected for the same reasons. This information, in turn, also enables the uncertainty inherent in other reconstructions to be reduced. It can be stated, for example, that Hoppe's (1974) Scandanavian ice may have reached Foula (see fig 1.1.9.), but could not have advanced much farther west. The same applies to Mykura's (1976) local ice cap (see fig 1.1.2.).

5.3. QUESTION TWO.

If present, what areal and physical form did this ice take ?

5.3.1. RECONSIDERATION.

It has been argued that the available evidence precludes an extensive grounded ice mass, or a floating ice shelf, in the present study area at any time for which sedimentary material has been preserved. The existence of proximal and distal glaciomarine deposits, and in the case of unit 2 orthotills, also indicate that active ice must have occurred somewhere nearby. The most obvious location would be to the south and east of the major sedimentary basins identified, on the modern basement platform around the Orkney and Shetland archipelagos. The problem is that no relict Quaternary sediments have been preserved in these areas to the same degree as they have farther north and west. Hence no till or orthotill deposits are preserved on this platform to indicate where terrestrial ice, or the grounding line of an iceshelf, occurred.

5.3.2. FACIES GRADIENTS.

In this situation the only possible approach that can be employed to assess this question is to use facies gradients. This means determining, from analogues, the distance over which the transition from till to marine sediments is likely to occur for any given ice source configuration. If this can be achieved, a projection can be made shoreward from the deposits identified in the present study to suggest an approximate location where tills might be found and, therefore, the possible spatial extent of any ice mass that existed.

There is a great range of quoted gradients in the literature, so any assessment that can be made will be subjective. Beyond ice shelf grounding lines, for example, it has been suggested that most of the rafted material (corresponding to the paratill zones in the present study) would be deposited within 10 to 15 kilometres of an ice front (Elverhoi & Solheim, 1983, 39),or alternatively, 60 to 90 kilometres beyond the calving line (Elverhoi & Roaldset, 1983, fig 2.4). For Antarctica it has been suggested that ice rafted debris might still be deposited 1000 kilometres from the coast (Drewry & Cooper, 1981, 119). On the basis of studies on early Quaternary deposits in the North Sea a distal glaciomarine zone (compound paratill) was identified that was 60 kilometres wide (Stoker & Bent, 1985, fig .6.) beyond the margin of a tidewater ice sheet. Elsewhere proximal, intermediate and distal glaciomarine zones have been attributed to distances of less than 1 kilometre, 1 to 100 kilometres, and over 100 kilometres respectively, from an ice front (Andrews & Matsch, 1983). In the case of more restricted outlet glaciers, deposition may be of an order of magnitude different. On eastern Baffin Island, for example, fjord-type glaciers produce distal glaciomarine sediments within 4 kilometres of the ice front (Mode et al., 1983, 505-6).

The use of facies gradients, therefore, needs some pre-assessment of the most likely form of the ice mass which produces these sediments. The idea of an ice shelf covering the continental margin has already been rejected, and the most probable ice morphology derived from the genetic interpretation in chapter four is a restricted, or semi-glaciated, coastline supporting outlet glaciers and lobes, rather than a continuous calving ice front (sections 4.3.3., 4.5.3. & 4.6.3.). In this instance ice shelf facies gradients would be inappropriate analogues. In the case of unit 4, for example, compound and residual paratills are located some 25 kilometres apart (84/04 & 80/09 respectively) and, as was stated in section 4.3.3., the residual deposits may have been laid down very close to an ice front. The orthotills from unit 2 in borehole 84/04 would also dictate an ice front in the immediate vicinity of this site if outlet glaciers are the proposed ice source. At the other extreme, the lacustrine or marine deposits in unit X, within 25 kilometres of the present coastline of Shetland, virtually assure the absence of any active ice over Shetland during the deposition of this unit (further discussion of this unit is given in chapter six).

The approach taken in the present study was to look at the facies associations which were preserved for each unit and attempt to derive an average gradient for that unit. This would take into account the local factors operative in the study area during sedimentation which would not be accounted for in using analogue gradients directly. This supposes the growth of physically and spatially similar ice masses for all the units, where the presence of ice is indicated. This is thought to be acceptable provided no arbitrary ice extent is presupposed. The spatial coverage of any ice mass will vary between units according to the severity of the environment and the amount of time during which conditions were amenable to ice expansion. The changes in ice cover will then produce two-dimensional variations in the facies gradients and the type of sediment preserved at individual borehole sites.

5.3.3. UNIT .-1.

In this unit residual paratills were found in the proximity of the modern shelf edge. Compared to unit 4 where these sediments occur only 25 kilometres from the present Shetland coastline, this could be taken to indicate the expansion of a large ice mass towards the shelf edge. However, other evidence is incompatible with this scenario. On the basis of the stratigraphic association derived in chapter three, unit -1 appears to be virtually the most recently deposited unit in the study area. If it were associated with such an extensive ice advance, more extensive sedimentary deposits, including tills and orthotills closer to the basement platform, might therefore be expected on the shelf (section 4.3.3.). As this unit was restricted around the shelfbreak this does not appear to have been the case. Inshore deposits could have been subsequently eroded away after ice retreat, but in this case more evidence should have been seen for the passage of ice in the underlying units in the form of consolidation, shearing or other post-depositional deformation. None of the underlying units showed any such features.

This led to the assumption that in the case of unit -1, deposition came from icebergs originating outside the immediate study area. The keel depth of these bergs led to them grounding in the vicinity of the modern shelfbreak and depositing any entrained material in that vicinity (see section 4.8.3.). A period of intense ice rafting would be supported by the scouring of the seabed surface inshore of this zone, and across the surface outcrops of all the other units identified in the present study (see fig 3.15.). These scours would be compatible with the decayed remnants of the large bergs depositing material around the shelf edge. If these large bergs gradually melted, depositing the material in their lower levels around the shelfbreak, they would eventually develop shallow enough keel depths to penetrate onto the shelf, producing scouring but no deposition (see fig 5.3.1.). This pattern of iceberg melt would also be compatible with the microfaunal assemblages indicative of cold, but ameliorating, oceanic conditions. The trend of these scours seems to indicate origins, or at least drift directions, from the north or south of the present study area.

This interpretation means that any indigeneous ice in the study area would have had to have been restricted entirely on the present basement platform, so that no erosion or deposition occurred beyond the basement margin. Moreover, this ice would either have to be "cold-based" so that very little eroded material was produced, or so restricted that the facies succession in front of the ice mass (fig 4.2.2.) terminated (deposition ceased) inshore of the modern basement margin. At a maximum, a stagnant (non-erosive) ice mass, restricted to the present Shetland landmass and possibly stretching as far west as Foula, would be possible with deposition beyond local outlet glaciers being restricted to within 5 kilometres of the ice front (section 5.3.2.). In the case of unit 4, however, the residual to compound paratill transition takes around 25 kilometres. If this is representative of the study area through time, it is equally possible that during the deposition of unit -1 no ice existed over Shetland, as distal sediments should then have been deposited beyond the basement margin.

5.3.4. UNITS .4., .2. AND .1.

These three units are considered together because they show similar characteristics. Unit 4, which was recovered at three sites shows the simplest pattern.

Borehole 80/09, just west of the basement margin, contains residual paratills that may have been deposited less than 1 kilometre from the orthotill/till zones (section 4.3.3.). This core lies between 15 and 25 kilometres from the present coastline of Shetland, whilst the compound paratills in 84/04 and 82/10 lie a further 25 kilometres offshore. Assuming a similar facies gradient to the east of 82/10 as can be seen farther north, residual paratills deposited close to an ice front might be expected just off the basement platform to the west of Foula (see fig 5.3.2.) around the site of borehole 84/02 (although at this site unit 4 deposits appear to have been removed before the deposition of the unit 3 material).

The 25 kilometre separation between facies types suggests that depositional gradients did not resemble those of glaciated fjords, where all deposition might terminate within 4 kilometres of the ice front (Mode et al., 1983). The observed gradient may, however, be a function of the location of the borehole sites. Borehole 80/09 may lie on the outer margin of the residual paratill zone, and 84/04 on the outer limit of the subsequent compound paratill zone. In this case the transition to compound facies could occur just to the west of borehole 80/09. However, this would still leave a 20 kilometre wide zone representing the compound paratill facies.

If more gradual facies transitions are envisaged, the attribution of 80/09 to a location within 1 kilometre of an ice front would represent the maximum possible limit of ice for that unit, and it would be more likely that on average the ice margin was located farther inshore. This is particularly true if the main sediment source is taken to be outlet glaciers which would tend to travel farther out than the ice mass from which they originated.

Assuming a maximalist location for the entire ice front, however, this would place the margin of the ice, during the deposition of unit 4, in the vicinity of the present margin of the basement platform (see fig 5.3.2.), west and north of Shetland and Foula.

In the case of unit 2 a more complete range of facies is preserved at various sites. The occurrence of orthotills at the site of 84/04 means that grounded ice reached the immediate vicinity of this core at various times during the deposition of this unit. This places an ice front (probably representing an extended outlet glacier/lobe) some 40 kilometres from the present western coastline of the Shetland Islands. Extending this margin southwards, it would pass between Foula and the site of borehole 84/02, where only residual paratills were recovered (see fig 5.3.3. & 4.5.12.). However, as the deposits in 82/10 appear to represent a transition between residual and compound paratill facies, this would make the residual paratill zone around Foula up to 65 kilometres wide. Moreover, this reconstruction would not follow that for unit 4 where the glaciomarine facies appeared to indicate a greater expansion of ice west of Foula (see fig 5.3.2.). If the unit 4 pattern was extended out another 25 kilometres, this would produce an ice front compatible with the evidence from 84/04, and would continue southwards to run close to 82/10. In this case till and orthotill facies might be expected at the site of 84/02. Their absence at this site could, however, be attributed to the erosion of the upper part of unit 2 during the formation of the "v" feature described in chapter three (see fig 3.7.).

The problem with this postulated ice limit is that only compound paratill deposits are preserved in 82/01 (see fig 4.5.12.).

If this reconstruction were correct, residual paratill or orthotill facies would be expected. No evidence for this kind of deposit was found, nor is there are any evidence that 82/01 underwent more post-depositional truncation than 82/10, so subsequent removal of this type of sediment is unlikely. A more restricted ice cover would appear to be the solution.

The main difference between this unit and unit 4 is the presence of orthotills in 84/04, and the glaciomarine transition facies in 82/10. Both of these differences indicate closer proximity, but this need not be a consequence of greater ice extent. In a semi-glaciated coastline setting, with expansion of outlet lobes or glaciers, a grounded ice mass could have had a roughly similar extent to that inferred for unit 4, but the outlet lobes could have been more extended, especially in the area east of 84/04 (see fig 5.3.3.). In the south another lobe could have extended over 84/02 (the record of this having been subsequently eroded away) to produce a more proximal facies at the site of 82/10 (see fig 4.5.12.). Such a lobe would not have been accompanied by greater expansion farther south, so 82/01 could have maintained a distal, compound paratill setting. The invocation of ice lobes, rather than outlet glaciers, would also provide a qualitative reason for the facies gradients for this unit being much larger than those observed for fjord-type outlet glaciers (Mode et al., 1983). Although more complex, this scenario makes a more economical use of the sedimentary evidence collected in the present study than does invoking a more extensive ice mass throughout the study area.

There is another possible explanation for the facies association at the site of 82/10. Bearing in mind the ice activity prevalent during the deposition of unit -1, it is possible that the residual to compound paratill transition at the site of 82/10 is a function of an influx of ice rafted material from seaward of the borehole site, with a greater frequency than that from the shoreward side facing the basement platform. This ice could either originate outside the study area, or could be the rafted remains of ice breaking off outlet lobes within the region. If the ice originated outside the immediate study area it probably came from northern Scotland, because the lithology of rock fragments in 82/10 resembles either indigeneous bedrock types from these areas or from the present study area. Without the input of this coarse material the sediments in 82/10 would have resembled the compound paratills from 82/01. As both are a similar distance from 84/02, where residual paratills were identified, this also makes a more logical interpretation of the spatial variation in the facies identified. The deposits from unit 2 are unlikely to have been deposited entirely by foreign ice, as may have been the case with unit -1, as they occur right up to the basement margin, whereas unit -1 deposits were restricted to locations around the shelfbreak. This would mean that grounded ice would be restricted to the basement platform and would contribute ice rafted debris to the inner shelf where foreign ice could not penetrate (see fig 5.3.3.).

Unit 1 shows a similar pattern to unit 2. Residual paratills were identified at the sites of boreholes 82/10 and 84/04 and compound paratills occurred in 82/01. The major difference from unit 2 was the absence of orthotills from the site of 84/04, and the indications from particle size signatures of environmental stability during the deposition of this unit (section 4.6.3.). The microfauna in 82/01 also suggest more ameliorative compound paratill conditions than occurred during the deposition of unit 2. All of this evidence suggests a more restricted ice cover than that inferred for unit 2.

The deposits in 82/01 again show a more distal and ameliorative environment than the sediments preserved from 82/10, which occur farther from the margin of the modern basement platform. This could also be a function of preferential iceberg deposition in areas beyond 82/01, coincident with the calving points of outlet glaciers or lobes, or the influx of deep-keeled debris-laden bergs from outside the immediate study area as was the case with unit 2. The microfaunal analysis for 82/01 would support this supposition as it indicates a quiescent hydrodynamic regime during sedimentary deposition. This would not be compatible with concentrated iceberg debris fall-out over this site. The higher gravel content in 82/10 and 84/04 could then be a function of the passage of such icebergs in these areas from localised outflow points. This higher ice rafted input would also discourage the growth of more diverse microfaunas. Other zones of concentrated outflow may have occurred between these two areas but this cannot be assessed with the limited geographical extent of the material recovered (see fig 5.3.4.).

Another reason for 82/01 being relatively isolated from coarse ice rafted input could simply be that it was more distant from the ice front. This would agree with the microfaunal analysis which indicates oceanic amelioration entering the study area, presumably from the south, in the vicinity of this core. It might, therefore, be expected that any ice margin facing this site would waste back eastwards/northwards, prior to contraction in areas east of 82/10 and 84/04. If this amelioration were associated with an incurring warm water current from the south, this would encourage iceberg tracks in areas to the north to maintain more northerly courses, westwards rather than southwards from the ice margin, and increase melting rates, so that little ice rafted debris could penetrate south to reach 82/01 (see fig 5.3.4.).

This scenario would appear to be more acceptable than assuming ice rafted material did not accumulate at the site of 82/01 because bergs grounded outside the area. Although the massive matrix in parts of 82/10 and 84/04 could be a result of keel-induced reworking, the fact that microfaunal analyses indicate similar water depths throughout the present study area means this reworking should also have occurred at 82/01. A uniform sea level would mean any locality would have an equal chance of being reworked unless processes such as those mentioned above were capable of producing an aspatial iceberg cover. Iceberg grounding alone is not, therefore, a process capable of producing all the features seen in unit 1.

5.3.5. UNITS .3. AND .0.

These two units were both ascribed to an environmental setting which did not correspond to any of the sediment types given in the facies succession model in chapter four (see fig 4.2.2.). Consequently the use of facies gradients along the lines used for the other units was not possible, not least because facies showed a marked textural similarity between sites. Refering back to the Yukon delta - Norton Sound analogue used in the environmental interpretation of these units, the physical dimensions of features in that area would appear to be the best basis for reconstructing conditions in the present study area.

Indications from the microfaunal analyses (see section 4.4.2.)

suggest that all the sediments recovered from unit 3 were deposited in water depths of around 20 metres. This physiographic setting would correlate with the Yukon prodelta area in Norton Sound, where graded sands in water depths of around 20 metres extend up to 100 kilometres offshore across the epicontinental shelf (Nelson, 1982a). An area of these dimensions could easily cover the entire shelf subcrop of unit 3 beyond the basement platform (see figs 3.2a to 3.3b).

Inshore of this prodelta zone would be a delta front platform (covered by grounded sea ice during the winter) of up to 25 kilometres in width, crossed by sub-ice channels. If it is assumed that the "v" feature around 84/02 (see fig 3.7. & chapter three) represented an area networked by these channels (see section 4.4.3.(4)), this would place the delta front platform in the vicinity of the margin of the modern basement platform. Other sub-ice channel areas may have occurred farther north but no direct evidence of these features can be seen in the sedimentary record (see fig 5.3.5.). The trend of this zone cannot be estimated south of 60 degrees north, as unit 3 disappears from the preserved sedimentary record beyond this point (figs 3.2a to 3.3b).

Inshore of this second zone in the Yukon delta, the actual delta plain is up to 40 kilometres wide (Dupre, 1982). If this dimension is transferred directly to the present study area it would place the delta head in the north over central Shetland which is physiographically improbable as there would then be virtually no drainage basin or erodible sediment source to charge the sub-ice channels, unless a major ice mass is invoked east of Shetland, debouching its sediment westwards across the modern watershed. This would, in either case, imply that Shetland was ice-free during the deposition of unit 3. However, the trend of the "v" feature in the south of the study area suggests that the major fluvial (and sub-ice) channel input came from the south. The major deltaic area may, therefore, have been situated on the basement platform north of the Orkney Islands, and with a maximum delta width of 40 kilometres, the main outflow point to the delta would be located just north of the modern Orkney archipelago (see fig 5.3.5.). It is possible that the sub-ice platform and delta were smaller than that associated with the modern Yukon. The extent of unit 3, however, especially west and north of the three recovery sites which are thought to lie on the prodelta (fig 4.4.9.), and the projected continuation of the unit onto the basement platform, indicate that the overall dimensions of unit 3 were not substantially less than those of its modern corollary.

In this case the Orkney Islands would appear to be the only site where active ice could have existed within the study area during the deposition of this unit. Shetland, apparently lying in an outer delta zone, may well have been isolated as a land mass (unless ice had encroached from the east). The size and physical characteristics of unit 3 suggests a very high coarse sediment input from predominantly fluvial rather than glacial sources, which may indicate that Orkney was ice-free, or covered by downwasting ice, capable of producing the large fluvial effluxes necessary to produce the "v" feature running towards 84/02.

In the case of unit 0 reconstructions of potential ice limits is effectively impossible. Both the sites where the unit was recovered are located at a great distance apart and well off the basement platform (see fig 5.3.6.). The genetic interpretation of this unit (section 4.7.3.) suggested a similar environmental setting to unit 3, but with a more temperate climate. This suggests that any sub-ice platform, in comparison to unit 3, would be restricted entirely on the modern basement platform, and any delta would extend even further south over Orkney. Further comment is unwarranted owing to the paucity of data available. There is, for example, no direct evidence for major sub-ice channels associated with this unit, and any deposits which once abutted or overlay the basement platform have been subsequently planed off (see fig 3.15.). It is suggested, however, that if this unit represents more ameliorative conditions than unit 3, there could have been no active ice over Shetland or Orkney during its deposition.

5.3.6. SUMMARY.

To summarize all the available evidence, it is apparent that ice was relatively restricted to areas on, and just beyond, the modern basement platform west of the Shetland Islands. Beyond this it can be stated that the ice was probably grounded on the platform and on its margin localised outlet lobes or glaciers calved into the shallow surrounding seas, depositing glaciomarine sediments across the shelf. This scenario applies to units 1, 2 and 4. In the case of unit 2 there was probably greater ice expansion with grounded ice lobes pushing out beyond the margin of the basement platform, in one case almost as far northwest as the site of 84/04.

In contrast, units -1, 0 and 3 indicate a reduced ice extent. In these cases it is possible that no active ice existed over, and west of Shetland, and north of Orkney. In the case of unit -1 glaciomarine sediments were deposited by floating ice originating outside the immediate study area. Units 3 and 0 were characterized by terrestrial fluvial inputs on a large scale. It is almost certain that no indigeneous ice existed over Shetland during these periods, although Orkney could have been partially covered by a downwasting grounded ice mass.

5.3.7. IMPLICATIONS.

In itself this information could support several suppositions made in previous reconstructions of the glacial history of the Shetland Islands. The broad, flat, basement platform, and shallow adjacent marine environment during the deposition of the various units described in the present study, virtually dictate that any ice mass on the platform must have been grounded, despite no tills being identified farther west. This would enable the rejection of Hoppe's (1974) interpretation of the onshore evidence in which he invoked calving ice just beyond the modern coastline of Shetland (see fig 1.1.7.). This also applies to Mykura's (1976, 110) later, local ice cap margin.

All of the other reconstructions detailed in chapter one assume grounded ice here, but, as in the present study, with no direct confirmatory sedimentological evidence. The facies gradients used in the present study, however crude, do represent some methodological improvement on the purely conjectural ideas of these previous authors. Moreover, the identification of the limits of the present basement platform and the absence of till deposits indicates that no direct evidence of grounded ice exists west of Shetland, so no investigation could obtain accurate information capable of confirming the location of the ice front in this area. Any interpretation of ice extent and morphology will, therefore, always be open to criticism within the present study area.

In this sense, although grounded ice may be inferred, its actual physical form will also remain open to conjecture. Although the reconstructions given in this chapter suggest an ice front from which outlet lobes or glaciers extended, the lack of a till masking the entire platform means that it is equally possible that the ice could have come entirely from outlet lobes or glaciers from source, and never have been part of a more continuous ice sheet cover of the basement platform. In this case the invocation of an ice cap west of Shetland would be inappropriate and several of the existing reconstructions would be compromised. The absence of sediment on the basement platform means this question will always remain open. As well as its areal extent, the accurate definition of the physical form of this ice will remain an insoluble problem if geological and sedimentological evidence is employed.

5.4. QUESTION THREE.

If present, what was the probable origin of this ice ?

5.4.1. RECONSIDERATION.

The most basic evidence for potential ice origins comes from the seismic analysis. In chapter three it was shown that the units identified dip away from the basement margin in a northerly and westerly direction. This indicates a sedimentary source on the basement platform. In conjunction with the facies gradients identified in section 5.3., it appears that ice masses existed on this platform and that they were the erosive sources for the deposited sediments.

With the first group of units (units 1, 2 & 4) an ice mass extending onto the basement platform to the west of the Shetland Islands (figs 5.3.2., 5.3.3. & 5.3.4.) would probably have originated over Shetland. Any ice flowing outwards from the backbone of the islands could be indigeneous ice which built up in situ, or it could have originated from an ice mass encroaching on Shetland from the south or east. The fact that most of the clastic material which could be identified resembled lithologies extant within the present study area might suggest that ice flows were of local origin. The absence of Scandanavian erratics in Shetland (see chapter one) is one reason for rejecting the possibility of ice encroaching on the islands from the east. However, other studies have suggested that even large ice masses might only erode and transport clastic material in a recognizable form up to 10 kilometres "down ice" (Rae, 1976). In this case any Scandanavian ice overriding Shetland from the east would not necessarily contain any lithologies from outside the immediate study area.

More reliable evidence for rejecting an ice flow from east of the islands comes from the borehole evidence in the central northern North Sea discussed in chapter one (section 1.4.2.). Here there is little evidence for grounded ice except for very early periods of the Quaternary. This would suggest that the ice west of Shetland originated locally.

There is also some evidence to suggest that ice did not approach Shetland from the south. The consistent compound paratill signature in borehole 82/01 for units 1 and 2, indicates a distal location for this site. This suggests that any ice front on the basement platform during these periods would need to swing eastwards south of 84/02 to produce this distal signature (figs 4.6.7. & 4.5.12.). This kind of ice front would, most logically, be associated with the southern margin of an ice mass which spread out concentrically from Shetland (see fig 5.4.1.). On the evidence from 82/01, for unit 1, it is also possible that temperate water masses flowing in form the south prevented further expansion towards Orkney (figs 5.3.4. & 5.4.1.), by bringing in more ameliorative climatic conditions to the basement area north of the Orkney Islands. The evidence from the present study cannot be used to state that no ice from Orkney crossed this platform, but the most economical interpretation of the information available is to invoke an ice mass originating over Shetland and debouching in all directions onto the modern basement platform, engulfing Foula (see fig 5.4.1.).

By contrast, the reconstructions for units -1, 0 and 3 suggest a different pattern. The absence of proximal glaciomarine deposits close to the basement margin, north and west of Shetland, suggests that no ice flowed out from these islands during the deposition of these units. If ice did exist (possibly in the case of unit -1) it must have been very localised (within the boundaries of the present land area of Shetland) and must have originated there, to prevent a facies succession developing which would deposit material beyond the basement margin. In the case of units 3 and 0 an entirely different sedimentological regime is indicated, suggesting no ice originated over Shetland, and probably over the platform north of Orkney. It may have been extant over southern Orkney, to provide the freshwater input to the deposited deltaic sequence, which is thought to have developed off the basement platform north of the islands (see fig 5.3.5.). It must be re-emphasized, however, that the reconstruction for unit 0 (section 5.3.5.) is highly subjective owing to the paucity of relevant data.

The only ice clearly represented during the deposition of these three units relates to the residual paratill of unit -1, which is thought to have been dropped by large icebergs which originated outside the immediate study area, and grounded around the modern shelfbreak. These icebergs could, in effect, have been dervied from any calving ice mass in the northern Atlantic or Arctic oceans, north or south of the present study area, on the basis of the preserved ploughmark tracks. The paucity of recovered clastic debris made it impossible to postulate on the exact origin of these bergs.

In summary, the potential ice origins identified in this investigation can be split into two groups. Units 1, 2 and 4 appear to have been associated with an ice mass originating over Shetland and flowing westwards over the basement platform. In the cases of unit -1, the icebergs depositing this unit originated outside the study area, whilst, with units 0 and 3, it is probable that no ice existed over Shetland. Ice may have encroached on southern Orkney (presumably from Caithness farther south) in the case of the two latter units.

5.4.2. IMPLICATIONS.

These conclusions are consistent with several of the theories discussed in chapter one, as many of them suppose an ice mass extant over Shetland at various stages. The conditions inferred for units 1, 2 and 4 appear to have been associated with an ice mass debouching off Shetland with restricted ice cover farther south on the basement platform. This is consistent with Peach and Horne's later glaciation (see fig 1.1.6.), Mykura's (1976) break-up stage and Hoppe's later ice cap (see fig 1.1.7.). Moreover, this ice cap invoked by Hoppe (1976, 206) to the west of Shetland could correlate with a potentially restricted ice mass west of the islands' watershed, which would be the maximum probable extent of any ice that existed in the present study area during the deposition of unit -1. Flinn's (1983) meltwater channels in Yell and Unst (see fig 1.1.8.) could also represent the ice front associated with a restricted ice cover during the deposition of this unit.

There are, however, some assertions which can be questioned in the light of the evidence gained during the present study. For example, the contrasts between the two sets of units identified above suggest that ice was never uniformly distributed across the basement platform. The contrasts suggest that diachronous ice expansion may have occurred through time. Firstly, centred over Shetland, with restricted growth farther south over the Orkney - Shetland platform and the Orkney Islands (units 1, 2 and 4) and secondly, possibly in areas bordering Caithness and mainland northern Scotland and the south of the Orkney Islands (units 3 and

0), when ice cover over Shetland was reduced. Consequently Flinn's assertion that Scottish ice and Scandanavian ice masses abutted on this platform (see fig 1.1.3.) can be rejected for the periods represented by the units analysed in the present study.

5.5.1. INADEQUACIES OF DATA.

What is apparent with the information analysed so far in this study is that individual units can be used to support various theories proposed to account for the glacial history of the Northern Isles, at various stages of their respective event sequences. As many of these theories are multi-staged it is important to reassess them in their sequential entirety. This requires that all of the units identified are fitted into a stratigraphic (chapters two and three) and a chronological framework. Chronology is of critical importance as was outlined in chapter one. Determining which unit or units relate to the Late Weichselian, for example, would enable a more rigorous reassessment of several of the theories which are taken to relate to this period.

Secondly, it is evident that to estimate glacial morphology over Shetland, the borehole material analysed so far has proved inadequate. For example, no complete facies succession has been identified for any unit. The absence of any sediment on the majority of the basement platform makes the resolution of this problem even more acute. The possibility that very restricted ice masses occurred over Shetland, or their absence entirely, means this question must be resolved if an accurate appreciation of the environmental conditions during the deposition of individual units is to be achieved, and a reliable critique of the existing theories for the glaciation of Shetland is to be derived.

These two problems were approached in the following ways :-

CHRONOLOGY.

The most obvious approach to the analysis of age relationships within the sediments described so far would be to use a suite of the currently available dating techniques, on various portions of the borehole material. The use of these techniques was considered to be of little relevance for a number of reasons. In the commonly used methods based on the analysis of bioclastic material :-

1) Bioclastic debris was often very small or heavily abraded. This made the identification of valve species virtually impossible in most cases, preventing the collection of large enough "assemblages" to carry out amino acid dating (AAR). It is possible to carry out AAR on foraminifera, but this type of analysis had not been carried out by the BGS during the microfaunal analyses quoted in the present study. Moreover, the poor recovery of foraminifera made it unlikely that sufficiently rich samples could have been collected at regular intervals to cover entire cores.

2) The fact that most of the bioclastic material seen in all of the units was considerably broken down, and the notable carbonate content in the fine fraction, suggested that any valves had undergone substantial post mortem reworking and comminution. Any dates obtained from this debris would, therefore, not necessarily

correspond to the approximate time of deposition of the unit in which the material was found.

3) With the chance of reworking being so high, any organic material may have undergone post mortem contamination by more recent deposits. In this case any dates obtained using radiocarbon would be misleading because it would only give minimum ages for deposition, and as the degree of contamination could not be assessed, a true date could not be derived.

It is possible to use techniques based on the sedimentological characteristics of the sediments. Palaeomagnetic dating was also rejected in the present study for the following reasons :-

1) Core recovery was often so bad that perhaps less than 10% of a borehole might be retrieved (the maximum was just over 30%). The collection of regularly spaced samples was, therefore, impossible. Any dates taken would consequently be aspatially distributed and important terminations and reversals could be absent from the preserved record altogether.

2) As well as poor recovery, the sediments that were recovered were often disturbed during drilling (this was particularly true for unit 3). This increased the likelihood of errors in any dates obtained from the sediments, and further reduced the amount of material from which reliable information could be gained.

In the light of these limitations, the most reliable approach to age assessment that could be used was the depth and characteristics of the sediment itself. Where laminations could be seen, together with features that could be associated with an approximate period of time, an estimate could be made of the average total time it would take for any given unit to be deposited. Features that could be used in this way are sulphide bands (associated here with spring/summer faunal "blooms") and sand layers (attributed to increases in spring sediment effluxes from ice masses). Elsewhere, if this kind of feature was absent, analogues (corresponding to those given in chapter four) could be employed to suggest potential sedimentation rates in any given environment and, knowing the average total depth of a unit, an assessment of the depositional timescale could still be made. When all the values for individual units are summed, an estimate of the total depositional time period represented by the sedimentary sequence can be made. This analysis is presented in chapter seven.

SEDIMENTOLOGY.

Additional information is necessary to resolve the research questions set for the present study. It was decided, therefore, to extend the sedimentological analysis to two further cores, situated close to the present coastline of the Shetland Islands on either side (east and west) of central Mainland. These cores were close enough inshore to have direct relevance to all of the theories outlined in chapter one. This analysis is presented in the following chapter.

CHAPTER .6.

INSHORE BOREHOLES

6.1. INTRODUCTION.

It has been stressed throughout the present study that sedimentary deposits are rare over the majority of the basement platform surrounding the Shetland Islands. The two boreholes analysed to complete this study came from two sedimentary basins, one on each side of the Shetland landmass. Borehole 80/08 came from the St. Magnus Bay Basin identified earlier in this study (see fig 3.16.). Borehole SLN 76/26 came from the eastern side of Shetland in an area not considered in the earlier part of the present study (see fig 6.1.1.).

The Quaternary deposits preserved between 1 and 0 degrees west are similarly restricted on the basement platform as those to the west of Shetland. This area has been extensively mapped by the Marine Geology Unit of the BGS. Published maps show a broad, flat, basement platform similar to that west of the islands, with bedrock frequently outcropping at the surface (see fig 6.1.1.). Into this surface are set basins of Quaternary sediments. Nowhere are thicknesses of sediment found comparable to those west of the islands. Maximum thicknesses are around 60 metres, and such occurrences are rare. Reappraisal of the seismic survey (project 77/07) covering this area confirmed previous interpretations made by the BGS. Consequently this information is not discussed in any detail here. East of 0 degrees the sediment cover thickens rapidly eastwards into the sequences in the Halibut Bank area discussed in section 1.4.2.

6.2. BOREHOLE 80/08.

LOCATION: 60°22.50'N 01°35.00'W | MAP AREA: Shetland

DEPTH DRILLED: 47.75 metres | WATER DEPTH: 140 metres

ROCKHEAD: 34.60 metres | PERCENTAGE RECOVERY: 43.4%

6.2.1. STRATIGRAPHIC LOCATION.

Borehole 80/08 was situated in the enclosed basin of St. Magnus Bay and was consequently isolated from the sediments previously described in chapters two to five. From the seismic analysis (chapter three) it was assumed, on the basis of unit outcrop and subcrop trends farther west, that St. Magnus Bay was most likely to contain sediments associated with unit X (see line 40; fig 3.2a). This seemed to be confirmed by the subsequent sedimentological analysis. The seismic appearance of this basin is shown in figure 6.2.1. which runs just to the south of the borehole site.

At the base of the core another unit was identified. As this area was isolated from the deposits dscribed earlier in this study, it could not be directly correlated with any of them. It was given a floating designation, as unit T, for this reason.

6.2.2. UNIT .X. Seabed to 29.50 metres.

FABRIC.

This unit could be divided into two subzones on the basis of its physical appearance and particle size characteristics.

The first subzone ran from the seabed to approximately 4.00 metres. It was composed of a gradation from a massive, olive-coloured (5Y 4/3) sandy-silt (see plate 6.2.1.) in an unconsolidated condition to an increasingly laminated silty-clay at the base of the subzone. Small bioclastic fragments, less than 5.00 millimetres in diameter, were present throughout the section.

The second subzone comprised the rest of this unit down to 29.50 metres. At the top of this subzone the outer core had a slate grey colour, but internally black sulphide streaking could be seen parallel to, and at angles to, the lamination. Below this the interior of the core became increasingly blackened (see plate 6.2.2.) by sulphides. Around 5.00 metres below the seabed the lamination was replaced by a massive to blocky matrix with rust-coloured streaks and dispersed sulphide marks (see plate 6.2.3.). Between 5.00 and 10.00 metres the matrix reverted to a massive, unconsolidated, blackened clay.

From this depth to approximately 20.00 metres, these fabric types are succeeded by an open ped-like fabric with frequent void spaces. This type of fabric has been attributed to the action of upward migrating gas (N G T Fannin, pers. comm.). At various depths the matrix in this section is olive-grey with rust-coloured streaks (see plate 6.2.4.) or blackened by sulphides (see plate 6.2.5.). It appears from the sulphide staining that the whole core was black at the time of initial recovery but subsequently, at various depths and on the core periphery, this material has oxidized in contact with the atmosphere to produce the olive-grey colour.

Below 20.00 metres the matrix again shows evidence of lamination and becomes increasingly consolidated. Below 25.00 metres the matrix also begins to grade from an olive-grey to a reddish-brown (5 YR 4/3) colour (see plate 6.2.6.).

No clastic or bioclastic debris was evident at any depth in this second subzone. No x-ray analysis was possible to confirm this observation because of the unconsolidated matrix in much of the unit.

COMPOSITION.

The first subzone, containing the sand-silt transition, contained between 0 and 10% gravel, 17 to 57% sand and 32 to 83% fines (see fig 6.2.2.). The matrix values ranged between 17 and 63% sand, 26 to 63% silt and 10 to 24% clay (see fig 6.2.3.).

There was a marked textural homogeneity within the second subzone. The samples from this part of the core contained no gravel, 2 to 8% sand and 92 to 97% fines (see fig 6.2.2.). The matrix composition ranged from 47 to 65% silt and 32 to 50% clay (see fig 6.2.3.).

MINERALOGY.

On the basis of clay mineralogy this unit could be divided into three subzones. Above approximately 12.00 metres, and below 20.00 metres, the diffraction patterns showed assemblages dominated by illite, followed by iron-rich chlorites with potassium feldspars, quartz and calcite in subsidiary amounts (see fig 6.2.4.). In the zone below 20.00 metres additional sodium- and calcium-feldspars were seen.

In the intermediate zone between 12.00 and 20.00 metres these minerals are complemented by the presence of smectites and chlorite-smectites (see fig 6.2.5.).

6.2.3. UNIT .T. 29.50 to 34.50 metres.

FABRIC.

Only one sample was obtained from this unit, in a semi-disaggregated state. From the material that remained intact it appeared that the unit was composed of a massive red (2.5 YR 4/6) sandy matrix containing numerous clasts in a subangular to subrounded form, and ranging up to 3.00 centimetres in length.

Below this unit one further sample was obtained. This was composed of a massive, red, consolidated sand. This was thought to represent the Permo-triassic sandstone which forms a bedrock inlier in St. Magnus Bay. This implies that the overlying unit (T) represents a lag deposit from this sandstone with the metamorphic clastic debris found in this unit coming from the surrounding basement lithologies from the onshore areas of Shetland.

COMPOSITION.

Unit T was coarser than the overlying unit and contained around 29% of its total in the gravel fraction. The rest of the total composition plot gave values around 50% sand and 21% fines (see fig 6.2.2.). The matrix values produced proportions of around 70% sand, 20% silt and 10% clay (see fig 6.2.3.).

The underlying Permo-triassic sandstone, in contrast, had a negligible gravel component of around 3%, with 75% sand and 22% fines. The matrix values ranged around 77% sand, 14% silt and 9% clay.

MINERALOGY.

The one sample from this unit, at 29.75 metres, was dominated by smectites and iron-rich chlorites, with additional proportions of illite, potassium- and sodium-feldspars (see fig 6.2.6.). The Permo-triassic bedrock produced a similar diffraction pattern.

SUMMARY.

This borehole clearly penetrated the entire Quaternary sequence still preserved in St. Magnus Bay. A summary log of the results is given in figure 6.2.7. No gamma log record was available for this core.

6.3. BOREHOLE SLN 76/26.

LOCATION: 60°37.96'N 00°24.00'W **MAP AREA: Shetland**

DEPTH DRILLED: 71.60 metres **WATER DEPTH: 134 metres**

ROCKHEAD: 57.30 metres **PERCENTAGE RECOVERY: 45.1%**

6.3.1. STRATIGRAPHIC LOCATION.

The location of this core made it impossible to correlate it directly with any of the deposits to the west of the Shetland Islands. It is thought that this site is located in the outer reaches of a Permo-triassic basin (Evans et al., 1982) like the one in St. Magnus Bay. On the basis of the sedimentological analysis (given below), and with regard to the location of this core, it seemed most probable that it correlated with the small amount of unit T recovered from the base of 80/08. This unit comprised the whole of SLN 76/26 above rockhead. The seismic appearance of this area, just to the south of the borehole site, is given in figure 6.3.1.

6.3.2. UNIT .T. Seabed to 57.30 metres.

FABRIC.

This unit showed no marked compositional changes throughout its depth, although on the basis of its fabric it could be divided into five subzones.

From the seabed to approximately 16.00 metres this unit is composed of a massive, dark reddish-brown (5 YR 3/3) consolidated silty-clay. Within this matrix is set a profusion of clastic fragments up to 1.00 centimetre in diameter. Schistose fragments are common and show a pronounced greenish hue. These clasts also break up very easily if disturbed indicating that they had decayed in situ.

From 16.00 to 21.00 metres the matrix is laminated. Apart from this the clastic inclusions and weathered schistose and gneissic fragments are similar to the zone above 16.00 metres (see plate 6.3.1.).

Below 21.00 metres the schistose fragments become more profuse. Clasts can be up to 2.00 centimetres in diameter. Most of the large fragments show signs of intense weathering and break down easily if touched (see plates 6.3.2. & 6.3.3.). The small clastic fragments predominate in this section, ranging up to 1.00 centimetre in diameter (see plate 6.3.2.). The matrix is massive, but retains the reddish-brown colour of the upper part of this core.

From 33.00 to around 45.00 metres the silty-clay matrix disappears and is replaced by a massive and consolidated "regolith" type of material, composed almost entirely of the debris produced by the weathering of clastic material (see plates 6.3.4. & 6.3.5.). All the schistose fragments broke down to a granular debris if extraction was attempted.

These sections are interspersed with zones up to 10.00 centimetres deep composed of massive reddy-brown sands (see plate 6.3.6.). These appear to be composed of the finer material produced by the breakdown of the regolith zones (see plate 6.3.7.).

Below 45.00 metres a transition begins into the bedrock. The massive, unconsolidated, sandy matrix reappears, and the size and abundance of the clastic material increases down core. Zones of weathered and contorted schistose material are increasingly common (see plate 6.3.8.) until they predominate just above the bedrock level at 57.30 metres.

COMPOSITION.

Despite the variation in appearance within this unit there are no distinct compositional changes. The one noticeable variation occurs in the subzone below 45.00 metres, in the bedrock transition zone. Here the samples contain slightly more gravel than occurred in the upper parts of the borehole. Overall the particle size signatures are misleading. The original depositional signature is not preserved because of the intense post-depositional weathering of much of the larger clastic debris which resulted in their breakdown during disaggregation for sieving analysis.

Overall composition ranges between 0 and 16% gravel, 25 to 50% sand and 41 to 75% fines (see fig 6.3.2.). The matrix values recalculated to 24 to 53% sand, 29 to 45% silt and 10 to 37% clay (see fig 6.3.3.).

MINERALOGY.

The clay mineralogy in this unit showed a threefold division. Above approximately 15.00 metres, and below 25.00 metres, the mineralogy consists of iron-rich chlorites and smectites with subsidiary proportions of illite, and in some instances potassium-feldspars, quartz, halite and calcite. Additionally, glycolated traces showed peaks at around 7.80 Å and 11.25 Å which probably represent components of chlorite- and mica-smectite respectively (see fig 6.3.4.). Glycolated smectite peaks occurred around 17.0 Å and 8.40 Å.

The intervening zone runs between 15.00 and 25.00 metres. In contrast to the flanking zones this section contains no smectites and the mineralogy is composed entirely of chlorites and illites (see fig 6.3.5.).

SUMMARY.

The summary log for this core is given in figure 6.3.6.

6.4. & 6.5. GENETIC INTERPRETATION.

The approach taken to the genetic interpretation of these two cores followed the same procedure as that used for the sediments described earlier, and outlined in sections 4.2.1. and 4.2.2. The unit X sediments identfied in borehole 84/03 are included in this chapter, with the discussion of the deposits from 80/08, so that this unit can be interpreted in its entirety. This will also produce a more reliable indication of conditions during the deposition of unit X than could have been achieved using only the two samples from 84/03.

UNIT .X.

6.4.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

The sediments in this unit could be divided into two subgroups. The first subgroup ran from the seabed to approximately 4.00 metres. It was characterized by a distribution dominated by the sand end-member, with subordinate amounts of silt and fines (see fig 6.4.1.). The absence of a gravel component enabled the rejection of a till and orthotill origin for this subgroup. The absence of a fine-skewed matrix also enabled the rejection of a marine/lacustrine origin.

The remainder of this core down to 29.50 metres, and the two samples from 84/03 (see section 4.9.1.), constituted the second subgroup. All of the samples in this subgroup produced a nearly identical particle size signature. They were characterized by a fine-skewed distribution containing no gravel and virtually no sand, the samples being fairly evenly distributed between the silt and clay end-members (see figs 4.9.1. & 6.4.2.). This fine-dominated matrix enabled the rejection of a till, orthotill and residual paratill origin. The absence of a gravel fraction also made it improbable that these sediments were compound paratills (as all the sediments of that type so far recovered contained at least some gravel). This left a marine/lacustrine origin for this subgroup. This correlated with the initial interpretation of the samples made from 84/03 (section 4.9.1.).

Carbonate content for all of these sediments varied markedly. In the first subgroup content ranged between 11 and 31%, whilst in the second larger subgroup the range was from 11 to 22%. The majority of this carbonate was calcitic in origin.

Organic content was high compared to the units discussed earlier in the present study, varying between 0.40 and 3.52%, from the base to the top of the second subgroup. The samples from the first subgroup all had values around 1.75%.

HYDRODYNAMIC INTERPRETATION.

The samples from both subgroups all plotted on low energy regime graphs, except for the uppermost sample (from 2.00 metres) in 80/08, which plotted in the lag deposit (Eh) zone of the high energy regime plot (see fig 6.4.3.). The remaining samples all clustered in zone A1 (see fig 6.4.4.) with only the two other samples from the first subgroup in 80/08 plotting slightly apart. These plots are indicative of a sediment deposited in a quiescent hydrodynamic environment by the settling out of progressively finer material from an aqueous suspension, in a relatively nearshore location. The fact that the majority of the samples plot outside the outer boundary curve indicates that none of these samples contain the anomalous amounts of coarse debris associated with ice rafting.

On asymptotic plots of silt:clay ratio against phi mean diameter a similar clustering of points occurs, to the right of the graph. This is indicative of deposition in an environment a long way from the shoreline or in very deep water (see fig 6.4.5.). The first subgroup plotted slightly farther to the left on this graph indicating a more proximal depositional location. The two samples from 84/03 plot between these two extremes indicating sedimentation in an intermediate to distal location (see section 4.9.1.). The vertical separation between these two subgroups suggests deposition of the unit under conditions of varying water depth, especially as the energy regime plots do not suggest any velocity fluctuations as a potential cause for coarser sediments, which would then plot as more proximal/shallower water deposits on this type of graph.

On plots of raw silt:clay percentages the two subgroups again divide, with the samples from 84/03 in an intermediate location (see fig 6.4.6.). This indicates that the first subgroup was deposited in shallower water than the second, which appear to have been deposited in intermediate to distal locations (around and below the 1:1 reference axis).

The possibility exists for these sediments that the indications of deep water/greater distance offshore may also be a product of sediment input or supply restrictions, especially if the deposits are of lacustrine origin. The hydrodynamic assessment techniques used in the present study only respond to particle size parameters, and do not react to physiographic influences on deposition. Therefore, a restricted sediment input to an inshore lake basin would produce a similar plotted position to an extreme distal marine sediment.

6.4.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The observation of fabric in 80/08 enabled a more detailed consideration of the origin of unit X than had been possible after the analysis of core 84/03 (see section 4.9.2.). The majority of this unit (below the sandy-silt of the first subgroup in 80/08) was very homogeneous. The sulphide blackening throughout the core indicates that the sediment was probably organic-rich at the time of deposition. Subsequent anaerobic decay producing the sulphides, together with the gas (probably methane) which migrated up through the core, then produced the gassifed fabric (see plate 6.2.4.). Since recovery several sections of the core have oxidized leaving either the rust-coloured streaks or the olive-grey matrix.

The quiescent conditions inferred from the energy regime plots would correlate with this sequence of events, as the absence of current activity in St. Magnus Bay would be required to prevent wave-induced mixing and oxygenation of the water, so that anaerobic conditions could be maintained.

The absence of gravel, and the unconsolidated matrix supports the rejection of the till and orthotill origins inferred on the basis of the particle size signature. The well sorted matrix and textural homogeneity also support the acceptance of a marine or lacustrine origin for unit X.

The increased sand and bioclastic element in the first subzone from 80/08, in conjunction with its high energy regime signature, is interpreted as a lag deposit overlying the majority of unit X and is not, therefore, considered to be representative of conditions during the deposition of the unit as a whole.

6.4.3. ENVIRONMENTAL INTERPRETATION.

The evidence discussed so far suggests that unit X is of marine or lacustrine origin (84/03 and second subgroup 80/08), together with some form of overlying, lag deposit (first subgroup 80/08).

The restricted "basin-like" outcrop of unit X in St. Magnus Bay suggests that these sediments are more likely to have been lacustrine. To the west, borehole 84/03 penetrates the largest outcrop of this unit (see fig 3.15.) which shows a similar "basin-like" morphology, unconformably overlying the units described earlier in this study. If unit X were this recent a more extensive cover of sediment might be expected if it were of marine origin. Moreover, deposits would be expected in other depressions such as the "v" feature to the west of Foula (see fig 3.2A) if deposition had occurred in a ubiquitous marine setting. This is not the case. Post-depositional erosion could have removed unit X from certain areas but, in the case of the "v" feature, this would require preferential erosion in that area to a depth of some 220 metres below modern sea level, in comparison to the surface level of the remaining unit X outcrops at around 140 metres below modern sea level. The lag deposit at the top of 80/08 clearly indicates some post-depositional erosion but the scale of this reworking means it cannot be invoked to produce the deeper and more widespread erosion required to produce the "v" feature, especially with the difference in base level between these two areas (see fig 3.17.).

A more economical interpretation of these features is to suggest that the "v" feature, and the basins in which unit X now lie, were both eroded (re-eroded in the former case) out at some stage post-dating the deposition of unit O at least (see section 3.4.4.). This seems sensible as the base of unit X around, and north of, 84/03 is approximately 220 metres below modern sea level i.e. at the same base level as the present "v" feature. Subsequently unit X deposits were laid down in the areas in, and west of, St. Magnus Bay, but sediment supply did not reach the "v" feature farther west. Post-depositional reworking then only affected the surface of areas where unit X had been deposited.

Restricted lacustrine, or semi-lacustrine (lagoonal deposition in a basin with a shallow access to the open sea) conditions would seem to be the most probable origin for this kind of aspatial deposition. This is certainly a more plausible alternative than invoking deep water marine conditions where deposition would be more ubiquitous. With St. Magnus Bay effectively isolated within the confines of the present Shetland landmass, the provision of only fine grained organic-rich sediment to this site precludes the existence of any kind of active ice mass over Shetland. Moreover, it also makes it improbable that highly active geomorphic processes, such as solifluction, were extant, as St. Magnus Bay would form an obvious depositional focus for any coarse-grained material moving off the adjacent landmass. With the rich organic content of this unit a full interglacial climate would seem to be indicated.

UNIT .T.

6.5.1. PHYSICAL CHARACTERISTICS.

PARTICLE SIZE DISTRIBUTION.

All of the samples from this unit came from SLN 76/26, apart from one sample from 29.75 metres in 80/08. Despite the differences in visual appearance (see section 6.3.2.) no differentiation of these deposits was possible on the basis of particle size signature.

The particle size curves indicate that this unit was composed of polymodal distributions with large proportions of sand and silt, and smaller amounts of gravel and clay (see fig 6.5.1.). The main variation occurred where the clay end-member was more significant at the expense of the other three constituents (see fig 6.5.2.). All of the samples were heavily consolidated. These characteristics enabled the rejection of a marine or lacustrine origin for this unit. None of the samples showed clear evidence of bimodality, and none of the clastic debris showed penetration features which also enabled the rejection of a compound paratill origin.

Organic content in this unit was very low ranging between zero and 0.4%. Carbonate content was also low ranging between 2 and 5%.

HYDRODYNAMIC INTERPRETATION.

Several features can be cited at this point which distinguished unit T from the deposits discussed so far in the present study :-

1) The rotted clastic debris in the matrix (plates 6.3.3. & 6.3.7.) suggested post-depositional weathering of this material. As none of the other units showed any evidence of this kind of phenomenon it seemed sensible to assume they had formed subaerially. This would suggest a terrestrial origin for unit T, in which case hydrodynamic assessment procedures would be inapplicable. Even if the unit was not initially deposited on land, it could be said that it had been subsequently exposed to subaerial processes.

2) None of the other units showed such marked visual changes over very short vertical distances (plates 6.3.1. & 6.3.6.). This kind of sharp and frequent facies change is uncharacteristic of the other water-laid sediments identified in the present study.

3) The visual appearance of the sediment showed only poorly developed lamination, and the absence of clast penetration features, which were characteristic of the paratills observed in the present study.

4) Micropalaeontological analysis indicated that this unit was effectively devoid of dinoflagellate cysts (Harland, 1976) and contained no benthonic foraminifera (see below). This could be indicative of extremely severe aquatic conditions, like those invoked for the deposition of the orthotills in 84/04 for unit 2. It is equally possible that the odd cyst that was recovered was a contaminant and the unit, therefore, contains no endemic water-borne fauna.

In total, these features suggested that the mass of unit T had not undergone extensive waterborne transport. Certain sections were partially sorted (see plate 6.3.6.), or had been deposited in water (see plate 6.3.1.), but these were small scale phenomena compared to the unit as a whole. Consequently it is assumed that hydrodynamic assessment techniques are not applicable for this unit.

6.5.2. SEDIMENTARY HISTORY.

DESCRIPTION.

The appearance of unit T sediments is not homogeneous and, as was mentioned above, did not have the appearance of any of the sediments discussed so far. The absence of distinct lamination and drop or fall-out structures around the clastic debris, plus the coarse skew of the matrix, and its polymodality, enabled the rejection of the remaining residual paratill origin. This left a till or orthotill designation. In the case of a till, studies of modern glacigenic sequences has indicated that vertical and horizontal variation in facies type might be quite common (Boulton, 1972, 377). Using this type of model the regolith zones identified in SLN 76/26 could be of supraglacial origin, or a coarse subglacial deposit. The intervening sand layers (plate 6.3.6.) could represent localised outwash deposits and the coarse laminated clays (plate 6.3.1.) shallow proglacial lake deposits. The majority of this unit, including the sample from 80/08, does show clasts in a matrix support characteristic of many basal tills (see plate 6.3.2.). In total, therefore, the visual description of unit T is compatible with the micro-environments associated with an active grounded ice mass. For this reason the remaining orthotill origin was rejected.

The interpretation of unit T as a till is more acceptable than invoking an orthotill origin. With melt-out and deposition through some form of marine water column, beyond a grounding line, more evidence of sorting and vertical consistency might be expected. No evidence of this kind of process is evident, and the weathered clastic debris requires that any such deposit was then exposed subaerially which would leave it open to reworking and the destruction of any laminated fabric.

MICROPALAEONTOLOGY.

The absence of benthonic foraminifera and dinoflagellate cysts has already been commented on. The few cysts that were recovered are archetypal Quaternary species, but little more can be said because of their paucity. They may be a result of down-hole contamination during drilling, as most of the sequence appeared to be completely barren.

This would help to confirm a terrestrial (till) origin for this unit. Even with severe proximal conditions more palynomorphs might be expected in the aqueous orthotill environment, where currents from more distal locations could carry them in post mortem. This, with the evidence discussed above, supported the rejection of an orthotill origin.

6.5.3. ENVIRONMENTAL INTERPRETATION.

The evidence presented above indicates that unit T probably represents a terrestrial till sequence, in contrast to the water-laid deposits discussed in the rest of the present study. This sequence may be a mixture of very coarse basal till, or supraglacial till, combined with outwash sands and proglacial clays. Apart from stating this, defining the type of ice responsible for its deposition is difficult, especially as the unit was only recovered from one site in any depth. As with the units west of the Shetland Islands, this unit is aspatially distributed on the basement platform to the east of the archipelago. Hence the elongated basin in which SLN 76/26 is situated (see fig 6.1.1.) may be the remnant of a more continuous cover of unit T over the entire platform, which has subsequently been eroded off the bedrock areas. In this case the same problems apply to the definition of ice morphology as were encountered in the initial assessment of the research questions for the present study (see section 5.3.6.).

Assuming a restricted ice cover over Shetland, with outlet glacier lobes, would be compatible with this evidence. The rapid vertical changes in facies appearance in this unit is more likely to have been formed close to a fluctuating glacier front than to an extended ice sheet margin. The regolith zones, which may represent coarse supraglacial debris, might not be expected with an ice sheet where subglacial erosion and transport is the dominant mode of debris transmission.

Other evidence might suggest that a continuous ice front was present. In a study of the limits of unit T, northeast of SLN 76/26, Long and Skinner (1985, fig .1.) marked a continuous arcuate band representing the terminal limits of the till, which suggests an ice sheet spreading into the adjacent Halibut Bank area. Their study was, however, only based on material recovered from the outcrops of the unit that remain today in the Unst and Fetlar Basins (see fig 6.1.1.), and therefore takes no account of the possibility that till once existed on the surrounding basement platform. For this reason the information they used cannot be used to differentiate between a continuous, or an aspatial, ice cover of the area during the deposition of unit T, and the deposits from SLN 76/26 cannot be taken as characteristic of the unit as a whole.

Another important factor which must be taken into account is the heavily weathered appearance of the clastic material. The unit

T sample from 80/08, in contrast, is not weathered like the deposits in SLN 76/26 which show evidence of breakdown as far as the bedrock transition. Different sedimentary histories are, therefore, preserved on each side of Shetland for the unit and this must reflect different environmental conditions on each side of the archipelago during or after the deposition of unit T.

The nature of the weathering implies intense chemical activity, especially in the liberation of chlorite from the schistose clasts (see plate 6.3.3.) and the breakdown of feldspar (see plate 6.3.5.) to iron oxides. This weathering must have postdated the deposition of unit T (as was stated earlier) because of the fragility of many of the clasts that remain. It was stated in section 4.10. that chlorite is characteristically produced in low temperature, exposed terrains under conditions of mild to intensive leaching. This suggests the tills in SLN 76/26 were subsequently exposed to severe permafrost conditions after their deposition, or at regular intervals during the sedimentation of the unit as a whole. With periodic ice retreat and the advance of periglacial conditions, the regolith zones could be interpreted as solifluction deposits rather than supraglacial till. This material was then heavily weathered prior to a subsequent ice advance. These readvances, with the accompanying disturbance and shearing of sub-basal debris, could then account for the distorted and mixed appearance of the regolith material (see plate 6.3.5). Subsequent periglacial phases, after a further retreat, would then break down the clastic material in the basal till zones left by the preceding advance (plate 6.3.2.).

This sort of fluctuation again suggests localised outlet glacier expansion, rather than the movement of a large ice sheet, which would not respond as violently to climatic oscillations and should not, therefore, produce the rapid changes in facies seen in this particular borehole. If this were the case several factors could account for the unweathered appearance of the sample from 80/08 to the west of the islands. The fact that this site is much closer to the watershed on Mainland than SLN 76/26 (see fig 6.1.1.) means that if an ice front were oscillating around the site of the latter core, assuming equivalent ice expansion east and west of the islands, the St. Magnus Bay area would have been covered by ice. If this ice were sufficiently thick to produce a base above the pressure melting point, freezing of the basal sediments would be impossible. A significant thickness of ice in St. Magnus Bay would be compatible with the geological evidence. As unit T deposits were found at the base of 80/08 in this depression, the area must have been an overdeepened basin at the onset of deposition. Ice leaving a central watershed to the east would consequently have to fill the depression before it flowed out westwards across the basement platform towards Foula.

In these circumstances two scenarios could explain the appearance and small subcrop of unit T in 80/08. In the first, if an ice mass originating over the modern watershed of Shetland flowed outwards across this site (see section 5.4.1.), the proximity of this area to the ice divide would mean that any ice would have had little time to produce significant amounts of basal debris which could then be deposited in the basin. Moreover, the ice in this basin would probably be isolated, by shearing in the ice mass at higher levels as ice thicknesses increased, which would leave a protective ice cover over the unit T deposits and prevent further accumulation of till in this locality. By contrast, closer to the ice margin near SLN 76/26, much more basal debris would have been produced and would then be available for deposition. In marginal areas east of St. Magnus Bay, no depressions, like those occupied by the two boreholes, existed so any marginal increases in till thickness have subsequently been eroded off the basement platform.

The other alternative is that unit T deposits were once much thicker in St. Magnus Bay, but have subsequently been eroded away as well, leaving either a lag deposit of the more coherant clastic material, or a basal zone of the unit to which contemporary periglacial activity did not penetrate. Considering the basin-like form of the bay, it provides a clearly defined sediment trap, closer to the proposed sediment source than SLN 76/26, into which basal debris could concentrate. A greater thickness of unit T might, therefore, be expected if post-depositional erosion is not invoked.

Considering how restricted the subcrop of unit T is in St. Magnus Bay, restricted till production close to an ice divide would be a more plausible explanation of its thickness than subsequent erosion. The enclosed depression would make sediment removal by any agent except ice very difficult, and till and later deglacial deposits would be more likely to concentrate in this depression than be removed from it. Assuming this type of debris-poor ice, close to an iceshed and which later decayed in situ, would also account for the paucity of deglacial material. The ice would protect the bay and tend to channel outwash material onto the basement platform to the west. This would continue until the ice in the bay had almost completely decayed, by which time the production of deglacial material from the central watershed would be relatively minor.

6.6. IMPLICATIONS.

6.6.1. RESEARCH QUESTION ONE.

The information provided by the analysis of these two final boreholes confirms some of the interpretations made earlier in the present study. Primarily, the existence of unit T indicates that at some stage grounded ice was present on the basement platform (see section 5.3.1.). However, the isolation of these deposits, in St. Magnus Bay and to the east of Shetland, with respect to the units defined earlier, prevents these tills being directly identified with any of these units. Unit T could equally well pre- or post-date all the sediments west of the Shetland Islands, except unit X which overlies it.

In the case of unit X the analysis from 80/08, indicating lacustrine or semi-lacustrine conditions in St. Magnus Bay, confirms the supposition that grounded ice was not in existence over Shetland during the deposition of this unit. To the contrary, this unit is more likely to relate to a de- or post-glacial period (see section 6.4.4.).

6.6.2. RESEARCH QUESTION TWO.

The areal extent of the ice west of Shetland cannot be estimated for unit T for the same reasons as for the other units (see section 5.3.6.). To the east of Shetland, the location of SLN 76/26 clearly indicates that grounded ice reached at least this far east and, according to Long and Skinner (1985) the ice front relating to unit T extended east of zero degrees west into the Halibut Bank area at its maximum.

The sediments in this unit also confirm that the ice was grounded and appeared to flow outwards from a divide in the locality of the present watershed over the islands. The deposits in 80/08 were preserved below an ice mass close to this iceshed, whilst those in SLN 76/26 were at various times alternately below the margin of this ice mass or beyond its outer margin, undergoing intense periglacial weathering.

The physical geometry of this ice cannot be accurately estimated because of the aspatial preservation of unit T deposits over wide areas of the basement platform. Using the estimated ice fronts from chapter five for the west of Shetland, and the ice limit in the east proposed by Long and Skinner (ibid.), this ice mass could have been evenly distributed on each side of Mainland. With regard to the outer margin of this ice, however, all that can be stated with certainty is that the facies variation in SLN 76/26 suggests that ice fluctuated through time at this site, and that the rapid facies changes indicate that this is more compatible with a reduced ice front, rather than a continuous ice sheet margin. On the western side of Shetland the reddish-brown colour of the thin till in 80/08, derived from the underlying Permo-triassic bedrock, may correlate with the red-brown till identified by Flinn (1978, 115) farther west on Foula. This indicates that the ice front associated with unit T could have penetrated at least this far west.

6.6.3. RESEARCH QUESTION THREE.

The origin of this ice would appear to be localised on Shetland. As was stated in section 6.6.2. the limits deduced for this ice suggest an ice mass moving away in all directions from what is the central high ground of Shetland today.

The composition of unit T also indicates this to be the case. The Permo-triassic sandstone basins existed before the Quaternary where unit T was recognized in the present study. The matrix of these tills is clearly derived from the sandstones. As no similar deposits are found farther east, in the northern North Sea, this precludes these tills from having been produced by Scandanavian ice encroaching on Shetland from this direction. The associated gneissic and schistose clastic material is that derived by the ice from the basement rocks of onshore Shetland. The less cohesive rocks appear to have been preferentially eroded by the ice moving off the backbone of the islands.

6.6.4. PREVIOUS THEORIES.

Little can be added to the discussion on the existing theories here, until all the units have been placed in the chronological framework which was considered to be essential for interpreting many of these multi-stage scenarios.

The fact that unit T does represent a till does confirm the presence of grounded ice on the basement platform around Shetland. This, in turn, confirms the rejection of a calving ice margin in the vicinity of the present coastline for at least the period represented by unit T, as was suggested by Hoppe (1974) and Mykura (1976, 110). Further discussion is reserved until chapter eight.

CHAPTER .7.

CHRONOLOGY

7.1. INTRODUCTION.

As was stated in section 5.5.1., the only feasible approach to the assessment of depositional age was to use the physical appearance of the sediments under study. Prior to this, however, a generalised impression of approximate age can be gained from the limited micropalaeontological data discussed in chapter four. Once this has been done a relative chronological framework for the present study area can be developed using sedimentary characteristics, and a depositional timespan can be derived.

7.2. MICROPALAEONTOLOGICAL CHRONOLOGY.

The micropalaeontological data presented in chapter four can be employed in comparison with type Quaternary occurrences and assemblages identified in other localities. Although there is a possibility that local physiographic or environmental factors could produce dissimilar assemblages in the present study area, the use of these assemblages comparatively is justified to produce an assessment of the general chronological setting.

7.2.1. DINOFLAGELLATE CYSTS.

Dinoflagellate cyst assemblages identified in the present study are less useful than the more ubiquitous benthonic foraminifera.

Results were only available for units 3 and -1 (see tables 4.4.2. & 4.8.1. respectively), with species also being recorded from units 2 and 1 in core 82/01. In all cases these assemblages were dominated by Bitectatodinium tepikiense, Operculodinium centrocarpum and other, unidentifiable, species of Spiniferites.

The two latter species are considered to relate to the Pliocene to Lower Pleistocene (Red Crag) transition (Cameron et al., 1984, 88), together with Protoperidinium species in the southern North Sea. Bitectatodinium tepikiense was also identified in Lower Pleistocene (Pastonian), and younger interglacial, deposits in this area (ibid., 89). This suggests that all of the sediments identified in the present study are potentially very old. Harland (1985b, 2) did, in fact, tentatively attribute the unit 3 to 5 transition in borehole 84/02 to the Red Crag. In this instance, however, the additional Lower Pleistocene species, Tectatodinium pellitum (Wall), particularly common in the Waalian/Eburonian (Stoker et al., 1985, 123) was dominant at the expense of the three species mentioned above. All the other assemblages did not contain Tectatodinium pellitum, or another Lower Pleistocene indicator, Operculodinium israelianum (Rossignol) Wall (ibid., 121), suggesting that they were deposited more recently. Bitectatodinium tepikiense only becomes predominant in assemblages from the Upper Pleistocene (post 128,000 years BP). With this species being characteristic of most of the samples described in the present study a Middle to Late Pleistocene age would seem more appropriate. Such an assumption would also correlate with Harland's (1983d) suggestion that the assemblages in unit -1, from borehole 82/11, are related to Formation 2 of Binns et al. (1974, 753), which the latter authors attributed to the "last" Weichselian period dating from around 25,000 years BP onwards.

If this later age is correct the Red Crag designation for the unit 3 to 5 transition in borehole 84/02 is probably a result of reworking of bedrock lag material during, or prior to, the formation of unit 3. This nevertheless does suggest the erosion of the present Tertiary bedrock subcrop level, west and north of the basement platform, may relate to the Early Pleistocene. The underlying bedrock, for example, produces an earlier Late Miocene to Pliocene age (Harland, 1983d, 2) which precludes this lag transition being a result of the in situ breakdown of the bedrock.

7.2.2. BENTHONIC FORAMINIFERA.

Reinforcing the interpretation made above is possible using the more extensive foraminiferal data. In none of the samples analysed within the present study area, and reproduced in this work, are archetypal Lower Pleistocene species found. These species include Elphidium Macellum (Fitchell & Moll), Elphidiella hannai (Cushman & Grant), Cassidulina teretis (Tappan) (Stoker et al., 1985, 121), Elphidium orogonense (Cushman & Grant), Elphidiella aff. E. sibirica (Goes), Cibrononion obscurus Gudina and Cibrononion incertum (Williamson) (Feyling-Hanssen, 1976a, 89). Cibicides lobatulus is present, however, and continues to form a component in most of the unit assemblages identified in the present study. Considering the chronostratigraphic sequence derived in chapter three the most likely location for this species, if it were an Early Pleistocene indicator, would be in unit 4. This lowermost unit is, however, the one unit in which Cibicides lobatulus is not found (see table 4.3.1.). This suggests that the presence of this species is not related to the age of the sedimentary sequence, but rather to some environmental factor peculiar to the present study area, for example, the high-energy shelf conditions inferred in chapter four.

If this is the case Cibicides lobatulus may be similar to

Elphidium clavatum which has also been identified in the southern North Sea from the Early Pleistocene (Antian - Baventian) (Cameron et al., op. cit., 91), right through to the Late Pleistocene/Holocene transition. Most of the assemblages delineated in the present study are dominated by this latter species which is characteristically dominant in Middle to Late Pleistocene deposits (Stoker et al., op. cit., 124). Other Middle Pleistocene dominants identified in these sediments include Cassidulina Reniforme, Elphidium orbiculare (in high glacial stages), Cassidulina laevigata, and Trifarina Angulosa (in interglacial faunas). This evidence correlates with the general interpretations made from the dinoflagellate cyst analysis, especially as the poor cyst recoveries would be compatible with Stoker et al. (ibid.) observation that the cyst record is depleted during the Middle Pleistocene (790,000 to 128,000 years BP).

The possibility that the sediments identified in the present study span into the Late Pleistocene cannot be discounted at this point. Elphidium clavatum remains as an Upper Pleistocene dominant, and is the predominant species in all of the units described in the present study area. Feyling-Hanssen (1976, 80) noted that in Arctic Canada Elphidium clavatum is characteristic of mid-Weichselian faunas of interstadial nature, postdating the Cromerian interglacial where the species is absent. This would preclude any of the assemblages being classed as Early (pre-790,000 years BP) Pleistocene deposits at least. Moreover, the absence of Cassidulina teretis in these sediments suggested that they were not pre-Eemian in age (ibid., 82). The Eemian is taken here as the transition to the Upper Pleistocene (post 128,000 years BP; Stoker et al., op. cit., 124), and the absence of this species in the sediments from the present study area would suggest a similar conclusion. The balance of the evidence, therefore, appears to suggest that the assemblages identified in the present study are Upper rather than wholly Middle Pleistocene in age.

Going beyond the basic occurrence of species, comparisons can be made using the relative importance of a group of dominant species. For example, in the northern North Sea Feyling-Hanssen (1980) identified several assemblages dominated by Cassidulina Reniforme and Elphidium clavatum (zones S,T & U, ibid.), similar to the assemblages noted in the present study, which he attributed to the Weichselian. The main difference between his assemblages and those defined in the present study area is the relative importance in the latter of Cibicides lobatulus which, as was stated earlier, may be a result of localised environmental factors. Considering the relative proportions of the first two species this kind of comparison suggests that units 3 to 0 could relate to Weichselian interstadials, although unit 3 bears more similarity to a stadial assemblage (zone U; ibid.) with high Arctic conditions. Unit 2 is similar to another stadial assemblage (zone S).

Unit 4, in contrast, has Cassidulina laevigata as a secondary dominant, rather than Cassidulina Reniforme as in units 3 to 0. High proportions of this species were attributed by Feyling-Hanssen (zone R; ibid.) to the Holocene, although Elphidium clavatum was absent in this zone whereas it occurred in unit 4 as a dominant (see table 4.3.1.). Added to the fact that unit 4 is the oldest unconsolidated Quaternary facies identified in the present study, it would appear that it is unlikely to be Holocene in age. The fact that Cassidulina laevigata is present is indicative of ameliorative conditions compatible with the onset of an interglacial period (see section 4.3.2.), as the faunal diversities are still so low. However, they could equally apply to a particularly ameliorative interstadial episode. Feyling-Hanssen does identify an Eemian or earlier interglacial fauna (zone W; ibid.) in which this species is a joint dominant. If this is applied to unit 4, it would be compatible with a Weichselian age for the overlying units (3 to 0). This would, in turn, make the entire Quaternary sequence Upper Pleistocene in age.

There remains a possibility that part of the sequence is older than the Eemian. Unit 3 bears some similarities to Feyling-Hanssen's zone X, which he attributes to the "great Saalian" glaciation (ibid., 183). This could imply that unit 4 is related not to the Eemian, but to the preceding (Holstein) interglacial, especially as this unit shows slight similarities to other Holsteinian sediments from the western North Sea (ibid., 188). This would produce a Middle to Late Pleistocene age for the entire sequence which would still be compatible with the foraminiferal species present and the paucity of dinoflagellate cysts detailed in section 7.2.1.

Drawing all of these indicators together the following statements can be made :-

1) The limited dinoflagellate cyst assemblages appear to indicate a Middle to Late Pleistocene age for all of the units identified in the present study.

2) The benthonic foraminifera similarly suggest that the presence of Early Pleistocene (pre-790,000 years BP) deposits in the present study area is unlikely. The characteristics of the foraminiferal assemblages could be compatible with Middle or Late Pleistocene sediments in respect of species extant, although a Late Pleistocene designation would make a more economical interpretation of the available evidence.

3) When species proportions are taken into account, the units identified in the present study area show some similarities with Weichselian stadial and interstadial faunas from the northern North Sea. Unit 4 may represent the early Upper Pleistocene, Eemian

interglacial. It is possible, but more unlikely, that this unit relates to the preceding Holstein interglacial with the overlying units corresponding with the Saalian and Weichselian periods i.e. dating from the late Middle Pleistocene onwards.

4) The paucity of evidence precludes further consideration here of units -1, -2 and X, except to say that they must postdate the underlying units.

5) The absence of any microfossils from the tills in unit T also prevents discussion on the age of this unit.

7.3. SEDIMENTATION RATES.

The following section is speculative. Exact sedimentation rates for any of the units identified in the present study cannot be unequivocally defined, and the variability in thickness prevents a finite depth relationship being placed upon them. Moreover, no accurate assessment can be made of potential post-depositional erosion. For this reason any timespan inferred will only relate to the sediments preserved today. It had to be assumed, therefore, that this kind of reworking had been minimal, as the stratigraphic interpretation in chapter three appears to suggest. With these factors in mind the approach taken was based on a qualitatively-defined average depth for each unit. This was combined with an inferred average sedimentation rate, itself related to the physical features of the units described in chapters two and six, and their palaeoenvironmental setting. Again this was a qualitative estimation as the limited sampling frame meant that no real assessment of the variation in deposition in time and space could be made. This kind of variation is common, particularly in glacially-influenced regions like the present study area.

7.3.1. AVERAGE SEDIMENTATION RATES.

The sedimentation rates derived in the following sections are based on the initial assumption that the palaeoenvironments inferred for the various units, in chapters four and six, do approximate the environmental conditions at the time of sedimentation. From this basis, environmental analogues from modern glacial areas will be used comparatively to suggest likely rates of sedimentation for the units identified in the present study area. These rates of sedimentation can then be multiplied against the average unit thickness, to obtain an estimated (average) depositional timespan for each unit.

Sedimentation rates quoted in the literature from glacially-influenced environments vary significantly, dependent upon the geometry of the depositing ice and its physiographic setting. With large ice shelves, such as that adjacent to the Weddell Sea in Antarctica, Orheim and Elverhoi (1981) noted maximum rates of deposition in the residual paratill zone. Rates are generally low, ranging between 2.00 and 7.00 centimetres per 1000 years. Similar rates occur in the orthotill, compound paratill and marine zones in the order of 1.00 centimetre per 1000 years, or less. Potentially higher rates in a residual paratill setting, of 1.70 to 8.20 centimetres per 1000 years, have been quoted from the Barents Sea in the Arctic (Elverhoi & Solheim, 1983, 30), with very low rates of 1.14 to 2.92 millimetres per 1000 years in extreme distal, marine, settings (Clark et al., 1980).

By contrast, fjord settings show much higher sedimentation rates and a more rapid lateral progression through the facies succession defined in figure 4.2.2. In Spitsbergen, Elverhoi et al. (1980, 33) estimated sedimentation rates on the basis of annual organic varves, and found them to be in the order of 5.00 to 10.00 centimetres per year in extreme proximal (orthotill) settings (Kongsfjorden, ibid.). This fell to 1.00 to 2.00 millimetres per annum in residual paratill zones, and 0.10 to 2.00 millimetres per annum in the compound paratill setting (Elverhoi et al., 1983, 146). The latter zone tended to occur close to fjord mouth's. With the retreat of fjord glaciers onto land, and the emergence of proglacial deltaic conditions, Hoskins and Burrell (1972, 549) quote postglacial mud deposition rates in the adjacent offshore areas of up to 1.00 metre per annum.

The difference between ice shelf and fjord deposition rates, therefore, appears to vary over several orders of magnitude. With the environmental interpretations for individual units made in the present study, it would seem sensible to use an average depositional rate somewhere between these two extremes for any given facies, as sedimentation from outlet lobes (excepting units 3, 0, X & T), or from debris-laden foreign ice (unit -1) is thought to have occurred. This would make sedimentation rates, on average, in the order of several metres per thousand years.

Unfortunately there is little comparative evidence from continental margin locations, like that west of the Shetland Islands, to use as more applicable analogues. Further analysis must, therefore, be based on the characteristics of the sediments analysed in the present study alone.

7.3.2. UNIT SEDIMENTATION INDICATORS.

The amount of information that can be derived from any one unit is largely dependent upon the extent of its recovery and its physical condition. Unit 3 sediments, for example, are generally massive with a sandy matrix prone to drilling disturbance. The record of sedimentation preserved is, therefore, not as useful as that from unit 2 which shows well developed lamination, clastic zonation and sulphide banding, all of which can aid in assessing the rate of deposition. For this reason each unit is considered separately.

UNIT 4.

Although the thin seam of this unit recovered from borehole 82/10 was laminated, it was effectively impossible to see any rhythmic succession within it (plate 2.2.10.). Close to the drill-damaged zones laminae were more apparent (plate 2.2.11.), varying on average from 2.00 to 4.00 millimetres in thickness.

In 84/04 the lamination at the base of the recovered section (plate 2.6.6.) shows a similar 2.00 to 3.00 millimetre spacing, although no further information could be gained by viewing this section under x-ray (plate 2.6.7.). Both of these sections were interpreted as coming from the compound paratill facies (see fig 4. 3.8.), which suggests that sedimentation rates could have been higher farther inshore.

In borehole 80/09, however, the massive and unconsolidated matrix prevented an inshore comparison. The profuse sulphide banding in this core may be indicative of extremely slow rates of accumulation, or the continuous deposition of organic matter. Rates of deposition had, therefore, to be estimated from the compound paratill zone.

UNIT 3.

The massive matrix in 82/10 and 84/04 (plates 2.2.9. & 2.6.5a.) made the estimation of sedimentation rate impossible in these cores, and the minor lamination in 84/02 was too indistinct to be of any use. Moreover, the absence of quoted sedimentation rates from the Yukon delta-Norton Sound analogue employed in chapter four makes the direct use of comparative rates virtually impossible. It was also suggested that unit 3 may have been deposited in a tectonic setting that was different to the present regime in Norton Sound (section 4.4.3.).

If these sediments do represent fluvially- rather than wholly ice- derived material, very high rates of sedimentation might be appropriate. Alternatively, if extensive shallow marine reworking of these sediments followed their deposition, the actual marine sedimentation rate preserved may have been very slow in net terms. Such reworking may have occurred as unit 3 deposits do show the graded characteristics present in Yukon delta sands which have been so modified (Nelson, 1982a).

In the absence of a more accurate estimator, the rate employed in the present study is based on the net sedimentation rate of the sands in Norton Sound during the Holocene. This gives a working average of around 1.00 metre per 1000 years (Nelson, 1982b, fig 4b).

UNIT 2.

This unit was the most extensively recovered in terms of separate borehole sites. The best information came from 82/10 which was set in the residual/compound paratill transition (see figs 4.5.12. & 4.11.1.). The physical features of this core provided several useful indicators for assessing the sedimentation rate. Rhythmic sand layers, attributed in the environmental interpretation to increases in annual turbidity and sediment outflow during the summer melt season triggering bottom currents, were observed at intervals of up to 10.00 millimetres, with an average of around 3.00 to 4.00 millimetres. In some circumstances sulphide bands could also be seen at 2.00 centimetre intervals, although there are instances where these features may be a result of drill damage (plate 2.2.3.). In the situations where drill disturbance could be discounted these bands, attributed in the environmental interpretation to spring microfaunal "blooms" following the break up of winter sea ice, were spaced 3.00 to 4.00 millimetres apart (plate 2.2.6.), which would dictate a similar annual sedimentation rate to that derived from the sand layers.

In contrast, the compound paratill sediments in 82/01 are very poorly laminated, so no estimate of average spacing is possible. Regularly spaced sand layers, or distinct sulphide bands were also absent in this core.

The residual paratill and orthotill deposits in 84/02 and 84/04 showed a similar paucity of well developed indicators. A higher rate than 3.00 to 4.00 millimetres per annum (3.00 to 4.00 metres per 1000 years) derived for the residual/compound paratill transition in 82/10 would be a sensible assumption, but any figure arrived at would be arbitrary. Further discussion is, therefore, unwarranted. For this reason the assessment of unit 2 is based on the deposits recovered from borehole 82/10.

UNIT 1.

A similar, but less severe, environmental setting for this unit, compared to unit 2, was defined during the genetic interpretation of these sediments in chapter four. Similar average sedimentation rates might, therefore, be expected. Similar problems to those encountered for unit 2 were also experienced for this unit. The residual paratill deposits from 82/10 and 84/04 are either massive or very poorly laminated so that rates of deposition cannot be assessed. Sulphide staining in 82/10 is also ubiquitous and is not concentrated in bands, nor were sand layers noted in this core.

The compound paratills in 82/01 also showed generalised sulphide staining (plate 2.3.1a.), although in some instances banding was apparent with zones under 2.00 millimetres in thickness (plate 2.3.1b.). This may indicate a very low sedimentation rate in the region of 3.00 to 4.00 millimetres per annum. Where present, lamination in this core showed a spacing consistent with other units, in the range of 2.00 to 4.00 millimetres in thickness. This would appear to confirm this rate of deposition. For this reason the calculation of sedimentation for this unit was based on the sediments from borehole 82/01, with similar average rates of deposition to unit 2.

UNIT 0.

Unit 0 was only recovered in two cores and the paucity of samples made even the genetic interpretation of the unit difficult (see section 5.3.5.). The attribution of this unit to a similar environment of deposition as unit 3, where sedimentation rates were virtually impossible to assess, adds to the problems in analysing unit 0. Like unit 3, the material recovered was generally massive with no evidence of bedding or lamination (plate 2.5.4.). If the clastic debris in this section is indicative of ice rafting a higher rate of deposition than unit 3 might be appropriate. However, borehole 82/11 penetrated only the upper half of this unit, so these clasts might not be characteristic of the unit as a whole at this site.

With the possibility of ice rafting, and the rapid thickening of the unit towards the shelfbreak, environmental conditions for this unit may have been closer to those of the overlying unit (-1), as any ice depositing in this area, considering the environmental interpretation for areas farther inshore, would have to have originated outside the immediate study area. With this in mind it was decided to combine the depositional rate inferred for unit 3 with a qualitative component to account for the less severe evidence of ice rafting than was seen in unit -1. In effect this gave a depositional rate similar to unit -1 (see below) of around 4.00 metres per 1000 years.

UNIT -1.

This unit, only recovered in borehole 82/11, does show evidence of lamination but the silty matrix meant this was very poorly developed (section 2.5.1.), so that no estimation of depositional rate could be made on this basis. Comparison could be made to residual paratill deposition rates from the other units discussed above, but the possibility that this unit represented deposition from ice originating outside the immediate study area meant that very different rates of deposition may have occurred. An arbitrary rate must therefore be used.

On the basis of the environmental interpretation made in chapter four (section 4.8.3.), and the ice mass reconstructions from chapter five (see fig 5.3.1.), it was suggested that this unit resulted from intense ice-rafted deposition. Although no certainty can be attached to this assumption, it would seem appropriate to assign a sedimentation rate compatible with the residual paratill zone where the most intense ice-rafted deposition would occur.

At the residual/compound transition in unit 2, rates of up to 10 metres per 1000 years were indicated. A level equal to, or higher than, this would therefore seem to be appropriate here, because of the indications for greater iceberg activity. However, if this ice came from outside the present study area, and may have travelled a considerable distance losing debris as it went, rates this high would probably be incorrect even with the greater intensity inferred from the profusion of clastic debris. For this reason, despite the differences in appearance and particle size signature, it was decided to assign a rate similar to the average rates for units 1, 2 and 4. A rate of approximately 4.00 metres per 1000 years was, therefore, employed.

UNIT -2.

Although no unit -2 deposits were recovered during the present study, initial drilling results from the 1985 BGS drilling season indicated that it probably consisted of an unconsolidated grey clay similar to unit X. As both of these units appear to represent the most recently deposited sediments in the present study area, inshore (unit X) and beyond the shelfbreak (unit -2), it seems sensible to assume that they relate to the last deglacial and the Holocene. This would give a working depositional timespan of 10,000 to 12,000 years for both of these units.

With an average (estimated) depth of around 50.00 metres for unit -2, this would give an average sedimentation rate of around

5.00 metres per 1000 years. This is higher than the rates for residual paratills identified for the other units in the present study area, but this probably reflects considerable reworking, and downslope transmission of fines, from the glaciated regions on the shelf during the Holocene. With the absence of exact information from this unit it was decided to base the analysis on unit X, and assume that unit -2 was deposited over an approximately similar period.

UNIT X.

The chronostratigraphic interpretation (chapter three) indicated that unit X was the most recently deposited facies in the present study area. For this reason it was assumed that it probably related to the Holocene at least.

Recovery from borehole 84/03 was too unconsolidated and drill-affected to be of any use in this context. This left the deposits from 80/08. Most of this core is either massive or broken up by gassified fabric (plate 6.2.4.) which made the identification of laminae or bedding impossible. The only laminated zone occurred at the base of this unit in the transition into unit T. In this zone the laminations divided into successions of approximately 2.00 centimetres in depth. This may, however, simply be indicative of depositional rate at that time, and with the absence of active, eroding, ice masses the rate for the rest of this unit may have been much lower.

The only feasible approach to assessment was, therefore, to reverse the procedure used for the underlying units and estimate the rates of deposition from an arbitrarily defined timespan of 10,000 to 12,000 years. With the average depth of unit X being around 50.00

metres this would give an average sedimentation rate of around 5.00 metres per 1000 years. The proximity of 80/08 to the Shetland landmass suggests such a high rate is acceptable as Hoskins and Burrell (1972, 549) quote clay deposition rates of up to 1.00 metres per annum in similar circumstances today. Using this comparison the rates for unit X are quite low.

UNIT T.

Depositional rates for terrestrial glacial sequences are very difficult to define. This is largely a function of the rapid changes in sedimentary conditions that occur under, and in front of, active ice masses. This makes terrestrial sequences a contrast to deposits from marine settings where deposition through a water column tends to eliminate such rapid spatial changes. As the unit T deposits identified in the present study cannot be fitted into the chronostratigraphic framework derived for the other units, and because of the large scale removal of unit T deposits from the basement platform, depositional rate would probably be of no use anyway in defining the depositional timespan for this unit. For this reason it was omitted from the following analysis.

7.3.3. ESTIMATED DEPOSITIONAL TIMESPAN.

Using the estimated rates of deposition defined in the preceding sections, an impression of the total timespan over which the sediments described in the present study were deposited can now be made. This is achieved by multiplying the average rate of deposition for each unit, in a given facies zone, by the average thickness of that unit (measured from the seismic data presented in figs 3.2a to 3.3b) in the area which is thought to contain this type of facies (defined from the facies succession diagrams in chapter four). Adding all of the totals together will give an overall estimate for the timespan represented.

UNIT 4. (Compound paratill zone).

Average estimated rate of deposition	4 metres per 1000 years
Average estimated unit thickness	30 to 40 metres
Average estimated depositional timespan	<u>10,000 years</u>

UNIT 3. (Norton Sound analogue).

Average estimated rate of deposition	1 metre per 1000 years
Average estimated unit thickness	50 metres
Average estimated depositional timespan	<u>50,000 years</u>

UNIT 2. (Residual/compound paratill transition).

Average estimate rate of deposition	3 to 4 metres per 1000 years
Average estimated unit thickness	40 to 60 metres
Average estimated depositional timespan	<u>10,000 years</u>

UNIT 1. (Compound paratill zone).

Average estimated rate of deposition	2 to 4 metres per 1000 years
Average estimated unit thickness	50 to 60 metres
Average estimated depositional timespan	<u>15,000 years</u>

UNIT 0. (Delta front with ice rafting?).

Average estimated rate of deposition	4 metres per 1000 years
Average estimate unit thickness	50 to 60 metres
Average estimated depositional timespan	15,000 years

UNIT -1. (Foreign ice rafting?).

Average estimated rate of deposition	4 metres per 1000 years
Average estimated unit thickness	50 to 60 metres
Average estimated depositional timespan	15,000 years

UNIT X. (Post- or de-glacial).

Average estimated rate of deposition	5 metres per 1000 years
Average estimated unit thickness	50 metres
Average estimated depositional timespan	10,000 years

7.4. CHRONOLOGICAL FRAMEWORK.

Using the average estimated depositional timespans from the previous section, an overall chronological framework for the present study area can now be formulated. The basic framework used for this purpose is that of Stoker *et al.* (1985) which was derived from studies on the Quaternary successions in the central North Sea. The combined chronologic timescale, with the information derived from the micropalaeontological analysis in section 7.2., and the depositional timespans derived in the previous section are summarised in table 7.4.1.

Synthesizing all of this information enables some of the ambiguities left by the micropalaeontological analysis to be resolved. The estimated depositional timespan for all of the units defined in the present study makes it very improbable that the majority of the sediments analysed are older than the Upper Pleistocene. This confirms the impression given by the microfaunal analysis, and suggests that assemblage comparisons with sediments from the northern North Sea is an acceptable technique. Most importantly, the calculated depositional timespan confirms that units 3 and 4 are probably no older than the Middle/Upper Pleistocene transition. The small amounts of unit 4 recovered could only be related to the late Saalian. This would account for the ameliorative foram assemblage, which could be taken as indicative of the initiation of ice melt and the onset of the transition into the subsequent Eemian interglacial. In this case the "Saal-like" assemblages in unit 3 would be the result of the reworking of the "high glacial" Saalian deposits during this interglacial.

At the top of the sequence, the apparent confirmation of Harland's (1983d) correlation of unit -1 with Binns et al. (1974) Formation 2 also adds weight to the chronological interpretation made in the present study.

CHAPTER .8.

CONCLUSION

8.1. INTRODUCTION.

With the analysis of the sediments for the present study completed, the final chapter will complete the investigation in two areas.

First, with the chronological framework and the genetic interpretation of the sediments completed it is now possible to reassess the main theories outlined in chapter one, in the light of the evidence accumulated during the present study. The main theories outlined in chapter one will be taken individually in the subsequent sections. This approach is taken here because the chronological sequence of events in each of these theories is now of major importance to the discussion, as opposed to the individual ice mass morphologies which were under consideration in chapter one.

After these theories have been reassessed, the second part of this chapter will consider the implications of the findings from the present study to the existing understanding of the Quaternary history of Northwestern Europe as a whole. A final brief section will indicate where future research will be required in the light of the findings of the present study.

8.2.1. PEACH AND HORNE'S THEORY.

CHRONOLOGY.

As was stated in chapter one, this theory was proposed before the modern understanding of glacial cyclicity was developed. For this reason no definitive interpretation can be placed on its two "main" and "later" phases of ice activity. They could equally represent successive stadials or widely separated full glacials. However, it was also stated in chapter one that where no specific statement on age was made, the theories would be attributed to the Weichselian stadials, as it is from these periods that the evidence, on which they are based, is most likely to have come.

For this reason it is assumed that this particular theory relates to the Middle (main) and Late (later) Weichselian stadials.

REASSESSMENT.

From the reassessment in chapter five, and section 6.6., it is apparent that none of the units analysed in the present study indicates the presence of Scandanavian ice over the Shetland Islands during the Middle Weichselian (unit 1), and possibly the subsequent interstadial (unit 0). This in itself enables the rejection of Peach and Horne's theory if it is assumed to relate to successive stadials at any time during the Upper Pleistocene. The chronological framework derived in the present study means that the latest period during which Scandanavian ice could have crossed Shetland and reached Foula and the shelfedge (see figs 1.1.1. & 1.1.4.) would be during the early stages of the Saalian, prior to the deposition of the remains of unit 4.

If this sequence of events is accepted, unit T could correlate with the Saalian if it represented a late downwasting stage of the main glaciation, when stagnating ice over Shetland was flowing under topographic control, and Scandanavian ice retreated eastwards across the northern North Sea.

Alternatively unit T could relate to the later local glaciation. This possibility has, however, already been criticized because the evidence west of Shetland suggests ice masses must have been larger than those Peach and Horne suggested calved close to the modern coastline. Moreover, the limits of unit T east of Shetland place a grounded ice mass farther east than the calving margin proposed by these authors.

Accepting a Saalian age for the main glaciation would also mean that the later glaciation would have to postdate the Eemian (unit 3) interglacial, and so would presumably correlate with the Early Weichselian (unit 2). As this unit appears to correspond with the maximum extent of ice west of the Shetland Islands (see fig 5.3.4.), this makes the acceptance of Peach and Horne's limited calving ice mass even more difficult. The only unit for which such a restricted ice mass could be envisaged would be unit -1, which is attributed here to the Late Weichselian. This would necessitate an extended time gap between the two phases of Peach and Horne's theory. This seems incompatible with the wording of their work. Peach and Horne's theory is consequently rejected.

8.2.2. CHAPELHOW'S THEORY.

REASSESSMENT.

Chapelhow's (1965) investigation produced a theory with many similarities to that of Peach and Horne (op. cit.). In her work, however, she implied that the Scandanavian ice and the local ice cap were both part of the same ice advance stage. In the same sense as Peach and Horne's theory, therefore, if this theory relates only to the Saalian, it can be rejected, as the onshore evidence on which the theory is based is unlikely to be Saalian in age. If Chapelhow's theory is set in a single stadial rather than a full glacial, it is even more incompatible with the timescale derived in the present study, Consequently this theory can also be rejected.

8.2.3. HOPPE'S THEORY.

CHRONOLOGY.

Hoppe's (1974) theory also seems to attribute the transition from a Scandanavian to a local ice cap to a single glacial phase. This could be an extended stadial, or two stadials separated by a climatically severe interstadial, as the wording of this work precludes there having been an ameliorative intervening interglacial/stadial. Hoppe states specifically that the striae on which he bases this theory relate to the Weichselian, falling between 35,000 and 12,000 years BP. This would indicate a Late Weichselian age (ibid., 208). If this is the case then his early phase can be attributed to the late Middle Weichselian (unit 1) onwards, at the oldest.

REASSESSMENT.

As has been stated earlier, Scandanavian ice cannot have encroached into the present study area since the Saalian. The placing of this ice configuration in the Weichselian can, therefore, be rejected, thereby invalidating Hoppe's two stage theory. A very restricted local ice cap in the Late Weichselian is compatible with the evidence produced in the present study (unit -1: see section 5.3.3.). However a continuous shift from the period of Scandanavian ice coverage to the local ice mass cannot then be invoked. This inconsistency means that Hoppe's theory can also be rejected in its present form.

8.2.4. MYKURA'S THEORY.

CHRONOLOGY.

Mykura (1976) is quite specific in attributing his maximal ice cover to the Weichselian "maximum". With the chronological and palaeoenvironmental framework defined in the present study, this maximum would appear to correlate with the Early Weichselian (unit 2), or possibly the Middle Weichselian (unit 1). In this instance Mykura's later stage, involving the radial outflow of ice from a local ice cap, could be attributed to the following (Middle and Late Weichselian respectively) stadial.

REASSESSMENT.

If this theory is limited to the Weichselian, it means that if a two stadial model is employed the theory must correlate with units 2 and 1 or 1 and -1. The former would seem to be more appropriate as the two stadials do not appear to have been separated by an intervening ameliorative interstadial. It cannot be stated with certainty that ice did not exist over the Shetland Islands during the deposition of unit 0, but the latter alternative would, on the balance of the evidence collected during the present study, require such an intervening period.

Accepting the former alternative also produces a closer fit with the other available evidence. The maximum ice extent west of Shetland (unit 2) would correlate with the presence of Scandanavian ice to the east of the islands in Mykura's maximum stage. If unit T then correlated with unit 2, the sediments in SLN 76/26 would represent the easterly outflow of local ice (see fig 1.1.2.). For this to be accepted, however, the location of SLN 76/26 means that the junction between Scandanavian and local ice would have to be placed farther east than Mykura originally indicated, so that only local ice covered and deposited material at the site of this core. To the south of this site, Scandanavian ice could have crossed Mainland in a westerly direction and then have merged with local ice to produce the ice margin west of Shetland and Foula.

Despite this potential correlation, the chronology is again open to question. On the basis of the evidence from the present study, and the borehole evidence from the northern North Sea, it seems unlikely that Scandanavian ice could have crossed this area after the Saalian.

The positioning of this kind of ice mass east of the Shetland Islands in the Early/Middle Weichselian is incompatible with this evidence. Mykura's theory can, therefore, be rejected, although as a proviso it must be added that his later stage could correlate with any of the later deposits identified in the present study (units 0 to -2).

8.2.5. FLINN'S THEORY.

CHRONOLOGY.

Flinn, over several works, gradually changed his chronological framework for describing the glacial history of the Shetland Islands. In his earliest works he appears to have presented two theories. In the first scenario a local ice cap was defined in the "last glacial maximum" with a Scandanavian ice cover during a "preceding glacial maximum". As was discussed in chapter one the former phase is open to several interpretations. In the present study it is taken to refer to the Weichselian maximum which, on the basis of the sediments analysed, probably occurred during the Early Weichselian (unit 2). In this case the preceding glacial would have occurred during the Saalian (pre unit 4).

In his second scenario, Scandanavian ice was envisaged over Shetland during the "last glacial maximum" (Early Weichselian) with the local ice cap being produced during the lateglacial or a deglacial period. This is taken here to correlate with the Late Weichselian to Holocene transition (units -1, -2 & X).

In later works Flinn reassessed these theories and concluded that no Scandanavian ice had existed over Shetland during the last glaciation of the area, and its presence would have to be attributed to a completely separate earlier glacial episode (again presumably the Saalian). During the "last glaciation" of the islands only a local ice cap was envisaged. This phase could correspond to the Late Weichselian, or the entire Weichselian as a whole, as Flinn is far from specific in his use of terminology.

REASSESSMENT.

The three scenarios mentioned above will be reassessed in sequence.

The first is compatible with the available evidence. The Saal is the only period when Scandanavian ice can be invoked encroaching on Shetland from the east. However, problems arise with the later stage. The evidence collected in the present study does suggest a local ice cap over Shetland during the (Early) Weichselian maximum, but also during at least one of the subsequent Weichselian stadials (unit 1). This might suggest that Flinn's information correlates with this later stadial, and not to the Weichselian maximum. However, there is no evidence for a reduced ice mass east of Shetland at any time during the Weichselian as this interpretation would require (Flinn, 1964, 338). This scenario can consequently be rejected.

In the second scenario the presence of Scandanavian ice is required over Shetland during the Early Weichselian. This means that it can be rejected. Moreover the environmental interpretation for the Late Weichselian (unit -1: section 5.3.3.) also suggests that little if any ice may have existed over Shetland at that time.

In the third scenario the presence of Scandanavian ice can again be attributed to the Saalian. The suggestion that the later local glaciation corresponds with the "last glaciation" suggests that this phase may represent the entire Weichselian. This would be compatible with both units 2 and 1, and the ice-free period represented by unit -1. This third scenario can, therefore, be accepted although this is based entirely on the interpretation made in the present study of Flinn's use of the term "last glaciation".

8.2.6. SUMMARY - NEW THEORY.

All of the theories that have so far been propounded to explain the glacial phenomena of onshore Shetland suffer from similar criticisms in the light of the limited offshore evidence derived in the present study. Although the actual physical features and ice configurations described in various stages of these theories may actually represent extant conditions in the study area at a given time, the temporal frameworks in which these stages are set are inconsistent with the chronological framework developed in the present study. Apart from this, several of the theories can also be rejected because the onshore evidence on which they are based was probably formed by denudational activity after the periods within which these theories would need to be set to be compatible with the evidence derived in the present study. Shetland may, at one time, have been overrun by Scandanavian ice, and later developed its own indigeneous ice cap, but the ways in which these events are presented in existing theories are insufficiently rigorous to enable their acceptance.

The sequence of events inferred in the present study avoids these criticisms. This study clearly associates distinct units, identified in the sedimentological and seismic analysis, with definite time periods or glacial phases (see table 7.4.1.). Although this timescale could be criticized, the association between the units will always remain constant. The use of offshore information enables this kind of approach because, in the present study area at least, a more complete chronostratigraphic sedimentary succession can be built up than is possible with the deposits preserved above sea level, and a more extended series of deposits is preserved offshore. Invoking the Law of Superposition, therefore, the chain of events defined for the units in this study will always remain in their present sequence.

It is proposed here that the last period during which the Shetland Islands could have been influenced by Scandanavian ice was during the Saalian (pre unit 4). After the subsequent (Eemian) interglacial (unit 3) when ice disappeared from both Shetland and probably the Orkney Islands farther south, a local ice cap became established, reaching its maximum westerly extent during the Early Weichselian (unit 2). This phase of ice activity continued, without recession, into the Middle Weichselian (unit 1) when the ice cap over Shetland gradually began to retreat. During the subsequent interstadial (unit 0) a marked amelioration occurred in the climate and ice probably disappeared from Shetland, and from Orkney to the south. In the ensuing Late Weichselian stadial (unit -1), both of these areas together with the north coast of Caithness were almost certainly ice-free, and only localised deposition occurred (unit X & -2) running through into the subsequent, deglacial, Holocene.

8.3. IMPLICATIONS OF THE PRESENT STUDY.

Having reassessed the various theories relating to the Quaternary history of the Shetland Islands, the remaining sections will consider the implications of the present study to the existing understanding of the Quaternary history of this region of northwestern Europe as a whole. This discussion will focus on the overall history of the northern North Sea followed by a more detailed consideration of the connotations for the glacial history of northern Britain, particularly northern Scotland. A final section will highlight areas where more information is still required and, consequently, where unresolved questions still exist in both the onshore and offshore records.

At the start of this section it is pertinent to reaffirm the findings of this study so far, with particular reference to the chronological framework represented by the sediments recovered. All of the remaining discussion in this chapter will cover only the Weichselian in detail. The only other period for which any date can be tentatively given appears to be the erosion of the pre-Quaternary Tertiary/Basement transition to bedrock. On the basis of the recovered dinoflagellate cysts this period may relate to the Early Pleistocene (Red Crag: see section 7.2.1.).

8.3.1. ICE SHEET RECONSTRUCTIONS.

Several reconstructions of the last ice sheets over northwestern

Europe have been mentioned in the course of the present study. It can be restated here that the evidence from the present study precludes the acceptance of "maximalist" reconstructions, such as those of Grosswald (1980), Andersen (1981) and Boulton (1979a), for the Weichselian. These models envisage a continuous ice cover from Scandanavia to the northern reaches of Britain and the continental margin to the west. In contrast, the palaeoenvironments and timescales derived in the present study correlate with the initial results obtained from boreholes in the central northern North Sea discussed in section 1.4.2. They indicate that no Scandanavian ice could have encroached on Shetland after the Saalian, and during the whole of the Weichselian it must have been restricted even farther east. The most logical terminal limit for this ice would be the western margin of the Norwegian Channel. Here the uppermost Weichselian (Tampen) formation has been tentatively identified as a terminal or lateral moraine ridge relating to the outer margin of a Scandanavian ice mass (A. Skinner, pers. comm.). This necessitates the acceptance of a more limited ice extent during the Weichselian with an ice-free North Sea (e.g. Boulton et al., 1985, 471).

This scenario would be compatible with other evidence from the North Atlantic. For example, Ruddiman (1977) presented a pack and iceberg flow pattern for the Weichselian with a northeasterly component running approximately parallel to the continental margin (ibid., 1823). This would mean little ice from the Arctic or Iceland would have reached Shetland, but ice from more southerly parts of the British continental margin could have done. This flow pattern is represented in the present study area west of Shetland by the iceberg scour patterns discussed in chapter three, with their southwest to northeast trends (see figs 3.14. & 3.15.). In addition, the iceberg encroachment pattern inferred for unit -1 illustrates a northeasterly trend, and the absence of clearly exotic erratics in this unit suggests the debris deposited was derived from similar basement areas to those around Shetland; possibly in western-northern Scotland and Orkney (see fig 5.3.1.).

The foraminiferal evidence for the incursion of warm ocean currents, from the southwest, during the deposition of unit 1 (see fig 5.3.4.) would also correlate with Ruddiman's (ibid., 1821) currents of warmer water along the western continental margin. By implication, with ice growth over Shetland around or preceding this period, this in turn agrees with Ruddiman et al.'s (1980, 54) conclusion that much of the ice growth in northwestern Europe must have occurred whilst the subpolar North Atlantic was still in a warm condition, as the presence of northerly-trending warm ocean currents occurs in tandem with the postulated maximum ice extent over Shetland (unit 2) during the Weichselian (see fig 5.4.1.).

8.3.2. DIACHRONOUS ICE EXPANSION.

Recent evidence from the Arctic (Boulton, 1979a), plus palaeoclimatic modelling of both ice sheet growth (Boulton et al., 1985), and local British glaciers (see section 1.3.), suggests that moisture provision and not temperature is the critical factor in ice expansion. This, in turn, implies growth along restricted meridional belts at any given time, and diachronous ice sheet expansion over the Northern Hemisphere as a whole. The results of the present study are compatible with this pattern.

The palaeoenvironmental reconstructions for the units identified in the present study indicate that ice growth was aspatial through time. For units 1, 2 and 4 ice expansion occurred over Shetland, with the influx of warm ocean currents, presumably accompanied by moisture-bearing winds (see fig 5.4.1. and section 1.3.). Between these periods (units 3 & 0) restricted or absent ice cover over Shetland is indicated, but ice may have expanded farther south over southern Orkney and Caithness. This suggests that latitudinal variation in precipitation-bearing depression tracks occurred throughout the Weichselian.

At certain times, with oceanic and atmospheric currents following more northerly courses, ice built up over the Shetland Islands and the Orkney-Shetland Platform. However, during the intervening periods the depression tracks and ocean currents could have moved southwards, starving the Shetland area of snowfall and producing a contraction, and possibly even the disappearance, of ice over Shetland (Sissons, 1981, 12). At these times ice masses over northern England and southern Scotland could have been expanding, whilst over Shetland the extension southwards of polar anticyclonic activity produced an increase in periglacial activity, in the lee of the precipitation-bearing cyclonic zones. This evidence, therefore, suggests that Shetland had, chronologically, a slightly different Weichselian history from the rest of Britain.

8.3.3. RELATIONSHIP TO SCOTLAND.

Evidence from northern Scotland and the Orkney Islands would appear to support this scenario. Recent evidence suggests that the last mainland Weichselian ice mass was much less extensive than had previously been thought. For example, in the Sea of the Hebrides Binns et al.'s (1974) Formation 2 (associated in chapter seven with the Late Weichselian unit -1; see table 7.4.1.) overlies a till deposit. From this it seems logical to assume a period of ice expansion here during the Middle Weichselian, or the subsequent interstadial (units 1 and 0 from the present study area farther north). Over Shetland, by contrast, ice appears to have reached its maximum extent during the preceding Early Weichselian (unit 2). On Orkney, between these two areas, Rae (1976, 225) concluded that the last ice activity there was Middle Weichselian or earlier, and that the ice involved had originated over northern Scotland or the Grampians (Sutherland, 1984c, 171). This would suggest that Orkney and northern Scotland preserve a similar glacial record. Similarly, to the west of northern Scotland, the last ice activity on St. Kilda is now thought to have preceded the Late Weichselian (Sutherland et al., 1984), and the earlier invasion of the archipelago by mainland Scottish ice would be compatible with a great Saalian glaciation. This would correlate with the last period during which Scandanavian ice occurred far enough west to have overrun the Shetland Islands. Therefore, although periods of ice activity on the northern continental margin appear to be inter-related, it is apparent that Shetland preserves a slightly different record from areas farther south.

Taking this evidence at a regional scale, a gradual southerly shift in the focus of ice activity, from the Middle Weichselian onwards, is apparent. At an early stage, ice activity optimized over Shetland (unit 2). As the atmospheric and oceanic currents gradually pushed south, the accompanying shift in the focus of snowfall produced a similar shift in the areas of ice growth. During the

Middle Weichselian ice expansion over northern Scotland overran Orkney, but by that time Shetland may already have had a contracting ice mass (unit 1). In the subsequent interstadial (unit 0) ice may have disappeared from both Orkney and Shetland in the north, and the outer islands of St. Kilda to the west. Consequently, in the Late Weichselian (unit -1) the Northern Isles, St. Kilda and Caithness were probably ice-free as the northern British ice masses decayed (Sutherland, 1984c, 190). At the same time ice masses over the Midlands and northern England expanded (Sutherland & Walker,1984, 703).

8.3.4. PERIGLACIAL EVIDENCE.

Assuming an ice-free Late Weichselian history for the whole of the northern reaches of Britain agrees with the available geomorphological evidence indicative of periglaciation. It has already been stated that anticylonic conditions conducive to periglaciation are likely to succeed a southerly movement of the major snow-bearing depression tracks. In these ice-free areas, for example, one can find evidence of cryoturbated tills attributed to the Late Weichselian in Caithness (Sutherland, 1984c, 170). On Lewis a Late Weichselian ice front is bordered by beach deposits which show extensive evidence of permafrost features (Sutherland & Walker, 1984). Similarly, on St. Kilda periglacial processes were identified as having been operative down to sea level (Sutherland et al, 1984) whilst ice fields were minor or completely absent. At the other extreme, there is evidence of periglacial action on the high ground in both Orkney and Shetland (Ball & Goodier, 1974: Goodier & Ball, 1975). In all of these areas, other common geomorphological phenomena attributable to periglacial action are the precipitous coastal cliffs, which drop vertically to wide rock platforms. These features have been attributed to periglacial action well beyond the margin of any extant ice fronts (Ballantyne & Gray, 1984, 267),and again suggest that all of these areas were ice-free during the Late Weichselian.

8.3.5. IMPLICATIONS - SUMMARY.

Drawing together all of the information produced during the present study, several implications for the Quaternary of northwestern Europe can be highlighted which must be taken into account by future investigations. Initially it must be re-emphasized that the deposits from the continental shelf margin that are still preserved today appear to date predominantly from the Late Pleistocene and, more specifically, the Weichselian. Foraminiferal and dinoflagellate evidence, however, suggest that the erosion of the underlying Tertiary/Basement bedrock transition (unit 5) relates to the very early Pleistocene (possibly the Red Crag). This may indicate that the most influential period in the Shetland Islands, in terms of glacial activity, correlates with the Early rather than the Late Pleistocene. It is possible, therefore, that many of the large-scale geomorphological phenomena attributed to glacial activity in this area could correspond with this earlier period. With the preservation of only Late Pleistocene sediments, there is also no evidence remaining in the present study area to assess its glacial history between these two phases of the Quaternary. However, if the Early

Pleistocene does represent the maximum influence of ice on the continental margin, and the later Saalian appears to be the last period during which Scandanavian ice could have encroached on Shetland, this does suggest that ice extent and influence gradually decreased during the successive stages of the Quaternary, at least in the region of the present study area.

Concentrating on the Late Pleistocene, the results of the present study support initial findings from boreholes in the northern North Sea indicating a restricted Scandanavian ice mass during the Weichselian (section 1.4.2.). The sediment record around Shetland indicates that the present study area was isolated from this, and possibly Scottish ice, during the last full stadial at least. The latest period at which Scandanavian ice could have affected Shetland was the Saalian. There is no direct evidence which supports the presence of Scottish ice over the Shetland Islands, although it is thought to have spread northwards over Orkney during the Middle Weichselian (Rae, 1976). The possibility remains, therefore, that Shetland could have remained isolated from any major continental ice masses, or highland ice sheets, throughout the Weichselian.

At a more localised level it is apparent that the size of Weichselian ice masses in the Shetland and continental margin area indicate a more restricted grounded ice cover than has previously been supposed. More specifically, there is no evidence that grounded ice ever reached the shelfbreak. This correlates with evidence from areas to the southwest, around the Outer Hebrides and St. Kilda, which, in turn, indicates that the continental margin environment may be important to an understanding of the Quaternary not as a glaciated tract, but as an area of sediment deposition. If preceding glacial phases had similar westerly ice limits, the sediments preserved close to or beyond the shelfbreak may cover a similarly extended timespan as those in the North Sea, except that in this case their physiographic setting would reduce the possibility of the sediments being re-eroded by subsequent ice advances.

Comparing the Weichselian record inferred for Shetland in the present study, with studies from other areas of northern Scotland, a pattern is apparent. The oldest Weichselian deposits are preserved around Shetland, with a gradual decrease in age as sequences are traced southwards. This is indicative of a gradual shift in the regional focus of ice growth and sediment deposition during this glacial period. Ice activity maximized over Shetland during the Early Weichselian, and over Orkney and Caithness during the Middle Weichselian. In the Late Weichselian ice activity disappeared from all of these areas, and on the shelf margin to the southwest, as ice masses expanded over more southerly reaches of Britain. Invoking uniformitarianism, it is possible that this aspatial ice expansion may also be characteristic of preceding glacials. In either case it is suggested that this latitudinal shift is supportive evidence for the theory which suggest that precipitation and, therefore, the positioning of the circumpolar convergence zones in the atmosphere and oceans, are the governing factors in the growth and maintenance of ice masses during Northern Hemispheric glaciations. Moreover, the evidence from Shetland and areas to the south suggests that an arid subpolar desert effect occurred in the lee of these precipitation zones.

These implications have a bearing, in turn, on the theories previously forwarded to account for the glacial phenomena of the

Shetland Islands. Primarily, the present study suggests that much of the surface morphology of Shetland, previously interpreted as a result of glacial activity, may in fact be a consequence of periglacial action during the Late Weichselian and preceding interstadial. If this is the case, the evidence used to support the existing theories of Shetland's glacial history has been misinterpreted, and all of the theories can be rejected in part, if not in their entirety. Such a revised interpretation would, moreover, make a more economical use of the available onshore evidence. For example, the production of Shetland's coastal cliffs can be more easily explained invoking subaerial weathering during the extended period of the Late Weichselian stadial, as opposed to the last de- and post-glacial period as several of the existing theories require if an ice mass is envisaged over Shetland during the Late Weichselian maximum.

A reduced sea level with subaerial weathering would also be more compatible with the erosion of the lower boundary of the unit X deposits. The areas where unit X now occurs could represent the zones of erosion created by the decay and melt of the Early to Middle Weichselian ice masses, (which had directly deposited units 1 and 2) during and after the subsequent interstadial (unit 0 onwards). At the same time meltwater from Orkney debouching northwards (as it may have done during the deposition of unit 3) could have produced the secondary erosion of the "v" feature noted in this area at a similar base level to unit X (see chapter three). Subsequent periglacial activity would then provide erosion products only to offshore areas relatively close to the coastlines. Hence the deposition of unit X is reminiscent of deposition in a shallow lake connected to the sea, which received only fine-grained sediments from onshore areas via processes such as creep and solifluction. With no transportationally-competent processes acting under periglacial conditions, coarser grained sediments were restricted to the immediate coastline and never reached the areas where unit X was deposited. In the case of Orkney, the "v" feature was even farther away from the contemporary coastline and did not receive even this fine-grained material.

The limited outcrop of unit X also suggests that where deposition did occur, it was only in those basin-like areas where the water column was slightly deeper. Over the majority of the basement platform, the reduced sea level (attested to by the weathering of the coastal cliffs virtually down to the level of the basement platform) enabled the turbulence created by wave action to maintain any suspended sediment in suspension. Noticeably, the sulphide blackening in unit X suggests deposition in stagnant water which must have existed below the level of this turbulence. The penetration of wave activity to the surrounding platform would also help to account for the absence of debris on the basement areas today. Active currents in these areas could have produced the comminution of any coarser grained material that was deposited there.

A synthesis of this evidence, suggests that there was no extensive ice cover over the Shetland Islands during the Late Weichselian stadial. This is the major reason for rejecting most of the theories that have previously been forwarded to describe the islands' glacial history. Other reasons include criticisms of their methodologies and the absence of accurate chronological frameworks (as was discussed in chapter one and at the start of the present chapter).

8.4.1. FUTURE RESEARCH - OFFSHORE.

The findings of the present study highlight several areas where further information is required to resolve some of the questions posed during the present study. Primarily, it has been shown how important an accurate understanding of the offshore Quaternary record must be to the overall understanding of the Pleistocene of northwestern Europe. The analysis of further boreholes, such as those detailed in section 1.4.2., would be an initial step to mesh the results of the present study with existing knowledge on the behaviour of the margins of the last Fennoscandanavian ice cap.

Also with this in mind, the findings of the present study could be supported or rejected if the micropalaeontological succession identified west of Shetland could be related to the existing documented successions in the central North Sea, and farther south around the northwestern coast of Scotland and in the Minch. A spatial impression of species variation linking these areas is essential if the tentative dates inferred for the sediments described in the present study are to be accepted.

Related to the chronological framework, the present study has also illustrated that a substantial time gap exists between the erosion of the pre-Quaternary bedrock surface and the deposition of the sediments that remain today. This suggests either that somewhere on the continental margin sediments might be preserved from these periods or that the sediments from these intervening periods have been eroded away, presumably during the Saalian.

8.4.2. FUTURE RESEARCH - ONSHORE.

The re-examination of the existing theories proposed to describe the glacial history of the Shetland Islands indicates that substantial reassessment of the onshore glacial record may be required. The indications for variation in the severity of ice growth over Shetland, and the possibility that the area might have been ice-free during the Late Weichselian, suggest that periglacial landforms may be much more widespread than has previously been thought. The synthesis produced in the present study, for example, allows a greater time period for the weathering of the coastal cliffs of both the Northern Isles and the north coast of Caithness. Moreover, the suggestion that the whole of this area may have been ice-free during the Late Weichselian implies that these features, which are similar in geomorphological terms, are also similar genetically.

There is other evidence that Shetland may be a relict periglacial landmass. Unit T deposits, for example, indicate that periglacial processes may have been widespread even during periods of ice growth (section 6.5.3.). One of the earliest theories on the glaciation of the Shetland Islands mentions the absence of marine material in the tills (Peach & Horne, 1879, 800) and "numerous small moraines" (ibid., 791) not seen elsewhere in northern Scotland. This clastic-rich moraine could well be the result of periglacial activity alone, with downslope movement producing the ridges in conjunction with solifluction processes. In later studies, the unstratified nature of the tills was also commented upon (Chapelhow, 1965, 65) and this would also be characteristic of an unsorted periglacial regolith, particularly considering the small proportions of clay observed in these "tills" and the frequent occurrence of large boulders (ibid., 69). There is also the evidence from Ronas Hill that periglacial phenomena cannot be explained away as being of postglacial origin alone (Ball & Goodier, 1974). In total, this evidence suggests that periglacial rather than glacial processes may have sculptured much of the present surface of the Shetland Islands.

In these circumstances, a review of the evidence on which all of the previous theories on Shetland's glacial history were based, might undermine their basic premise, that the majority of the features accessible today on the surface are of glacial origin. If this were to occur a reassessment of the glacial history of the islands would seem to be required, which would in turn help to support or reject the findings of the present study.

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