UNIVERSITY OF SOUTHAMPTON

The deep seabed environment of the UK continental margin – integration and interpretation of geological and biological data

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Doctor of Philosophy

SCHOOL OF OCEAN AND EARTH SCIENCE

December 2003

UNIVERSITY OF SOUTHAMPTON
ABSTRACT
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Until recently the seafloor environment of the continental slope west of Shetland was relatively unknown, particularly with regards to its biology but also the general seabed environment. Since the AFEN (Atlantic Frontier Environmental Network) survey, using sidescan sonar, seabed photography and seabed sampling in 1996 in order to establish an environmental baseline for this region, the 'Atlantic Frontier', the knowledge and understanding of the environment has greatly increased. Two main layers, a warm-, upper layer overlying a cold-, deeper layer, within the hydrography (Turrell *et al.*, 1999) and the macrofauna (Bett, 2000a, 2001a; Narayanaswamy, 2001) but little is known about the megafaunal distributions.

In this study, a total of 19 photographic stations have been used with 18 stations from the AFEN sampling programme carried out in 1996 (Bett, 1997) and one station (M200) from a Department of Trade and Industry (DTI) survey in 2000 (Bett, 2001b). The processing and analysis of these photographs resulted in a total of 4537 photographs covering approximately 87,760 m^2 of the seabed. The main aim of the study was to analyse this extensive collection of photographic material with the key objectives being the integration of biological and geological data to further the understanding of the seabed sedimentary environment and develop an overview of the biological communities that inhabit the continental slope west of Shetland.

The results presented illustrate a complex sedimentary environment with a number of sediment zones present as well as a current regime with strong currents flowing towards the northeast on the upper continental slope, while relatively weaker currents flowing towards the south-southwest are found at depth within the Faroe-Shetland channel. In addition, two large-scale patterns and a number of local-scale patterns have been identified within the megafaunal distribution. The variations in the megafaunal distributions show a division of the fauna into a two-layer system as well as some bathymetric variations along the continental slope west of Shetland. Within these two regional systems there are a number of local-scale features including the iceberg plough mark zone, the 'sponge-belt' and a novel discovery on a sand contourite at the bottom of the continental slope.

The division of the megafauna into two layers with a boundary at approximately 600 m appear to reflect the distribution of the water masses within the Faroe-Shetland Channel with a warm-, upper layer overlying a cold-, lower layer. Two of the main bathymetric trends are the increase in megafaunal density with depth along the continental slope and the decrease in species diversity with depth, the latter a result indicating that the suggested generalisation that the deep sea has uniformly high species diversity may be too simplistic.

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ACKNOWLEDGEMENTS

I wish to thank my supervisors at the Southampton Oceanography Centre Dr Brian Bett, Dr Doug Masson and Dr Martin Sheader, for their guidance, wise words and support throughout the Ph.D. I would also like to thank them for giving me unique opportunities to work at sea and to attend national and international conferences. I would also like to thank them for their useful comments and discussion during the preparation of this thesis.

I would also like to thank the Atlantic Frontier Environmental Network for funding the Ph.D. and the University of Southampton for funding my tuition fees. Many thanks to the Head of Department of the George Deacon Division for allowing me access to all the facilities. Thanks must also go to the officers and crews on RRS *Challenger,* RRS *Charles Darwin* and RRS *Discovery* for making my experiences at sea so memorable and exciting. Last but certainly not least I would like to thank my family and friends for all their support and understanding during the last few years and completion of this thesis. A special thanks to my wife Lucy for all her support, encouragement and love and to my two boys Felix and Sebastian, for making life interesting, fun, and full of happiness.

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The offshore area north and west of Scotland, known as the 'Atlantic Frontier' or the 'Atlantic Margin', has in recent years become of increased interest to oil and gas companies. In particular the area west of Shetland has been given most attention with the hope that the oil fields there will, if not replace the fields in the North Sea, at least supplement them to meet the energy needs for the early parts of the 21st century. Furthermore the Department of Trade and Industry (DTI) has in recent years been encouraging the industry to consider the wider development of the region as a whole, particularly in the matter of pipelines and other infrastructure (AFEN, 2000).

Planners and prospective developers of major projects in the UK are, since the introduction of Environmental Assessment (EA) legislation in 1988 (through the Environmental Impact Assessment legislation in the European Community Directive of 1985), under obligation to follow strict planning practices including carrying out Environmental Assessments (Glasson *et al.*, 1994). In addition, there may furthermore be sites within the Atlantic Margin protected by the EU Habitat Directive and Natura 2000 now being applied to the full extent of the UK Exclusive Economic zone (EEZ, 200 nm) (O'Briain, 1998). In a general sense, the aim of the legislation is to ensure sustainable management and allow development in harmony with the environment. In respect to the Atlantic Margin, this legislation has played a part in producing the environmental surveys described below.

Exploration for oil and gas in the offshore area around the edge of the continental shelf to the west of the Shetland Islands has been carried out since the 1970s, the first well was drilled in 1972 and the Clair Field discovered in 1977 (Clarkson, 1998; AFEN, 2000). Since then additional fields including the Foinaven Field (by BP in 1992), have been discovered during the 16th licensing round.

The early initiatives in co-operative environmental activities in the Atlantic Frontier region began in 1994. This collaboration arose from discussions between operators in the region (known as the West of Shetland Group), the regulators, the Department of Trade and Industry (DTI) and their advisors, the then Scottish Office Agriculture Environment and Fisheries Department (SOAEFD now Fisheries Research Services, FRS), and the Joint Nature Conservation Committee (JNCC). One aim of the collaboration was to find the best means to collect the required baseline environmental data to provide the necessary understanding of the environment to minimise adverse impacts in the deep waters of the Atlantic Margin (Mirzoeff, 1998; AFEN, 2000).

In order to manage the development of the region as a whole (oil, gas, pipelines and other infrastructure) the Atlantic Margin Joint Industry Group (AMJIG) was formed. This organisation acts as a liaison and co-ordinating group for Exploration and Production activities in the region. A number of sub groups were then established under AMJIG, one of which was the Atlantic Frontier Environmental Network (AFEN, members list in Appendix A), which took over the management of the environmental programme for exploration and production activities on the Atlantic Margin. It comprises representatives from each of the operating companies, the Department of Trade and Industry, the Scottish Office (now Scottish Executive) and the Joint Nature Conservation Committee.

One of the first tasks commissioned by AFEN was a literature survey of all available relevant scientific data covering both the licensed area and the wider Atlantic Frontier region. On the basis of this information, AFEN formulated four main programmes: a seabed survey, the Atlantic Margin Environmental Survey (AMES) in 1996 covering approximately 20,000 km^2 (figure 1), seabird and cetacean (visual) monitoring, cetacean monitoring with seabed hydrophone arrays and a beached oil (tarball) fingerprinting survey (Masson *et al.*, 1996; Bett, 1997). These activities continued with a second seabed survey in 1998, carried out to cover the 17th licensing round, consisting of a number of exploration blocks with a total area coverage (figure 1) in excess of 40,000 km^2 (Masson *et al.*, 1996; Bett and Masson, 1998; Bett, 1999). New studies addressing oil spill modelling and coastal defence strategies, seabird monitoring and further analyses of the 1996 survey biological material were added to the programme.

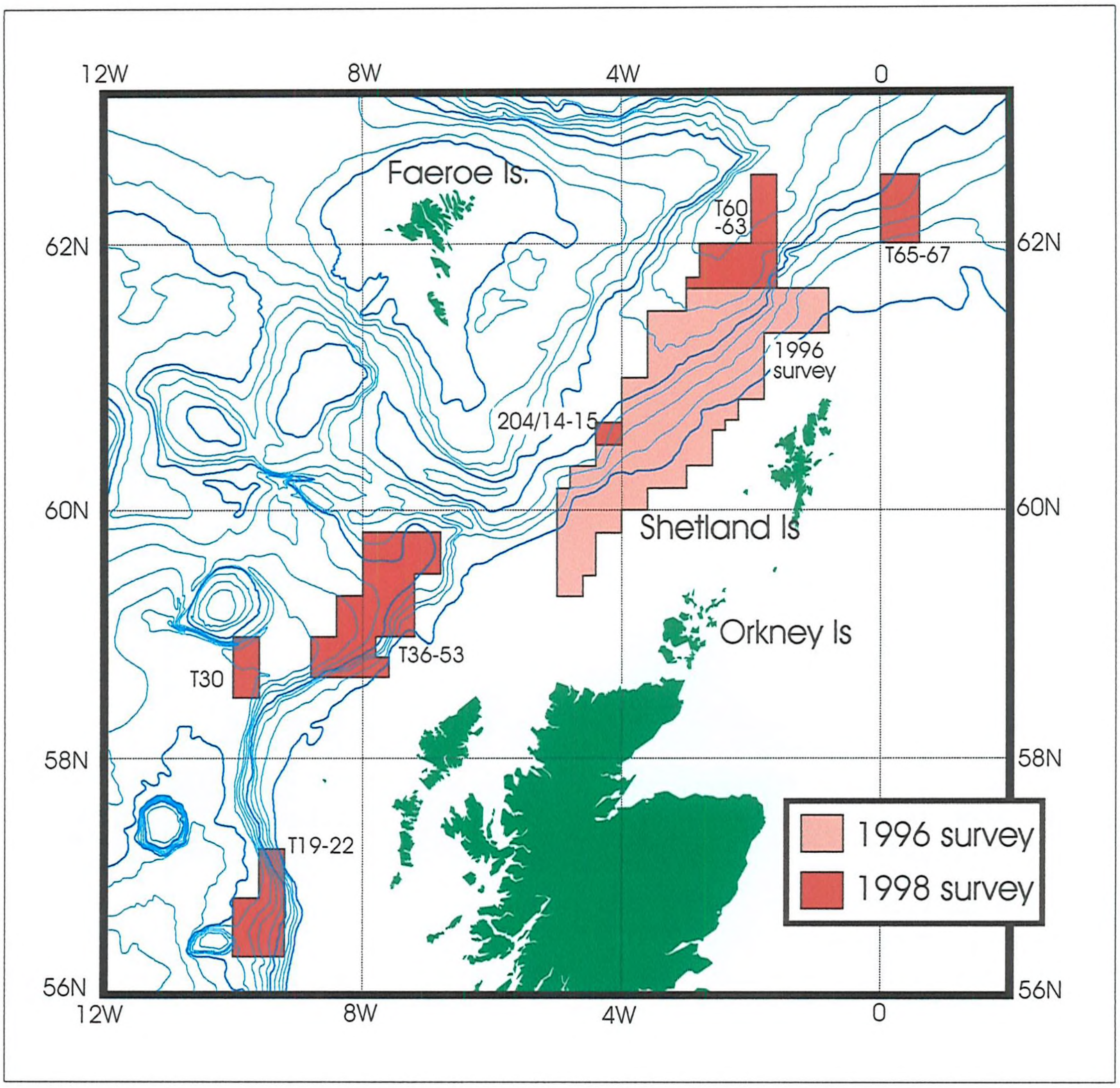


Figure 1. The AFEN Atlantic Margin Environmental Surveys of 1996 and 1998 (bathymetry in 200 m intervals).

Surveys of the size of AMES 1996 and 1998 collect a vast amount of information, which is often difficult to assimilate and analyse completely within the tight time constraints of the commercial world. AFEN therefore decided to provide additional funding for research, in the form of PhD studies, to further investigate aspects of the data collected.

1.2 AIMS

The main aim of this study is to analyse an extensive collection of photographic and video material in order to characterise and understand the seabed environment of the Atlantic Margin, particularly the area west of Shetland. The study aims to assess biological, physical and geological features from the photographic material and attempt to establish relationships between these features and those revealed by sidescan sonar and direct seabed sampling in the same deep-water areas. The key objectives are:

- The integration of biological and geological data at a range of scales from individual cores to regional assessments of the whole west of Shetland slope.
- To understand the seabed sedimentary environment and the processes that created it and continue to influence its geological character.
- To develop an overview of the biological communities that inhabit the continental slope and how they are related to the environment.

As part of the efforts to establish an environmental baseline for the region, the 1996 and 1998 AFEN surveys collected a large amount of data in the form of sidescan sonar and seabed sample data. In addition, an extensive collection of photographic and video material was acquired and the main objective of this project is to integrate this material with the existing sidescan sonar imagery and seabed samples. The photographic material forms a key link between the two other datasets, providing information on a scale intermediate to that of the sidescan sonar and sample material. The photographic material will be processed, analysed and interpreted with the general aim of improving the knowledge of the biological, physical and geological features in the region and to establish relationships between features found on the photographs and those revealed by sidescan sonar and direct sampling in the same deep-water areas.

Sidescan sonar images collected with the Southampton Oceanography Centre (SOC) Towed Ocean Bottom Instrument (TOBI) system typically give a resolution of approximately 10 m. Seabed samples on the other hand resolve features at the centimetre and millimetre scale. The photographic material provides a link between the two techniques. It allows the seafloor environment to be investigated without disturbing the natural processes acting there, and may show features not revealed by either the sidescan sonar or direct sampling techniques. It allows 'ground-truthing' of sedimentary features not immediately identifiable from the sonar images alone. And it may also be the only means of assessing the seabed fauna in 'rough ground' areas, such as the Wyville Thomson Ridge, where physical sampling is difficult or impossible.

The distribution and structure of the macrofauna in the area to the west and north of Shetland has been established through the analysis of the seabed samples from the 1996 and 1998 AFEN surveys (Bett, 2000a; Bett, 2001a; Narayamaswamy, 2001). To improve the understanding of the overall ecology and the biological distributions in this region, the photographic material will be used to allow mapping of the megafauna (the megafauna are typically defined as the fauna identifiable on seabed photographs) and allow comparisons of the two data sets. The potential comparisons include general faunistic distribution patterns, including bathymetric and along slope variations and the relative effects of physical and sedimentary factors.

A final consideration is the possibility of including some areas of the AMES survey regions of particular rarity and scientific interest into the Convention for the Protection of the North East Atlantic (Gubbay, 1999) and Natura 2000 within the EU Habitats Directive (JNCC, 2002).

2 THE ENVIRONMENTAL SETTING

2.1 THE REGIONAL SETTING

2.1.1 The deep sea

Our perception and understanding of the oceans have changed markedly over time (Pinet, 1992) but despite the fact that the oceans, with an average depth of approximately 3700 m, cover approximately 70 % of the planet surface it can still claim the title 'the last frontier on Earth'. The latter particularly refers to the deep sea, the remoteness of which always has caused scientists great difficulty, both financial and technical, in their attempts to study and increase the understanding of this part of the ocean. In terms of physiography the oceans can be divided into three regions: the continental margins (consisting of the continental shelf, the continental slope and the continental rise), the ocean basin floor (the abyssal plains, abyssal hills, seamounts and the trenches) and the mid-ocean ridge systems. (Tait, 1981; Chester, 1990; Pinet, 1992). The deep sea is considered to start at the edge of the continental shelf (Thiel, 1975; Gage and Tyler, 1991), the shelf break, which is typically found at approximately 130 m but can be found at a depth of more than 200 m (Pinet, 1992).

2.1.2 The deep-sea region west of Shetland

The continental margin northwest of the British Isles, known as the 'Atlantic Margin', stretches from the Hebrides Shelf to the West Shetland Shelf and borders three deep-water basins, the Rockall Trough, the Faroe Bank Channel (FBC) and the Faroe-Shetland Channel (FSC) (figure 2.1). The Rockall Trough, which reaches some 3000 m in depth west of Scotland, is bounded to the north by the complex of the Wyville Thomson Ridge and the Faroe Bank (Bett, 2001a). Both the FBC and FSC are found to the north of this ridge system, the latter being the deep-water channel separating the Faroe Plateau from the Scottish Continental Shelf (Turrell *et al.*, 1999).

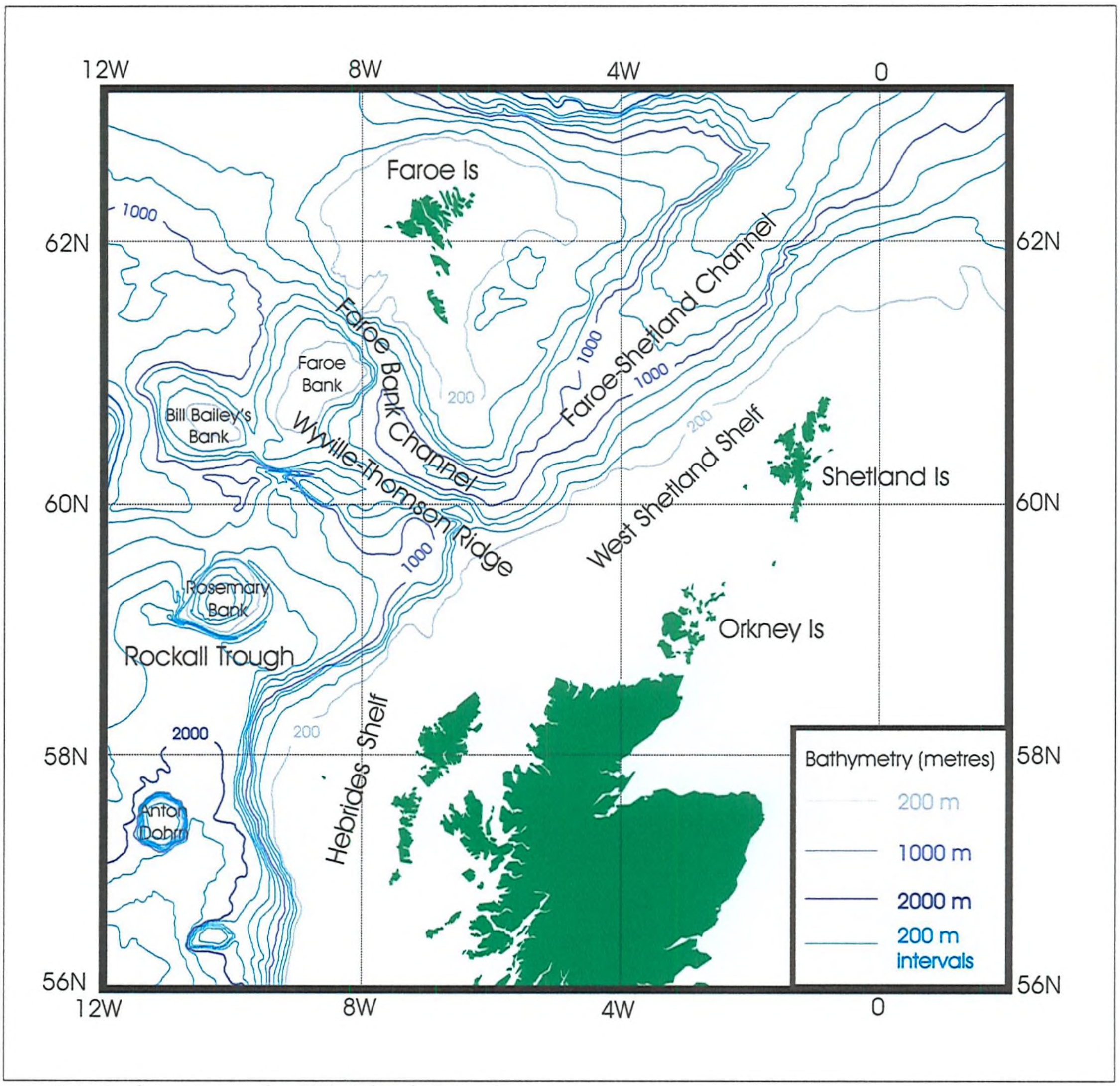


Figure 2.1. Bathymetry at the UK Atlantic Margin

The continental shelf west of Shetland varies between 50 and 200 km wide when the whole Scottish coast is considered. The shelfbreak is often recorded to be at about 200 m depth but varies between 120 m to 250 m in the West of Shetland region (Stoker *et al.*, 1993). The profile varies considerably between sites. In some areas the profile is smooth, gentle and the break difficult to locate, whereas in other areas the boundary is sharp. The angle of the continental shelf is gentle and seaward at between 0.07° and 0.2°, whereas below the shelf break the angle is increased to values of about 0.9° to 4.0°. The continental slopes are relatively narrow compared to the shelves and angles on the upper West Shetland Slope are typically less than about 1°, increasing to values between 1.5° and 2° mid-slope, before decreasing towards the basin floor (Stoker *et al.*, 1993, Stoker, 1995). The FSC lies in a southwesterly-northeasterly direction between 60°N 06°W and 63°N 01°W and extends for over 400 km before opening into the Norwegian Basin (Stoker *et al.*, 1993). The basin floor of the FSC is generally smooth to undulating. To the south of

60°30'N, the basin narrows from 30 km to about 20 km and the floor slopes southwards with depths ranging from 950 m to over 1200 m. To the north of 60°30'N, the basin floor slopes gently northwards from about 1000 m to over 1700 m, and widens from 30 km to over 65 km. The Channel is connected to the Norwegian Sea where the depth is approximately 2000 m and with the Atlantic to the southwest, through the Faroe Bank Channel with a sill depth of 850 m, and to the south, across the Wyville Thomson Ridge with a sill depth of about 450 – 600 m (Dooley and Meincke, 1981; Holliday *et al.*, 2000). The depth throughout the channel itself is approximately 1000 m (Dooley and Meincke, 1981; Masson, 2001).

2.2 EARLY EXPLORATION OF BRITISH DEEP-SEA WATERS

The history of the study of life inhabiting the deep oceans only extends for approximately 200 years. The exploration of the deep sea, with particular regards to the fauna, started in the early years of the nineteenth century. Explorers such as Sir John Ross, Michael Sars, James Clark Ross and J. Hooker discovered fauna from depths exceeding 600 m. These and other early discoveries fuelled the interest of many scientists to study the ocean environment.

One of the pioneers was Charles Wyville Thomson, who together with William B. Carpenter organised one of the first deep-sea exploration cruises in British waters (Gage and Tyler, 1991). They managed to persuade the Royal Society of London to get the British Royal Navy to help them undertake cruises to the north and west of Britain. The first onboard the *H.M.S. Lightning* in the summer of 1868 followed by another two onboard *H.M.S. Porcupine* in the summers of 1869 and 1870 (Thomson, 1873; Menzies *et al.*, 1973; Gage and Tyler, 1991; Pinet, 1992). One of their key observations was the difference in bottom-water temperature at two locations relatively close together. Deep-water temperatures south of Torshavn were found to be in the range of 0.5°C to 1.1°C whereas at a location only 100 km to the south a temperature of 4.6°C was observed at comparable depths (Thomson, 1873; Menzies *et al.*, 1973; Adams, 1995). The bottom-living animals at the two sites were as different as the temperatures. Furthermore, the collected bottom-living animals enhanced their surprising and extraordinary discovery considering that the general perception at the time was a deep-sea environment practically devoid of life. Theories like the 'Azoic zone' of Forbes (little life below 0.6 km), and other views about life in the deep sea, were about to be challenged (Menzies *et al.*, 1973;

Gage and Tyler, 1991; Adams, 1995), and the deep sea shown to be a much more variable environment than was originally predicted (Lalli and Parsons, 1993; Tyler, 1995).

Scientists from several nations, including Norway (Blindheim, 1995), Denmark (Buch, 1995) and the UK, subsequently started to study the waters north and west of Scotland, and the Faroe-Shetland Channel in particular. Two standard survey lines crossing the deep-water channel lying between the European continental shelf and the Faroe Plateau were established in 1893 - the beginning of an hydrographic survey that has lasted for over one hundred years (Turrell, 1995; Turrell *et al.*, 1999). It is one of the longest series of oceanographic records available, and aims to explain the unusual hydrographic conditions found in the Faroe-Shetland Channel (Turrell, 1995).

2.3 THE HYDROGRAPHIC SETTING

The northeastern part of the North Atlantic is unique in the sense that it is much warmer at the surface than other ocean areas at similar latitudes (Westerberg, 1970; Hansen and Østerhus, 2000). The main reason is the large northward transport of warm water with the North Atlantic Current (forming the northern branch of the Gulf Stream), which crosses the Greenland-Scotland Ridge to enter into the Nordic Seas where it is converted to colder water masses through heat exchange with cold atmosphere (Worthington, 1970) and lateral mixing with polar waters (Ellett and Roberts, 1973). This water returns southwards partly in the surface waters along the Greenland coast and partly at depth at several locations across the ridge (Holliday *et al.*, 2000). The water exchange across the Greenland-Scotland Ridge thus plays a key role in the global thermohaline circulation as well as the regional climate in northern Europe (Hansen and Østerhus, 2000).

In the eastern North Atlantic the returning water mass is undiluted Norwegian Sea Deep Water, NSDW (also known as the Arctic Bottom Water, ABW). This, the densest water mass of the world's oceans (Tomczak and Godfrey, 1994), is restricted to the immediate vicinity of the Greenland-Iceland-Scotland Ridge. It does, however, contribute to the formation of the North Atlantic Deep Water (NADW), which forms the main water mass within the 1000 m to 4000 m depth range in the Atlantic Ocean.

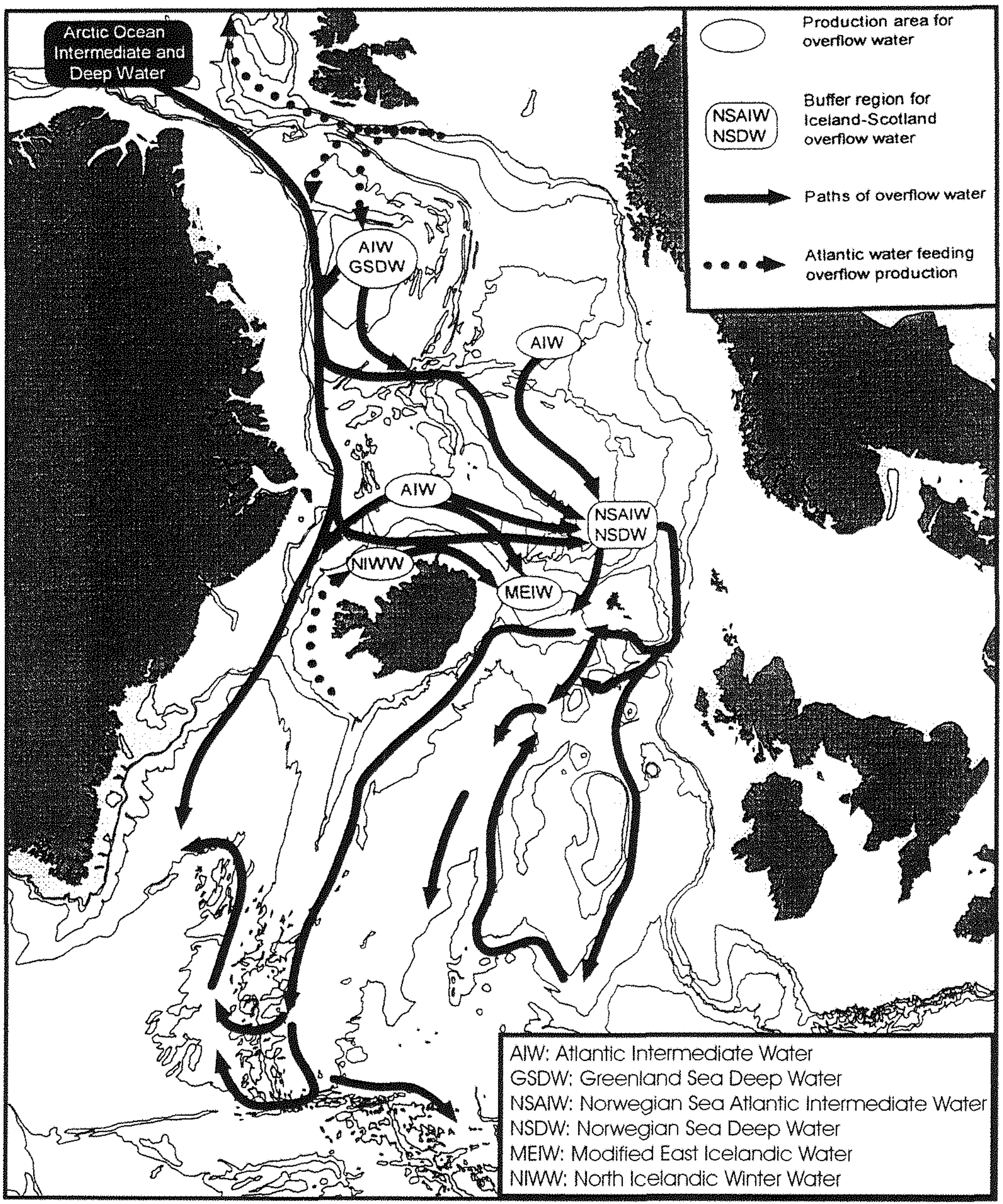


Figure 2.2. The major flows in the lower layer in the Northeast Atlantic (from Hansen and Østerhus, 2000).

The NSDW is formed in the Norwegian Sea (figure 2.2) after which some of it flows north into the central Polar Basin via the Lema Trough (Gage and Tyler, 1991). The rest flows south-westwards over the sills of the Greenland-Iceland-Scotland Ridges, a water mass known as the Arctic Bottom Water overflow (Tomczak and Godfrey, 1994). It has been suggested that a total of 4 Sv flows through this Ridge system, with the Faroe Bank Channel (through the Faroe-Shetland Channel), which has the deepest passage in the ridge system by some 200 m (Steele *et al.*, 1962; Crease, 1965; Hansen, 1985), and the Iceland-Faroe sill passing some 1 Sv each, and the Denmark Strait contributing 2 Sv (Tomczak and Godfrey, 1994). Some of this cold water, in the region of 0.1 to 1.2 Sv (Dooley and Meincke, 1981; Hansen, 1985), does periodically spill over the Wyville Thomson Ridge from the Faroe Bank Channel into the northern Rockall Trough (Ellett and Roberts, 1973; Ellett *et al.*, 1986; van Aken and Becker, 1996; Turrell *et al.*, 1999; Holliday *et al.*, 2000). The various water mass paths of the NSDW join up and flow towards the southwest (although some may enter the Rockall Trough directly; Lee and Ellett, 1965; Jones *et al.*, 1970) along the Mid-Atlantic Ridge (Reykjanes Ridge) until they cross through the Charlie-Gibbs Fracture Zone, eventually reaching the Labrador Sea to form what is known as the North Atlantic Deep Water (Jones *et al.*, 1970; Gage and Tyler, 1991; Bersch, 1995). On leaving the Labrador Sea, most of the NABW flows down the western side of the Atlantic Ocean but a smaller amount does also penetrate into the European Basin across the crest of the Reykjanes Ridge (Lee and Ellett, 1965; Ellett and Martin, 1973; Lonsdale and Hollister, 1979), where it mixes with Norwegian Sea Deep Water and Antarctic Bottom Water to form another arm of the North Atlantic Deep Water, NADW, (Dickson and Kidd, 1986; Howe, 1995).

The loss of water through the deep basins is replenished (estimates ranging from 2 – 8 Sv; Tait, 1957; Worthington, 1970; Dooley and Meincke, 1981), particularly in the north-eastern Atlantic (figure 2.3), by the warm and saline Gulf Stream, or the North Atlantic Current, which flows at the surface from the Gulf of Mexico into the Norwegian Sea and later into the Iceland and Greenland Sea gyres, eventually contributing to the formation of Norwegian Sea Deep Water. The arriving water mass is often known as Modified North Atlantic Water (figure 2.3) but is also known as North Atlantic Central Water (Hansen and Østerhus, 2000). A certain contribution is also deriving from the North Atlantic Water, a water mass formed in the Biscay-Porcupine Bank continental shelf area (Ellett and Martin, 1973, Hansen and Østerhus, 2000). This water mass, which may (Tait and Martin, 1961, 1965), or may not (Hill and Mitchelson-Jacob, 1993), have influence from Mediterranean water, arrives in the Nordic Seas through the slope current along the continental margin of northwest Europe (Huthnance, 1981; Booth and Ellett, 1983; McCartney and Talley, 1984; Hill and Mitchelson-Jacob, 1993; Hansen and Østerhus, 2000; Holliday *et al.*, 2000). It flows up the Rockall Trough until it reaches the Wyville Thomson Ridge where the deeper fraction (>500 m) is restrained by the ridge and flows westwards while the upper fraction forms the current flowing into the Norwegian Sea (Howe, 1995). The extent of this contribution is still unknown but this current is believed to exert considerable influence on sedimentation along the continental slopes west of Scotland (Kenyon, 1986; Howe, 1995).

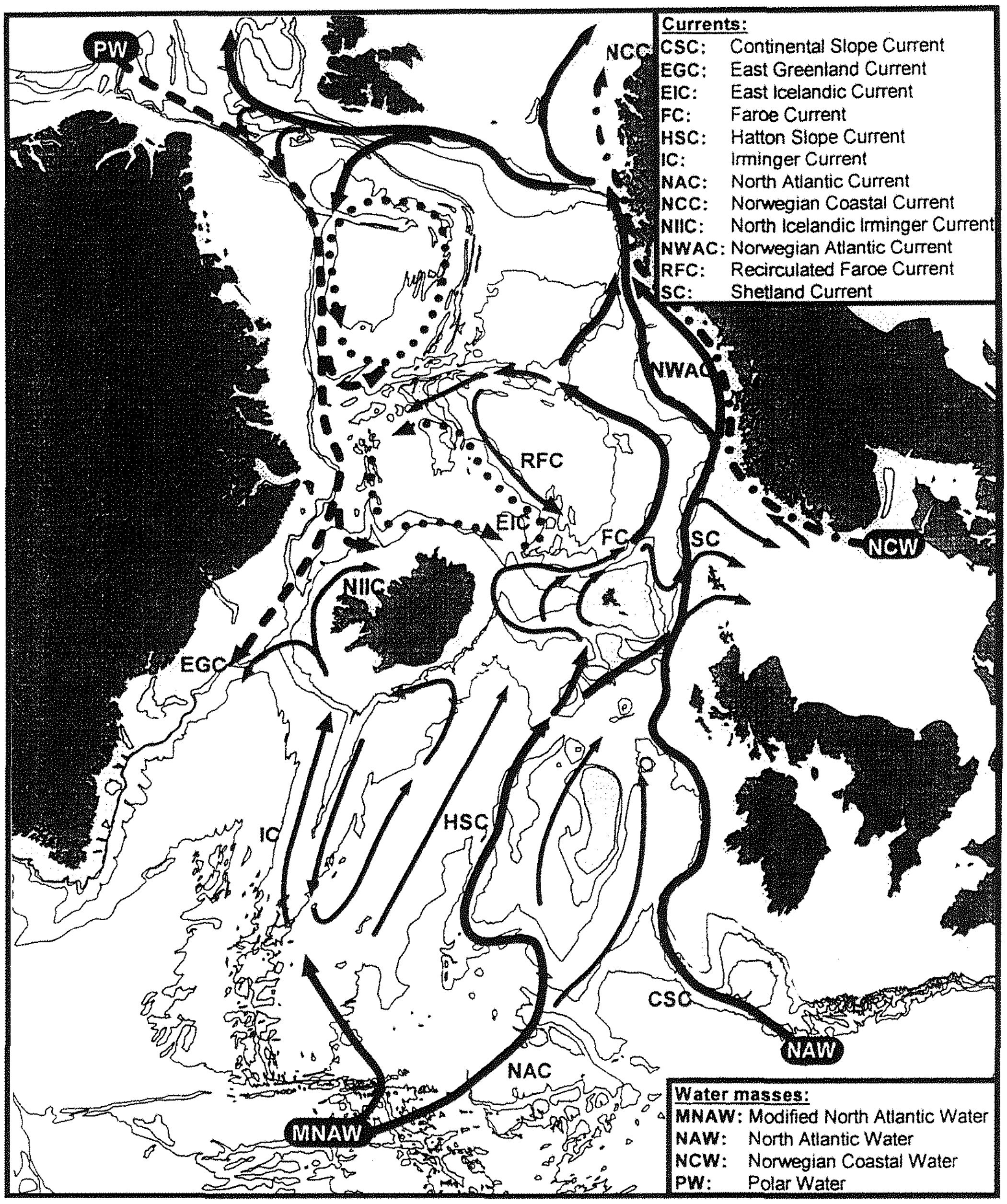


Figure 2.3. The major flows in the upper layer in the Northeast Atlantic (from Hansen and Østerhus, 2000).

2.3.1 *Water masses and circulation in the Faroe-Shetland Channel*

The FSC has been the subject of many scientific cruises throughout the last century and it is probably the most studied ocean area in the world (Hansen, 1985). However, the basic circulatory patterns and the volume of water transported through this channel are still being debated as a result of the complexity of the hydrography in the area.

A number of water masses have been recorded in the region but broadly the hydrographic regime consists of an upper layer of warm North Atlantic Water moving towards the northeast, overlying a cold Norwegian Sea bottom water layer flowing towards the south/southwest (Tait and Martin, 1965; Dooley and Meincke, 1981; Hansen, 1985; van Aken, 1988; Schlitzholtz, 1995; Turrell, 1995; Turrell *et al.*, 1999; Masson, 2001). The boundary between the warm and cold waters is dynamic (Bett, 2001a) and the surface water mass has typically been reported to extend down to 400-500 m (figure 2.4), but has also been recorded to penetrate down to 750 m on the Scottish continental slope (Tait and Martin, 1961).

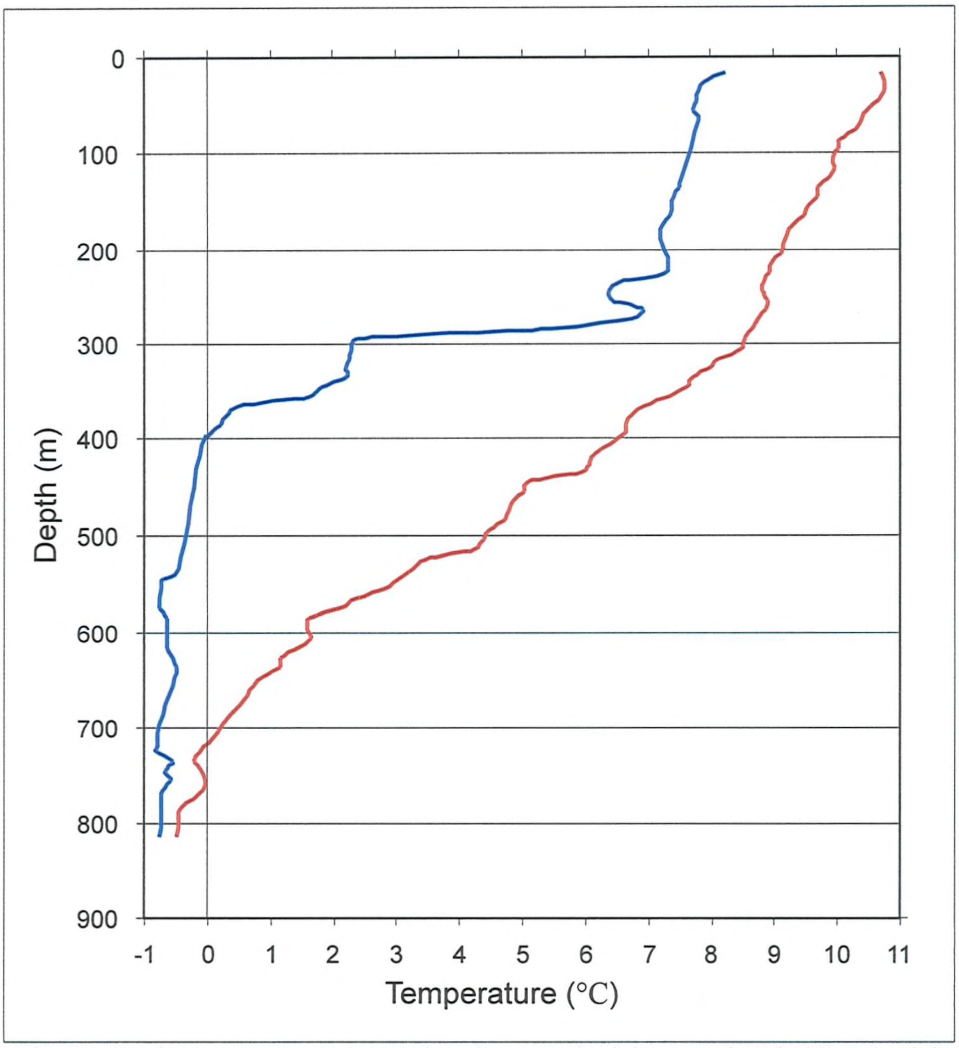


Figure 2.4. The water column temperature range (maximum and minimum values in 10 m depth bands) of the eastern Faroe-Shetland Channel encountered by TOBI sidescan sonar instrument during AMES 1996; approximately one month of observations (from AFEN, 2001).

Since the first discovery of the two layers of cold and warm water within the FSC in the late 1860s, different authors have reported a variety of divisions of these layers into three (Tait and Martin, 1961; Westerberg, 1990), four (Dooley and Meincke, 1981, Hansen, 1985) and five (Tait and Martin, 1965; van Aken, 1988, Hansen and Østerhus, 2000) different water masses. One reason for the variety in the number of water masses identified appears to be related to an observed change in the characteristics of the water masses during the last 100 years. In one of the most recent studies, Turrell *et al.* (1999), five water masses have been recognised (figure 2.5 and table 2.1). Two distinct surface waters: North Atlantic Water (NAW) and Modified North Atlantic Water (MNAW), have been identified. Below these two there are three additional water masses: Arctic Intermediate Water (AIW), Norwegian Sea Arctic Intermediate Water (NSAIW) and Faroe-Shetland Channel Bottom Water (FSCBW), formerly identified as Norwegian Sea Deep Water (NSDW). Prior to the 1960s, the NSAIW was identified as a salinity minimum but not as a separate water mass. In the period 1960-1980 this salinity minimum disappeared only to re-appear in the 1980s and it has now been classified as NSAIW (Turrell *et al.*, 1999).

2.3.1.1 North Atlantic Water (NAW)

The North Atlantic Water is confined to the Scottish continental slope on the eastern side of the Faroe-Shetland Channel and is generally present inshore of the 400 m depth contour. It is associated with the Slope Current that flows northwards along the shelf edge into the Norwegian Sea. It is believed to originate from the southern edge of the Rockall Trough, an area where North East Atlantic Central Water is dominant, giving it high salinity and warm temperatures, typically more than 8 °C. The water mass is believed to flow along the eastern margin of the Rockall Trough and the Faroe-Shetland Channel until it reaches the Norwegian Sea.

2.3.1.2 Modified North Atlantic Water (MNAW)

The Modified North Atlantic Water dominates the surface waters, down to 400 m, of the Faroe Shetland Channel in terms of areal extent, covering the central and western side of the channel. It originates from the North Atlantic Current. The water mass flows towards the Faroes to the west of the Rockall Trough and inundates the Faroe Bank and Faroe Bank Channel areas (Turrell *et al.*, 1999). From there it flows northwards around the Faroe plateau in a clockwise circulation, arriving in the Faroe-Shetland Channel from the northeast. Below 100 m, very little escapes through the Faroe Bank Channel (Turrell *et al.*, 1999). It recirculates and joins the NAW flowing into the Norwegian Sea and it has temperatures in the range 6.5 to 8 °C.

2.3.1.3 Arctic Intermediate Water (AIW)

The Arctic Intermediate Water is also known as the Arctic Intermediate/North Icelandic Water (AI/NIW) to indicate the area of origin north of the Iceland-Faroe Ridge (Turrell *et al.*, 1999). The water is created from a mixture of Arctic and saline Atlantic waters during winter convection on the north Icelandic shelf. From its site of origin and just south of the polar front it flows around Faroe between the Atlantic and the Norwegian Sea Deep Water. The AIW occupies a relatively narrow band across the channel in the depth range 400-600 m on the Faroe side of the channel just beneath the MNAW. Along the west Shetland continental slope, this water mass lies just beneath the NAW and the depth band is shallower than on the Faroe side. Analysis has indicated that little of this water escapes through the Faroe Bank Channel and most of it (up to 75 %; Dooley and Meincke, 1981) is therefore recirculated within the Faroe-Shetland Channel (Turrell *et al.*, 1999). The typical temperature range of this water mass is 2 to 5.5 °C.

2.3.1.4 Norwegian Sea Arctic Intermediate Water (NSIW)

A second intermediate water mass within the Faroe-Shetland Channel is the Norwegian Sea Arctic Intermediate Water (NSAIW), also known as the Norwegian Sea Intermediate Water (NSIW). It occupies the depth band 600-800 m on the Faroe side, while on the Scottish side this band is much shallower and occasionally the NSAIW does not extend to the Scottish continental slope, allowing the AIW and the saline waters beneath to mix. The NSAIW is most likely created, with typical temperatures of -0.5 to 0.5 °C, in the surface waters north of the Arctic front in the Arctic domain of the Icelandic and Greenland Seas. It is then subducted beneath the front and flows down into the Faroe-Shetland Channel between the saline Atlantic water and the colder Norwegian Sea water.

2.3.1.5 Faroe-Shetland Channel Bottom Water (FSCBW)

The Faroe-Shetland Channel Bottom Water is the water mass with the highest density and lowest temperatures (< -0.5 °C) in the Faroe-Shetland Channel and therefore occupies the deepest parts of the Channel (below 800 m). The FSCBW was originally thought to be pure NSDW but it is now believed to be a mixture between NSDW and intermediate water masses, proportions of which vary decadally (Turrell *et al.*, 1999). The change is related to the rate of formation of NSDW in the Greenland Sea and Iceland Sea central gyres. During years of low production, the level of the NSDW is not high enough to reach above the sill depth (approximately 1500 m) at the entrance to the Faroe-Shetland Channel and the contribution of NSDW to the bottom waters of the Channel is reduced leading to a reduction in the volume of water entering the FSC (Turrell *et al.*, 1999) and the North Atlantic to form North Atlantic Deep Water, a finding supported by Tait and Martin (1961, 1965).

Water mass	Depth range	Area	Temperature (°C)	Salinity
Surface waters				
North Atlantic Water (NAW)	0 – 400 m (~ 500 m)	Scottish slope	> 8 °C	35.25-35.38
Modified North Atlantic Water (MNAW)	0 – 400 m (~ 500 m)	Central channel and Faroe side	6.5 - 8 °C	35.10-35.30
Intermediate waters				
Arctic Intermediate Water (AIW)	400 – 600 m	Across channel	2.0 - 5.5 °C	34.91-35.00
Norwegian Sea Arctic Intermediate Water (NSAIW)	600 – 800 m	Across channel	-0.5 - 0.5 °C	34.89-34.90
Deep water				
Faroe-Shetland Channel Bottom Water (FSCBW)	Below 800 m	Across channel	< - 0.5 °C	34.92

Table 2.1. Faroe-Shetland Channel water masses with their position, salinities and temperature ranges (from Turrell *et al*, 1999).

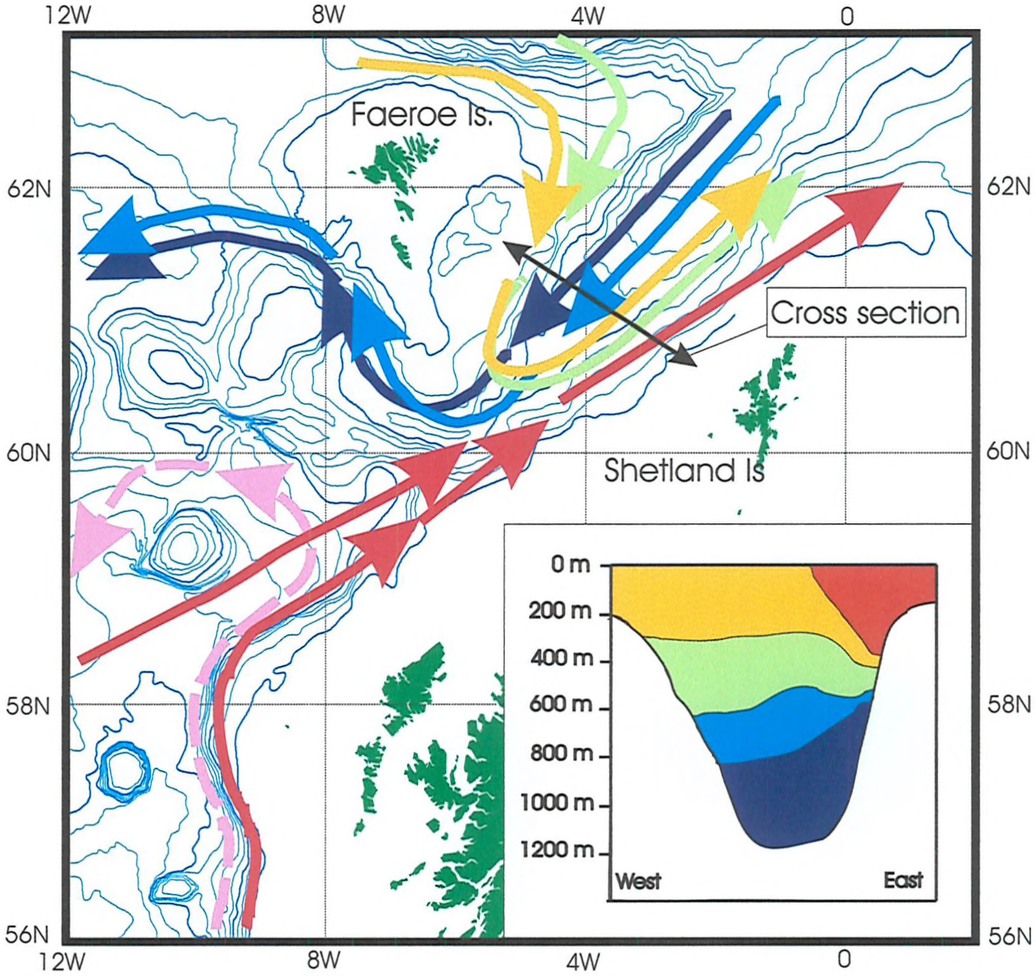


Figure 2.5. Cross section of the Faroe-Shetland Channel with its water masses and the circulation of the water masses within the Faroe-Shetland Channel: Red: North Atlantic Water (NAW); pink: NAW returning at depth, restricted by Wyville Thomson Ridge; yellow: Modified North Atlantic Water (MNAW); green: Arctic Intermediate Water (AIW); light blue: Norwegian Sea Arctic Intermediate Water (NSAIW); and dark blue: Faroe-Shetland Channel Bottom Water (FSCBW) (after Turrell *et al.*, 1999).

2.3.2 The currents and tides in the Faroe-Shetland Channel

Evidence for the presence of strong bottom currents in the deep sea have been found from many sources including seabed photographs (e.g. Heezen and Hollister, 1971; Howe and Humphery, 1995; Masson, 2001) and current meter data (e.g. Lonsdale and Hollister, 1979; Booth and Ellett, 1983; Hill and Mitchelson-Jacob, 1993; Howe, 1995; AFEN, 2000). Within the deep sea, currents may originate from two forces: thermohaline and tidal. The thermohaline circulation arises from density differences produced by thermal and salinity changes in seawater and originates from the formation of dense water masses in the North Atlantic and the Antarctic (Pinet, 1992; Tyler, 1995). Superimposed on the thermohaline flow are currents with a tidal component (tides and internal waves). Other features such as eddies, believed to cause 'benthic storms' (short-duration, high-energy events; Hollister and McCave, 1984) characterised by alternating direction of flow and strong current velocities (Howe, 1995), may also result from the two main forces (Tyler, 1995).

2.3.2.1 Currents and current speeds

Current speed will have a fundamental effect on both sediment dynamics and the biological communities in an area. The speeds of the currents flowing towards the northeast along the continental margin of Scotland have been obtained from measurements and estimated from studies of sedimentary structures (Kenyon, 1986; Masson, 2001). There is evidence of strong currents, typically 0.3-0.6 m/s (Saunders, 1990) flowing towards the northeast, a flow largely attributed to the Slope Current and covering the outer shelf and upper continental slope regions (table 2.2). Even stronger currents have been found on the inner Shetland shelf where tidally induced current speeds of 1 m/s and wave-induced currents of up to 4 m/s have been reported Stoker *et al.* (1993). Current-speed records for the cold-water (FSCBW) flowing towards the south at depths below 800 m in the Faroe-Shetland Channel are rare but typical speeds are between 0.1-0.2 m/s (Saunders, 1990) with peak velocities being 0.6 m/s or more (Stoker *et al.*, 1993; Masson, 2001). The understanding of current flows and speeds on the lower continental slope west of Shetland at depths between about 500 and 900 m is somewhat incomplete. Kenyon (1986) reports the presence of weak currents towards the northeast (deduced partly from the lack of sedimentary features). Masson (2001) reports a flow (in the depth range 750-950 m) both towards the northeast and the south/southwest, indicated by ripples and other bedforms, with current speeds of about 0.3-0.4 m/s but some of the features may be relict.

Location/current type	Depth range	Flow direction	Current speed	Author/s
Inner continental shelf				
Wave-induced	(~ 100 m)	northeast	4 m/s	Stoker *et al.*, 1993
Tidally-induced	(~ 100 m)	northeast	1 m/s	Stoker *et al.*, 1993
Outer continental shelf				
Slope current	~ 200 m	northeast	0.1-0.2 m/s	Burrows *et al.*, 1999
Slope current	~ 200 m	northeast	0.84 m/s (peak)	Stoker *et al.*, 1993
Slope current	~ 200 m	northeast	0.75 m/s (peak)	Masson, 2001
Upper continental slope				
Slope current	Down to 500 m	northeast	0.75 m/s (peak)	Kenyon, 1986
Slope current	Down to 500 m	northeast	0.84 m/s (peak)	Stoker *et al.*, 1993
Slope current	Down to 600 m	northeast	0.75 m/s (peak)	Masson, 2001
Lower continental slope				
Slope current?	500 – 800 m	northeast?	weak	Kenyon, 1986
Slope current?	750 – 950 m	NE/SW?	0.3-0.4 m/s	Masson, 2001
Deep water				
Deep FSCBW flow	> 800 m	south/ southwest	0.1-0.2 m/s	Saunders, 1990
			0.6 m/s	Stoker *et al.*, 1993

Table 2.2. Currents and current speeds in the Faroe-Shetland Channel.

Similar speeds to those recorded in the FSC have been recorded off the Scottish continental slope (table 2.3), an area believed to feed the surface waters of the Faroe-Shetland Channel with warm, saline water (Booth and Ellett 1983; Howe, 1995; Howe and Humphrey, 1995), and the Faroe Bank Channel (with maximum speeds of 1.09 m/s at 760 m depth within the Faroe Bank Channel; Crease, 1965).

Location/current type	Depth range	Flow direction	Current speed	Author/s
Hebrides slope				
Slope current	90-490 m	northeast	0.2 m/s	Booth and Ellett, 1983
Slope current	169 m	northeast	0.3 m/s	Howe and Humphrey, 1995
Slope current	457 m	northeast	0.25 m/s	Howe and Humphrey, 1995
Slope current	600 m	northeast	0.48 m/s	Howe, 1995
Slope current	1000 m	northeast	0.25 m/s	Howe, 1995
Slope current	1035 m	northeast	0.15 m/s	Howe and Humphrey, 1995

Table 2.3. Current speeds on the Hebrides slope.

2.3.2.2 Internal tides and oscillations

Internal tides cause wave-like oscillations of isotherms within the body of the ocean with a tidal period. Helland-Hansen and Nansen first discovered an internal tide in the Faroe-Shetland Channel in 1909 and called this phenomenon a 'boundary wave' (Sherwin, 1995). However, their results proved to be somewhat inconclusive. Since then internal waves within then Faroe-Shetland Channel have been largely neglected apart from occasional reports including that of a US Navy submersible in 1976. It reported periodic 'swirls of sand and dust (mud)' where the current rapidly increased to 2.5 knots, the temperature dropped and the direction of the current flow shifted by about 20 degrees, an effect that may also be attributed to small-scale eddies and 'benthic storms' (see Hollister and McCave, 1984; Sherwin, 1991, 1995; Tyler, 1995). In the 1990s, however, Fredriksen *et al.* (1992) and Klitgaard *et al.* (1997) attributed the development of sponge and cold-water coral populations on the Faroese shelf to increased detrital flux caused by increased vertical mixing resulting from the internal tide (figures 2.6 and 2.7). Sherwin (1991) reported both theoretical and observational evidence to support the presence of internal tides (amplitude of 37 m) at the deep pycnocline in the Faroe-Shetland Channel (c. 600 m depth). There are a number of theories for their creation, one being through the M_2 tidal mode (a semi-diurnal component of the tide principally attributed to the gravitational forces of the moon) moving northwards and across the Wyville Thomson Ridge, which is believed to be a major source of internal energy (Sherwin, 1991). The internal wave propagates northeastwards, parallel to the bottom contours, with a speed of about 0.6 m/s (Sherwin, 1995) and it may find a path at the boundary between two of the water masses where propagation is made easier.

The effects of such a 'boundary wave' will most likely be significant for the fauna present along the continental slope west of Shetland. There are several water masses with large temperature differences (range 8 °C to – 0.5°C) converging at about 500 m depth on the slope (Turrell *et al.*, 1999). The movement of these water masses as well as the oscillation of the internal tide is likely to change the position of these water masses vertically on the slope causing large temperature fluctuations in the 500 - 600 m depth band, and possibly deeper. TOBI CTD data (from AMES 1996; AFEN, 2000) show considerable variation in temperature in the water column (see figure 2.4) and a current meter temperature record (lasting 10 months during 1995/1996) from a site west of Shetland at 550 m (sensor placed approximately 2 m off the seafloor) revealed periods of extremely rapid change in temperature from -0.5°C to 8.0°C within an hour (the recording interval), although it should also be noted that the temperature was <1.0°C for the majority of the 10 month instrument deployment (AFEN, 2000; Masson, 2001). In addition to the effects on the fauna, there are also likely to be some effects (e.g. sediment accumulation and erosion; Stoker *et al.*, 1998) on seabed sedimentary features found on the continental slope, particularly at the boundary between the upper, warm and lower, cold layer, where the direction of flow may be reversed (see Masson 2001).

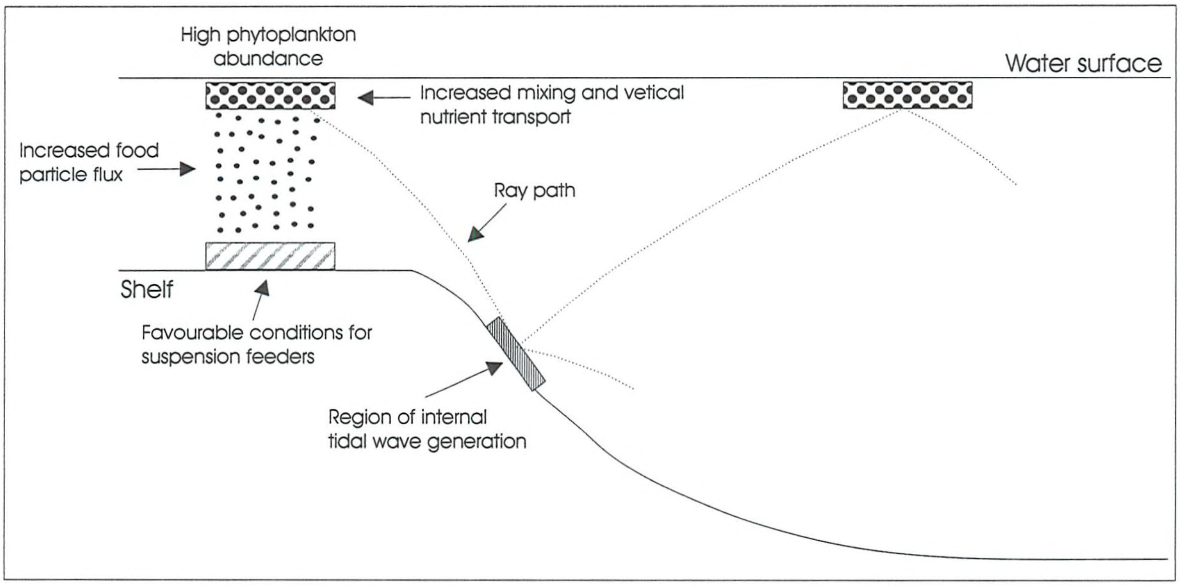


Figure 2.6. Increased particle flux at the shelf edge as a result of the propagation of internal waves (mechanism in surface waters; re-drawn from Klitgaard *et al.*, 1997).

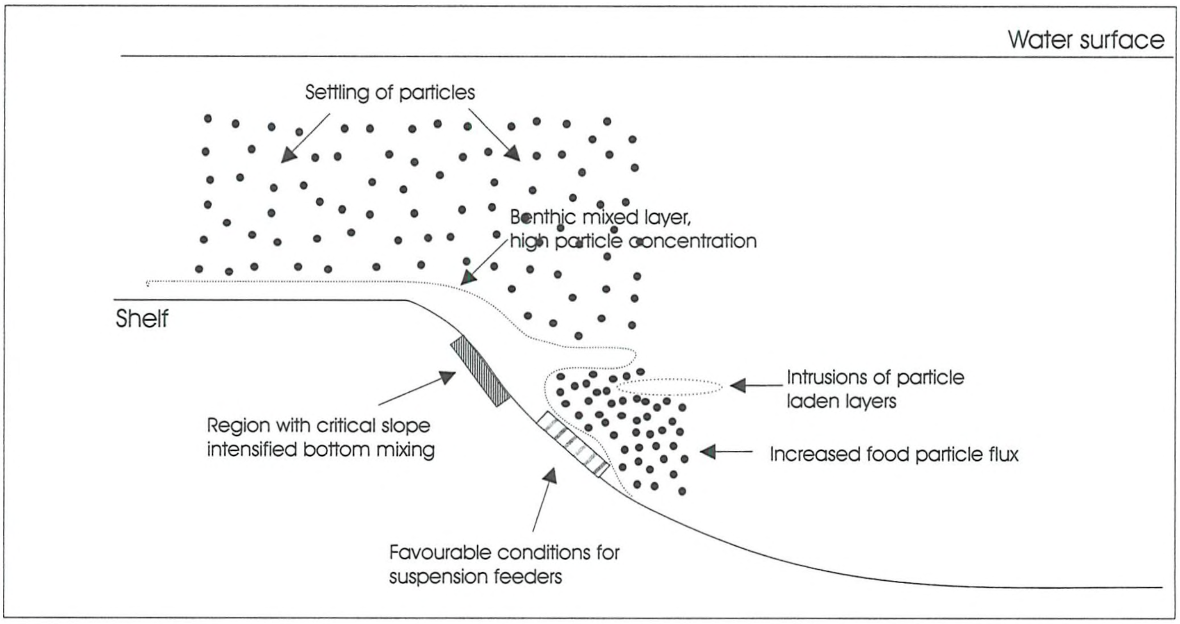


Figure 2.7. Increase in particle flux as a result of the intensification of bottom mixing in areas with a critical slope (mechanism in deeper waters; re-drawn from Klitgaard *et al.*, 1997).

2.4 THE GEOLOGICAL SETTING

2.4.1 INTRODUCTION

The geology of the area north and west of Scotland was little known before the 1960s (Kenyon, 1987; Stoker *et al.*, 1993) although some detailed geological surveys on adjacent land areas, including the Outer Hebrides and St. Kilda, had been carried out. Thousands of kilometres of seismic-reflection data have now been collected in connection with hydrocarbon exploration, predominately over the shelf and slope to the north and west of Shetland (Kenyon, 1987; Stoker *et al.*, 1993; Ebdon *et al.*, 1995). The crustal structure under the north Scottish shelf and Faroe-Shetland Channel was first investigated by seismic-reflection experiments in 1972, followed by the earliest exploration for hydrocarbons commencing in the same year (Stoker *et al.*, 1993; Ebdon *et al.*, 1995).

2.4.2 THE EVOLUTION OF THE FAROE-SHETLAND CHANNEL

Prior to the Mesozoic (250 million years ago) the North Atlantic did not exist as an ocean and the continental plates of North America, Greenland and Western Europe were joined together to form one landmass, Laurasia (Naylor and Mounteney, 1976; Bramwell, 1990; Pinet, 1992). Around this period the compressive regime changed to one of extension and crustal collapse and seafloor spreading in the North Atlantic was initiated. The first trough, a poorly defined triple junction in the Porcupine Seabight, is believed to represent the first attempt to create a northward extension but the line appears to have shifted westward to the Rockall Trough causing a partial separation (rifting) between the continental plate of Western Europe and that of Greenland and the Rockall Plateau. This rifting is believed to be the major event in the formation of the Faroe-Shetland Basin and sediments found in cores show Lower, Middle and Upper Jurassic ages indicating that the Faroe-Shetland Basin had formed by the early Jurassic (Hitchen and Ritchie, 1986; Haszeldine *et al.*, 1987; Masson, 2001). The Faroe-Shetland Basin was a branch of three basic trough systems within western Europe, forming a pattern of narrow, interlinked and faultbounded continental troughs. These roughly parallel features extending from the Arctic Circle in the north, down both sides of the British Isles: (figure 2.8)

1) A North Sea System of interlinked troughs from the continental shelf west of Norway, through the North Sea and into southern Europe.

2) A Skagerrak System consisting of the Oslo Rift and its continuation into the Skagerrak; the Danish-Polish Trough and the West Norway Trough.

3) A West Britain System extending from the West Shetland area through the Rockall Trough and the Rockall-Hatton Bank areas, and including the Porcupine Seabight and the Celtic Sea and Western Approaches troughs.

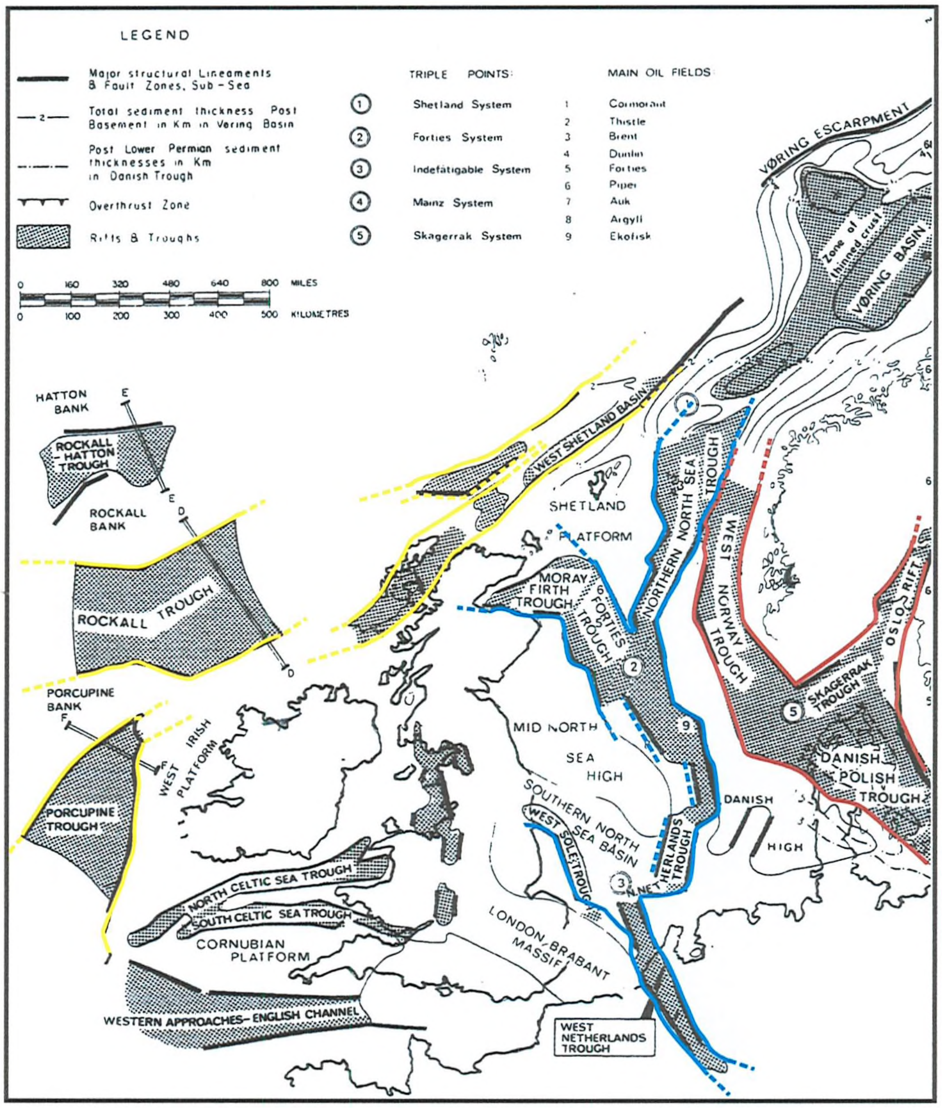


Figure 2.8. The three basic trough systems in western Europe (yellow: the West Britain System; blue: the North Sea System; red: the Skagerrak System and d-d, e-e and f-f are locations of seismic profiles; from Naylor and Mounteney, 1976).

The rifting (separation) that created the three trough systems ceased by the Middle to Late Cretaceous (60 to 90 million years ago) and the axis of active seafloor spreading again shifted westwards by some 1500 km to finally form a successful northward extension of the Mid-Atlantic Ridge system between Greenland and the Rockall Plateau (Naylor and Mounteney, 1976; Scrutton, 1986; Mudge and Rashid, 1987), a spreading axis that has maintained its position from the Early Tertiary to the present day where the rate of spreading is approximately 1.2 cm year^{-1} (Naylor and Mounteney, 1976).

Periods of widespread subsidence followed the initial rapid Lower Tertiary separation (rifting) of Greenland from North-west Europe, and the Rockall Trough along with much of the continental shelf to the north and west of the British Isles became submerged (Naylor and Mounteney, 1976; Ebdon *et al.*, 1995) with marine conditions producing a thick layer of accumulated marine sediments. Intense deformation in the region of the Wyville Thomson Ridge occurred in the Mid-Tertiary, forcing this area to take up much of the plate stress (Ebdon *et al.*, 1995) and both the Wyville Thomson and the Ymir ridge are believed to have been formed at this time (Scrutton, 1986; Andersen and Boldreel, 1995a; Andersen and Boldreel, 1995b).

To date most of the successful commercial oil and gas discoveries in the Northwestern European shelf have been associated with the thick sediments infilling the fault-bounded troughs in the North Sea area. Given their similar structures, it is believed that other troughs and platform flanks west of the British Isles are likely to present favourable conditions for oil exploration. Triple plate junctions occur throughout these rifted systems and are associated with hydrocarbon reserves. The West Britain System, which includes the West Shetland Basin and Northern North Sea Trough, has a triple junction centred just north of the Shetlands and this region has in recent years received a lot of attention for the potential hydrocarbon reserves in the area (Haszeldine *et al.*, 1987; Stoker *et al.*, 1993; Clarkson, 1998). Other triple junctions within the North Sea are the Forties (including the Forties, Ekofisk and Piper oil fields) and the Skagerrak triple junctions.

2.4.3 THE WEST OF SHETLAND REGION (SHELF, SLOPE AND CHANNEL BASIN)

2.4.3.1 Geology and geological composition

Continental crust about 30 km thick, mostly comprising basement Lewisian gneiss, is believed to underlie the whole of the Faroe-Shetland Basin (and northern part of the Rockall Trough). Beneath the major rift axis the crust is stretched and thinner compared to adjacent shelf areas (Naylor and Mounteney, 1976; Scrutton, 1986; Haszeldine *et al.*, 1987; Mudge and Rashid, 1987; Stoker *et al.*, 1993) and some work supports the theory that oceanic or quasi-oceanic crust is base to both the northern part of Rockall Trough and the Faroe-Shetland Basin (although seismic and magnetic anomaly profiles do not yield observations characteristic of normal oceanic crust), with continental crust forming the Faroe Plateau and the continental shelves and parts of the slopes of western Scotland and Shetland (Scrutton, 1986; Haszeldine *et al.*, 1987).

The regional structural evolution of the area west of Shetland from the Devonian is closely linked to the history of the North Atlantic region. The area west of Shetland has undergone episodic extension, resulting in the formation of a complex system of NE-SW trending basement highs and asymmetric basins with equally complex stratigraphic sequences present ranging from the Upper Palaeozoic to the present (Naylor and Mounteney, 1976; Duindam and van Hoorn, 1987; Stoker *et al.*, 1993; Ebdon *et al.*, 1995). The present-day geological composition on the shelf and slope is an oceanward-dipping wedge (particularly on the outer shelf and upper slope) of Tertiary sediments overlying the complex basin system (Duindam and van Hoorn, 1987; Stoker *et al.*, 1991) while the west of Shetland basin is covered by Late Palaeozoic and Triassic strata overlain by a thin Jurassic-Cretaceous sequence and a Tertiary-Quaternary sequence (Scrutton, 1986; Duindam and van Hoorn, 1987). The Faroe Basin was a major Cretaceous depocentre, which towards the north and northwest becomes obscured by basaltic rocks (Duindam and van Hoorn, 1987).

Present-day bathymetry (figure 2.1) and modern water circulation (figure 2.5) have developed since the mid-Tertiary when abyssal water circulation began causing erosion of older Tertiary deposits (Stoker *et al.*, 1991; Stoker *et al.*, 1993). At about 2.5 Ma there was a cooling of the climate culminating in widespread glacial activity on at least three occasions from 0.44 Ma until the present (Stoker *et al.*, 1993). During this period sedimentation is likely to have been affected by glacial-interglacial cycles and changes in sea level (Stoker *et al.*, 1991). Grounded ice-sheets extending to the shelf-edge are believed to have occurred during glacio-eustatic falls in sea level, depositing coarse debris directly on to the slope and basin plain. The depositional setting is envisaged to have been associated with a grounded submarine ice-sheet margin (Stoker and Holmes, 1991). In contrast, during interglacial periods sea levels would have been higher and the continental shelf would have been submerged. Hemipelagic sedimentation (settling of grains from suspension and currents) would have predominated on the slope and basin plain comprising a mixed facies assemblage of downslope deposits together with suspension sediments, both being locally modified by bottom currents (Stoker *et al.*, 1991).

2.4.3.2 Overview of seabed sediment, sediment bedforms and transport

The seabed surface is essentially a relict surface from the late Pleistocene and the sediment present indicates an ice-rafted and therefore pre-Holocene origin (Stoker *et al.*, 1991; Stoker *et al.*, 1993; Stoker, 1995; Masson, 2001). It is covered by a patchy veneer of unconsolidated sediments consisting of a mixture of both terrigenous (sediment derived from mechanical weathering of rocks on land) and biogenic carbonate material. There is a great deal of variability in sediment grain size, both in a local and regional respect but in general sediments rich in sand and gravel dominate the shelf areas while mud-rich sediments dominate the lower slopes and the basin floor (Stoker *et al.*, 1993). The survey area is fully covered by seabed sediment charts compiled by the British Geological Survey (BGS 1:250,000 sea bed sediments: Flett, Millar, Foula, Judd). These charts largely confirm the expectation that sediment type varies with depth, grading from coarse sands on the shelf edge to finer sediments on the floor of the Faroe-Shetland Channel (AFEN, 2000), where the 'mud-line' (a definition introduced by Le Danois (1948) as the upper limit of deep-sea conditions of soft and muddy seafloor sediments, the sand/mud boundary, with faunal elements characteristic of such habitat (Stanley and Wear, 1978; Kenyon, 1986) is difficult to establish but appears to occur at depths below 500-600 m (Kenyon, 1986), or even deeper (see Masson, 2001).

The terrigenous component is mainly derived from glacially related processes during the late Pleistocene (Stoker *et al.*, 1993; Masson, 2001). Since the last rise in sea level, the area has received little terrigenous sediment input but the sediment, particularly the sand fraction, has been reworked throughout the Holocene by bottom currents (Stoker *et al.*, 1993). Present day sediment input is thought to be largely restricted to biogenic carbonate sediments that have been accumulated through the Holocene (Light and Wilson, 1998). These predominantly exist on the inner and outer shelf but become rare at the shelf break and down the slope (Stoker *et al.*, 1993). During the period of lower sea level (early Holocene) the main carbonate production occurred in what is now the deeper part of the shelf. This centre of production has now shifted to the inner parts of the shelf, although some production is likely to occur on the outer parts of the shelf as well (Stoker *et al.*, 1993; Light and Wilson, 1998).

The variation in sedimentary features and processes west of Shetland appear to be strongly related to depth. Largely based on the interpretation of sidescan sonar data (figure 2.9), the area can be summarised into five different zones as follows (Stoker *et al.*, 1993; Masson *et al.*, 1996, 1997; AFEN, 2000; Masson, 2001):

(i) Inner continental shelf

The inner part of the West Shetland Shelf consists of significant amounts of gravel and sand deposits. The sand is transported away from regions of high hydraulic energy, mainly the elevated parts of the seabed (which are therefore characterised by gravelly deposits), and redeposited in the surrounding low-lying seafloor, where the currents are weaker, commonly forming sand waves and sandbanks (Stoker *et al.*, 1993; Stoker *et al.*, 1998). The net direction of transport, mainly by tidal currents, is towards the north with no evidence for transport of sediment from the inner to the outer shelf. Storm surge transport of sediment tends to be towards the coast (Kenyon, 1986; Stoker *et al.*, 1993).

(ii) Outer continental shelf (120-200 m water depth)

This zone is dominated by a variable cover of sand, in streaks and patches, overlying a gravel substratum. Sand cover is generally in the range 25-50% but varies from less than 5% to almost 100 % cover (Stoker *et al.*, 1993; Masson, 2001). The dominant bedforms are 1) elongated sand patches (indicating predominant transport towards the northeast and east-northeast), 2) areas of relict iceberg plough marks (gravel edges of plough marks largely filled with younger finer-grained sediments) (Belderson *et al.*, 1973), and 3) sand sheets burying older seafloor topography (Masson, 2001). The third type is most common, covering >75% of the seafloor, increasing towards the east where near 100% coverage is reached. There is net sediment transport towards the NE/ENE, with limited supply of sediment to the slope (Stoker *et al.*, 1993; Masson, 2001).

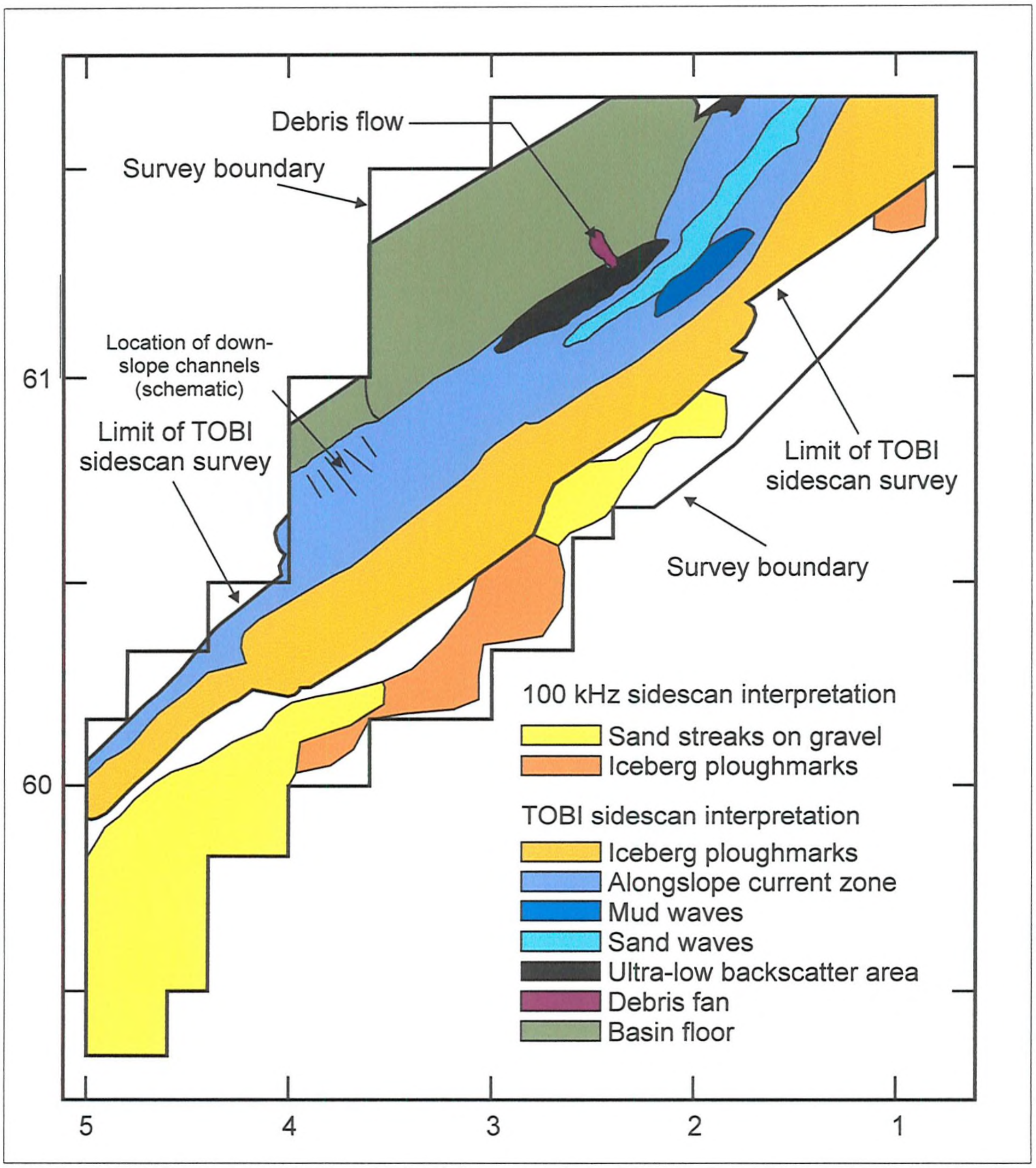


Figure 2.9. Sidescan sonar (100 kHz and TOBI) interpretation of the continental slope west of Shetland (adapted from Masson, 2001).

(iii) Upper continental shelf (200 to about 500 m water depth)

This zone is dominated by iceberg plough marks (most between 200 and 450 m but the deepest at about 500 m) with few post-glacial sedimentary features superimposed on the plough mark morphology (Belderson *et al.*, 1973; Masson, 2001) and particularly striking for the lack of submarine canyons (Stoker, 1995). Few plough marks have any topographic relief as they have been filled in with younger sediment. Gravel, often coarse, and sand dominate the seafloor sediments, where the gravel substrate is found in the ridge areas of the plough marks and relatively finer material, mainly sand, is found in the central grooves (Stoker *et al.*, 1993). Few bedforms are present, apart from comet marks and a field of barchan sand waves. These indicate net transport of sediment towards the northeast (Kenyon, 1986, 1987; Stoker *et al.*, 1993) and also a limited sediment supply (Masson, 2001).

(iv) Lower continental shelf (c. 500 m to c. 1000 m water depth)

The seafloor consists of a thin (5-15 cm) mixed, gravel/sand sediment, where variable amounts of small sand bedforms overlie a predominantly sand and gravel seafloor (Masson, 2001). In the southern part (south of 61°05′N), slope parallel erosional features (small- and large-scale furrows) dominate and large-scale depositional bedforms are absent. North of 61°05′N, depositional features such as mud waves (at 500-650 m), sand waves (at 600-750 m) and sand sheets (the ultra-low backscatter area at 750-950 m) dominate (Masson, 2001), where the latter is a sandy contourite deposit (Masson *et al.*, 1996, 1997; Bett, 2001a). There are also a total of fifteen downslope channels (from about 650 m and ending at about 1000 m; see mid-region figure 2.9) believed to be feeders for a glacial age debris flow fan (a relict feature only visible as a slight bulge). There is also a well-defined slope failure (or debris flow) feature (see figure 2.9) centred on 61°12′N, 03°30′W in an area of erosion. The transport of sediments is believed to be towards the southwest in the whole of this deep region, but evidence for this is somewhat incomplete (see hydrography section 2.3) (Masson, 2001).

(v) Faroe-Shetland Channel floor (>1000 m water depth)

The basin-floor consists of a thin layer (1-5 cm) of post-glacial sediments dominated by mud and muddy sands with some gravel, the latter being largely relict from the late glacial. The seafloor is mostly flat-lying and largely devoid of any distinctive current-induced morphology (Stoker *et al.*, 1991; Stoker *et al.*, 1998; Masson, 2001).

2.5 THE ECOLOGICAL SETTING

2.5.1 Introduction

The ecology of an area is influenced by a combination of complex environmental (e.g. sediment type, temperature, hydrography, salinity and oxygen concentrations) and biological interactions (e.g. food supply, feeding mode and bioturbation) (Belyayev *et al.*, 1973; Tait, 1981) as well as anthropogenic factors in some areas (e.g. Pearson and Rosenberg, 1978). The first two sets of factors exhibit vertical gradients establishing depth "zones" with different living conditions (Lalli and Parsons, 1993) and the fauna can be divided into shallow, bathyal (or slope) and deep-water zones (where the bathyal group consists of a transitional fauna comprising species from both the shallow and deep-water; Menzies *et al.*, 1973; Grassle *et al.*, 1979; Gage and Tyler, 1991), according to these environmental conditions. Although there are arguments regarding the definition of these depth-related zones as they are dependent on specific hydrological and ecological features for each geographical region (Menzies *et al.*, 1973). It has been suggested that temperature is one of the most important factors controlling the distributions of aquatic animals (Westerberg, 1990; Gage and Tyler, 1991) and it is one of the characteristics that distinguishes different water masses. Temperature has been used to classify benthic assemblages (Glemarec, 1973; Dyer *et al.*, 1983) where thermal stability was the main factor determining benthic community composition. However, rather than there being just one controlling factor, it may be a combination of factors that ultimately produce the observed community structure (Tait, 1981).

The Faroe-Shetland Channel is, as noted above, a very complex basin, both with regards to hydrography and geology. Although it was one of the first deep-sea areas to be dredged for life during the HMS *Lightning* cruise of 1868 and later on the HMS *Porcupine* cruises of 1869 and 1870 (Thomson, 1873), little is known about the faunal composition and benthic populations in the area and much of the information still based on the nineteenth century dredgings. However, with the large amount of data collected during the large-scale AFEN surveys of 1996 and 1998, together with the BIOFAR (Benthic BIOlogy of the FARoe islands) programme established by the Nordic Council for Marine Biology in 1988 (Nørrevang, 1992), our knowledge and understanding of the biology and ecology of this area is increasing.

2.5.2 Benthic populations on the continental shelf west of Shetland

There is relatively little available information on the abundance, biomass and composition of the benthic populations, both with regards to the mega- and macrobenthos, of the shelf area west of Shetland. The mega- and macrofauna present on the continental shelf will therefore be described together, divided into the epibenthic and the infaunal populations.

2.5.2.1 Epibenthic populations

On the continental shelf west of Shetland the epibenthic populations are best known as this group is easiest to study using trawls and photographic surveys (Aspinall *et al.*, 1992). Studies such as that of Dyer *et al.* (1982), using a combination of a Granton trawl and a headline camera are particularly useful in sampling large areas of low population density. This, together with a few other studies, have indicated a generally strong similarity between the west of Shetland shelf benthic communities and those of the northern North Sea, areas with stable temperatures between 6-7°C and salinities at 35.0-35.2, waters believed to originate from the Slope Current west of Scotland (Dyer *et al.*, 1982; Dyer *et al.*, 1983; Cranmer *et al.*, 1984; Aspinall *et al.*, 1992).

The echinoid *Cidaris cidaris* and the serpulid polychaete *Ditrupa arietina* were considered to be particularly characteristic of the West Shetland Shelf area, being rare in the North Sea (Dyer *et al.*, 1982), while Aspinall *et al.* (1992) include *Cidaris cidaris, Echinus elegans* and *E. tenuispinus* in the group particularly characteristic of the *outer* West of Shetland shelf, stating that these species are only found below the shelf edge further south in the Rockall Trough (Gage *et al.*, 1985; Aspinall *et al.*, 1992). Other dominant fauna (see table 2.4) of the current swept seabed west of Shetland includes the tube dwelling polychaete *Hyalinoecia tubicola*; the asteroids *Asterias rubens*, *Porania pulvillus, Luidia ciliaris* and *L. sarsi*; and the echinoid *Echinus acutus (*Dyer *et al.*, 1982, 1983). Cranmer *et al.* (1984) also noted the squat lobster *Munida rugosa*, the anthozoan *Actinauge richardi* and sea pen *Pennatula phosphorea*, the latter having a large population west of Shetland, while Basford *et al.* (1989) noted the echinoids *Spatangus purpureus*, *Psammechinus miliaris* and *Echinus acutus* and the asteroid *Asterias rubens* in an area southwest of the Shetland Islands. The solitary cup-coral *Carophyllia smithii* has also been shown to be locally common (Wilson, 1975).

Area	**Physical characteristics**	**Key fauna**
West Shetland Shelf Depth: 100-200 m	Strong tidal and storm-driven currents Mixed glaciomarine sandy/gravelly sediments Linear bedforms	**Polychaetes:** *Hyalinoaecia tubicola, Ditrupa arietina* **Molluscs:** *Aporrhais pes-pelecani, Astarte sulcata, Venus ovata, Spisula elliptica* **Echinoderms:** *Cidaris cidaris, Echinus tenuispinus, Spatangus purpureus, Echinocardium flavescens, E. pennatifidium, Echinocyamus pusillus*

Table 2.4. The seabed environment and some key fauna of the West Shetland Shelf (from Aspinall *et al.*, 1992).

The major influence on the characteristic faunal groups of the West Shetland Shelf, as identified by Dyer *et al.* (1982 and 1983) is believed to be the rock-gravel substratum together with the Atlantic water and its associated plankton community (Dyer *et al.*, 1983). However, the West Shetland Shelf benthos could be separated from those of the northern North Sea; however, the use of 'Arctic bobbins' (guards fitted to the footrope of the trawl to protect the net against the rough grounds) may have influenced the sampling efficiency and contributed to the distinctiveness of the West Shetland Shelf fauna region.

Estimates of population densities on the West of Shetland shelf are, as with other data, fragmentary and sparse. Dyer *et al.* (1982) report some values estimated from photographs and trawls (table 2.5).

Faunal group	**Genus/species**	**Density from photographs**	**Densities from trawls**
Cnidaria	*Pennatula phosphorea*	14 ind./100 m^2	Not caught
Polychaeta	*Hyalinoecia tubicola*	142 ind./100 m^2 *	142 ind./100 m^2 *
	Ditrupa arietina	>1000 ind./100 m^2	Not caught
Crustacea	*Nephrops norvegicus*	1 – 10 ind./100 m^2	3 ind./100 m^2
Echinoidea	*Cidaris cidaris*	9 – 22 ind./100 m^2	4 – 100 ind./100 m^2
	Echinus acutus	7 – 168 ind./100 m^2	Up to 50 ind./100 m^2
Asteroidea	*Asterias rubens*	< 2 ind./100 m^2	< 2 ind./100 m^2

Table 2.5. Population densities of some species on the continental shelf West of Shetland (from Dyer *et al.*, 1982). * The values given without indication of recording method

Cranmer *et al.* (1984) added further data on standing stocks. *Actinauge richardi* was found all over the northern North Sea but was most common west of Shetland with values of around 9 individuals/100 m^2 (from photographs). *Munida rugosa* was recorded at approximately 3 individuals/100 m^2 and *Pennatula phosphorea* was recorded in numbers of 480 individuals/100 m^2, a value far exceeding that reported by Dyer *et al.* (1982). South-west of Shetland faunal densities were lower (table 2.6), values that may attributed to the use of an Agassiz trawl (Basford *et al.*, 1989).

Faunal group	**Genus/species**	**Densities from trawls**
Asteroid	*Asterias rubens*	1 - 4 ind./1000 m^2
Echinoid	*Spatangus purpureus*	1 - 4 ind./1000 m^2
	Psammechinus miliaris	1 - 4 ind./1000 m^2
	Echinus acutus	5 – 9 ind./1000 m^2

Table 2.6. Faunal densities from the continental shelf southwest of the Shetland Islands (from Basford *et al.*, 1989)

The values in table 2.5, and perhaps the other values as well, should be viewed with some degree of caution. The sampling efficiency of trawls and photographic instruments have been shown to be different in several studies (e.g. Rice *et al.*, 1982; Rice and Collins, 1985; Cailliet *et al.*, 1999). Towed gear (e.g. trawls and sledges) sampling is often inconsistent (e.g. vertical movement of the gear off the seabed and not sampling all types of fauna) and the towed distance is often only approximate. Photography will provide estimates of faunal densities from the surface of the seafloor but the observed densities may not 'adequately' represent all the fauna present in the top section of the substrate, as some fauna may be buried deeper into the sediment. In addition, identification of fauna seen on photographs may be difficult.

Dyer *et al.* (1982) gave estimates of *Ditrupa* and *Pennatula phosphorea* abundances from photographs on the west of Shetland shelf, but none were caught in the trawls. Rice and Collins (1985) also reported similar results of sampling inconsistency using photographs and trawls for these two above species. Furthermore, many of the *Ditrupa* individuals seen in the photographs may only have been empty tubes (Dyer *et al.*, 1982). In addition, the abundance of *Nephrops norvegicus* may be underestimated, as they typically remain in burrows during the day and although their burrows were common, individuals were rarely seen. Macrofaunal biomass values for the west of Shetland shelf are almost entirely absent, with the only estimated values reported by Aspinall *et al.* (1992) at 1-4 g dry weight/m^2.

2.5.2.2 Infaunal populations

Relevant data are sparse despite the fact that surveys on the shelf west of Shetland started in 1882 with Tizard and Murray (Aspinall *et al.*, 1992). These records include fauna such as the mollusc *Venus ovata* and the spatangoid *Spatangus purpureus* in communities characteristic of sandy current-swept bottoms (Aspinall *et al.*, 1992). Other data exist including unpublished reports by the British Geological Survey (BGS) and some records from grab sampling by the Scottish Marine Biological Association in the region of the Wyville Thomson Ridge from 1976. These records confirm, according Aspinall *et al.* (1992), the prediction that the community composition on current-swept coarse deposits west of Shetland will be dominated by the species found by Eleftheriou and Basford (1989) to be characteristic of the coarse sediment north and east of Shetland. Biomass is dominated by carnivorous polychaetes such as *Goniada maculata, Glycera lapidum* and *Protodorvillea kefersteini* (Eleftheriou and Basford, 1989). The BGS data show the presence of molluscs such as *Spisula elliptica* and *Moerella pygmaea* in shallower areas, while other species such as *Puncturella noachina* and *Alvania* spp. and the echinoid *Echinocyamus pusillus* occur over a wider depth range (Aspinall *et al.*, 1992).
Künster *et al.* (1992) report a sediment median grain size of >500μm on the West of Shetland shelf with the fauna being dominated by the echinoid *Echinocyamus pusillus*; the polychaetes *Sphaerosyllis bulbosa, Glycera celtica, Glycera lapidum* and *Pisione remota*, and the mollusc *Spisula elliptica.* All of these species are found in coarse sediments in the North Sea, with the exception of *Sphaerosyllis bulbosa* and *Glycera celtica*, which are restricted to the coarse sediments along the Scottish east coast, the former being found east, south and southwest of Shetland (Künster *et al.*, 1992). Species number and diversity increase gradually from the <30 m assemblages in the North Sea to the 30-70 m assemblages and are highest in the areas deeper than 70 m (Künster *et al.* 1992). Biomass is low (Künster *et al.* 1992) with a benthic infaunal standing crop of approximately 1.4 g dry weight/m^2, similar to that of the northern North Sea (see Aspinall *et al.*, 1992).

2.5.3 Deep-sea populations in the Faroe-Shetland Channel

One important discovery by the HMS *Lightning* and HMS *Porcupine* cruises was the presence of a conspicuous deep-water fauna in a cold-water layer consisting of pycnogonids (*Collossendeis proboscidea)*, echinoderms (the echinoid *Pourtalesia jeffreysi* and the asteroid *Hymenaster pellucidus*) and amphipod species now known to be characteristic of the deep Arctic and Norwegian Seas (Aspinall *et al.*, 1992). More recent trawling carried out by the Scottish Marine Biological Association has also shown the faunal composition of the Faroe-Shetland Channel to be a southern extension of the deep-sea benthic fauna characteristic of the Norwegian and Arctic Seas (Aspinall *et al.*, 1992). Despite these early studies, the available information remains rather sparse, the lack of information is particularly marked when the information available west of Shetland is compared to that of the Faroe side of the Channel where the BIOFAR programme has been in operation since 1988 (see section 2.5.3.3).

2.5.3.1 The continental slope West of Shetland - megafauna

Between the late nineteenth century trawlings and the AFEN surveys in the 1990s very little work has been carried out in the Faroe-Shetland Channel. Some preliminary qualitative results of the AFEN 1996 survey described by Masson *et al.* (1996) and AFEN (2000) have revealed a megabenthos exhibiting substantial variation in abundance and composition within the survey region. The variations seen in the megafauna are believed to be related to depth trends reflecting the responses to both hydrographic and sedimentary parameters (Bett, 2000a). Hard substrata (gravel, pebbles, cobbles and boulders) are relatively rare in the deep sea on a global scale, but are readily available on the west of Shetland continental slope, particularly on the upper part of the slope. This is likely to have a very marked influence on the biological communities present (Masson *et al.*, 1996).

Aspinall *et al.* (1992) produced a qualitative summary of the benthic fauna west of Shetland divided into two main depth bands (table 2.7). There are few estimates of megafaunal standing crop from the continental slope of the Faroe-Shetland Channel. Biomass values for the Faroe Bank Channel are available and are thought to be representative of the area in general (Aspinall *et al.*, 1992). On a sand-gravel deposit wet-weight biomass was estimated at c. 20g/ m^2, a value comparable to available data for similar depths in the Rockall Trough (Aspinall *et al.*, 1992). These data should, however, be considered with caution as the environmental setting is highly variable within the Atlantic Margin region and the generalisation of Aspinall *et al.* (1992) may have to be reconsidered once more west of Shetland data have been analysed.

Area	Physical characteristics	Key fauna
Faroe-Shetland Channel: upper slope Depth: 200 –500 m	Strong north-flowing slope current Mixed glaciomarine gravelly sediments Iceberg plough marks	**Many species observed on the continental shelf plus:** **Molluscs:** *Limopsis aurita* **Echinoderms:** *Spatangus raschi* **Coral:** *Lophelia pertusa*
Faroe-Shetland Channel Depth: 500 – 1500 m	Variable southward flowing, sub-zero temperature deep-sea current Mixed glaciomarine deposits with increased mud content	**Pycnogonida:** *Colossendeis proboscidea, Boreonymphon abyssorum, Nymphon elegans* **Echinoderms:** *Ophiopus articus, Ophiopecten gracilis, Hymenaster pellucidus, Poutalesia jeffreysi, Brisaster fragilis*

Table 2.7. Summary of benthic environment of the West of Shetland region (from Aspinall *et al.*, 1992).

Aspinall *et al.* (1992) furthermore suggested that there is a faunal boundary at depths between 400 – 500 m in the Faroe Bank Channel and that this pattern may extend to other areas within the Faroe-Shetland Channel. Above the boundary, particularly 250 m and shallower, most taxa are believed to be characteristic of the whole of the West Shetland Shelf. This boundary may be reflected in the distribution of many faunal groups including the crustacean genus *Munida*, a genus with different species distributed within particular depth intervals. Three species are 'potentially' found west of Shetland and their typical bathymetric distribution is shown in table 2.8 (Rice and de Saint Laurent, 1986). If, however, the boundary as described by Aspinall *et al.* (1992) is present west of Shetland the bathymetric distribution of this group, and potentially other groups, may be different to their distributions as recorded in other areas in the Northeast Atlantic.

Species	**Depth range**
Munida rugosa	30 – 300 m
Munida sarsi	200 – 800 m (most abundant 250 – 400 m)
Munida tenuimana	> 550 m (typical 700 – 1400 m)

Table 2.8. Depth distribution of some species of *Munida* west of Shetland (from Rice and Saint Laurent, 1993)

Within the published AFEN (Bett, 2000a; 2001a) megafaunal data (qualitative summary) two local-scale variations in the megafauna (within the iceberg plough marks and the sand contourite) and two biologically mediated habitats (the sponge-belt and the deep-water coral *Lophelia)* have been described.

The features seen in the iceberg plough marks from the continental shelf (see above) extend down to the upper continental slope (c. 500 m) and are essentially the same. The second localised fauna is that of an abundant surface-dwelling population of enteropneusts on the sandy contourite at about 900 m west of Shetland.

The two biologically mediated habitats have been described from the BIOFAR programme (see section 2.5.3.3 below) and while the 'sponge-belt' appears to be a significant feature west of Shetland, *Lophelia* appears to be less common (Bett, 2001a). The 'sponge-belt' on the West Shetland Slope was found at about 500 m, a depth at which sub-zero temperatures could be experienced (Bett, 2001a). In contrast, the belt around the Faroe Islands was found in temperatures of about 5°C suggesting that local hydrodynamics (see section 2.5.3.3 below), rather than temperature, may be significant in controlling the distribution of the 'sponge-belt' (Bett, 2001a).

Wilson (1979b) and Rogers (1999) reported the distribution of *Lophelia pertusa* in Scottish waters, including several sites along the continental slope immediately west and north of Shetland at depths between 200 and 500 m. However, it was noted that the coral was less common in this region compared to other sites in the northeast Atlantic (Bett, 2000a), a fact essentially in agreement with the observations made by Wilson (1979b).

2.5.3.2 The continental slope West of Shetland - macrofauna

Prior to the AFEN surveys of 1996 and 1998 the macrofaunal communities along the continental slope west of Shetland were almost entirely unknown. Analysis has now been carried out on the AFEN 1996 data looking at the larger (500µm) size fraction (Bett, 2000a) and also on the smaller size fraction (>250-500µm) along a bathymetric transect west of Shetland (Narayanaswamy, 2001).

The abundance and biomass of deep-sea macrofauna is generally believed to decrease with depth, mainly as a result of food availability (Gage and Tyler, 1991). However, this trend was not observed for either size fraction on the West Shetland Slope. Both sets of data appear to indicate a general decrease in abundance with depth from the shelf but with a peak mid-slope (small; 550 m and large; 700 m) then declining again to the floor of the Faroe-Shetland Channel, although it was speculated that sampler bias may have influenced the results to some extent (Bett, 2000a). Different sampling devices had to be used in the survey area as a result of the varied seafloor, and the comparison of samples obtained from different sampling devices may complicate interpretations (Bett *et al.*, 1994; Bett, in press). Biomass values are constant for both size fractions over most of the depth interval although there are marked peaks at 550 m (Narayanaswamy, 2001) and between 300 and 400 m (Bett, 2000a).

Species diversity has been shown to broadly decrease with depth, although there is a maximum at about 450-550 m in the smaller size fraction (Narayanaswamy, 2001) and a local maximum at 400-500 m in the larger (Bett, 2000a). Within the smaller size fraction strong correlations were found between diversity and grain size (positive) and temperature (positive) (Narayanaswamy, 2001). Within the larger size fraction significant correlations have been found between diversity and clay content and depth but these did not appear to explain the local maximum (Bett, 2000a). However, habitat temperature range appears to vary in a similar manner to diversity and may be the strongest controlling factor for the larger (>500μm) macrofauna along the West Shetland Slope (Bett, 2000a). Other biological factors have also been suggested. The enhanced diversity at 300-600 m corresponds with the depth range where the epifauna is best developed (Bett, 2000a). The epifauna may increase the number of available habitats and therefore potentially increase the overall diversity of the macrofauna inhabiting this zone. Bett (2000a, 2001a) further suggested that the 300-600 m depth band is an ecotone where two different 'communities' meet. Diversity may be enhanced as a result of the presence of species from both 'communities' and potentially other species restricted to the ecotone itself. Species from both the 'cold-' and 'warm-water' faunas together with 'specialist' species would be present, enhancing species diversity.

In the analysis of the large-scale macrofaunal distribution, Bett (2000a) revealed two major features from classification and ordination. Firstly, the distribution of the fauna strongly reflects the distribution of water masses in the Faroe-Shetland Channel, i.e. an upper (shallow) warmer layer, a lower (deep) cold layer, and an intermediate or transitional zone. Secondly, within these layers there is a strong bathymetric gradient in the distribution of the macrofauna.

The fauna was analysed in relation to the three layers, or depth bands, warm, intermediate and cold. The three most dominant species in each depth band were analysed illustrating a range of responses to the temperature/depth gradient. Some species (e.g. *Ditrupa*) were restricted to the warm band, some (*Spiophanes*) were most abundant in the warm but extended into the intermediate, some were maximally abundant in the intermediate band but extended into the warm (*Scionella*) or cold (*Paramphinome*) bands, and some were most abundant (*Maldaninae*) in the cold band but extending into the intermediate band. For the whole macrofaunal dataset the percentage of species restricted to a particular temperature band were: warm 23.6%, intermediate 18.0% and cold 7.8%. Molluscs were shown to be most frequent in warm and warm/intermediate waters whereas isopod and tanaid crustacean species were particularly well represented in intermediate and/or cold waters.

Although zonation of the fauna based on water masses is useful, Bett (2000a, 2001a) reported that the West Shetland Slope spanned a number of environmental gradients without distinct boundaries. The most obvious examples are the hydrographic parameters, as witnessed by variations in water temperature. Depth-related parameters such as sediment grain size and organic content should also be considered. However, the best description of the macrofaunal distribution on the West Shetland Slope may, according to Bett (2000a), be the ecotone concept as mentioned above. The ecotone represents an overlapped boundary between two 'communities' (the warm and the cold water masses) containing some elements from both communities and potentially some specialist 'edge species' (Bett, 2000a; Bett, 2001a), a description that appears to be similar to that of the bathyal depth zone, consisting of transitional fauna between the shallow and deep-water regions (Menzies *et al.*, 1973; Parsons *et al.*, 1984; Gage and Tyler, 1991).

2.5.3.3 The Faroe Islands

In contrast to the West of Shetland region, the Faroe Islands have been studied in some detail, particularly through the BIOFAR programme. Of particular interest to the general ecology of the region are two significant 'biological habitats': the bank-forming coral *Lophelia pertusa*, and that referred to by fisherman variously as "*ostur*", "*ostebund*" or "*cheese bottoms*" and their faunal associates (Fredriksen, 1992; Jensen and Fredriksen, 1992; Klitgaard, 1995; Klitgaard *et al.*, 1997).

The presence of "*ostur*", or the sponge-belt, has been well-known among fishermen but went undetected during earlier investigations. The sponge-belts are now known to exist in many parts of the region and they are typically found on coarse sediment (coarse sand, gravel and pebbles) in long narrow zones close and parallel to the shelfbreak at depths of about 200-300 m, although in some areas the belt can reach depths of 600 m (Klitgaard *et al.*, 1997). The estimated densities of large sponges ranged from 1 ind./10-30 m^2 (from photography) to 1 ind./10-50 m^2 (from dredging). The sponges constitute more than 90% of the biomass (excluding demersal fish) and high diversities of up to 50 different species of sponge have been recorded, including *Geodia barretti, G. macandrewi, Isops phlegraei* and *Stryphnus ponderosus*, all of which can reach sizes of more than 20 cm in diameter (Klitgaard *et al.*, 1997). In addition, a large number of species (100+) were found to be associated with sponges. In contrast to tropical waters where many obligate sponge associates are found, the epi- and infauna associated with sponges around the Faroes were shown to be facultative inhabitants representing the fauna present in the local area (Klitgaard, 1995).

The bank-forming coral *Lophelia pertusa* has recently been give a lot of attention in relation to the development of the deep-water oil and gas industry within the FSC. *Lophelia* is widely distributed in the North Atlantic (east and west; Rogers, 1999). Within the north-east Atlantic it has been recorded from Norway (Mortensen, 2001) down to the Rockall Trough (Wilson, 1979a, b) and through Biscay, down the Iberian peninsula on to west Africa and it appears to be most frequently encountered on the shelf and upper slope at depths of 200-400 m, where temperatures generally range from 4-8° (Freiwald, 1998; Bett, 2001a). Around the Faroe Islands *Lophelia* shows a wide, albeit patchy, distribution in discontinuous areas parallel to the shelfbreak or along the slope in depths ranging from 200-600 m and it has a rich associated fauna of nearly 300 species using the coral not only as a site for feeding but also as a refuge (Fredriksen *et al.*, 1992).

It has been speculated that the reason for the presence of the *ostebund* and *Lophelia* may be related to hydrographic conditions, and the internal tide in particular (see hydrography section 2.3) (Jensen and Fredriksen, 1992; Klitgaard *et al.*, 1997). The fauna, including the coral and sponges themselves, mainly consist of suspension feeders utilising the increased levels of food availability as a result of higher levels of suspended particles (produced by the propagation of an internal wave or, through the intensification of bottom mixing in areas with a critical slope) in the water column compared to other sites (Frederiksen *et al.*, 1992). The influence of an internal tide has been shown to occur in other areas of the Faroe-Shetland Channel (Sherwin, 1991 and 1995) and it may influence the distribution patterns of sponges and coral elsewhere in the channel.

Other BIOFAR studies include that of the octocoral, *Paragorgia arborea*, which has also been recorded in Faroese waters (Tendal, 1992). It is associated with water of North Atlantic Water origin (temperature of 6-9°C) at depths ranging from 260 to 300 m, southeast of the Faroe Islands, in locations where maximum current velocities have been measured at about 45-60 cm/s.

Emson *et al.* (1994) reported a rich species diversity of ophiuroids around the Faroe Islands, where they form a large, conspicuous and ecologically significant element of the benthic fauna. Hydrographic conditions seem to exert the main influence on the fauna but the variable nature of the substratum also exercises a strong control over ophiuroid distribution (Emson *et al.*, 1994). At the larger scale, most ophiuroids around the Faroes fall into a 'warm-water' category as most individuals found inhabit regions influenced by North Atlantic Water. Included in this group are *Ophiacantha abyssicola*, *Ophiactis balli, Ophiura ophiura* and *Ophiura albida*. Only five of the species found were considered to be 'cold-water' or Arctic species, including *Ophiopholis aculeata, Ophiacantha bidentata, Ophioscolex glacialis*, *Ophiura sarsi* and *Ophiura robusta. Ophiactis abyssicola* may also be considered to be an Arctic species as in the deeper parts of its range (total range: 260 – 1320 m) it appears to be associated with the Norwegian Sea outflow (Emson *et al.*, 1994).

Ophiopholis aculeata is a shallow water species (shelf and upper bathyal region) associated with the colder water and it was the most common ophiuroid found during BIOFAR. *Ophiura sarsi* is also abundant and it is found along the upper slope where sandy conditions prevail. It is generally considered to be a shallow water Arctic species but around the Faroe Islands it seems to be associated with the lower layers of the North Atlantic surface water rather than the deeper Norwegian Sea water (Emson *et al.*, 1994). Species of the 'warm' water, e.g. *Ophiacantha,* together with the Euryalae, Ophiomyxidae and Ophiacanthidae generally, are suspension feeders and associated with the 'sponge belt' (Emson *et al.*, 1994).

3 METHODS AND TECHNOLOGY I

3.1 FIELD METHODS

The AFEN seabed surveys of 1996 and 1998 were different in approach to previous surveys in the region. Statutory and company initiated seabed surveys in the areas of the UKCS explored previously had essentially been point source surveys around a drilling location or platform. The philosophy had been to carry out a baseline, pre-operational survey based on sample grids or transects and to revisit these sites at intervals over the following years to monitor the changes in contamination levels and effects on the seabed communities. This necessitates the ability to return to the sample location, preferably to the exact same spot, but at least to within a few metres. This is just possible in shallow water depths and where low current speeds are experienced, although even here it is often unsatisfactory.

The survey design adopted by AFEN was a combination of seabed mapping using sidescan sonar imaging followed by sampling the seabed sediments using a range of equipment to suit the sediment types encountered. These two principal tools were supplemented by seabed photography to help 'ground truth' the sonar images and provide a broader view than that derived from individual core samples. The intent was for the sample sites to be located based on the information, particularly on sediment fabrics, obtained from the sidescan imaging. The first survey was carried out in the summer of 1996 (for the 16th licence round) and a further survey was carried out in the summer of 1998 to cover the blocks licensed in the 17th round (the licence round being the method by which the UK Government allocates areas to oil and gas companies for exploration of hydrocarbon reservoirs).

3.1.1 Sidescan sonar

There are numerous types and varieties of sidescan sonar (Blondel and Murton, 1997). For the purpose of the AFEN surveys TOBI (Towed Ocean Bottom Instrument), a 30 kHz sidescan sonar instrument, was used for the deep-water work (>200 m) and a 100 kHz sidescan was used in areas with a water depth <200 m.

TOBI is primarily used for deep-sea surveys and can be operated in depths from 200 to 6000 m (Masson *et al.*, 1996, 1997; Masson, 2001). The instrument consists of a two-body tow system providing a highly stable platform. The sidescan sonar vehicle is neutrally buoyant and is connected to a depressor weight (600 kg) via a neutrally buoyant umbilical (Masson *et al.*, 1996). The depressor weight is in turn connected, via a conducting swivel, to the survey vessel's armoured coaxial tow cable. The vehicle is towed behind the ship at approximately 3 knots and it is kept between 200 and 400 m above the seafloor. It operates at 30 kHz, giving a resolution of between 5 to 10 m (range dependent), and is able to cover a 'swath' of 6 km (3 km to either side of the instrument) (Blondel and Murton, 1997). During the surveys the position of the TOBI instrument was obtained by the use of a 'Nautronix' transponder beacon fitted to the vehicle and the ship-mounted 'Nautronix' Ultra Short Base Line (USBL) navigation package (Masson *et al.*, 1996). In addition to the sidescan and the positioning instruments the vehicle also carries a 7.5 kHz profiler, a three-axis fluxgate magnetometer, a CTD and a pitch and roll sensor.

The standard sidescan sonar instrument used at shallower depths and during a more recent detailed study of the 'Darwin Mounds' (chapter 9) area was a 100 kHz system. The instrument was towed behind the ship at a speed of about 3 to 4 knots and it is kept between 25 and 50 m (ideally 25-30 m) above the seabed giving a swath of about 600 – 800 m (300 – 400 m either side of the instrument). Maximum resolution obtained using this frequency is 1 - 2 m (Masson, 2001).

The total seabed area surveyed during the two AFEN surveys (1996 and 1998) was approximately 60,000 km^2 in water depths ranging from 120 to 2,200 m (Bett and Masson, 1998). The sidescan sonar maps were used to guide the various aspects of the seabed sampling and photography programme to ensure that the effort was distributed over the range of environmental variation encountered. In turn, the samples and the photographs were used to help 'groundtruth' the sidescan sonar material (Bett and Masson, 1998).

3.1.2 Seabed photography

The seabed photography was carried out using two systems: WASP and an epibenthic sledge but only the photographs obtained using WASP were used in this particular study.

3.1.2.1 WASP (Wide Angle Seabed Photography)

WASP is a vehicle designed to be towed behind a ship. It is a photographic instrument platform consisting of a tubular steel frame (3 m in length) with a 35 mm still camera (mounted vertically downward), a video camera, lights (for the video filming), an inclined flash unit (for still photography) and an altimeter. WASP is towed at a speed of about 0.5

knots and it is kept close to the seabed, typically between 3 and 6 m. The height off the seafloor is monitored using the altimeter and photographs and video films are only recorded when within a pre-set range (1-10 m). The video runs continuously as long as the instrument is within the pre-set range. The still camera, typically carrying Kodak Eastman E5279 colour negative, 35 mm cine film, operates every 10 seconds and for each photograph the time, date and altitude is recorded. The total film capacity is 1000 frames and typically a run (or transect) lasts approximately 60 minutes. The areal coverage of a photograph varies with altitude but for biological analysis a coverage of 10 to 30 m^2 is preferable. A particular advantage of the WASP instrument is the fact that it is not in contact with the seabed. Observations can therefore be carried out over most seabed types. Furthermore, there is no or little impact on the fauna surveyed. A disadvantage is the variation in the resolution of the footage obtained dependent on altitude, which may vary rapidly when operated in heavy swells.

3.1.3 Direct seabed sampling

The region covered in the two AFEN surveys encompasses a wide variety of different surface sediment types, ranging from fine sandy muds to gravel, cobbles and boulders. For this reason, no single seabed sampler is suited to all sampling sites. To cover all these seabed types, three different samplers have been used: Megacorer, Box corer and the Day grab (for full survey details see AFEN, 2000). The Megacorer is a hydraulically damped multiple corer similar to the sampler described by Barnett *et al.* (1984) and equipped with up to 12 tubes with internal diameters of 10 cm. The efficiency of this gear, together with the multiple corer, in sampling even the finest particles without being effected by bow-waves is evident from the success in sampling the easily resuspended phytodetrital flocs that may be encountered at the sediment surface (Billett *et al.* 1983; Barnett *et al.*, 1984; Rice *et al.*, 1986; Thiel *et al.*, 1988/1989; Gooday and Lambshead, 1989; Gage and Tyler, 1991; Bett *et al.*, 1994; Bett, in press). The box corer used in the survey work was a large spade USNEL-type (United States Naval Electronic Laboratory) box corer (Hessler and Jumars, 1974), which has become one of the standard gears for quantitative deep-sea sampling and takes relatively undisturbed samples of 0.25 m^2 (Gage and Tyler, 1991). The Day grab is a quantitative sampler of the seabed, taking samples of a surface area of 0.1 m^2 (Holme and McIntyre, 1984). The Day grab is considered to take samples of inferior quality compared to both the Megacorer and Box corer (Bett, 2001a) but one of the advantages of this equipment is its capability to take samples on most substrata.

3.2 LABORATORY METHODS

3.2.1 Photographic analysis

The photographic analysis predominantly refers to the analysis of 35 mm still camera photographs but in some cases video footage, where available, has also been used to aid the analysis or verify the presence of certain features.

3.2.1.1 Film viewer

The analysis of the photographic material was carried out using a Carl Zeiss microfilm viewer. The viewer consists of a light source, a white screen, a set of four lenses (magnification of 6.5, 9.0, 13.0 and 17.5) and a winding mechanism. During the analysis the positive film is illuminated and projected onto the white screen through one of the lenses. The most practical magnification for analysis in this project was 9.0 giving an approximate projected image size of 32.4 cm by 22.6 cm.

3.2.1.2 Frame identification

The WASP films typically consist of 200-300 frames on a roll. Each frame of the photographs has date, time, frame identification number and the altitude above the seafloor printed on it (figure 3.1). These details are recorded onto the film, to the right of the photograph.

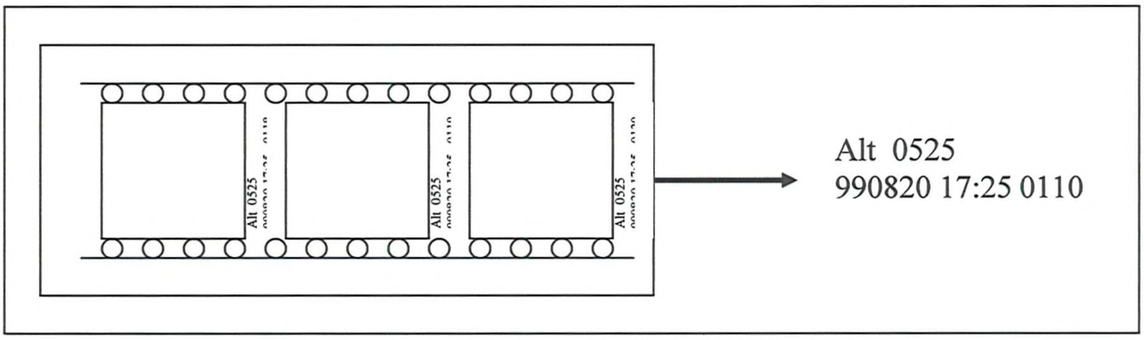


Figure 3.1. Example of three frames with their frame identification details, altitude, date, time and the frame number.

3.2.1.3 Scaling

The actual sizes of the seafloor coverage, animals and other features identified in the photographs can be obtained using a formula (see below), the known dimensions of the frame, the acceptance angles and the altitude (Huggett, 1987; Huggett, 1990). Calibration of the WASP camera has given the acceptance angles (the camera angles determining the width, in both x and y, of the seafloor coverage) in water of 35° (for y) and 50° (for x) (Bett, pers.comm.). By knowing the altitude for each frame and these angles the true sizes of features on the seafloor can be calculated (figure 3.2).

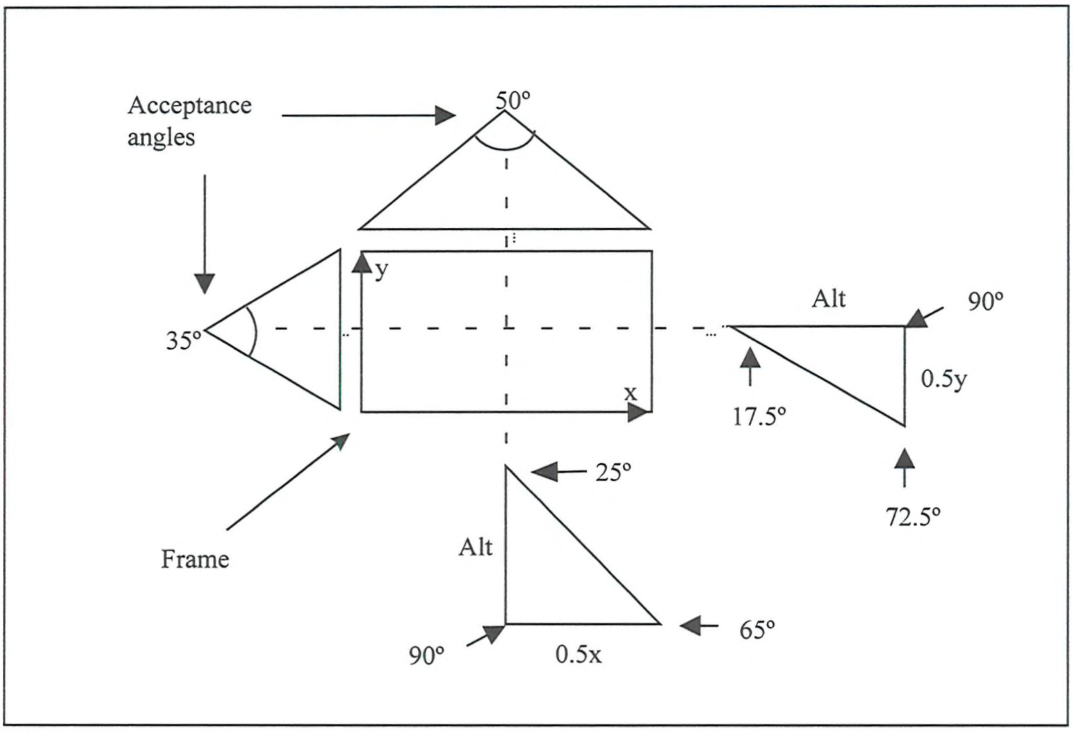


Figure 3.2. A photographic frame with x-axis, y-axis, acceptance angles and the altitude (alt).

The x-axis (2 × 0.5x) at the seafloor is therefore:

$$2 \times 0.5x = (2 \times alt \times \sin(25)) / \sin(65) \quad \text{from} \quad 0.5x / \sin(25) = alt / \sin(65)$$

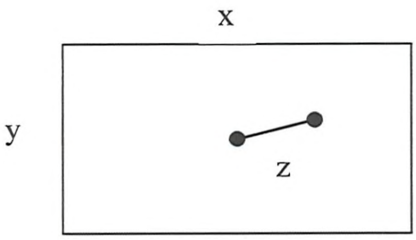
And the whole y-axis (2 × 0.5y) at the seafloor is:

$$2 \times 0.5y = (2 \times alt \times \sin(17.5)) / \sin(72.5) \quad \text{from} \quad 0.5y / \sin(17.5) = alt / \sin(72.5)$$

The sizes of features or fauna seen on the seafloor can be calculated using either x or y as the co-ordinate, basing the calculation on the above. If z is the size of a feature on the seabed as measured from a photograph, then the true size of this feature can be calculated, using x as the co-ordinate:

$$\text{True } z = \frac{(\text{image } z \times 2 \times \text{alt} \times \sin(25))}{\text{image } x \times \sin(65)}$$

or, using y as the co-ordinate:



$$\text{True } z = \frac{(\text{image } z \times 2 \times \text{alt} \times \sin(17.5))}{\text{image } y \times \sin(72.5)}$$

3.2.1.4 Quantification

The densities of faunal (megafauna) and other features on the films were obtained by identifying and then counting the number of these animals or features on each frame. The densities were calculated simply by dividing the total number of animals seen by the total seafloor area coverage.

The seabed coverage of each frame depends on the distance of the camera above the seafloor (altitude), and these values change for each frame. The actual seafloor coverage for each photograph was calculated from the known camera acceptance angles and the altitudes. In addition, some of the consecutive frames along the WASP run overlap, leading to parts of the seafloor being visible on more than one frame. The counting procedure has accounted for this overlap and fauna or other features were only counted once. The total seafloor coverage was also influenced by overlap and seafloor coverage was adjusted to allow for subsequent analyses.

The varying altitude of the WASP also introduces difficulty in reliably identifying and counting smaller megafaunal organisms. Care must therefore be taken in selecting frames suitable for analysis.

3.2.1.5 Orientation

The position and direction of travel of the WASP instrument at each sampling site are known from the navigational systems used as described above. This information, together with the overlap of consecutive frames discussed above, allows the orientation, or direction, of any features (e.g. current-related) seen on the photographs to be established. Note that it is not 'safe' to assume the WASP vehicle is orientated along the direction of travel, e.g. the vehicle may be crabbing as a result of near bottom currents. The true orientation of a particular feature on a photograph is determined by establishing the direction of travel along the seafloor from the photographs. This is achieved by finding an overlap of two consecutive frames covering the same section, or at least part of the same section, of seafloor. Any permanent features, such as rocks, can then be used and their relative positions on the seabed on the two frames determined. The two frames are then drawn relative to one another, matching the positions of the permanent features (figure 3.3). The orientation of seabed features can then be related to the true direction of travel on the photographs and then to the recorded navigational data for the WASP vehicle.

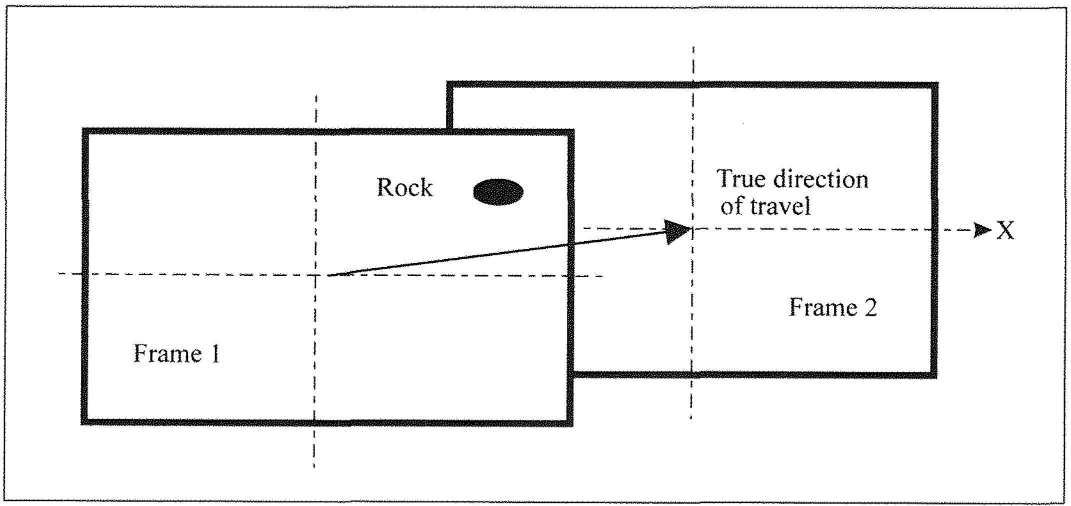


Figure 3.3. Illustration of the determination of the true direction of travel using two consecutive frames in a photographic run.

3.2.1.6 Initial photographic analysis

Prior to any detailed analysis of the photographs a quick inspection of the film was normally carried out. The aim was to get a general understanding of the available material and to examine the quality of the film. The presence of frame numbering, altitude, date and time was verified and the start and end frame numbers recorded. A brief description of the features (geological, biological, physical and any other features of interest) present was also made.

3.2.1.7 Seabed features

The seabed analysis consisted of a description of the seabed stating the type of substratum (gravel, sand, pebbles etc.) and noting other features including larger rocks and boulders (the latter are features that may be analysed using digital techniques to assess the coverage of drop stones, which are common all along the continental shelf west of Shetland). Any other particular features including ripple effects, unusual/particular streaks or patterns, small failures and other features that may be of interest were also recorded. Indicators of currents and their direction were also noted. These included scouring effects behind rocks or permanent fauna, sediment waves or ripples or even sedentary fauna being forced in a particular direction. The analysis of the latter requires some caution, as the current seen on one photograph may not always be the residual or main current direction. The true current direction was then determined as described above (section 3.2.1.5).

3.2.1.8 Biological features

The faunal analysis consisted of counting and identification of megafauna as far as possible. Ideally the megafauna should be identified down to species level but this is often difficult, as this level of identification often demands access to specimens. The analysis was carried out on each frame, allowing for overlap of consecutive frames to avoid counting the same animal twice. Sizes of the fauna were also measured on the projected photograph and the true sizes were then calculated, as described above (section 3.2.1.3), and recorded. In addition, '*Lebensspuren*', or tracks produced by animals on the seabed, were recorded, drawn and described as far as possible.

3.2.1.9 Other observations

Other observations, additional to the above, including trawl marks, artificial material (ropes, nets etc.) and other unusual features were recorded with the aim to determine what is present and assess how widespread these features are.

3.2.1.10 Frame selection

Frame selection is the process where photographs are excluded prior to further analysis and it consists of two stages. The first stage eliminates any frames of poor quality and the frames are assessed in terms of quality of focus, level of exposure (over- or underexposure), the vertical status and the general quality of the photograph. The second stage of frame selection involves the exclusion of frames using altitude as a parameter, where frames exposed in excess of a pre-determined altitude are excluded. This process is considered an important aspect of photographic analysis and a separate study has therefore been carried out (see chapter 4).

4 METHODS AND TECHNOLOGY II: THE EFFECTS OF FRAME SELECTION ON PHOTOGRAPHIC ANALYSIS AND RESULTS

4.1 INTRODUCTION

The use of underwater camera systems to record the physical and biological attributes of the seafloor has a long history (Machan and Fedra, 1975; Barker *et al.*, 1999) with the first successful biological photographs of deep-water benthos taken in 1939 (Holme, 1985; Southward and Nicholson, 1985). Many of the features on present-day remotely operated cameras are based on the systems introduced in the 1940s including flash lighting, towed vehicles and time-lapse automatic exposure (Southward and Nicholson, 1985). Initially still cameras were used but more recently underwater video is often added to the sampling procedures of many surveys to improve and add to the data collection (e.g. Lythgoe, 1985; Bett, 1997, 1999, 2000b; AFEN, 2000). There are many types of platforms on which cameras are mounted including moored camera systems using time-lapse photography (e.g. the pop-up lander Bathysnap; Lampitt and Burnham, 1983, Bett, 2003), towed camera systems either on (sleds; Rice *et al.*, 1994; Bett *et al.,* 1995) or off (e.g. WASP; Bett, 2001a and Towed Automatically Compensating Observation System (TACOS); Barker *et al.*, 1999) the seabed as well as submersibles (e.g. Alvin; Cailliet *et al.*, 1999) but deep-sea bottom photography is still far from being a routine operation and the analysis of photographic material is also difficult and costly, factors likely to contribute to the lack of published photographic material (Southward and Nicholson, 1985).

Photographs resulting from the different platforms are either vertical (i.e. directly from above the seabed) or at an angle. Vertical photographs can be analysed for example as described in chapter 3, or as described by Rosman and Boland (1986), while oblique photographs are analysed using a perspective grid of some kind (e.g. Cailliet *et al.*, 1999), often a version based on the Canadian grid as described by Wakefield and Genin (1987). The analysis of photographic material, particularly deep-sea photographs, is often difficult unless there are additional seabed samples from the same sites to verify the identities of fauna but even though the results are likely to be improved with these samples available (Barraclough Fell, 1967), it is still difficult. The catches may not always include all the fauna observed on the photographs and in addition, the analysis of the photographs may yield quite different results, particularly when photographic survey results are compared to those obtained from trawls (e.g. Rice *et al.*, 1982; Rice and Collins, 1985; Nybakken *et al.*, 1998; Cailliet *et al.*, 1999). One factor of the analysis of photographs is frame selection, a process that may influence the results considerably, but rarely appears to be investigated in detail.

Frame selection is an important aspect of photographic processing and analysis, not only because it may lead to the loss of some of the data, depending on how it is carried out, but also because these effects may substantially affect the final results with regards to aspects such as faunal and *lebensspuren* density. The process of frame selection involves the exclusion of unsuitable frames, which is a subjective process, before final analysis and it is a practice common to photographic studies (e.g. Young *et al.*, 1985; Bett *et al.*, 1995; Roberts *et al.*, 2000). The selection of frames is carried out after the processing of the films involving the detection and counting of features, as the rejection of frames prior to processing could lead to the loss of some features. During the selection of vertically mounted photographs, frames are typically assessed for suitability in terms of quality of focus, level of exposure (over- or underexposed), the vertical status (whether the camera was vertical or not during exposure of the film) and the general quality of the photograph (Young *et al.*, 1985; Cailliet *et al.*, 1999; Roberts *et al.*, 2000). However, few studies appear to include the effects of altitude at the time of exposure as an aspect of frame selection and use this parameter to exclude frames prior to analysis, apart from when this effects the quality of the frames (as for example in the survey tests by Barker *et al.*, 1999) leading to over- and underexposure or frames that are out of focus.

The use of altitude as a parameter for frame selection where frames are excluded because they are too far away from, or too close to, the seabed when exposed will not only effect the total seafloor coverage but also any calculations based on these area coverage values including faunal and *lebensspuren* densities. This aspect is most relevant to studies where the photographs are obtained through a vertically mounted camera system that is moving vertically throughout a survey. It is, however, less relevant to studies where vertical photographs are taken at a pre-set altitude throughout the survey (although it may be important when the densities of features are calculated as the distance off the seafloor may have a considerable effect on the final results), for example using 'jump' camera, or similar, systems (Roberts *et* al., 1994; Roberts *et al.*, 2000), or oblique photographs taken using towed sleds (e.g. Kidd and Huggett, 1981; Chapman, 1985) or off-bottom frames (Young *et al.*, 1985), fixed moorings (Smith *et al.*, 1986; Rice *et al.*, 1994) or using other platforms, where the altitude also is set at a pre-determined range (e.g. Barker *et al.*, 1999).

In this study deep-sea photographs from the AFEN survey of 1996 (Bett, 1997) have been used (figure 4.1). The photographs were obtained from the WASP (Wide-Angle Seafloor Photography) system where the camera is vertically mounted and the altitude varies throughout the survey. The aim of this study is to assess the effects of frame selection; primarily the second phase of frame selection, on some of the results from this photographic survey and to decide at what level this selection should be carried out. The process of frame selection particular to this project is described and the results as well as the effects of various levels of frame selection are discussed.

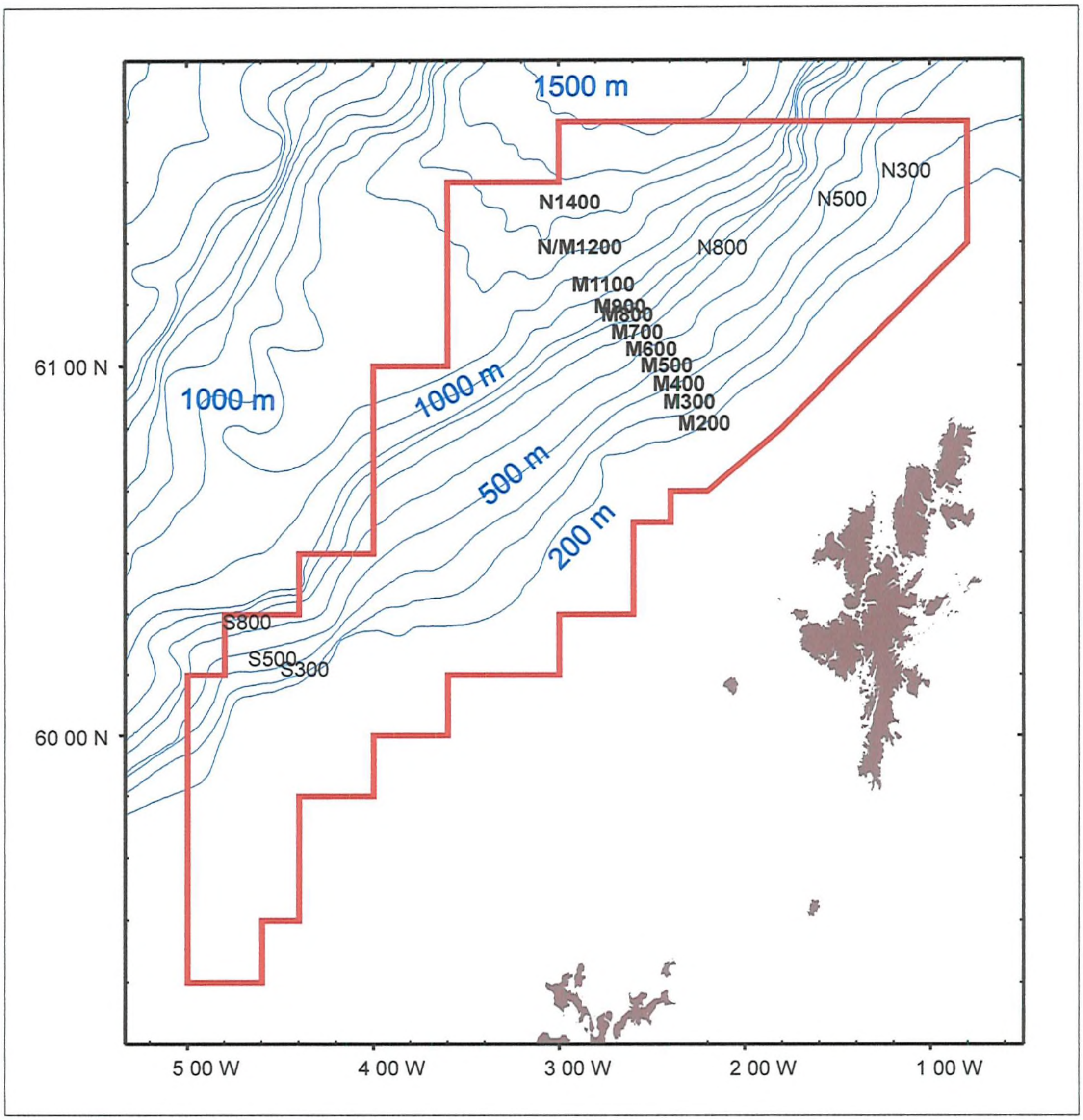


Figure 4.1. Photographic (WASP) sampling sites from AMES 1996 and DTI 2000. Sites in bold are part of the bathymetric transect west of Shetland.

4.2 METHODS

The general methodology for the study is covered in chapter 3. Additional and specific methods to this chapter are as follows. In this study a total of 19 photographic sites were used, where 18 sites are from AMES 1996 (Bett, 1997) and one (M200) from the White Zone Environmental Survey in 2000 (Bett, 2001b). 13 sites are from the bathymetric transect at depths from 200 m down to 1400 m, three sites from the northern sector at depths from 300 m to 800 m and three sites in the southern sector at depths from 300 m to 800 m. The locations of the sampling sites can be seen in figure 4.1, and the details of these sites are given in table 4.1.

Station (Site)	Location	Depth	Frame identification	Film run	Number of frames
55456#1 (M200)	60° 52.80 N 02° 19.13 W	209-204 m	027 - 341	15 m colour	315
53913#1 (M300a)	60° 53.96 N 02° 22.07 W	290 – 275 m	435-543	5 m colour	109
53926#1 (M300b)	60° 53.96 N 02° 22.15 W	294 – 278 m	2140 - 2249	4 m colour	110
53928#1 (M400a)	60° 56.70 N 02° 25.91 W	390 – 370 m	2506 - 2725	7 m colour	221
53914#1 (M400b)	60° 57.74 N 02° 24.98 W	410 – 397 m	560 – 665	7 m colour	106
53925#1 (M500)	60° 59.54 N 02° 29.79 W	507 – 496 m	1780 - 2103	12 m colour	324
53916#1 (M600)	61° 02.49 N 02° 33.95 W	595 – 580 m	019 - 317	11 m colour	299
53985#1 (M700)	61° 05.40 N 02° 38.12 W	685 – 672 m	014 – 128	5 m colour	115
53924#1 (M800)	61° 07.99 N 02° 42.00 W	798 – 781 m	1545 – 1762	10 m colour	218
53984#1 (M900)	61° 09.57 N 02° 43.90 W	912 – 881 m	012 – 356	12 m colour	344
53923#1 (M1100)	61° 12.85 N 02° 49.41 W	1088 m	1164 – 1495	12 m colour	332
53981#1 (N/M1200)	61° 19.20 N 02° 58.23 W	1209 – 1203 m	371 – 690	10 m colour	320
53980#1 (N1400)	61° 26.65 N 03° 00.07 W	1408 – 1401 m	011 - 346	12 m colour	336
53810#1 (N300)	61° 31.45 N 01° 10.72 W	300 – 303 m	012 – 313	12 m colour	302
53921#1 (N500)	61° 15.97 N 01° 48.01 W	496 – 486 m	680 – 788	5 m colour	109
53922#1 (N800)	61° 19.05 N 02° 10.85 W	812 – 787 m	815 – 1118	12 m colour	304
53948#1 (S300)	60° 10.57 N 04° 25.64 W	304 – 324 m	3130 – 3357	9 m colour	228
53949#1 (S500)	60° 12.16 N 04° 36.71 W	512 – 504 m	007 – 113	3 m colour	107
53950#1 (S800)	60° 18.41 N 04° 44.11 W	816 – 829 m	009 – 346	13 m colour	338

Table 4.1. The photographic (WASP) sampling stations of AMES 1996 (the locations refer to the positions at the beginning of the transects and frame identification refers to the number printed on the frame at the time of exposure).

All 19 sites west of Shetland were utilized and all the photographs were initially assessed. The photographs were processed and analysed for all details including fauna and *lebensspuren*. Frames were then selected for further analysis; the selection procedure can be divided into to two parts: 1) selection based on the quality of the frame (with factors including over- and underexposure, focus and vertical status) and 2) a selection based on the altitude at the time of exposure (some photographs are included for illustration purposes). The first phase of frame selection was carried out eliminating all unsuitable frames regarding quality of the frames. The second phase of the analysis involved studying the variation in the proportion of frames available for analysis at different altitudes to assess any patterns or changes with different altitudes. The proportions were simply calculated by dividing the number of frames available at a particular altitude by the total number of frames available at that particular site. In addition, the total faunal density, involving all the fauna present at each site, was calculated and these values were plotted against altitude to assess the presence of any patterns or changes in apparent density with altitude.

Finally, faunal and *lebensspuren* densities at different sites at different altitudes were calculated by dividing the number of individual taxa or *lebensspuren* by the total seafloor coverage for the particular altitude range. Confidence limits, based on the median values, have been calculated using bootstrapping (see e.g. Cressie, 1993; Sokal and Rohlf, 1995; Krebs, 1999) and 'the first percentile method' in particular, where bootstrap resampling (with replacement) of the original data is carried out 1000 times to generate the bootstrap distribution of the median values (Manly, 1991). The 95% confidence intervals are given by values less than 2.5% and exceeding 97.5% of the generated distributions (Manly, 1991). In some cases there were insufficient data points to allow confidence limits to be calculated as the majority of frames were eliminated after the second phase of frame selection. Some of the results were illustrated by plotting the density values against altitude.

4.3 RESULTS

A total of 4537 photographs were analysed and the total number of frames for each site (prior to any processing or analysis) can be seen in table 4.1. After the first part of frame selection (in which unsuitable frames have been excluded) a total number of 4368 photographs were available for analysis and the available frames at each depth can be seen in the second column in table 4.2. A total of 169 photographs have therefore been excluded, all of which have been removed from further analysis as a result of the total lack of exposure (frames are entirely black), possibly as a result of some technical problems with the camera system. None of the photographs were excluded as a result of over- or underexposure, low quality focus or because the camera was obviously deviating from the vertical position.

4.3.1 Proportions of frames available at different altitudes

The proportions of frames available for analysis at each of six camera altitude ranges at the different sites can be seen in table 4.2, results further illustrated in figure 4.2. The camera altitude ranges include all the frames with altitudes equal to, or less than, the altitude values indicated in the table and figure and these are proportions of the total number of frames available after the first frame selection.

Site	**Total number of available$^+$ frames**	**Altitude**					
		≤ 8 m	**≤ 7 m**	**≤ 6 m**	**≤ 5 m**	**≤ 4 m**	**≤ 2.5 m**
M200	315	1.00	1.00	1.00	1.00	0.98	0.56
M300a	109	0.97	0.95	0.42	0.09	0.00	0.00
M300b	109	1.00	0.99	0.96	0.49	0.00	0.00
M400a	106	0.98	0.91	0.49	0.08	0.00	0.00
M400b	221	0.97	0.88	0.47	0.12	0.01	0.00
M500	314	0.98	0.89	0.61	0.28	0.07	0.00
M600	298	0.99	0.98	0.86	0.37	0.04	0.00
M700	114	0.92	0.84	0.37	0.15	0.03	0.00
M800	215	0.98	0.83	0.52	0.24	0.07	0.00
M900	340	0.96	0.79	0.59	0.27	0.06	0.00
M1100	330	1.00	0.79	0.25	0.09	0.02	0.00
N/M1200	312	0.94	0.79	0.48	0.20	0.08	0.01
N1400	208	0.99	0.83	0.49	0.16	0.04	0.00
N300	302	1.00*	1.00*	1.00*	1.00*	1.00*	1.00*
N500	108	0.98	0.97	0.46	0.06	0.00	0.00
N800	297	0.95	0.81	0.57	0.19	0.04	0.00
S300	226	0.91	0.73	0.38	0.12	0.03	0.00
S500	107	0.98	0.89	0.08	0.07	0.00	0.00
S800	337	1.00	0.93	0.41	0.06	0.00	0.00

Table 4.2. The variation (proportions) in the number of frames available for analysis at different altitudes at different sites west of Shetland. $^+$ The total number of available frames refers to the number of frames available after the first stage of frame selection (* = no altitude records available).

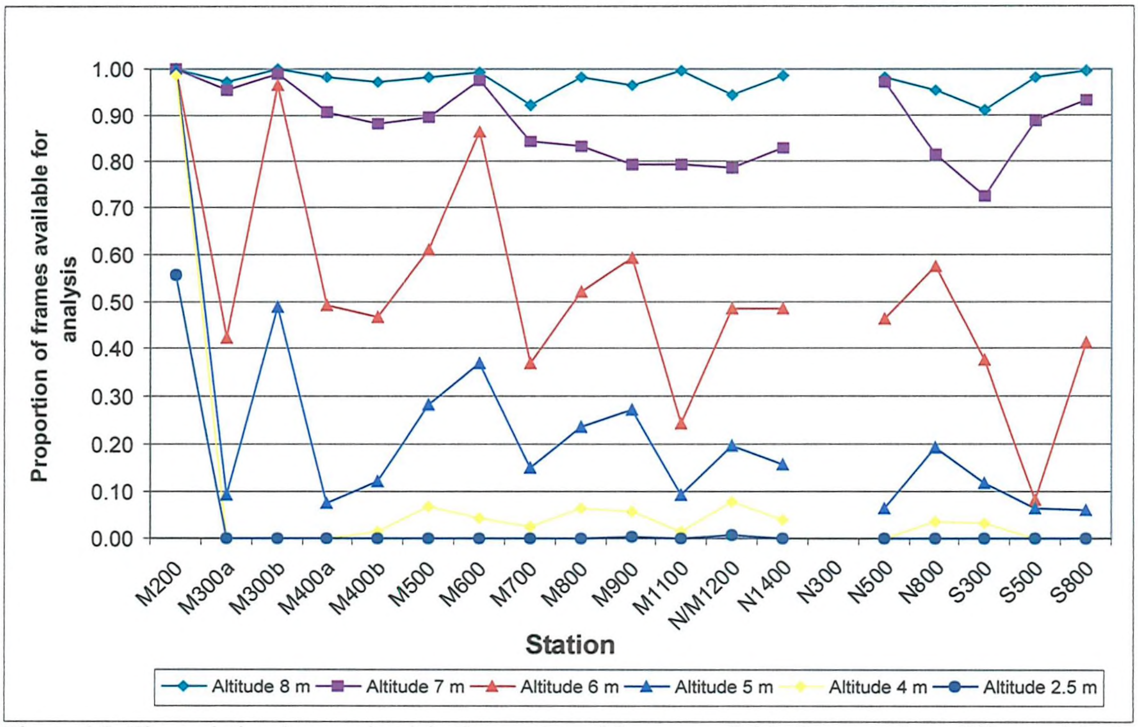


Figure 4.2. The variation (proportions) in the number of frames available for analysis at different altitude ranges at different sites west of Shetland.

Frames are available for analysis at all sites when the camera altitude range is 8-5 m (i.e. 8-0 m, 7-0 m, 6-0 m and 5-0 m), however, ranges from 5 m to 4 m and 2.5 m the proportions are much smaller and even reach zero at the 4 m and 2.5 m altitude ranges for many of the photographic runs. The overall proportion of frames available (see table 4.3) at the 7 m or 8 m altitude ranges is approximately 80 % or more (the mean value is c. 88 %) but drops considerably to approximately 40-50 % at the 6 m altitude range (the mean value is c. 52 %) and down to 10-20 % at the 5 m altitude range (mean value is 22 %). There are less than 8 % of photographs available for analysis when the altitude range is 4 m, or less (if station 55456#1, a photographic run at 200 m where most photographs have been taken close to the seafloor, is excluded). At altitude ranges of 2.5 m, or less, the great majority (17 out of 18 sites) of sites are without data points.

Mean values (± S.D.)	**Proportion of frames available at the different altitude ranges**					
	≤ 8 m	**≤ 7 m**	**≤ 6 m**	**≤ 5 m**	**≤ 4 m**	**≤ 2.5 m**
Excl. 53810#1	0.97 (0.03)	0.88 (0.08)	0.52 (0.23)	0.22 (0.23)	0.08 (0.23)	0.03 (0.13)

Table 4.3. The mean proportion values (± standard deviation (S.D.)) of frames available for analysis at the different altitude ranges as seen in table 4.2 (excluding station 53810#1).

Note in addition the apparent decrease in the number of frames available for analysis with depth *within* each altitude range (see figure 4.2), a pattern particularly evident in the 7 m, 6 m and 5 m altitude ranges (follow the purple, marine blue and red plots from 200 m down to 1400 m) along the bathymetric transect (i.e. among the first 13 sites in the plot). The proportions are higher at the shallower depths than those at depth, although there is considerable variability in the data points and the pattern is less evident at the northern and southern photographic runs (the last five sites in the graph, figure 4.2).

4.3.2 Proportions of frames containing megafaunal data

In table 4.4 the variation in the proportions of the frames containing megafaunal data, for a number of sites, within the different altitude ranges can be seen.

Altitude range	**Station number (add #1 with all stations) and mean values**							
	53914	**53916**	**53924**	**53925**	**53928**	**53948**	**55456**	**Mean** (± S.D)
All frames	0.906	0.997	0.842	0.761	0.959	0.894	0.956	0.935 (±0.060)
≤ 8 m	0.904	0.997	0.858	0.776	0.967	0.917	0.956	0.947 (±0.057)
≤ 7 m	0.906	0.997	0.939	0.811	0.969	0.951	0.956	0.960 (±0.047)
≤ 6 m	0.923	1.000	0.973	0.916	0.990	0.976	0.956	0.978 (±0.032)
≤ 5 m	1.000	1.000	0.980	0.978	0.963	1.000	0.956	0.982 (±0.038)
≤ 4 m		1.000	1.000	1.000	1.000	1.000	0.955	0.996 (±0.013)
≤ 2.5 m							0.931	0.977 (±0.040)
≤ 2.0 m							0.882	0.882 (*)
≤ 1.5 m							0.778	0.778 (*)

Table 4.4. Examples of stations from west of Shetland with proportions of frames containing megafaunal data within each altitude range. The mean and standard deviation (S.D.) values represent the values for all 18 WASP sampling sites, excluding station 53810#1 (* = unable to calculate as a result of lack of data points).

Note the overall high proportions of frames containing megafaunal data available for analysis even when all frames are investigated, with the lowest proportion being 76 %. The results indicate an increase in the proportion of frames containing data from using 'all the frames' range to the '4 m-altitude' range, reaching 100 % at the '4 m altitude' range in most (11 out of 18 sites) cases (a pattern seen in the other raw data not shown here). Among the few sites containing data on frames closer than 4 m there appears to be a decrease in the proportion of frames containing megafaunal data with decreasing altitude, a pattern also evident in overall mean values (table 4.4). Station 55456#1 appears to support the mentioned pattern, indicating that there is less biological data to be observed when the altitude is low as a smaller area of the seafloor is covered and smaller proportion of the frames therefore contain megafauna. Note, however, that while the frames at low altitudes record real zero values (i.e. frames with no megafauna present), the frames at high altitudes (≥7 m) without recorded data may still contain fauna. Some of these frames may be real zero values but there are also likely to be frames with undetected fauna as a result of the high altitude. In addition, at high altitudes the fauna are more difficult to identify.

These investigations indicate that frame selection may be most appropriate when the photographs have altitudes of 4 m to 6 m but less so when the altitude is 2.5 m or less (lack of available frames), or in excess of 6 m (detection and identification is difficult). However, both the high- (>6 m) and the low-altitude (<4 m) photographs are still valuable, where the latter are particularly useful for identification of fauna as well as determinations of spatial patterns and faunal densities and the former are valuable in studies of larger features, such as coral mounds and sediment bedforms.

4.3.3 The variation in faunal and lebensspuren density with altitude

In addition to identifying the proportion of frames available for analysis at different altitude ranges, the variation in faunal density with different altitudes has been investigated and two examples are given in figure 4.3. Broadly the graphs indicate an increase in apparent faunal density with a decrease in altitude, a pattern seen at all sampling sites. Within this broad pattern, however, the plots on the graphs are variable, with fluctuations all along the graphs and the patterns are not easily put into any type of mathematical function. In the majority of graphs there is a relatively sharp increase in faunal density at some point along the graphs. Because of the difficulty in attaining any mathematical functions for the graphs it is therefore difficult to objectively identify the point of sharpest change in the curve, e.g. the angle of the tangent. However, it does appear possible to find a point along the curve on the graph visually, particularly with the aid of the added trend lines. Vertical dotted lines have therefore been added to the graphs in figure 4.3 to illustrate the approximate position of these "cut-off" points. The results demonstrate a general increase in apparent faunal density with a decrease in altitude and the cut-off points appears to be at approximately 6 m in altitude for the two sites, a result also seen in the majority of the sites, although there appears to be some variation in the position of the cut-off point between the graphs with some cases where it is found closer to 5 m and others where this point is found at higher altitudes. This pattern is present at 15 of the 18 sites but it does, however, become less obvious and the cut-off point is difficult to identify in three of the graphs. It should also be added that station 55456#1 has no photographs with altitudes greater than 4.3 m and a cut-off point at 6 m would therefore not be obvious from this set of available data.

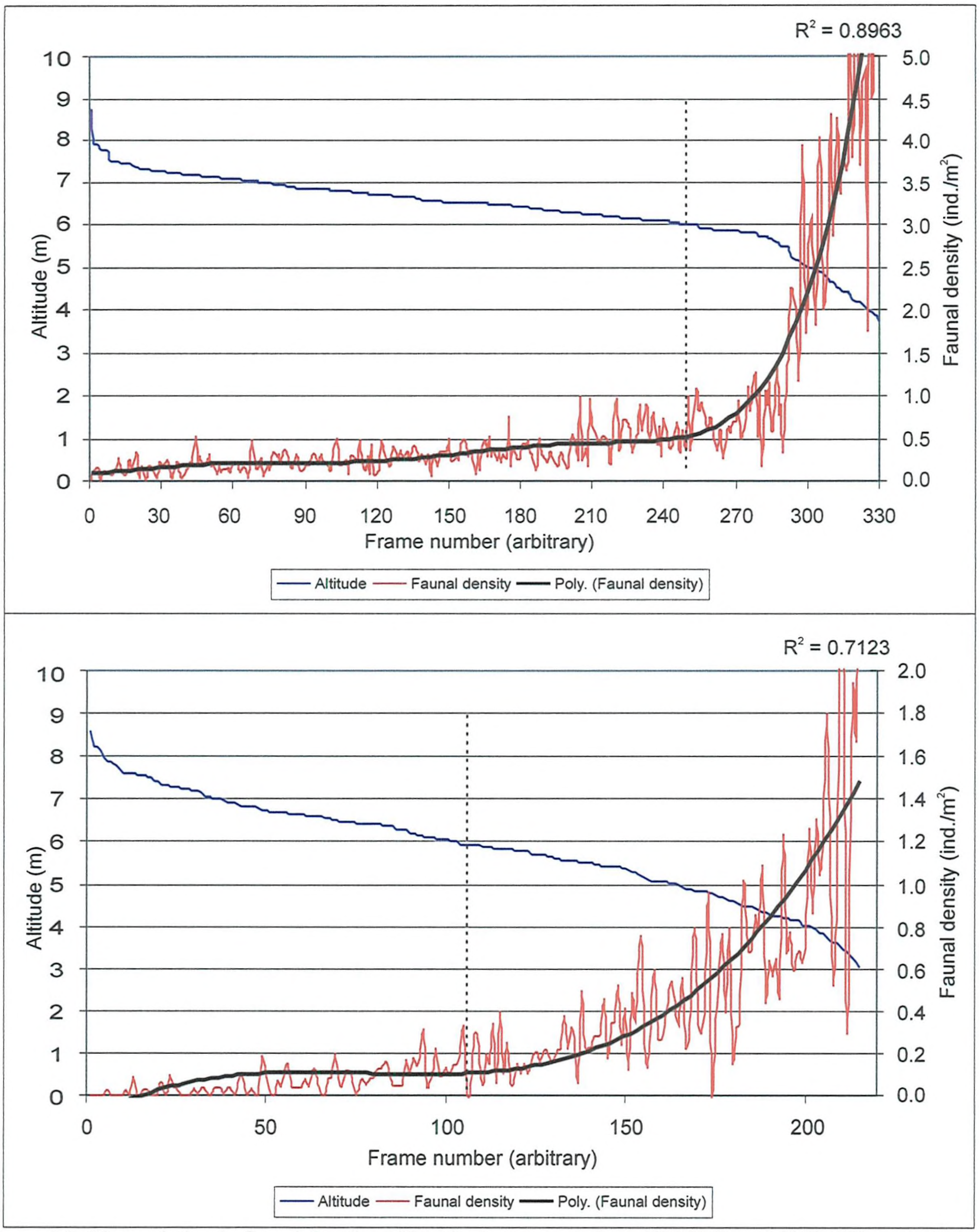


Figure 4.3. The variation in faunal density with altitude at two stations (53923#1 and 53924#1) west of Shetland. The solid lines are 'best-fit' polynomial trend lines illustrating the overall change in faunal density with altitude. The vertical dotted lines indicate the approximate positions of the cut-off points where there is a large increase in faunal density with a decrease in altitude.

To study these results further, faunal densities have been plotted against camera altitude (figure 4.4). These results again illustrate an increase in faunal density with a decrease in altitude. The recorded density values are close to zero at altitudes in excess of 8 m (presumably largely attributed to the fact that the fauna is difficult to detect at high altitudes) but at 7 m the values are slightly higher, values increasing even more rapidly at altitudes of ≤6 m.

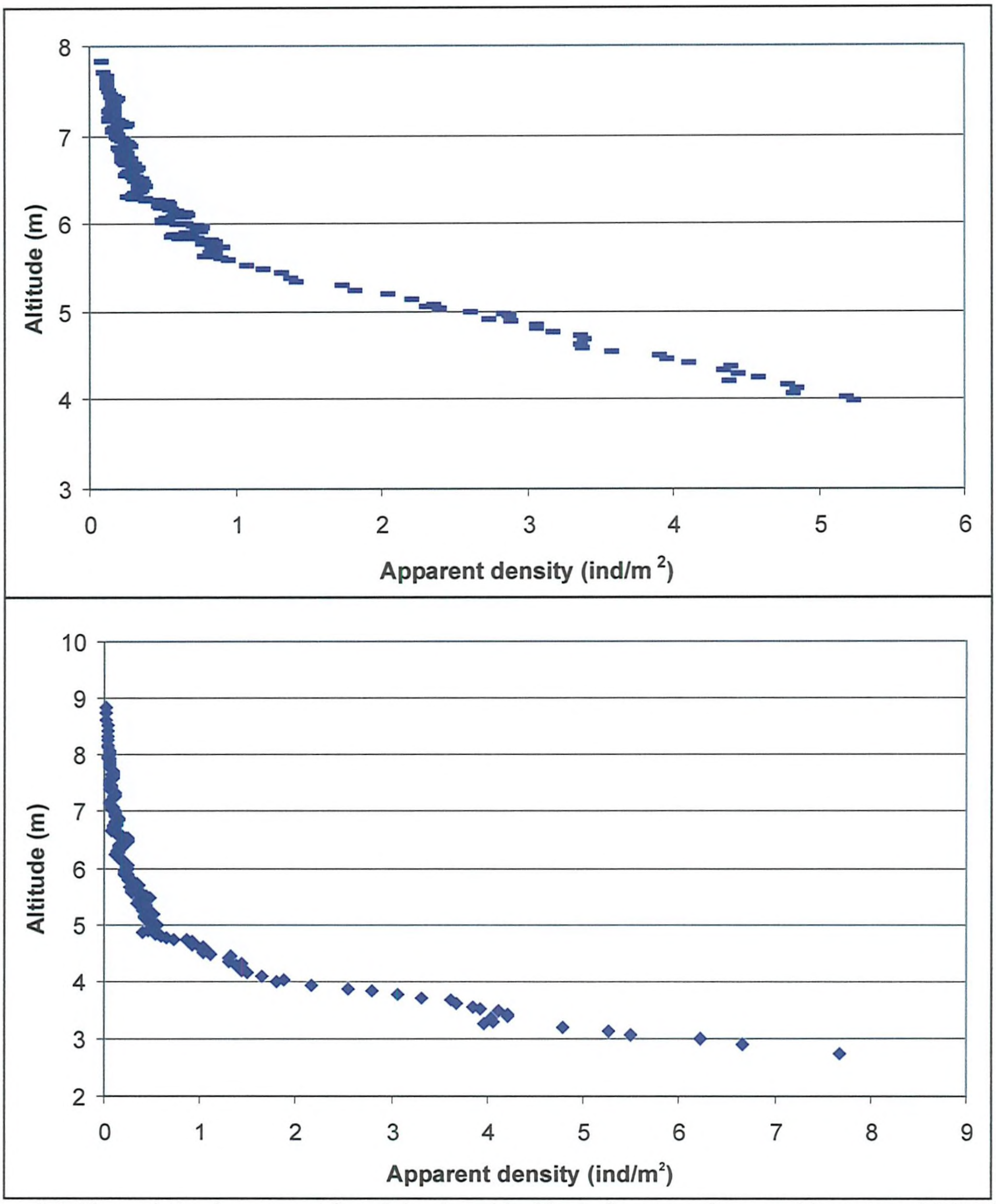


Figure 4.4. The variation in apparent faunal density with altitude from two photographic stations (53923#1 and 53981#1) west of Shetland.

The cut-off points observed in the plots in figure 4.4 are similar to those in figure 4.3 with the areas of the sharpest increase appearing to occur at approximately 6 m for most of the sites. As with figure 4.3 there are a number of sites where the cut-off points occur at approximately 7 m altitude. The majority do, however, appear to occur at approximately 6 m altitude.

Table 4.5 details the variation in apparent density of a selection of taxa with altitude. The data are from the bathymetric transect at depths from 300 m to 1200 m and the fauna range in size from a few centimetres (e.g. enteropneusts) to c. 20 cm (e.g. asteroids) or even more in some cases (e.g. some pycnogonids), an important factor with regards to detection and counting of the fauna.

Station	**Taxa**	**Faunal density (ind/m^2) at different altitudes**					
		≤ 8 m	**≤ 7 m**	**≤ 6 m**	**≤ 5 m**	**≤ 4 m**	**≤ 2.5 m**
53913#1	*Munida* sp.	0.034	0.035	0.056	0.136		
53913#1	*Stichopus* sp.	0.002	0.002	0.004	0.008		
53928#1	*Munida* sp.	0.019	0.022	0.039	0.100	0.323	
53928#1	Scallop	0.044	0.048	0.089	0.096	0.121	
53928#1	*Cidaris* sp.	0.031	0.031	0.045	0.088	0.243	
53925#1	*Munida* sp.	0.079	0.092	0.152	0.259	0.384	
53925#1	*Cidaris* sp.	0.011	0.012	0.016	0.016	0.024	
53925#1	Asteroid B	0.007	0.008	0.014	0.020	0.037	
53916#1	*Echinus* sp.	0.030	0.031	0.033	0.043	0.037	
53916#1	*Ceramaster* sp.	0.018	0.019	0.021	0.027	0.009	
53916#1	Encrusting sponge	0.331	0.339	0.378	0.487	0.834	
53924#1	Pennatulacea	0.009	0.012	0.020	0.044	0.103	
53924#1	Anemone B	0.049	0.064	0.111	0.164	0.170	
53924#1	Pycnogonid A	0.017	0.022	0.043	0.105	0.226	
53924#1	Enteropneusts	0.002	0.003	0.005	0.016	0.075	
53984#1	Enteropneusts	0.486	0.685	1.01	1.72	2.50	4.98
53984#1	Anemone B	0.560	0.659	0.754	0.850	0.909	0.552
53984#1	Pennatulacea	0.122	0.165	0.211	0.300	0.317	
53984#1	Pycnogonid A	0.012	0.017	0.026	0.050	0.063	0.276
53984#1	Sabellids	0.011	0.015	0.021	0.036	0.056	
53981#1	Anemone B	0.012	0.016	0.025	0.044	0.058	
53981#1	SDTP	0.063	0.085	0.162	0.358	0.743	1.174
53981#1	Pycnogonid A	0.003	0.004	0.009	0.029	0.083	
53981#1	Sabellids	0.171	0.223	0.412	1.189	3.410	9.194

Table 4.5. Variation in faunal density with altitude of a number of taxa along the bathymetric transect west of Shetland (SDTP=Surface dwelling tubiculous polychaete).

The results illustrate an increase in faunal density with a decrease in altitude for all the taxa. The increase in faunal density is in most cases an order of magnitude and in some cases in excess of that when, for example, comparing the values for the 8 m altitude range to those of 4 m. The values appear to depend to some degree on the size of the fauna. For example, the densities of the smallest fauna, such as enteropneusts, increase most dramatically when the photographs with the highest altitudes are eliminated but although the density values are likely to vary depending on the species analysed, the overall pattern is evident in the entire data set.

The column for the 2.5 m altitude illustrates the considerable increase in faunal density when the camera is close to the seafloor compared to those values where the camera is further away, a pattern particularly apparent when smaller fauna are analysed. The photographs in figure 4.5 illustrate this further.

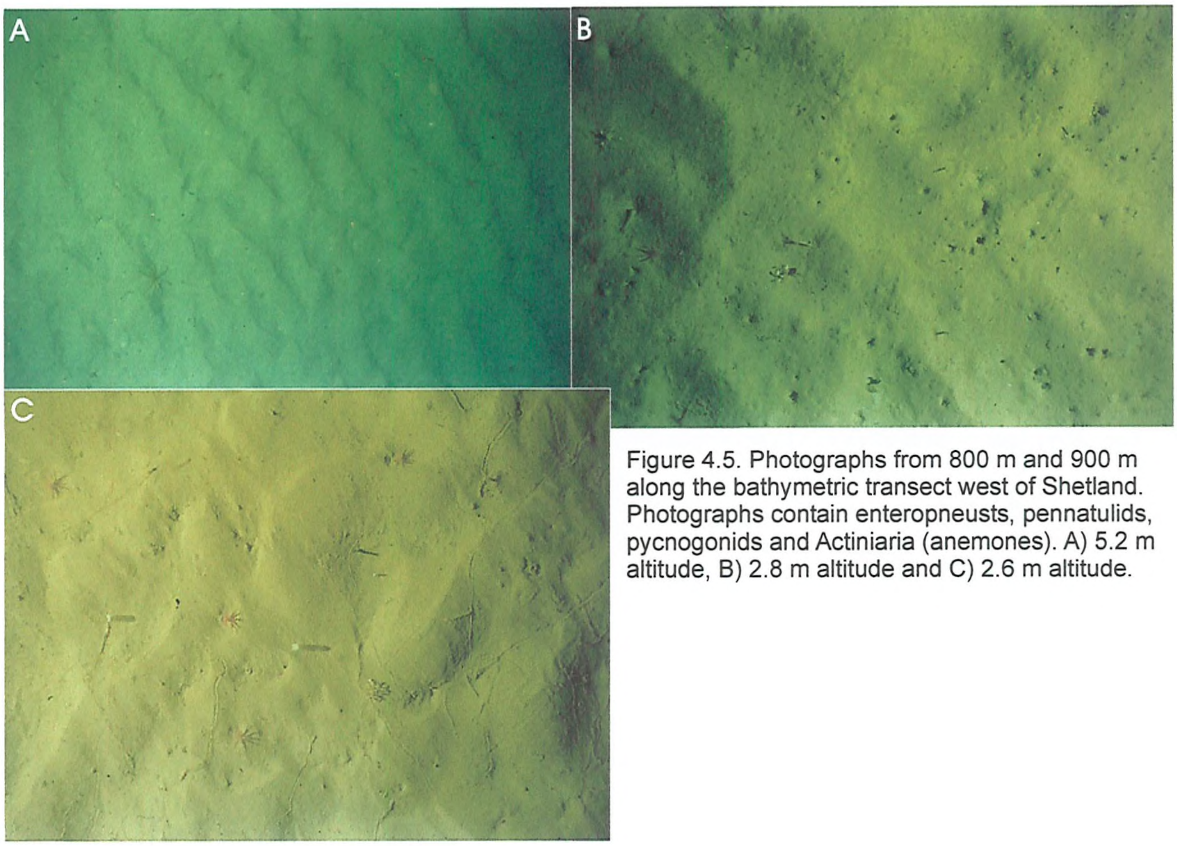


Figure 4.5. Photographs from 800 m and 900 m along the bathymetric transect west of Shetland. Photographs contain enteropneusts, pennatulids, pycnogonids and Actiniaria (anemones). A) 5.2 m altitude, B) 2.8 m altitude and C) 2.6 m altitude.

The three photographs are from the same substratum and contain the same fauna but they were taken at different altitudes. The most obvious difference is in light levels between the three photographs leaving the overall quality of the first frame (altitude 5.2 m) with regards to analysis inferior to the other two. This difference in quality when aiming to analyse the photographs is particularly evident when the smallest megafauna such as enteropneusts are studied, but other fauna such as Actiniaria (anemones) and pycnogonids are also difficult to identify and count at high altitudes. As the photographs illustrate, it is relatively easy to identify and count the fauna when the altitude is 2.6 m, but it becomes more difficult when the altitude increases to 2.8 m and much more so when the altitude is 5.2 m. The risks of overlooking some fauna therefore grow with an increase in altitude, a fact also noted in section 4.3.2.

In addition to the faunal densities described above, some examples using *lebensspuren* densities are given in table 4.6 and figure 4.6. As with the faunal densities, the analysis of *lebensspuren* along the bathymetric transect west of Shetland shows increased density values with a decrease in altitude. Note in addition the lack of frames at altitudes of 4 m, making comparisons between the different altitude ranges difficult.

Site	***Lebensspuren* density (traces/m^2) at different altitudes**					
	All frames		**≤ 6 m altitude**		**≤ 4 m altitude**	
	Density	**Median (95% CL)**	**Density**	**Median (95% CL)**	**Density**	**Median (95% CL)**
M200	0.203	0.182 (0/0.225)	0.203	0.182 (0/0.230)	0.211	0.186 (0.058/0.230)
M300 (a)	0.011	*	0.019	*		*
M300 (b)	0.028	*	0.030	*		*
M400 (a)	0.019	*	0.031	*		*
M400 (b)	0.029	0.031 (0/0.055)	0.038	0.049 (0/0.051)		*
M500	0.012	*	0.018	*	0.043	0 (0/0.107)
M600	0.002	*	0.002	*		*
M700	0.005	*	0.020	*		*
M800	0.078	0.092 (0.082/0.098)	0.126	0.121 (0.112/0.137)	0.264	0.254 (0.231/0.307)
M900	0.452	0.377 (0.276/0.533)	1.015	1.094 (0.972/1.247)	2.510	2.545 (2.029/3.107)
M1100	0.124	0.040 (0.034/0.044)	0.158	0.068 (0/0.094)	0.317	0.113 (0/1.467)
M1200	0.057	0.030 (0/0.038)	0.101	0.062 (0.057/0.069)	0.346	0.169 (0.137/0.248)
M1400	0.059	0.059 (0.047/0.059)	0.097	0.070 (0.061/0.095)	0.394	0.360 (0.247/0.471)

Table 4.6. Variation in *lebensspuren* density with changes in altitude (with 95 % confidence limits (CL) from bootstrap calculations based on median values; * = median and the 95% confidence limits are all equal to zero).

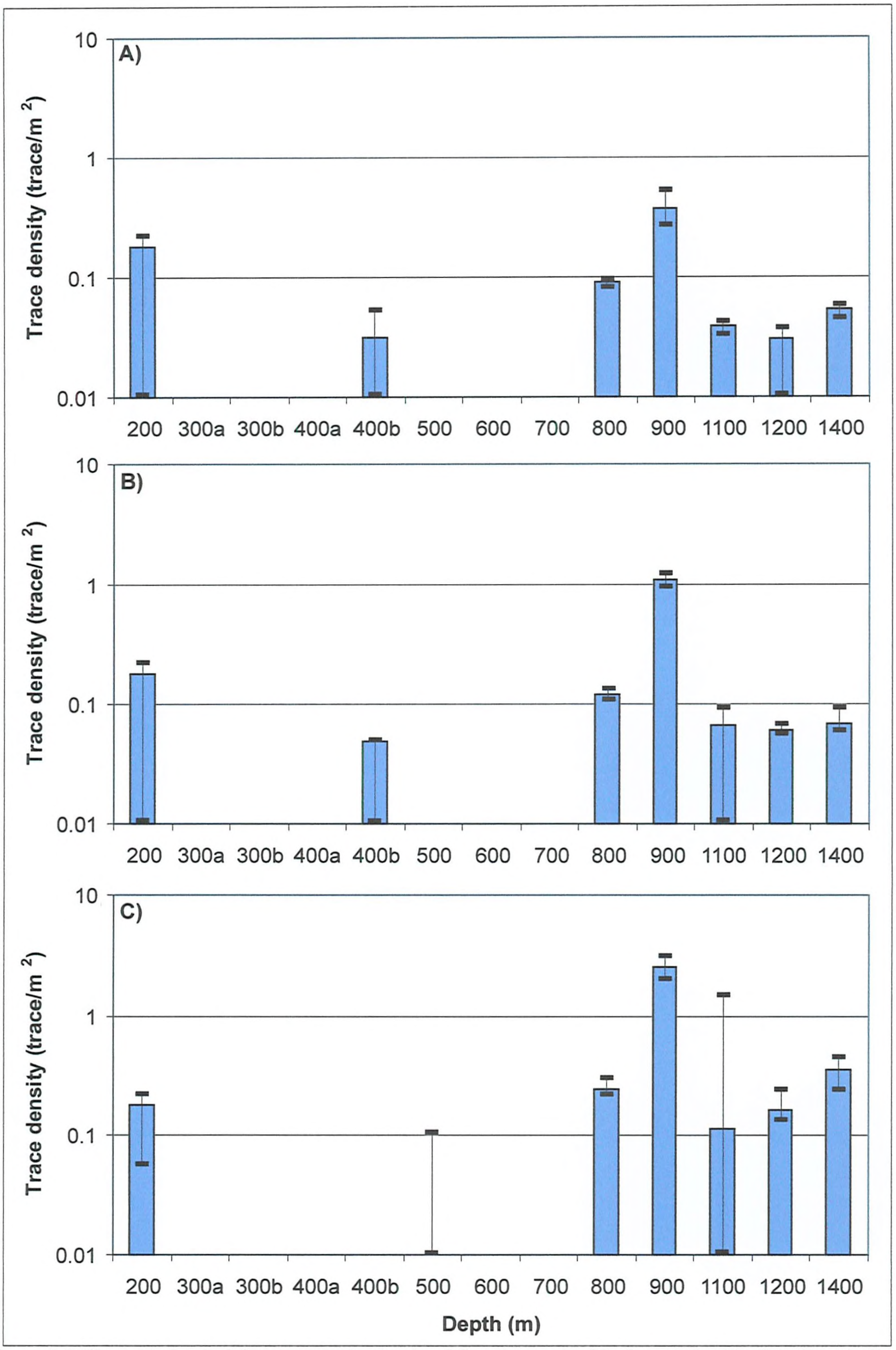


Figure 4.6. The variation in *lebensspuren* density (total for all traces) with changes in altitude using: a) all frames; b) frames at altitudes of 6 m, or less; and c) altitudes of 4 m, or less) along the bathymetric transect (depths referring to the sites in table 4.1) west of Shetland (median and 95% confidence limits obtained from bootstrapping calculations).

4.4 DISCUSSION

The process of frame selection is in most studies carried out on the basis of the quality of the photographs (e.g. Young *et al.*, 1985; Bett *et al.*, 1995; Roberts *et al.*, 2000), a process referred to as the first stage of frame selection in this study, but this process is not always described fully, or at all in some cases (e.g. Conant *et al.*, 1981; Dyer *et al.*, 1982; Cranmer *et al.*, 1984; Langton *et al.*, 1990). The second stage of frame selection as described here is rarely, if at all, carried out and the effects of excluding frames as a result of the altitude have therefore not been investigated. One reason for this is that few studies are carried out using a vertically mounted camera system (e.g. WASP as is this study) where there are fluctuations in altitude. Many studies use pre-set altitudes using for example sleds (virtually no fluctuation: e.g. Kidd and Huggett, 1981; Rice *et al.*, 1994) or trawls with headline cameras (with some fluctuations: e.g. Dyer *et al.*, 1982; Cranmer *et al.*, 1984) instead and therefore overcome this problem to some extent, although other problems such as damage to, or loss of, the gear or sinking into the sediment may occur instead (e.g. Chapman, 1985).

4.4.1 The proportion of frames available at different altitude ranges

As noted in figure 4.2, there is a decrease in the proportion of the number of frames available for analysis at lower altitude ranges, results indicating that the preferred altitude intervals are somewhere in excess of 4 m to allow sufficient number of frames to be available for analysis. In addition to this overall pattern there also appears to be a smaller proportion of frames available for analysis at greater depths within each altitude range. This may be coincidence but the pattern does appear to be present and it is most likely explained by the sea state. In rough seas the vertical movements of the ship, and therefore the WASP instrument, increase and the difficulty in operating and keeping the WASP instrument close to the seafloor therefore increases.

4.4.2 Proportion of frames with available megafaunal data

The proportion of frames with observed and recorded data at the 7 m and 8 m altitude ranges is lower (table 4.4) than at other ranges, partly as a result of fairly dark images (flash unit not powerful enough to fully illuminate the seabed) but also as a result of the lack of identifiable (i.e. difficult to see) and countable megafauna due to their sizes in relation to the distance of the camera from the seabed. At 6 m and 5 m altitude ranges these proportions of frames with data are higher than those at 7 m and 8 m ranges as well as those where the altitudes are 2.5 m or less (table 4.4). This overall pattern indicates a restriction in any selection of the frames (i.e. cut-off point for frame selection) to a medium (5-6 m) altitude range (i.e. 6-0 m or 5-0 m), as the proportion of frames available for analysis is highest in these ranges. It could be argued that the 4 m range (4-0 m) also should be considered as the cut-off point for frame selection and therefore exclude frames with altitudes in excess of 4 m, but the proportion is much lower (76.6 %) than at the 5 m (98.6%) and 6 m (97.8%) ranges and a lot of information might be lost, making this range less suitable.

4.4.3 The effects of frame selection on faunal density

The suggestion in the previous two sections of using an altitude range in the region of 4-6 m is further supported when figure 4.3 is consulted. However, rather than suggesting the whole range, these plots indicate a cut-off point at about 6 m (ranging between 5 m and 6 m where most appear to be closer to 6 m), where there is a sharp increase in apparent faunal density indicating that the frames within the 6 m altitude range are most appropriate to use. From the previous sections this range has in addition been shown to contain a high proportion of frames containing data while still retaining a large proportion of frames for analysis. The higher altitude ranges (>6 m), where density values are lower and identification and counting of fauna is particularly difficult, would therefore be excluded. To include photographs in the 7 m-altitude range may also be possible. One advantage (referring to this study in particular) would be to allow more frames to be available for analysis (see table 4.2 and figure 4.2). However, detection and counting of fauna at this altitude is more difficult, potentially leading to underestimates of the densities of some faunal groups such as the scallops and enteropneusts. The density values at 7 m altitude are for some fauna half of those calculated at 6 m altitude (table 4.5). It might be possible to use frames with higher altitudes in future studies by using for example a more powerful flash unit but in this study, photographs with altitudes in excess of 7 m are difficult to use. The stronger flash lights may alleviate some of the identification and counting problems, however, if these lights are too strong, photographs taken close to the seafloor are likely to become overexposed and there may also be some additional problems such as increased backscatter (Huggett, 1990). Furthermore, small fauna will still be difficult to identify and count as a result of the relationship between the size of the animals and the distance from the seabed. A different focus may be beneficial but again it may lead to other unforeseen problems where frames at other altitudes may become unusable. Therefore, on the evidence so far, it seems most appropriate to use the 6 m altitude range for frame selection for further analysis.

As was described in chapter 2, there is very little available biological data, such as faunal and *lebensspuren* densities, in the area northwest of Scotland and particularly west of Shetland. It is therefore difficult to compare the results from this study to similar work in the same region. In addition, there are even fewer studies where vertically mounted cameras have been used to survey the seafloor making the comparative analysis harder still. Dyer *et al.* (1982) used a headline camera and trawls to study the North Sea benthos with some sites west of Shetland. There is no information about the altitudes of the headline camera apart from stating that "the height was not absolutely constant". Some faunal densities were, however, reported from the west of Shetland continental shelf (table 4.7).

Taxa (previous studies)	**Densities from photographs**	**Taxa (this study)**	**Densities from photographs**
Cidaris cidaris *	0.09 – 0.22 ind./m^2	*Cidaris* sp	0.03 – 0.24 ind./m^2 (400 m) 0.01 – 0.02 ind./m^2 (500 m)
Echinus acutus *	0.07 – 1.68 ind./m^2	*Echinus* sp.	0.03 – 0.04 ind./m^2 (600 m)
Asterias rubens *	< 0.02 ind./m^2	Asteroid B sp *Ceramaster* sp.	0.01 – 0.04 ind./m^2 (500 m) 0.02 – 0.03 ind./m^2 (600 m)
Pennatula phosphorea *	0.14 ind./m^2	Pennatulacea	0.01 – 0.10 ind./m^2 (800 m) 0.12 – 0.32 ind./m^2 (900 m)
Munida rugosa +	0.03 ind./m^2	*Munida* sp.	0.03 – 0.14 ind./m^2 (300 m) 0.02 – 0.32 ind./m^2 (400 m) 0.08 – 0.38 ind./m^2 (500 m)

Table 4.7. Population densities from photographic surveys of some species on the continental shelf west of Shetland (from Dyer *et al.* (1982), Cranmer *et al.* (1984) and the continental slope (this study – see table 4.6) respectively (* = Dyer *et al.* (1982) and + = Cranmer *et al.* (1984)).

The density values from these two studies are similar in range at least to this study, although it should be noted that both studies by Dyer *et al.* (1982) and Cranmer *et al.* (1984) were carried out on the continental shelf while this study is from the continental slope and channel basin and the values may therefore not be directly comparable. Some of the taxa used for comparisons are not the same either but as the identity of the fauna from this study has been difficult, at least these comparisons give some indication of the quality of the results. Furthermore, the two studies were carried out using headline cameras on trawls, a fact that may also lead to differences in the results, although this is not apparent here. Assuming the data from the two other studies are representative for the region and the fauna, the results from this study are within the density ranges for almost all the fauna at almost all depths regardless of the altitude range used, although the differences appear to increase when the deep-water sites are compared to the shelf sites.

Examples of other studies that potentially could be used for comparison purposes are summarised in table 4.8.

Taxa (previous studies)	**Densities from photographs**	**Taxa (this study)**	**Densities from photographs**
Echinus affinis * (Porcupine Sea bight)	0.08 ind./m^2 (980 m)	*Echinus* sp	0.03-0.04 ind./m^2 (600 m)
Pennatulacea + (N. Rockall Trough)	0.11 ind./m^2 (1295 m)	Pennatulacea	0.01-0.10 ind./m^2 (800 m) 0.12-0.32 ind./m^2 (900 m)
Munida tenuimana + (N. Rockall Trough)	0.45 ind./m^2 (721 m) 0.40 ind./m^2 (885 m) 0.05 ind./m^2 (1108 m) 0.11 ind./m^2 (1295 m)	*Munida* sp.	0.03-0.14 ind./m^2 (300 m) 0.02-0.32 ind./m^2 (400 m) 0.08-0.38 ind./m^2 (500 m)

Figure 4.8. Examples of faunal densities from two other studies with photographs from sleds (Rice *et al.*, 1982) and from oblique (Roberts *et al.*, 2000) photographs (* = Rice *et al.*, 1982; + = Roberts *et al.*, 2000).

The density values from these other two studies are also within or close to the results from this study, although there are some differences but these may simply be explained by biological or ecological reasons or by the difference in photographic equipment used. The selection of altitude range for analysis therefore appears less important when the faunal densities are consulted, however, comparisons with studies more comparable to this study would be required to assess this further and this is the case with *lebensspuren* as well. It is therefore difficult to assess whether a frame selection where photographs taken far away from the seafloor, which often means they have less or are without data, are eliminated may improve the density results providing a better match to the true benthic faunal densities or not. It appears from the above data, particularly in studies of the smaller sized megafauna, that the results most likely will improve (table 4.5) if there is some level of frame selection, and high altitude frames are eliminated.

4.4.4 Improvements to the study

There are a number of potential improvements that could be made to this study including further statistical analysis. To enable statistical analysis to be carried out, there is a need for replication of samples with a minimum of two, and preferably more, samples from any one site (McIntyre *et al.*, 1984; Skoog *et al.*, 1994). In this study there is only one photographic sample from each site (apart from at 300 m and 400 m in the middle section where two samples are available. Although it could be argued that a film provides a better representation of the megafauna and other seabed features compared to other methods of sampling as it covers a much larger area. To improve the results, however, a minimum of two photographic runs would be required, although this may be a difficult requirement to fulfil as it would most likely increase the cost of the survey substantially and furthermore lead to a much longer (double) processing and analysis stage of the project. One other possible solution to improve the results could be to treat one photographic run as three separate entities where the film is divided up into two or more parts using some randomisation method. The photographic runs have a total of at least 100 photographs and many have around 300 photographs available for analysis, all of which would most likely be sufficient for a satisfactory analysis and results.

An additional potential improvement would be to collect the photographic material at altitudes in the range 3 to 6 m rather than the present 0 to 10 m range. The quality of the analysis would most likely improve as more fauna and other features would be identified and more photographs would then be available for processing and analysis. On the other hand, there could potentially be some loss of unusual features, as a smaller proportion of the seafloor would be sampled in any one survey. In addition, as was illustrated in figure 4.2, there is an increased difficulty in near-seabed operation with heavy seas and to aim for obtaining photographs within the 3-6 m altitude range may therefore be unrealistic as the weather is unpredictable. It should, however, also be noted that the results from this study may need further investigation and future work would include obtaining additional runs with photographs ranging from 1 m to 10 m from the same region to assess the results further and perhaps consider the need for a standardisation of altitude to obtain similar results for densities of fauna and *lebensspuren* and other features.

4.5 SUMMARY AND CONCLUSIONS

The summary of results from this study (figure 4.7):

- The general decrease in the proportion of frames available for photographic analysis with a decrease (figure 4.2) in altitude leaves approximately 50 % of frames available for analysis at the 6 m altitude range but only c. 20 % at the 5 m altitude range and only 8 % at the 4 m altitude range, essentially restricting the useable range of frames to 5 – 8 m.
- The proportion of frames with megafaunal data increase from the 8 m to the 5 m altitude range but at 4 m this pattern reverses and decrease down to 2.5 m, indicating an ideal useable range for final analysis between 5-6 m. Photographs with altitudes of 4 m, or less, are valuable for faunal detection and identification as well as faunal density studies.
- Apparent faunal and *lebensspuren* density increase with a decrease in altitude with a sharp increase in density values at 6 m altitude, indicating that frames with altitudes in excess of 6 m should be eliminated prior to further photographic analysis, a fact further supported by the photographs that illustrate the increased difficulty in analysing photographs with altitudes in excess of 6 m.

The analysis of all the photographic data from this study illustrates the need to select a proportion of the data for final analysis. One method of doing this is to use the altitude as a deciding factor of the number of frames to include in the study. The most appropriate range has been shown to be either 5 m, 6 m or 7 m but considering the lack of data points in the 5 m altitude range and the difficulties in identifying and enumerating fauna and other features at 7 m, the 6 m altitude range is the most appropriate level for frame selection for this study as it eliminates most of the frames that have little identifiable fauna, or other features, while retaining the majority of the data (5 m altitude range would not). It furthermore leaves a sufficient number of frames available for analysis at all sampling sites, an aspect that would not be fulfilled had a lower altitude been selected. Photographic analysis may benefit from some level of standardisation where a level of the altitude is the deciding factor rather than simply using frame selection to subjectively exclude poor quality frames. This may, however, be a difficult task to carry out in real terms as surveys use different camera systems and often have different sampling requirements and criteria. In addition, sampling in the deep sea is particularly difficult and costly, and there may be a need to use all available (after the first stage of frame selection to ensure the highest possible quality) data.

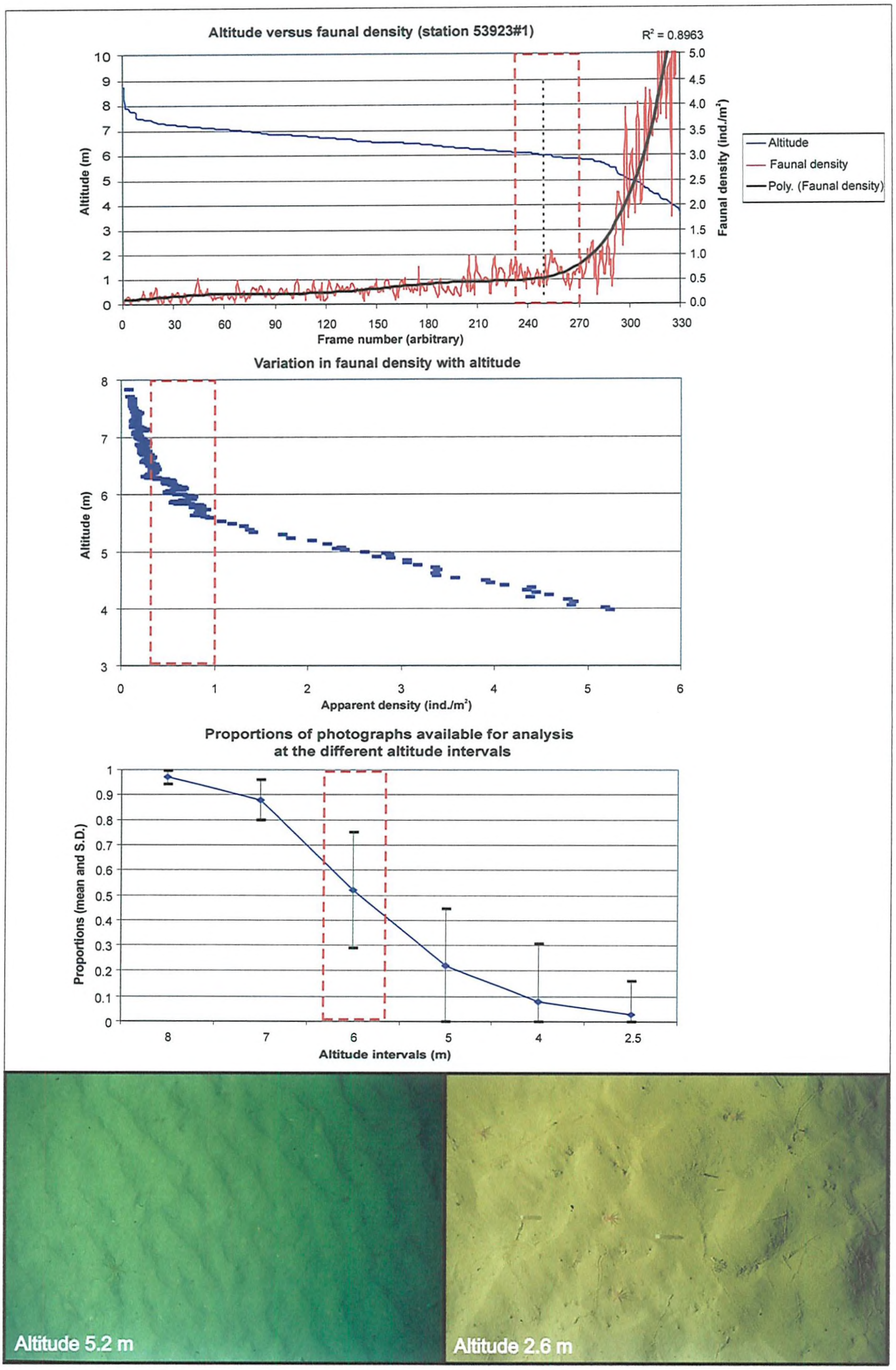


Figure 4.7. Summary with the red rectangles indicating the positions of the 6 m altitude intervals.

5 AN ANALYSIS OF THE SEAFLOOR ENVIRONMENT ALONG A BATHYMETRIC TRANSECT WEST OF SHETLAND USING THE PHOTOGRAPHIC INSTRUMENT WASP (WIDE-ANGLE SEAFLOOR PHOTOGRAPHY)

5.1 INTRODUCTION

The seafloor environment west of Shetland was relatively unknown prior to the AFEN 1996 and 1998 surveys, but the understanding of this area has now increased considerably through a number of studies (AFEN, 2000, 2001; Bett, 2000a; Narayanaswamy, 2001; Masson, 2001). Prior to 1996, only a few studies had included seabed-sampling sites in the Faroe-Shetland Channel (e.g. the large BIOFAR programme around the Faroe Islands) and the majority of those were located on the continental shelf west of Shetland (e.g. Dyer *et al.*, 1982, 1983; Cranmer *et al.*, 1984). This is despite the remarkable discovery of a complex structure in these waters over 100 years earlier, when a warm, upper layer overlying a cold, deeper layer was first noted (Thomson, 1873). The presence of at least a two layer system in the channel has been examined recently: the hydrography (Turrell *et al.*, 1999) and the macrofaunal ecology (Bett, 2000a, 2001a; Narayanaswamy, 2001), but very little has been reported on the megafauna (often defined as fauna visible on photographs or caught by trawls; Rice *et al.*, 1982; Gage, 1986; Lampitt *et al.*, 1986; Gage and Tyler, 1991) along the west of Shetland continental slope and channel floor.

The hydrographic regime within the Faroe-Shetland Channel is complex, being an important element of the 'conveyor belt' (see chapter 2) affecting most parts of the oceans, with five different water masses (see chapter 2 for more detailed information) forming a cold-, deep-water layer underlying a warm-, shallow-water layer (Tait and Martin, 1965; van Aken, 1988, Turrell *et al.*, 1999; Hansen and Østerhus, 2000). Turrell *et al.* (1999) suggests that the deep layer consists of Arctic Intermediate Water (AIW), Norwegian Sea Arctic Intermediate Water (NSAIW) and Faroe-Shetland Channel Bottom Water (FSCBW) and the shallow layer consists of the North Atlantic Water (NAW) and Modified North Atlantic Water (MNAW). The boundary between the two layers occurs at between 400 m and 600 m, separating water with temperatures of approximately 6.5 - 8 °C (shallow layer) and -0.5 – 5.5 °C (deep layer) (Turrell *et al.*, 1999). In addition, the current regime also largely follows this overall pattern with current flow in the upper (< 600 m) layer being towards the north-northeast at speeds of up to 0.8 m/s (Kenyon, 1986; Stoker *et al.*, 1993; Masson, 2001) and towards the south-southwest in the deep (> 800 m) layer at speeds of up to 0.6 m/s (Saunders, 1990; Stoker *et al.*, 1993). The depth of the boundary at which these currents flow in opposite directions has not quite been established (see e.g. Stoker *et* al., 1993; Masson, 2001) but the current speed and direction is likely to have a fundamental effect on both sediment dynamics and the biological communities in an area.

The sedimentary environment, like the hydrography, is complex but as with overall sedimentary distributions throughout the world's oceans (e.g. Pinet, 1992), sediment grain size decreases with depth along the continental slope west of Shetland (see chapter 2 for more details), although there is a great deal of variability in sediment grain size at both local and regional scales in this area (Stoker *et al.*, 1991; Stoker *et al.*, 1993; Stoker, 1995; Masson, 2001). The seabed surface is essentially a relict surface from the late Pleistocene with both terrigenous (mainly derived from glacially related processes; Stoker *et al.*, 1993; Masson, 2001) and biogenic sources (produced mainly on the inner and outer shelf; Light and Wilson, 1998) and the sediment can be described (largely from sidescan sonar interpretations) in a number of depth-related zones: iceberg plough mark zone, the along-slope current zone; a sand contourite and the channel floor (see chapter 2; Masson *et al.*, 1996, 1997; Masson, 2001).

Faunal distributions also vary with depth and although more is known about the macrofauna, the distributions of megafauna are in many respects believed to vary with depth in a similar manner to the macrofauna (Gage and Tyler, 1991). Quantitative data for megafauna are scarce but as with the macrofauna, there is a general expectation of a decrease in megafaunal density and biomass with depth (Tait, 1981; Carney *et al.*, 1983; Parsons *et al.*, 1984; Lampitt *et al.*, 1986; Gage and Tyler, 1991; Lalli and Parsons, 1993; Gage *et al.*, 2000), expectations that might have supported early theories, including the 'azoic zone' theory by Forbes (little life below 0.6 km). This theory assumed little or no life in the deep sea as well as a more stable environment in the deep sea compared to that of the shallow water environment (Menzies *et al.*, 1973; Rex, 1983; Gage and Tyler, 1991; Tyler, 1995). In the last 100 years, however, these theories have been challenged and the deep-sea environment has recently been shown to be more variable than was originally thought (Gage and Tyler, 1991; Lalli and Parsons, 1993), a fact exemplified by the relatively strong currents seen on the lower slope west of Shetland (see chapter 2; Masson, 2001) and the description of the internal tide within the Faroe-Shetland Channel (see chapter 2; Sherwin, 1991, 1995) but also from deep-sea photographs showing scouring and rippling (e.g. Heezen and Hollister, 1971) and other evidence including those of 'benthic storms' (Hollister and McCave, 1984) and temporal variations in phytodetritus (e.g. Billett *et al.*, 1983; Rice *et al.*, 1986; Gooday and Turley, 1990; Bett *et al.*, 2001b). Since the 1960s the early concepts of decreasing diversity with increasing depth has also been challenged and although the causes of diversity gradients are not well understood, a number of theories have been proposed, including the equilibrium theory exemplified by Sanders Stability-time theory (Sanders, 1968) where the diversity essentially decreases with an increase in disturbance (defined as any population reducing effect; Gage and Tyler, 1991) and biological interactions mediate competition resulting in organisms specialising into niches avoiding competitive exclusions. Non-equilibrium theories have also been suggested where there is a 'parabolic' curve response in species richness (diversity) to disturbance where at low levels of disturbance diversity is low but diversity increases with an increase in disturbance until a cut-off point where diversity again decreases (see Gage and Tyler, 1991, Gage *et al.*, 2000). A similar response has been seen against bathymetry in a number of studies, with a diversity maximum at intermediate (bathyal) depths (Rex, 1981; Maciolek *et al.*, 1987; Paterson and Lambshead, 1995), a pattern believed to occur within the megafauna as well as the macrofauna (Rex, 1981, 1983; Gage and Tyler, 1991). It should, however, also be noted that other studies have shown species diversity to be equally high in shallow-water settings (Poore and Wilson, 1993; Gray, 1994) and perhaps indicating that the generalisation that the deep sea is uniformly a high diversity habitat may be too simplistic (Poore and Wilson, 1993; AFEN, 2000; Gage *et al.*, 2000).

As illustrated above, many environmental parameters in the ocean vary with depth and the bathymetric transect west of Shetland is an example of a regional study of the environmental features found on the Atlantic Margin consisting of a number of sites from the upper continental slope to the deep waters of the Faroe-Shetland Channel (Bett, 1997). The aim of the study is to further the knowledge about the environment west of Shetland and describe the sediment and the biological distributions, particularly the megafauna, and any other features identified along the continental slope and channel floor. The transect is located immediately to the west of the Shetland Islands (figure 5.1) and there are a total of 13 photographic sites ranging in depth from approximately 200 m to 1400 m (table 5.1), with 12 sites from AMES 1996 and one (M200) from a Department of Trade and Industry survey in 2000 (Bett, 2001b).

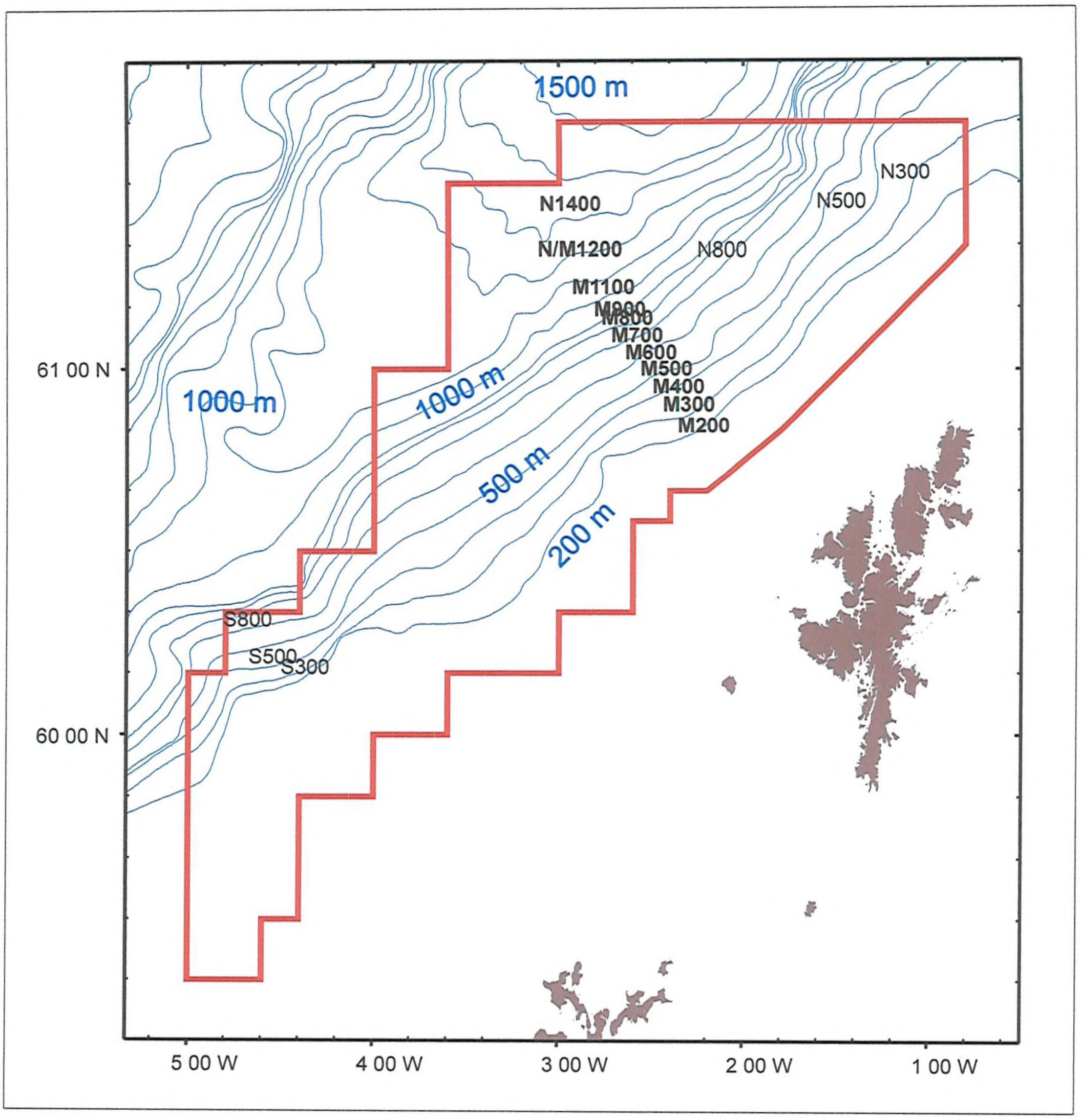


Figure 5.1. Photographic (WASP) sampling sites from AMES 1996 as well as the 200 m site from a DTI survey in 2000 (see table 5.1 for details). Sites in bold are part of the bathymetric transect west of Shetland (stations 53913 – 53926 and 53928 – 53914 are located in close proximity of M300 and M400 respectively).

In table 5.1 all the station numbers, the positions and the total number of frames available from each site are given. The sites are identified as M300, N1400 etc., indicating in which area the site is located, where M stands for mid section and N stands for North section. All sites presented here are, however, part of the bathymetric transect. In addition to the above, the frame identification numbers, as recorded on the films (see chapter 3), and the length of each recorded film can also be seen in table 5.1. There is one photographic run at each depth apart from those at 300 m and 400 m, where there are two runs.

Station (Site)	**Location**	**Depth**	**Frame identification**	**Film run**	**Number of frames**
55456#1 (M200)	60° 52.80 N 02° 19.13 W	209-204 m	027 - 341	15 m colour	315
53913#1 (M300a)	60° 53.96 N 02° 22.07 W	290 – 275 m	435-543	5 m colour	109
53926#1 (M300b)	60° 53.96 N 02° 22.15 W	294 – 278 m	2140 - 2249	4 m colour	110
53928#1 (M400a)	60° 56.70 N 02° 25.91 W	390 – 370 m	2506 - 2725	7 m colour	221
53914#1 (M400b)	60° 57.74 N 02° 24.98 W	410 – 397 m	560 – 665	7 m colour	106
53925#1 (M500)	60° 59.54 N 02° 29.79 W	507 – 496 m	1780 - 2103	12 m colour	324
53916#1 (M600)	61° 02.49 N 02° 33.95 W	595 – 580 m	019 - 317	11 m colour	299
53985#1 (M700)	61° 05.40 N 02° 38.12 W	685 – 672 m	014 – 128	5 m colour	115
53924#1 (M800)	61° 07.99 N 02° 42.00 W	798 – 781 m	1545 – 1762	10 m colour	218
53984#1 (M900)	61° 09.57 N 02° 43.90 W	912 – 881 m	012 – 356	12 m colour	344
53923#1 (M1100)	61° 12.85 N 02° 49.41 W	1088 m	1164 – 1495	12 m colour	332
53981#1 (N/M1200)	61° 19.20 N 02° 58.23 W	1209 – 1203 m	371 – 690	10 m colour	320
53980#1 (N1400)	61° 26.65 N 03° 00.07 W	1408 – 1401 m	011 - 346	12 m colour	336

Table 5.1. Station data of the photographic (WASP) sites along the bathymetric transect west of Shetland (the locations refer to the positions at the beginning of the transects and frame identification refers to the number printed on the frames at exposure).

5.2 METHODS

All sites have been surveyed using the photographic instrument WASP (Wide-Angle Seafloor Photography). Deep-sea photographs from the 13 sites along the bathymetric transect west of Shetland at depths ranging from 200 m to 1400 m have been analysed (figure 5.1 and table 5.1). In general there are approximately 200 to 300 frames for each run, the equivalent of 10 to 12 m of film (table 5.1). Two photographic runs were completed at 300 m and 400 m (i.e. two films per depth) and the results from these films have been calculated and described together for those two depth intervals. All frames have been processed and analysed as described above (chapter 3) and total of 3149 seabed photographs were available for analysis from the 13 films (table 5.1). All the photographs were used during the processing of the films and subsequently examined for suitability for use in the study. Photographs were rejected if they were over- or underexposed. In addition, frame selection (see chapter 4) was carried out where all photographs with altitudes in excess of 6 m were excluded from the final analysis.

The photographic analysis involved observing and recording details regarding the sediment, the megafauna and any evidence of hydrographic action. Notes were also made regarding any other natural (e.g. slumps) or artificial (e.g. trawl marks) effects observed on the seabed. The sediment analysis was of a descriptive nature, where the seabed environment was described as far as possible for each frame. The megafauna was described and/or identified as far as possible, and then counted. Information about *lebensspuren* was also noted and these results are given in chapter 6. Information about the currents were obtained by studying evidence on the seabed (scouring or deposition behind rocks or sediment bedforms such as sand waves or ripples) or by noting the direction in which fish, stalked sponges or other fauna, responded to flows. Fish are often found facing the current while stalked sponges and other sedentary fauna often bend in the direction of the current. The latter observations were always treated with caution as these indicators may not show the residual current direction but when these are treated together with other features, such as the sediment features, a more reliable result can be obtained.

5.2.1 Seabed analysis

The seabed analysis was carried out taking notes of the general seafloor environment with descriptions of the majority type of sediment present with additional notes with regards to larger features such as boulders. This information was then used to produce a qualitative scale of the sediment as a whole from the WASP analysis for the entire transect to obtain values, rather than descriptions, and allow comparisons with other data. A scale from 1 to 5 was created, where very fine sediment was given the number 5 while a very coarse seabed was given a number 1. Sites with a number of different types of sediment (e.g. within the plough mark zone) were given a value reflecting the most common type of seafloor present but taking all sediment types into account as far as possible. In the case of the 300 m and 400 m WASP runs, a value was given for each site, as with the others, and a mean value was then taken for the two sites at these two depths. These values were then used to calculate the Spearman rank correlation coefficients (see faunal analysis section 5.2.3.2), comparing these results with the environmental variables.

To enable correlation analyses to be carried out, the environmental data from AFEN 1996 (AFEN, 2000) was used (see sampling methods in chapter 3). This included the particle size analysis data (Phi), the silt and clay content as well as the carbon and nitrogen content (table 5.2). In addition, the temperature data from the TOBI survey was also used but as temperature data only cover the depth range 200 – 800 m within the bathymetric transect, the temperature at 800 m (-0.44 °C) has been extrapolated to all the deeper stations (900 – 1400 m) to allow for the correlation analyses for the entire bathymetric transect. This extrapolation is based on the information described in chapter 2.3, where it has been shown that the temperature is fairly constant at < - 0.5 °C for depths below 800 m.

Site	Depth	Phi	Wentworth scale	Carb	Org	S and C	TOC	TON	C/N
A3	160	1.12	Medium sand	28.49	0.31	0.26	0.18	<0.01	
Tr200	200	1.33	Medium sand	47.61	0.59	0.95	0.07	<0.01	
E3	222	0.70	Coarse sand	37.30	0.99	0.82	0.37	0.03	14.8
Tr300	286	1.18	Medium sand	22.06	0.63	0.70	0.07	<0.01	
E4	296	0.95	Coarse sand	27.43	0.63	4.61	0.58	0.07	0.80
AD1	324	1.84	Medium sand	12.81	0.34	1.75	0.14	<0.01	
H5	390	0.33	Coarse sand	49.04	1.49	2.86	1.43	0.10	14.0
L5	407	1.53	Medium sand	19.39	0.66	1.87	0.06	<0.01	
L5	408	1.38	Medium sand	27.07	1.25	1.22	0.10	<0.01	
L4	490	1.06	Medium sand	18.39	1.42	4.06	0.25	<0.01	
L4	494	1.44	Medium sand	20.31	1.23	2.53	0.14	0.01	17.0
P5	510	0.16	Coarse sand	16.01	1.45	1.96	0.31	0.01	37.0
Tr600	591	1.63	Medium sand	13.85	1.48	3.95	0.16	0.01	19.0
Tr600	591	1.74	Medium sand	15.01	1.42	6.63	0.31	<0.01	
AC1	575	1.13	Medium sand	14.12	3.82	1.65	1.00	0.11	9.0
S2	697	3.39	Very fine sand	14.76	1.39	14.40	0.42	0.03	12.2
S2	698	3.41	Very fine sand	23.00	1.48	13.44	0.48	0.03	15.6
S1	716	2.98	Fine sand	15.60	1.38	8.40	0.40	0.03	15.7
Tr800	789	3.48	Very fine sand	18.93	1.37	11.11	0.36	0.02	14.7
Tr800	792	3.50	Very fine sand	16.71	1.35	11.29	0.23	0.02	14.0
U3	825	2.25	Fine sand	11.97	1.19	4.98	0.74	0.07	10.5
Tr900	898	2.87	Fine sand	12.59	1.40	3.99	0.15	<0.01	
Tr900	899	3.05	Very fine sand	11.53	1.07	5.47	0.20	<0.01	
U1	922	2.88	Fine sand	8.76	1.06	4.33	0.66	0.06	10.3
X2	1046	2.49	Fine sand	17.76	1.61	9.70	0.40	0.05	8.17
W1	1069	3.20	Very fine sand	14.60	2.49	28.56	0.56	0.05	10.8
X1	1116	5.03	Medium silt	23.68	0.95	59.92	0.40	0.04	10.4
W3	1168	2.30	Fine sand	17.50	1.69	8.86	0.82	0.09	9.0
Y3	1213	2.90	Fine sand	15.18	1.73	25.60	0.52	0.05	10.7
Y4	1325	3.21	Very fine sand	18.98	2.46	19.62	0.82	0.09	9.0
Y5	1362	3.99	Very fine sand	19.99	2.66	38.40	0.56	0.06	8.75
Z2	1388	4.21	Coarse silt	19.91	3.03	44.90	0.65	0.07	9.00
Z1	1411	4.37	Coarse silt	25.99	2.36	40.32	0.63	0.07	9.44

Table 5.2. Sediment stations from AFEN 1996 used for correlation analysis studies with the WASP sites. Depth in m, Phi is the mean Phi value, Carb = carbonate content (% dry weight), Org = organics (% dry weight), S and C = silt and clay content (% dry weight), TOC = total organic carbon (% dry weight), TON = total organic nitrogen (% dry weight), C/N = carbon to nitrogen ratio.

As there are a large number of stations spread all over the AFEN 1996 sampling survey area, three seabed samples for each WASP site (table 5.2) were selected to allow for analysis and comparisons with the WASP data. The selection of these sediment stations was carried out by plotting all the stations and then selecting the sediment stations closest to the WASP sites in depth and distance (see table 5.2 and figure 5.2). The mean values were then calculated for each depth interval and used in the correlation analysis studies.

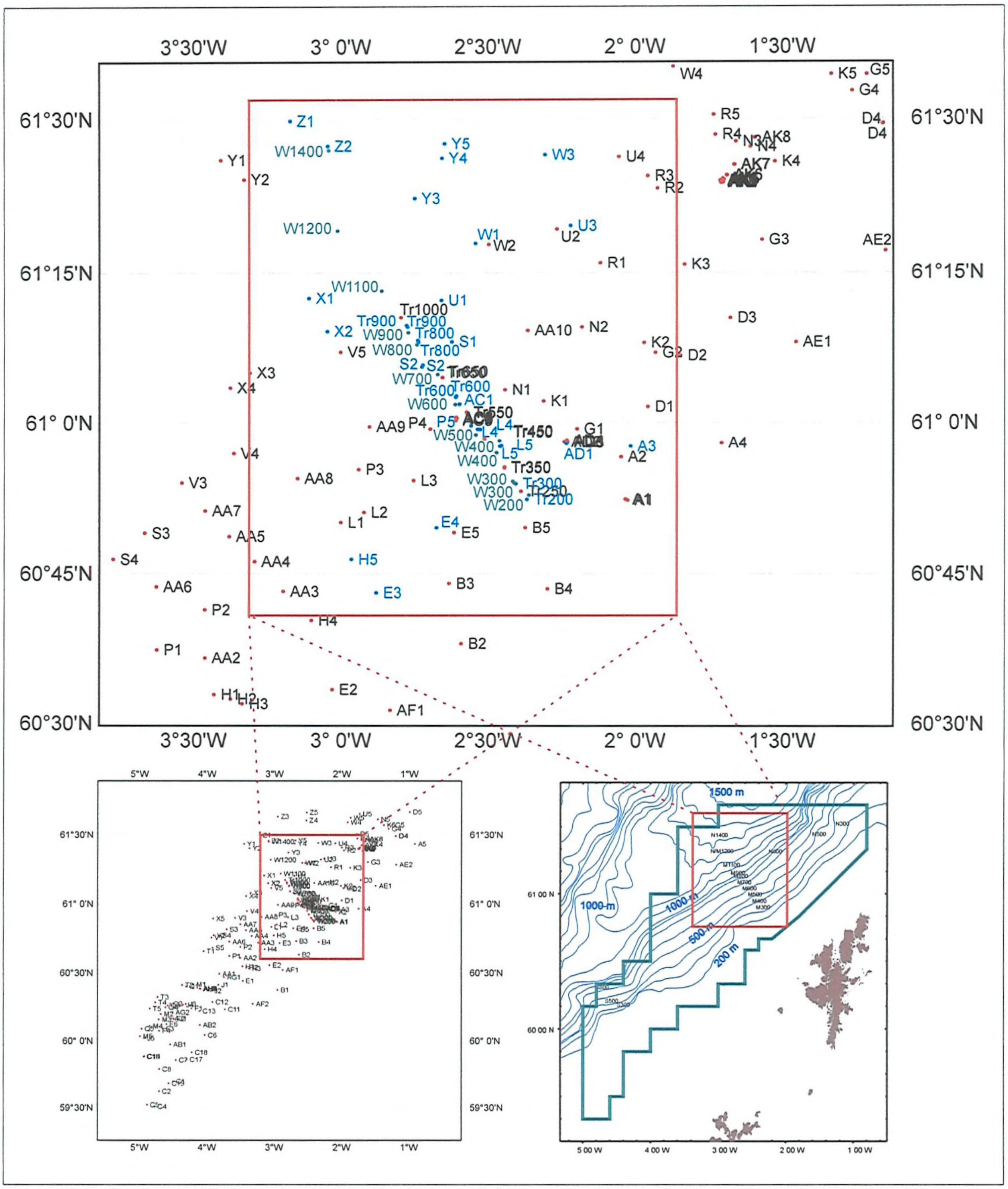


Figure 5.2. Sediment stations from AFEN 1996 used for correlation analysis studies with the WASP sites. All sampling stations (lower left) can be seen in relation to the AFEN 1996 survey area (lower right) and the close-up (large map) showing the WASP sites (green) in relation to the seabed sampling stations (blue) and all the remaining stations (black) not used for the analyses.

5.2.2 The faunal analysis

There are a number of techniques used to analyse multi-species data. In this study the approach suggested by Field *et al.* (1982) is used. They preferred 'letting the species tell their story' and search for patterns amongst the biological variables with an attempt to interpret these in terms of environmental data. The megafauna present at the sites along the bathymetric transect will first be described in general, with a brief description of the dominant fauna present at each depth interval. The identification of megafauna on photographs is notoriously difficult (Barraclough Fell, 1967; Jumars and Eckman, 1983; Holme, 1985; Southward and Nicholson, 1985) and in most cases the fauna in this study have been identified to phylum, class or order level. In some cases it has been possible to determine the genus of the fauna and a few have been identified to species level. The identification process has been carried out using a number of different sources (see references) from the literature and the internet but also with assistance from a number of scientists (table 5.3). The megafauna was then analysed using univariate (abundance and diversity) and multivariate (cluster analysis and ordination) methods.

Megafaunal group	Scientist
General megafauna	Dr B.J. Bett
Crustacea	Dr M.H. Thurston
Echinodermata and Holothuroidea in particular	Dr D.S. Billett
Asteroidea	Dr K.L. Howell

Table 5.3. Megafaunal groups and scientists assisting in the identification of these groups.

5.2.2.1 Abundance

In this study density is used as an abundance parameter to allow comparisons between different sites and regions but the numbers of individuals examined have also been included to allow assessments regarding the size of the analysed samples. Confidence limits, based on the median values, have been calculated using bootstrapping (see e.g. Cressie, 1993; Sokal and Rohlf, 1995; Krebs, 1999) and 'the first percentile method' in particular, where bootstrap resampling (with replacement) of the original data is carried out 1000 times to generate the bootstrap distribution of the median values (Manly, 1991). The 95% confidence interval is given by the values that are less than 2.5% and exceed 97.5% of the generated distributions (Manly, 1991).

5.2.2.2 Diversity indices

A variety of diversity parameters have been calculated to assess the variation in diversity with depth but also to assess any differences between different methods. The results have been calculated using PRIMER (version 5) and the corresponding equations are given in Clarke and Warwick (1994).

5.2.2.2.1 Shannon-Wiener diversity index

This is the most commonly used diversity index and it can be calculated using $\log_2$, $\log_{10}$ or $\log_e$ (Clarke and Warwick, 1994) but $\log_e$ (simply Shannon-Wiener hereafter) has been used in this study to allow comparisons with other studies including those of Bett (2000a) and Narayanaswamy (2000) in particular.

$$H' = - \sum_i p_i (\log p_i)$$

where p_i is the proportion of the total count arising from the ith species. This measure incorporates both the species richness and equitability components.

5.2.2.2.2 Species richness

Species richness is often given as the total number of species, a value very dependent on the sample size. Margalef's index (d), which incorporates the total number of individuals, is therefore often used and the equation is:

$$d = (S - 1) / \log N$$

where S is the number of species and N is the total number of individuals (Clarke and Warwick, 1994).

5.2.2.2.3 Equitability

Equitability expresses how evenly the individuals are distributed among the different species and it is most commonly expressed as Pielou's evenness index (Clarke and Warwick, 1994):

$$J' = H' (\text{observed}) / H' \max$$

where H′ max is the maximum possible species diversity (the Shannon diversity index value) which would be achieved if all species were equally abundant (=log S). The calculations will result in values between 0 (zero) and 1 (one), where 1 indicates high evenness (or equitability) and 0 indicate dominance.

5.2.2.2.4 Rarefaction

The rarefaction technique was initially devised by Sanders (1968), however, Hurlbert (1971) modified the formula to take patchiness into account and produce unbiased estimates. The plots are produced with the number of individuals on the x-axis against the number of species on the y-axis. The steeper and more elevated the rarefaction curve, the more diverse the community is (Clarke and Warwick, 1994) and the equation is (from Gage and Tyler, 1991):

$$E(S_n) = \sum_{i=1}^{s} \left[1 - \frac{\genfrac{}{}{0pt}{}{N-N_i}{n}}{\genfrac{}{}{0pt}{}{N}{n}} \right]$$

where $E(S_n)$ is expected number of species; N is the total number of individuals recorded; N_i is the number of individuals in the *i*th species in the sample and n is the number of individuals in the hypothetical sample from which the number of species is estimated.

5.2.2.2.5 Species accumulation curves

Species accumulation curves are used as a method of detecting the rate at which new, previously unrecorded, species appear in the samples (see e.g. Clarke and Warwick, 1994). The samples are typically arranged along an environmental gradient (e.g. depth) and can then be used to detect areas of rapid changes in the species composition. The curves are calculated by first adding all the different species at the first site and then cumulatively adding any further new species found at each site along the environmental gradient. These curves have been plotted against depth to determine where the greatest rate of change occurs along the bathymetric transect.

5.2.3 Further statistical analysis

The megafaunal composition was studied by examining the variation in the composition of the phylum groups with depth but also by carrying out multi-variate analysis to investigate any potential groupings or clustering in the data.

5.2.3.1 Multi-variate analysis

Further analysis of the megafaunal data was carried out using multi-variate analysis to assess the similarity of the fauna at the different depth intervals. The megafaunal density data were transformed to fourth root to down-weigh the importance of common types of megafauna in relation to rarer types. The transformed data was then analysed using cluster analysis and ordination.

5.2.3.1.1 Cluster analysis

The data was first analysed using the Bray-Curtis similarity coefficient (using Primer version 5) followed by a cluster analysis where the sites were group averaged and the resultant dendrogram plotted.

5.2.3.1.2 Ordination by Multi-Dimensional Scaling (MDS)

Multi-Dimensional Scaling (MDS) was also carried out to further assess the presence of any similarities between the different depth intervals along the transect. This method attempts to place the samples on a ‘map’, often in two dimensions. The success of the mapping is measured by a ‘stress coefficient’, which reflects the extent to which the ordination gives a simple visual representation of ‘closeness’ of the species composition for any two samples (Clarke and Warwick, 1994).

5.2.3.2 Spearman rank correlation coefficient

A number of different results from the megafaunal data analyses were compared to the environmental variables west of Shetland, including the variation in temperature with depth as well as a number of sedimentary and other variables to assess which, if any, variable had the largest influence on the distribution and diversity of megafauna along the bathymetric transect west of Shetland. These comparisons were carried out using Spearman rank correlation coefficient (r_s):

$$r_s = 1 - ((6\Sigma d^2)/(n^3 - n))$$

where *n* is the number of units in a sample, *d* is the difference between ranks (Elliott, 1971; Fowler and Cohen, 1992). The results from the correlation analyses have been discussed in conjunction with the results in the various sections.

5.2.4 Analysis of the physical parameters

The positions of any scouring, deposition or ripple/waves effects on the seabed as seen on the photographs were first determined during the processing of the films. The direction of travel on the photographic run was subsequently determined by comparing two successive frames and by comparing these results to the ship's travel direction (see chapter 3), from which the direction of any currents could be established.

In the case of scouring or deposition around rocks, only the position of the feature was recorded in relation to the rock while in the case of the sand ripples or waves, the size of the ripples or waves were also measured to enable some estimates to be made with regards to the current speeds in the area. These estimates are difficult to make without exact knowledge about the grain size in the sediment in question but these, and therefore the current speeds, can be estimated from the combined analysis of the photographs and sediment data collected during the AFEN 1996 surveys with the information from bedform analyses (e.g. Leeder, 1982; Open, 1989).

5.2.5 Assessment of other features

The photographs were also assessed for the presence of any artificial artefacts and any slumps or failures and recorded during the processing of the films.

5.2.5.1 Trawling

Marks observed on the sediment surface believed to have been created by trawling have been recorded. The total number and the density values for these marks have been calculated. The density values have been calculated using the entire photographic runs rather than using the available photographs after frame selection as most marks are only visible on the higher altitude frames. The sizes of these marks have not been measured, as they were too large and only parts of the tracks were visible on the photographs.

5.3 RESULTS

Of the original 3149 frames available from all the films, a total of 1757 usable photographs (with a coverage of 23,311 m^2) were available for analysis after the two stages of frame selection. The exclusion of unsuitable frames, stage one of frame selection, left 2991 frames (with a total seafloor area coverage of 53,473 m^2) and the exclusion of frames where the altitude was greater than 6 m, stage two of frame selection, left 1757 frames. Over 90% of all these frames contained megafaunal data for analysis (table 5.4).

Site	M200	M300	M400	M500	M600	M700	M800	M900	M1100	N/M1200	N1400
%	95.6	98.1	95.7	91.6	100	100	97.3	100	100	100	100

Table 5.4. Percentage of frames containing observed and recorded megafaunal data (300 m and 400 m are mean values for the two sampling runs at each depth).

5.3.1 Seabed analysis

The photographic analysis of the seabed along the bathymetric transect revealed a general pattern where the sediment becomes finer with depth (table 5.5 and figure 5.3). At the shallower sites the sediment has a large proportion of gravel, cobbles and boulders while at the deeper sites sand and mud are the dominant sediment types, although the latter is difficult to identify with certainty. Evidence of iceberg plough marks is present between 200 and 400 m with three types of seafloor present, 'fine', 'medium' and 'coarse' sediment areas (see also Bett, 2000a; Bett and Axelsson, 2000). The plough marks have formed a relatively open sediment area with finer material (sand and gravel) while the 'coarse' material is found at the edges of the iceberg tracks, areas marked by accumulations of glacial erratics (cobbles and boulders). Between 400 m and 600 m the sediment is predominantly gravel and sand while below 600 m, sand and mud become the dominant sediment types, although there is some variation between sites. Drop-stones of a variety of sizes are present throughout the transect, a characteristic of the Faroe-Shetland Channel (Stoker *et al.*, 1998).

The values for the sediment grading (from the WASP analysis) have also been included and these have been produced to allow comparisons with other data. The scale from 1 to 5, where 1 equals very coarse sediment and 5 equals very fine sediment, indicates as the general descriptions above, that the sediment gets finer with depth (table 5.5 and figure 5.5) but there is also some variation along the transect.

Station (Site)	Depth (m)	Sediment grading*	Sediment description
55456#1 (M200)	204 – 209 m	2-3	Evidence of three sediment types; 'coarse', 'medium' and 'fine'. 'Coarse' dominated by boulders, cobbles, pebbles and gravel on sand; 'Medium' dominated by sand and gravel and 'fine' dominated by (rippled) sand.
53913#1 (M300a)	290 – 275 m	2	Two types, 'medium' and 'coarse'. 'Medium' dominated by sand and gravel, 'coarse' dominated by gravel, pebbles, cobbles and boulders
53926#1 (M300b)	294 – 278 m	2	Evidence of two types, 'medium' and 'coarse'. Medium' dominated by sand and gravel, 'coarse' dominated by gravel, pebbles and occasional boulders.
53928#1 (M400a)	390 – 370 m	2	Evidence of two types, 'medium' and 'coarse'. 'Medium' dominated by sand and gravel; 'coarse' dominated by gravel, pebbles and boulders with sand.
53914#1 (M400b)	410 – 397 m	2-3	Gravel and sand dominate the sediment with gravel seemingly contributing with the largest component. No clear divisions into ‘types’ of seafloor.
53925#1 (M500)	507 – 496 m	2-3	The sediment is dominated by sand and gravel but pebbles, cobbles and boulders are also present at high concentrations throughout the run.
53916#1 (M600)	595 – 580 m	2	The sediment is classified as ‘coarse’, dominated by gravel and pebbles with sand with a high concentration of cobbles and boulders present throughout the run.
53985#1 (M700)	685 – 672 m	3-4	The sediment is dominated by a thin layer of sand overlying coarser material (gravel, pebbles and cobbles) with drop stones being present in a large quantity.
53924#1 (M800)	798 – 781 m	4	Sand dominates the sediment
53984#1 (M900)	912 – 881 m	4	Sand dominates the sediment
53923#1 (M1100)	1088 m	3-4	Pebbles and small cobbles dominate and are overlaid by a thin veneer of fine material, sand and/or mud, throughout the run. Large boulders, drop stones, are also present.
53981#1 (N/M1200)	1209 – 1203 m	5	Fine sand and/or mud dominate the sediment.
53980#1 (N1400)	1408 – 1401 m	5	Fine sand and/or mud dominate the sediment.

Table 5.5. Sediment analysis from WASP photographs along the bathymetric transect west of Shetland (* the WASP sediment grading as described in the methods section 5.2.1).

The results from the correlation analysis, where the sediment classification from the photographic analysis is correlated with that from the seabed sampling analysis (AFEN, 2000), can be seen in table 5.6. The most significant correlation is found between the WASP sediment analysis results and depth ($p < 0.01$) but a significant correlation is also found with sediment size (Phi - mean) and the silt and clay content ($p < 0.05$). The depth trends in WASP sediment grading and seabed sample grain size are given in figure 5.3.

Environmental variables	**WASP sediment analysis**		
Depth	0.827**		
Phi (mean)	0.659*		
Phi (median)	0.618		
Silt and clay content	0.664*		
Significant levels (two-tailed test; from Fowler and Cohen, 1992)	*Tabulated value*	*Significance level*	*Description*
	0.818	0.01**	*Highly significant*
	0.623	0.05*	*Significant*

Table 5.6. Correlations (Spearman rank correlation coefficient) between environmental parameters and the WASP sediment analysis results along the bathymetric transect west of Shetland (n = 11).

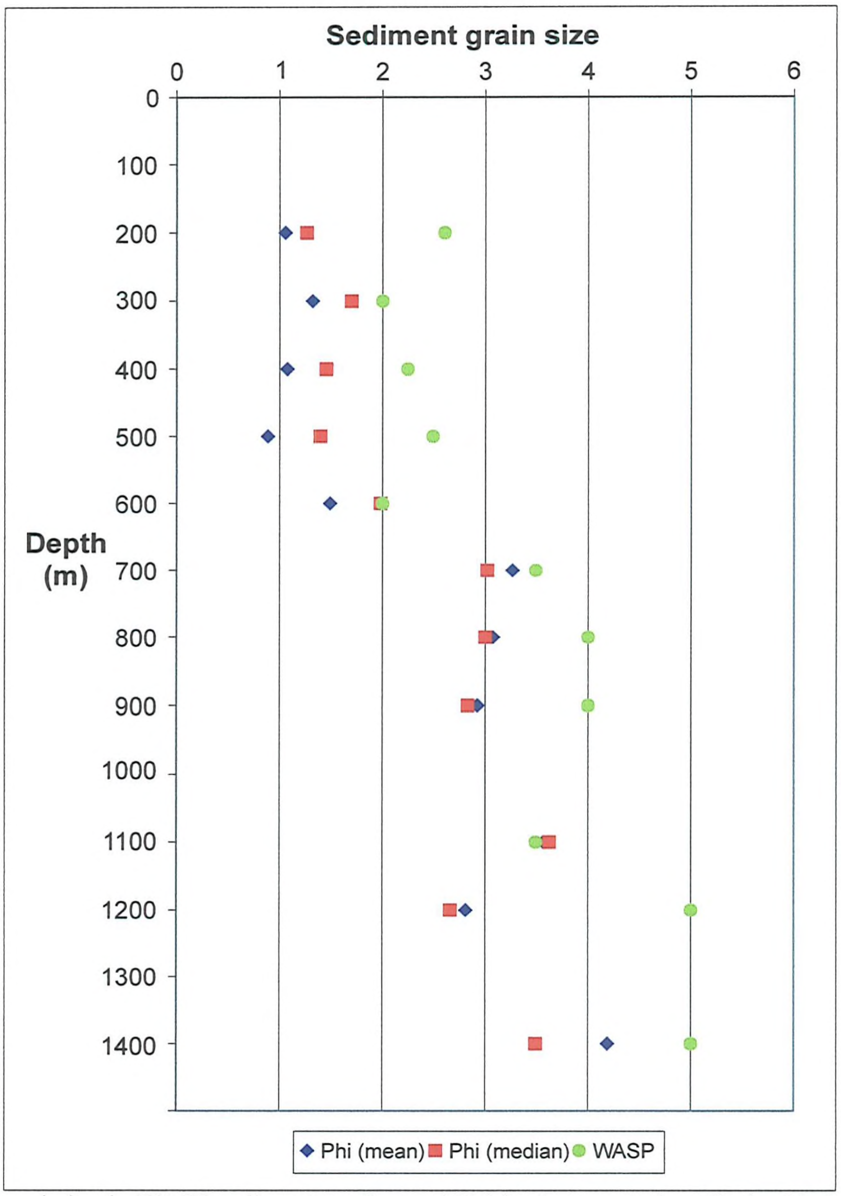


Figure 5.3. The variation in WASP sediment grading and Phi (both mean and median) with depth along the bathymetric transect west of Shetland.

5.3.2 Faunal analysis

The total number of megafauna recorded was 20,672 individuals (29,401 individuals prior to the two stages of frame selection). The number of individuals as well as the number of different taxa recorded at the different depth intervals are given in figure 5.4.

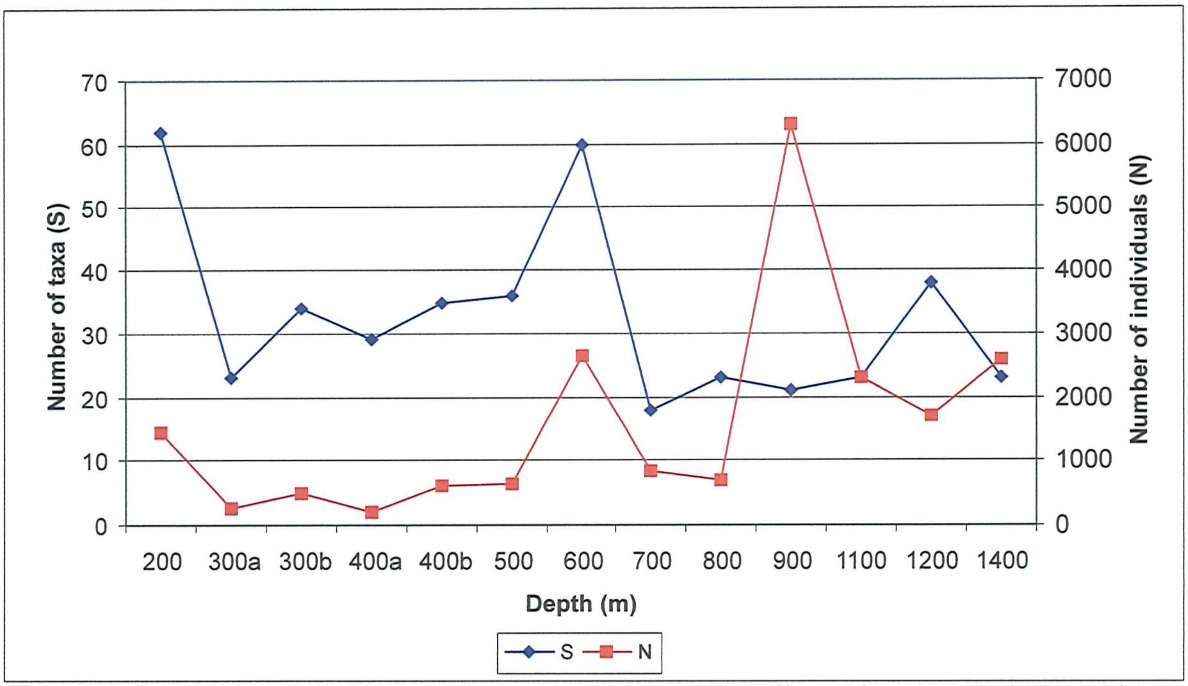


Figure 5.4. The number of individuals (N) and taxa (S) present at the different sites along the bathymetric transect west of Shetland.

Overall the fauna is dominated by cnidarians (30.2%), polychaetes (26.9%), porifera (9.3%), enteropneusts (9.1%), molluscs (7.8%) and crustaceans (6.5%), together representing nearly 90% of the megafauna present. The echinoids, asteroids, pycnogonids, ophiuroids and the fish contribute with between 1 - 2 % each while the remaining fauna represent less than 1 % each. The unknown and unidentifiable fauna comprise approximately 1.6 % of the total fauna observed. It should be noted that the proportion representing the Porifera is an underestimate as the large number of sponges observed at 500 m have not been recorded and counted fully as the numbers are so high.

The photographic analysis revealed considerable variation in megafauna with depth along the transect (table 5.7). On the upper part of the continental slope (300 – 500 m), within the iceberg plough mark zone, the megafaunal distribution relates to the two 'types' of seafloor present and there seem to be different megafaunal associations linked to the 'type' of sediment present (see chapter 8). At approximately 500 m the 'sponge-belt' is the dominant feature, where a large abundance of sponges of many different species dominate the megafauna. Between 600 m and 800 m the megafauna is sparse and dominated by polychaetes, anemones, soft corals and pycnogonids, although sponges are also frequently observed on the shallower section of this range. Between 800 m and 1000 m enteropneusts, anemones, pycnogonids and sea pens dominate the megafauna, and below 1000 m soft corals, anemones, polychaetes, pycnogonids and ophiuroids dominate the megafauna.

Station	**Depth**	**Megafauna**
55456#1 (M200)	204 – 209 m	Megafauna dominated by squat lobsters (*Munida* sp.) and scaphopods but many groups are present including cushion stars (asteroid), polychaetes (mainly sabellids), decapod shrimps (?*Crangon* sp.), bivalves (?scallops) and ophiuroids.
53913#1 (M300a)	290 – 275 m	'Stalked' anemones (bringing the feeding tentacles above the seabed), squat lobsters (*Munida* sp.), bivalves (scallops), gastropods and a variety of fish dominate the fauna. Squat lobsters are more abundant on the 'coarse' sediment type than on the 'fine' while bivalves are more abundant on 'fine' sediments.
53926#1 (M300b)	294 – 278 m	'Stalked' anemones dominate the megafauna but bivalves (believed to be scallops), gastropods, brittle stars, asteroids, squat lobsters (*Munida* sp.) and a variety of fish species (e.g. ling and red fish) are also present.
53928#1 (M400a)	390 – 370 m	Sponges (mainly fan-shaped and massive), bivalves (scallops), echinoderms (particularly Cidaridae) and squat lobsters (*Munida* sp.) dominate the megafauna. *Munida* sp. is more abundant on coarse rather than fine sediments while scallops (and spatangoids) are more abundant on fine sediments.
53914#1 (M400b)	410 – 397 m	Sponges (mainly fan-shaped and massive), bivalves (scallops), echinoderms (particularly Cidaridae), squat lobsters (*Munida* sp.) and sea squirts dominate the megafauna. *Munida* sp. is more abundant on coarse rather than fine sediments while scallops (and spatangoids) are more abundant on fine sediments.
53925#1 (M500)	507 – 496 m	The 'sponge-belt', where a large amount of sponges of a large variety of species dominate the fauna. Soft corals are also abundant. Other important megafaunal groups are *Munida* sp. (most likely *Munida sarsi*), cidarids and asteroids.
53916#1 (M600)	595 – 580 m	The megafauna appears generally sparse dominated by sponges (massive, globiferous, branched and particularly encrusting), echinoids (believed to be *Echinus* sp.) and asteroids (believed to be *Ceramaster* sp.).
53985#1 (M700)	685 – 672 m	The megafauna is generally sparse, dominated by polychaetes (sabellids), soft corals, sponges (massive and globiferous), pycnogonids, gastropods and surface dwelling fauna (unknown but possibly polychaetes).

53924#1 (M800)	798 – 781 m	Anemones (cerianthids and one other taxon), polychaetes, pycnogonids (≥2 species), gastropods and sea pens dominate the megafauna. A variety of fish species (e.g. rays and eel pouts) are also present.
53984#1 (M900)	912 – 881 m	The megafauna is dominated by enteropneusts (acorn worms), anemones (cerianthids and one other taxon), pycnogonids (≥2 species), sea pens, polychaetes (believed to be sabellids) and gastropods.
53923#1 (M1100)	1088 m	The megafauna appears sparse but dominated by polychaetes (sabellids and a surface dwelling tubiculous polychaete), soft corals, anemones (cerianthids), ophiuroids (?*Ophiomusium lymani*), echinoids (believed to be spatangoids) and a variety of fish species. Pycnogonids (>2 spp. including *Colossendeis* sp.).
53981#1 (N/M1200)	1209 – 1203 m	The megafauna is dominated by polychaetes (sabellids and a surface dwelling tubiculous polychaete), soft coral, anemones (cerianthids and one other taxon), ophiuroids (?*Ophiomusium lymani*) and gastropods.
53980#1 (N1400)	1408 – 1401 m	Soft coral, anemones (cerianthids), polychaetes (sabellids), stalked sponges, ophiuroids (?*Ophiomusium lymani*) and echinoids (spatangoids) dominate the megafauna. Other fauna include pycnogonids, sea pens and fish.

Table 5.7. Megafaunal analysis from photographs along bathymetric transect west of Shetland ('stalked' refers to anemones where the body extends above the seafloor, while the tentacles are only visible in the other anemones).

5.3.2.1 Abundance (faunal densities)

The density of the megafauna along the bathymetric transect is illustrated in table 5.8 and figure 5.5. The median values appear to be slightly higher at greater depth, although densities at 200 m and 600 m (700 m in respect of mean densities) are also relatively high. There appears to be a decrease megafaunal density from the shallower sites (i.e. 200 m) down to approximately 500 m and then the values increase again to reach a mid-slope maximum at 600 m. Below 600 m the values yet again decrease down to the lower part of the slope where another high value is found at 900 m. Below 900 m the values appear to decrease again with the lowest value within the deeper sites recorded at 800 m and 1200 m. Note the possibility of an underestimate in faunal density at 500 m in particular, where the quantification of sponges was not carried out.

The confidence intervals suggest that the 200 m, 900 m and 1400 m sites, and to a lesser extent the 600 m site, are significantly different to the other sites. The high density values observed at depth are mainly attributed to the high numbers of sea pens, soft corals and anemones (see table 5.8) but also the unidentifiable fauna (speculatively identified as tubiculous polychaetes) present at these depths (1100 m, 1200 m and 1400 m), while enteropneusts, anemones, pycnogonids and sea pens are most abundant at 900 m. Sponges are frequently observed at 600 m while scaphopods and polychaetes appear to be characteristic of the 200 m photographic run, the densities of which are given in table 5.8 together with some of the other dominant taxa at the different sites along the bathymetric transect. The Spearman's rank correlation analyses (table 5.9) give significant ($p<0.05$) results between mean megafaunal density and sediment grain size (mean and median Phi) but no other significant results have been found with regards to megafaunal densities.

Site	**Mean density (ind/m^2)**	**Median density (ind/m^2)**	**Median 95 % confidence limits**
M200	1.23	1.21	1.08 – 1.36
M300	0.32	0.26	0.23 – 0.30
M400	0.27	0.16	0.13 – 0.19
M500	0.22	0.10	0.07 – 0.12
M600	0.69	0.60	0.52 – 0.66
M700	1.24	0.30	0.23 – 0.41
M800	0.41	0.15	0.11 – 0.19
M900	2.12	1.24	1.06 – 1.51
M1100	1.74	0.33	0.30 – 0.36
N/M1200	0.77	0.23	0.21 – 0.28
N1400	1.61	1.26	1.19 – 1.33

Table 5.8. Megafaunal densities (individuals/m^2) along the bathymetric transect west of Shetland (mean and median density with 95 % confidence intervals).

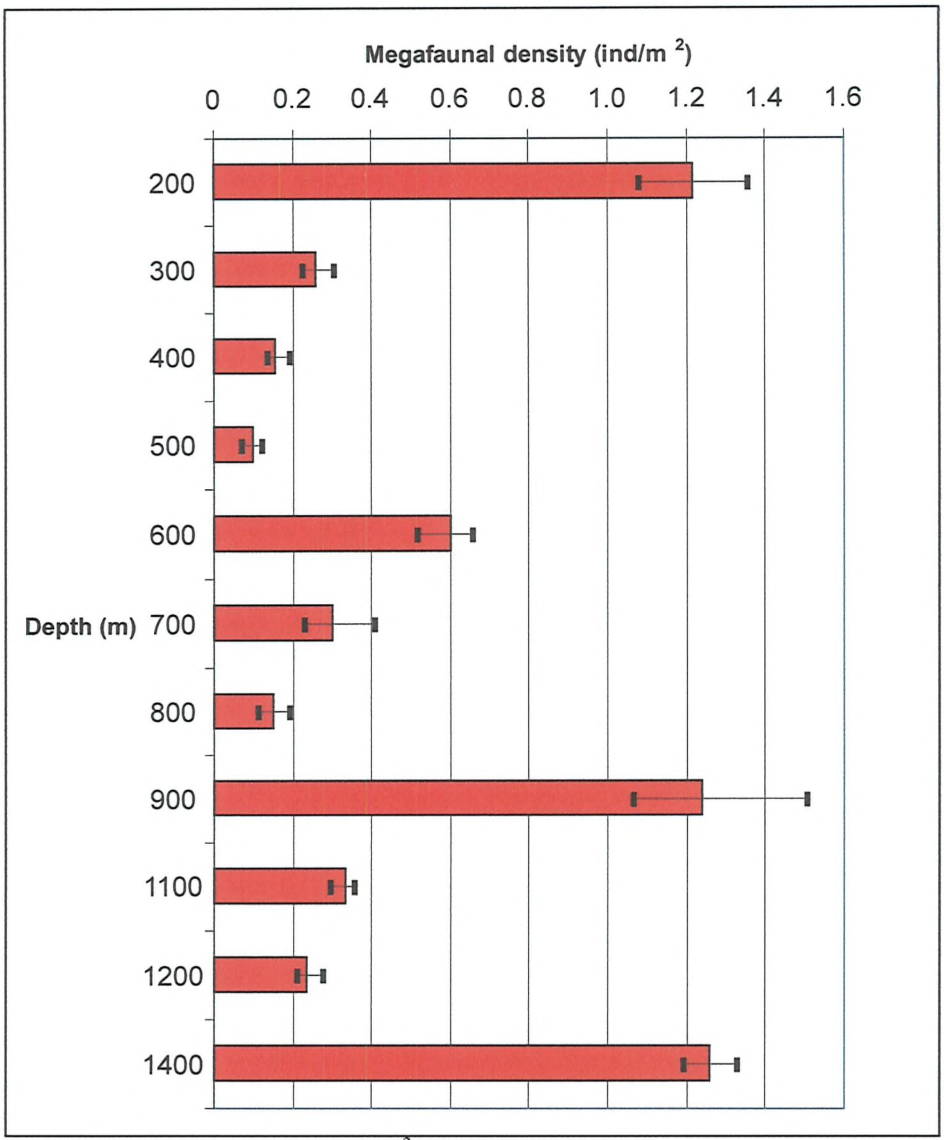


Figure 5.5. Megafaunal densities (individuals/m^2) along the bathymetric transect west of Shetland (median and 95 % confidence intervals).

Environmental variables	**Megafaunal density (mean)**	**Megafaunal density (median)**
Depth (m)	0.591	0.273
Temperature (°C)	-0.500	-0.118
Phi (mean)	**0.664**	0.427
Phi (median)	**0.664**	0.318
WASP sediment interpretation	0.582	0.241
Silt and clay content	0.545	0.264
Total organic carbon (%)	0.143	-0.002
Carbonate content (%)	-0.400	-0.164
Organic content (%)	0.436	0.182
Clay/nitrogen ratio	-0.161	-0.530
Total organic nitrogen (%)	0.048	-0.075
Significant levels (two-tailed test; from Fowler and Cohen, 1992)	*Tabulated value*	*Description*
	0.818	*Highly significant*
	0.623	*Significant*

Table 5.9. Correlations (Spearman's rank correlation coefficient) between environmental parameters and megafaunal densities (n = 11) along the bathymetric transect west of Shetland.

The megafaunal densities in table 5.10 show that some taxa are only present at certain depth intervals with the scaphopods (*Antalis entalis*) and *Hyalinoecia tubicola* together with a decapod (with a straight abdomen, possibly *Crangon* sp.) being seen only at 200 m. Other fauna, for example *Munida* sp., scallops, *Stichopus* sp. (most likely *Stichopus tremulus*) and red fish (?*Sebastes* sp.), are present on the upper continental slope (≤600 m) while the pycnogonids, soft coral, cerianthids, stalked sponges (possibly *Hyalonema* sp.), rays (*Raja* sp), eelpouts (?*Lycodes* sp. A) and eels (may also be eelpouts, *Lycodes* spp.) are found at the lower part of the continental slope or the channel floor (≥600 m). In addition, the relatively high density values of the enteropneusts and the surface dwelling tubiculous polychaetes at 900 m and 1100 m respectively, should also be noted as these values are considerably higher than most others, apart from the soft coral densities at 1400 m.

Station	**Taxa**	**Density (ind/m^2)**	**Description/other**
55456 (200m)	Scaphopoda	0.383	Believed to be *Antalis entalis*
	Munida sp.	0.267	
	Sabellid sp.	0.063	
	Decapod sp.	0.058	Natantia (?*Crangon* sp.), four white spots on abdomen
	Cushion A	0.056	Red colour, most likely *Porania pulvillus*
	Munida rugosa	0.033	Red band across front of carapace
	Scallop sp.	0.021	
	Hyalinoecia tubicola	0.011	White, long tubes
	Echinus A	0.011	White with short spines, ?*Echinus acutus* or *esculentus*
53913 (300m)	'Stalked' anemone	0.106	Body/trunk visible above the seabed
	Munida sp	0.057	
	Scallop sp.	0.040	
	Gastropod sp.	0.031	
53926 (300m)	'Stalked' anemone	0.115	Body/trunk visible above the seabed
	Munida sp	0.019	
	Scallop sp	0.059	
	Gastropod sp.	0.023	
53914 (400m)	Fan-shaped sponge	0.043	
	Scallop sp	0.040	
	Munida sp.	0.026	
	Cidaris sp.	0.028	Most likely *Cidaris cidaris*
53928 (400m)	Scallop sp	0.089	
	Cidaris sp.	0.045	Most likely *Cidaris cidaris*
	Munida sp.	0.039	
	Massive sponge	0.044	
	Sea squirt	0.030	
53925 (500m)	*Munida* sp.	0.152	
	Cidaris sp.	0.016	Most likely *Cidaris cidaris*
	Asteroid B	0.015	Strong orange colour, five arm
53916 (600m)	Encrusting sponge	0.378	Typically white
	Massive sponge	0.072	
	Echinus A	0.034	White with short spines, ?*Echinus acutus* or *esculentus*
	Globiferos sponge	0.028	
	Branched sponge	0.026	
	Ceramaster granularis	0.021	

53985	Polychaetes	0.667	Most likely sabellids
(700m)	Soft coral	0.252	
	Globiferous	0.212	
	Massive sponge	0.029	
	Pycnogonid sp.	0.015	
	Surface dwelling fauna	0.010	Elongate animals producing narrow furrows*
53924	Anemone B	0.111	Orange colour, no body visible, tapering tentacles
(800m)	Polychaete sp.	0.108	?Sabellids
	Pycnogonid sp. A	0.043	As B in size, but no white spots
	Cerianthid B	0.040	Body above seabed, light tentacles with dark centre/disc
	Pycnogonid sp. B	0.031	Small (10 cm), parasites (white spots) on joints of leg
53984	Acorn worm	1.012	
(900m)	Anemone B	0.754	Orange colour, no body visible, tapering tentacles
	Sea pen	0.212	
	Pycnogonid sp. B	0.051	Small (10 cm), parasites (white spots) on joints of leg
	Pycnogonid sp. A	0.026	As B in size, but no white spots
	Cerianthid B	0.023	
53923	Tubiculous ?polychaetes	1.147	Large (thick) surface dwelling polychaetes?
(1100m)	Sabellids	0.227	
	Soft coral	0.193	
	Cerianthid B	0.108	Body above seabed, light tentacles with dark centre/disc
	Ophiumusium sp	0.011	Large ophiuroid *?Ophiumusium lymani*
53981	Sabellids	0.412	
(1200m)	Tubiculous ?polychaetes	0.162	Large (thick) surface dwelling polychaetes?
	Soft coral	0.046	
	Cerianthid B	0.036	Body above seabed, light tentacles with dark centre/disc
	Anemone B	0.025	Orange colour, no body visible, tapering tentacles
53980	Soft coral	0.948	
(1400m)	Sabellids	0.258	
	Cerianthid B	0.254	Body above seabed, light tentacles with dark centre/disc
	Stalked sponge	0.062	Thin stalk with a white bell-like feature at the top end
	Ophiumusium sp	0.028	Large ophiuroid *?Ophiumusium lymani*

Table 5.10. Megafaunal densities (individuals/ m^2) of some of the dominant and distinct taxa at the different depth intervals along the bathymetric transect west of Shetland (* = poor quality frames making identification particularly difficult; and 'stalked' refers to anemones where the body extends above the seafloor).

5.3.2.2 Megafaunal diversity indices

The results from the species diversity analyses indicate an overall decrease in diversity with depth (figure 5.6) with regards to both Shannon-Wiener species diversity and species richness (Margalef's diversity index). The Shannon-Wiener diversity index value is highest at 200 m and the lowest at 1100 m (figure 5.5) but overall illustrating a monotonic response to the depth gradient. The diversity values are similar on the upper part of the slope down to 400 m but below 400 m there appears to be a fairly rapid decrease in diversity. The highest species richness (Margalef) value is found at 200 m while the lowest is found at 900 m but the pattern is complex. As with species diversity, however, there appears to be a point of rapid change with depth dividing the continental slope into two groups with the boundary occurring between 600 m and 700 m. The shallower sites (200 – 600 m) have similar species richness values, while the deeper sites (700 – 1400 m) have similar values, although one of the sites at 300 m and the site at 1200 m brings the results of the two groups closer together.

There are several significant correlations between both species diversity and species richness and the environmental parameters (table 5.11). Both indices are significantly correlated ($p<0.05$) with depth, temperature and sediment grain size. Species diversity is furthermore correlated ($p<0.05$) with silt and clay content as well as organics and carbonate content.

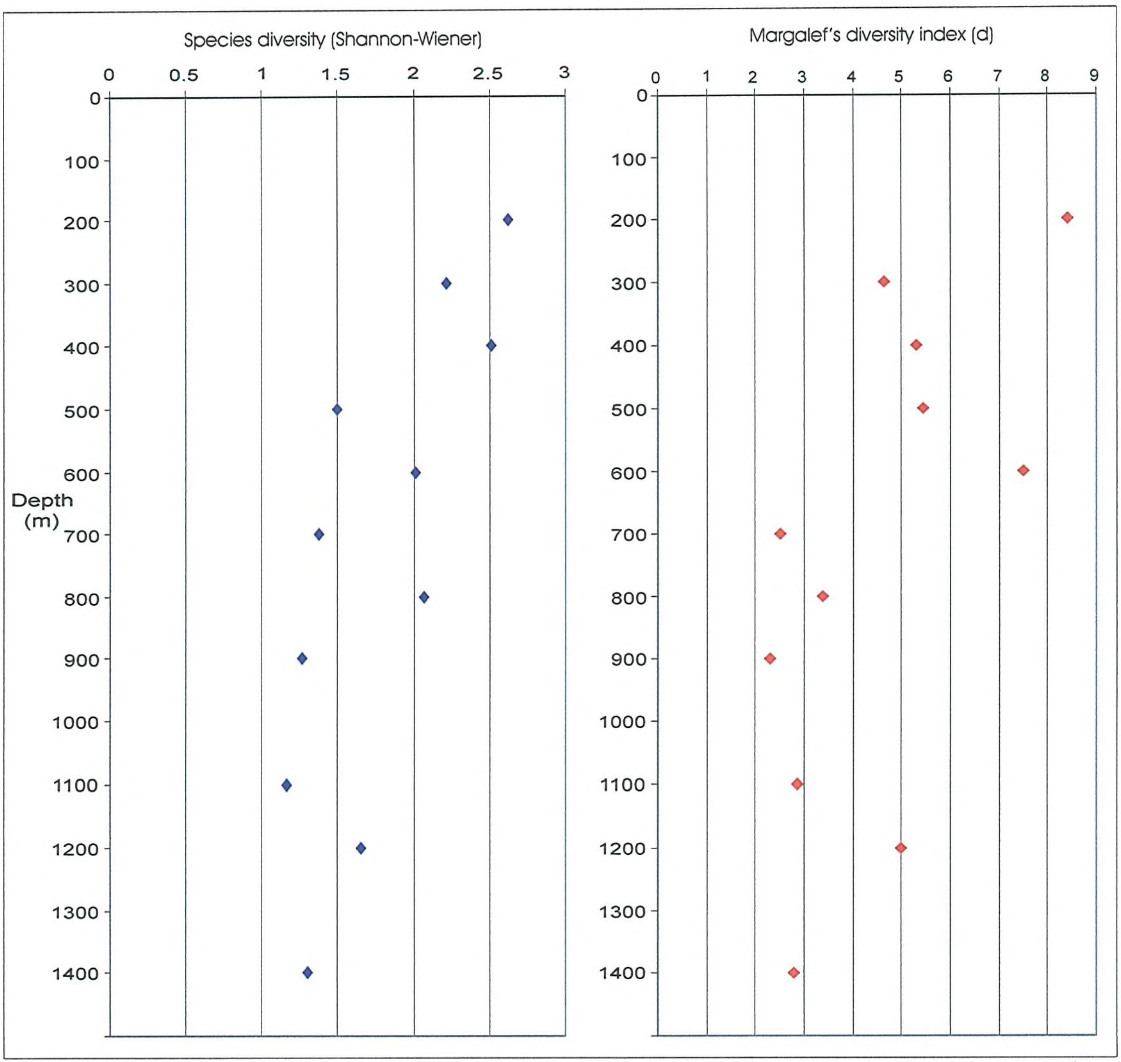


Figure 5.6. Results from the Shannon-Wiener species diversity and Margalef's species richness analyses along the bathymetric transect west of Shetland.

Environmental variables	**Species diversity (Shannon-Wiener)**	**Species richness (Margalef, d)**	**Pielou's evenness index (J)**	**Rarefaction E(s_{500})**
Depth (m)	**-0.764**	**-0.627**	**-0.700**	**-0.764**
Temperature (°C)	**0.755**	**0.691**	**0.664**	**0.818***
Phi (mean)	**-0.682**	**-0.791**	-0.500	**-0.818***
Phi (median)	**-0.755**	**-0.800**	-0.555	**-0.845***
WASP sediment interpretation	-0.491	-0.555	-0.523	**-0.650**
Silt and clay content	**-0.700**	-0.600	-0.573	**-0.664**
Total organic carbon (%)	-0.248	-0.286	-0.070	-0.448
Carbonate content (%)	**0.655**	0.327	**0.627**	0.445
Organic content (%)	**-0.709**	-0.436	-0.618	-0.545
Clay/nitrogen ratio	-0.291	-0.207	-0.134	-0.189

Significant levels (two-tailed test; from Fowler and Cohen, 1992)	*Tabulated value*	*Significance level*	*Description*
	0.818	*0.01*	*Highly significant**
	0.623	*0.05*	*Significant*

Table 5.11. Correlations (Spearman's rank correlation coefficient) between environmental parameters and megafaunal diversity indices (n = 11) along the bathymetric transect west of Shetland.

The variation in equitability and Simpson's dominance index with depth along the bathymetric transect west of Shetland are given in figure 5.7. The overall trend suggests a decrease in evenness with depth with largely a mirror image seen in the Simpson's dominance index, although there are some differences. The highest equitability value is found at 400 m and the lowest at 1100 m. As with the previous two indices, there appears to be a point of rapid change and in this graph it occurs between 400 m and 500 m. Again the shallower sites (200 – 400 m) have similar values (evenness in the species distribution) and the deeper sites have similar values (dominance by a few species), with one exception seen at 800 m, where the equitability is similar to those of the shallower sites.

Within the overall increase in the Simpson's dominance index (figure 5.7) with depth the lowest value is found at 400 m and the highest at 500 m, closely followed by the value at 1100 m. As with the previous indices, there appears to be a division of the data into two layers with a boundary between 400 m and 500 m, with low values at the shallower sites (200 – 400 m) and high values at the deeper sites (500 – 1400 m). Overall, there is therefore evenness at shallower depths and dominance at depth, with the only exception found at 800 m, where there is higher equitability in the species present. The correlation analyses (table 5.11) revealed significant correlations ($p<0.05$) between Pielou's evenness index and both temperature and depth, a result also seen in species (Shannon-Wiener) diversity and species richness. A significant correlation is also found between evenness and carbonate content ($p<0.05$).

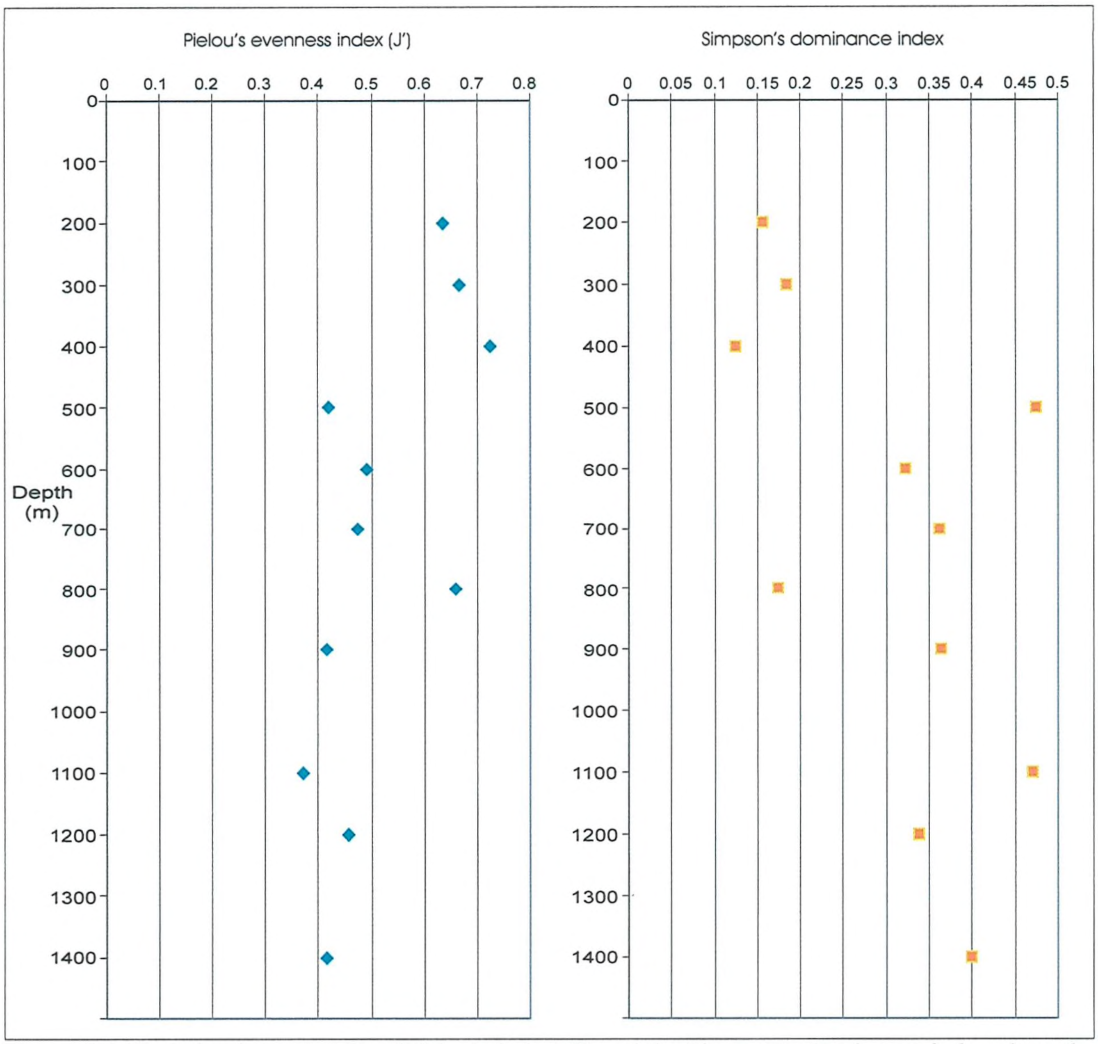


Figure 5.7. Variation in equitability (Pielou's index, J') and the Simpson's dominance index along the bathymetric transect west of Shetland.

The results from the rarefaction curves (figures 5.8 and 5.9), where high species diversity is found when the curves are steep and more elevated, are as with the other results complex but show that species diversity is highest at 200 m and 600 m and lowest at 900 m. Apart from the diversity values recorded at 600 m, species diversity appears to decrease with depth (although variations occur between the depth intervals), an overall result very similar to the other diversity results. Figures 5.8 and 5.9a furthermore indicate that there are three main groups in the data with different diversities, dividing the data into deep- and shallow-water sites. The first group with the highest diversity includes the 200, 300, 400, 500 and 600 m depth intervals. The second group includes depth intervals 800 m and 1200 m, while the third group contain the remaining depth intervals (700, 900, 1100 and 1400 m). Note that in some cases (notably 300 m, 400 m and 500 m) the available data (number of individuals detected) is restricted, making interpretations more difficult. An additional graph has therefore been produced where the calculated expected number of species in a sample of 500 individuals ($E(S_{500})$) have been plotted (figure 5.9b). The result illustrates a division of the sites into shallow- and deep-water groups. In addition, the result from Spearman's rank correlation analyses (table 5.11) of the data in figure 5.9b confirm that species diversity ($E(S_{500})$) is highly significantly ($p<0.01$) negatively correlated (i.e. positive with physical grain size) with mean phi and median phi (table 5.11) as well as positively correlated with temperature. In addition, significant ($p<0.05$) correlations (negatively) were found with depth, the silt and clay content and WASP sediment grading (i.e. positive with physical grain size; see table 5.11).

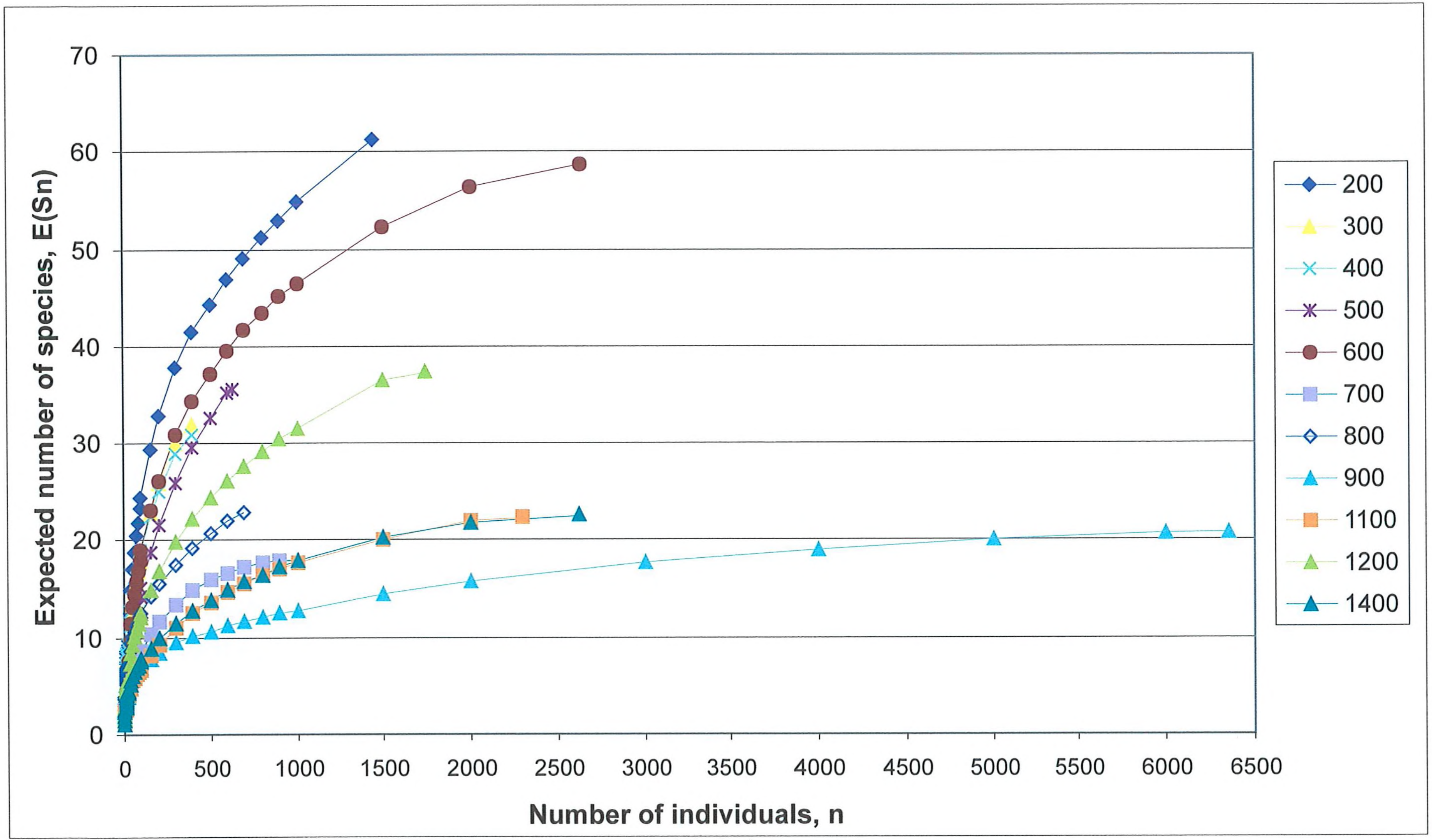


Figure 5.8. Rarefaction curves for the sites along the bathymetric transect west of Shetland.

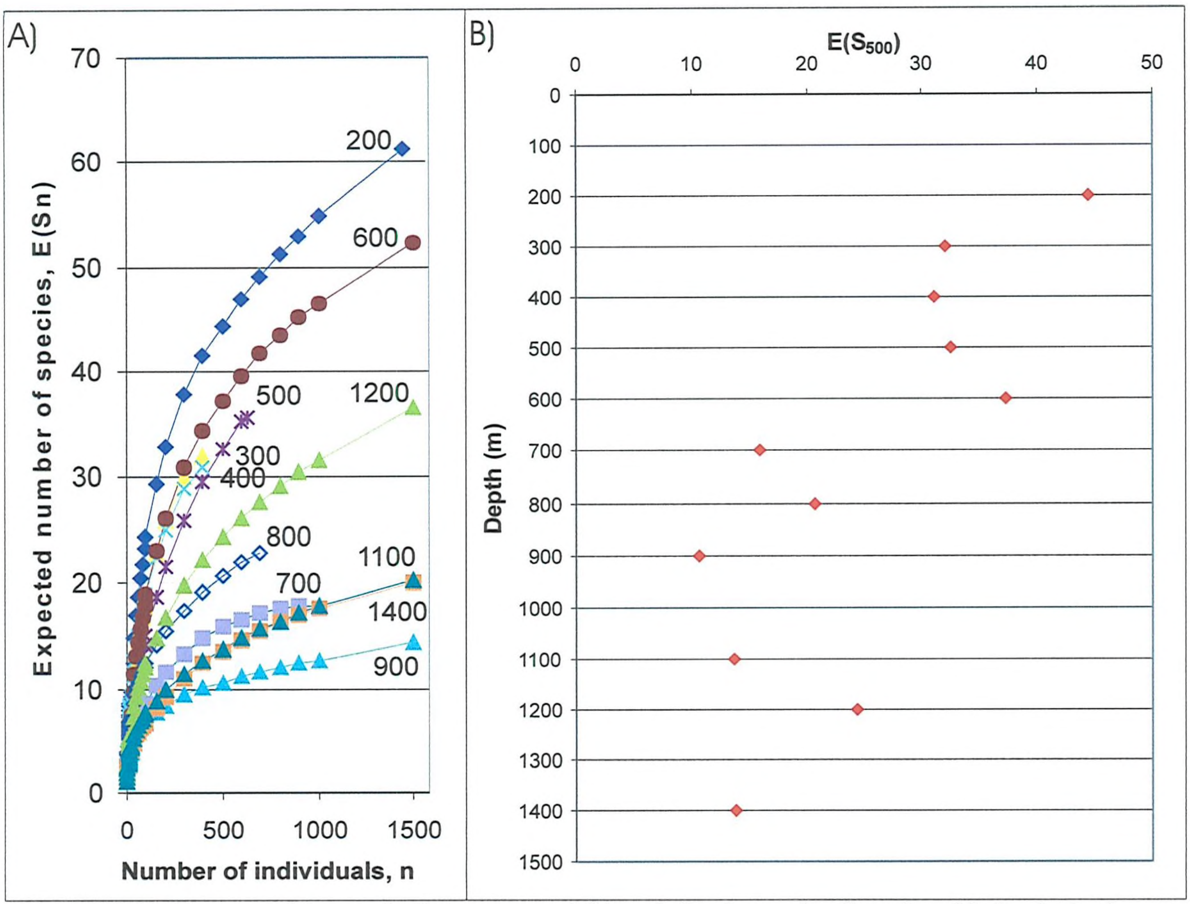


Figure 5.9. (a) Close-up of the rarefaction curves and (b) variation in species diversity with depth plotting the calculated expected number of species in a sample of 500 individuals ($E(S_{500})$) along the bathymetric transect west of Shetland.

5.3.2.3 Species (taxon) accumulation

The results from this study (figure 5.10), investigating the rate of change in fauna with depth, indicate that the greatest rate of change in the fauna occurs at 600 m. The rates of change are relatively uniform both above and below 600 m but the rate is relatively higher at depths above 600 m (200 – 500 m) compared to those of the deeper sites.

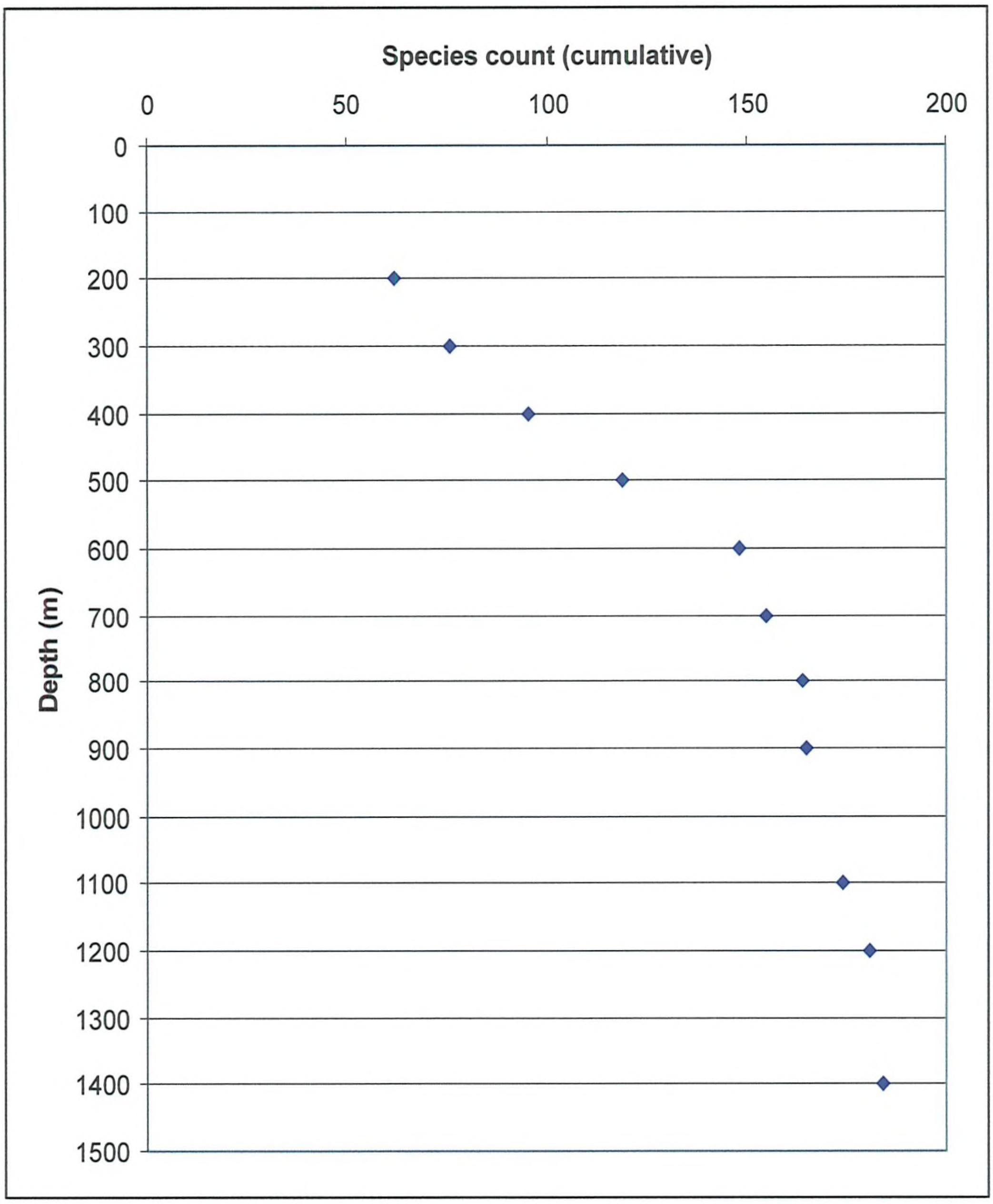


Figure 5.10. Species (taxon) accumulation curve along the bathymetric transect west of Shetland.

5.3.2.4 Megafaunal composition

The megafaunal composition along the bathymetric transect (figure 5.11) suggests that some groups are restricted to the upper continental slope, while other groups are observed only on the lower part of the slope. The most obvious examples are the distributions of crustaceans and pycnogonids (see also faunal densities in section 5.3.2.1). Crustaceans, dominated by the genus *Munida*, are present on the upper parts of the slope (<500 m) but are absent on the lower parts of the slope (>600 m), apart from a small proportion observed at 800 m. Conversely, pycnogonids (at least three different species) are absent from the upper part of the slope but are present on the lower part of the slope (>700 m).

Other groups are present along most of the slope but appear to be more dominant on one part of the slope. Sponges are most dominant in the 400 m to 700 m depth range while much less so in other depth bands (note that the proportion of sponges at 500 m is an underestimate). In addition, holothurians, molluscs, echinoids and asteroids are present at high proportions on the upper part of the slope while these values at depth are much lower. Polychaetes, and to a certain extent the cnidarians, are present at high proportions on the lower slope but less so on the upper part of slope, while enteropneusts (acorn worms), crinoids and bryozoans appear to be present at very limited depth intervals along the slope. The ophiuroids and the fish appear to be fairly evenly distributed all along the bathymetric transect.

Within these large-scale patterns there are most likely other distributions and although a faunal group (e.g. phylum) might be present along the whole of the bathymetric transect, it might consist of a several different species distributed at different depths or depth intervals (see discussion). In addition, different taxa of anemones are observed on the lower parts of the slope compared to those on the upper part of the slope. These types of distribution patterns are believed to be reflected in other taxa (e.g. echinoids, ophiuroids and molluscs) as well, but because megafaunal identification is difficult, any definite conclusions are difficult to make.

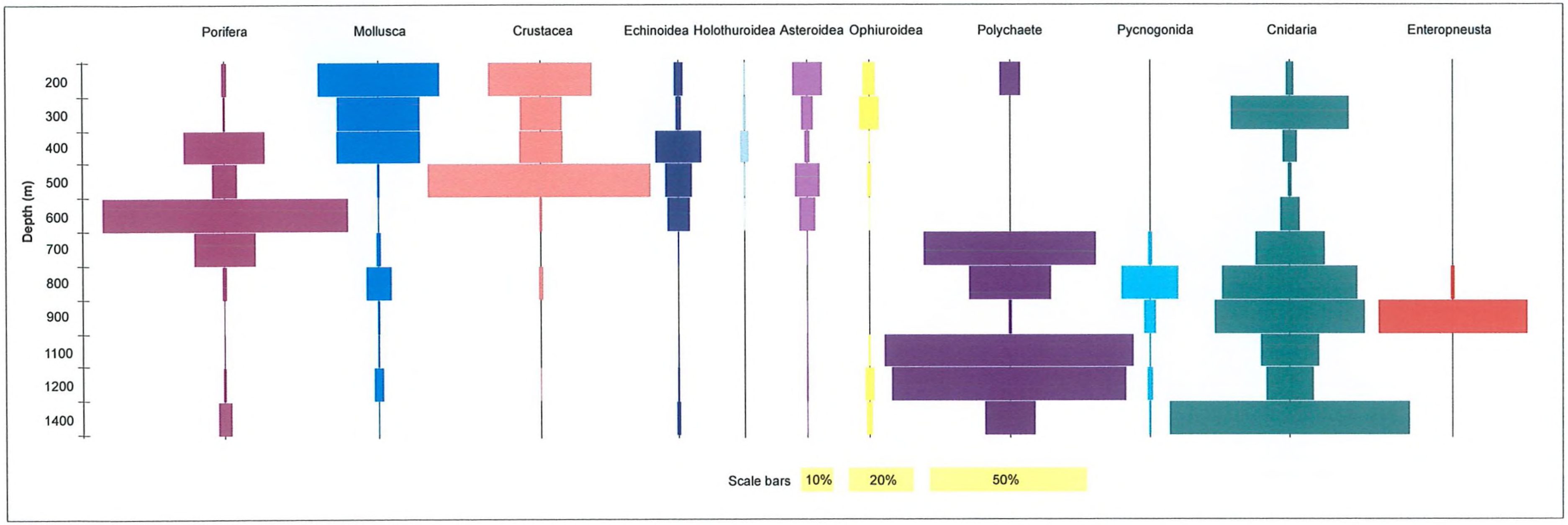


Figure 5.11. Megafaunal composition along the bathymetric transect west of Shetland (some of the minor groups (Bryozoa, Crinoidea, fish, Asideacea, Echiura and unknowns) have been removed from the figure to allow focus on the most important groups).

5.3.3 Further statistical analysis

5.3.3.1 Multi-variate analysis

5.3.3.1.1 Cluster analysis

The dendrogram reveals two main clusters, one containing the sites on the upper part of the continental slope down to 600 m and the other comprising the remaining sites at depths from 700 m to 1400 m (figure 5.12). This indicates a division of the sites into two layers with the boundary occurring between 600 m and 700 m.

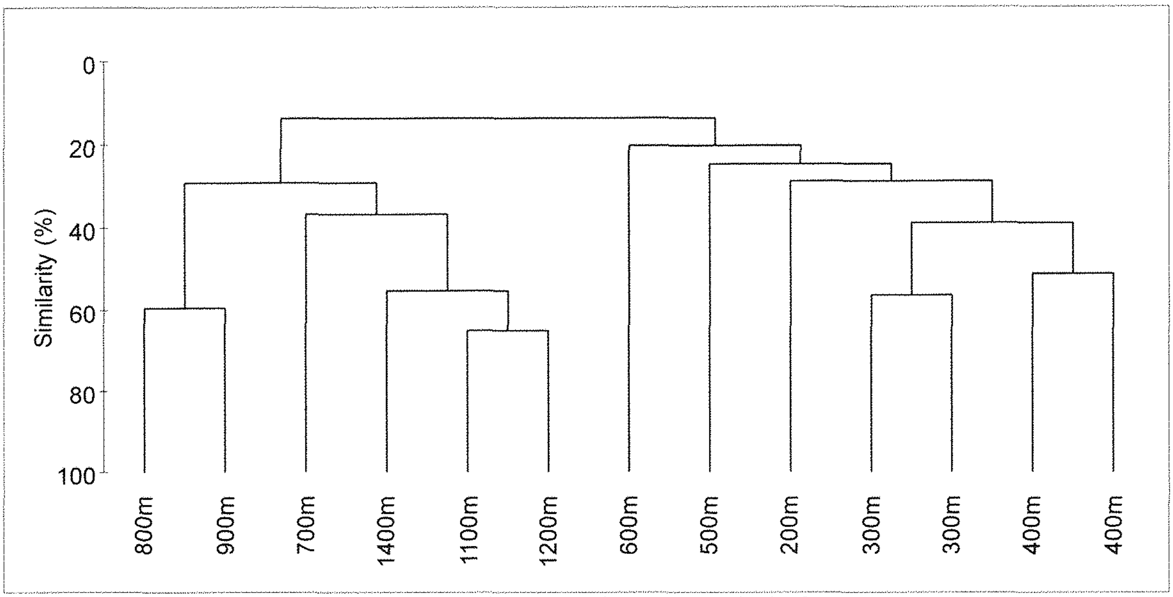


Figure 5.12. Cluster analysis (dendrogram) of the megafauna along the bathymetric transect.

5.3.3.1.2 Ordination by Multi-Dimensional Scaling (MDS)

The results from the non-metric multi-dimensional scaling (MDS) illustrate a configuration in support of the cluster analysis (figure 5.13). The deep-water sites (700-1400 m) have been grouped together and the shallow-water sites (200-500 m) have been grouped together with 600 m being the intermediate site. This pattern furthermore supports the suggestion of two layers being present along the bathymetric transect west of Shetland with a boundary at 600 m. There is in addition a depth trend among the shallower sites with the sites being ordered from 200 m to 600 m. The stress level of 0.11 is very close to the limit (< 0.1) indicating a 'good ordination with no real prospect of a misleading interpretation' (Clarke and Warwick, 1994). However, this relates particularly to the overall structure and any features observed on the fine structure therefore should be treated with some caution (Clarke and Warwick, 1994). Further examination of the data using MDS was therefore carried out on the shallow- and deep-water sites separately (figure 5.14, 5.15 and section 5.3.3.2).

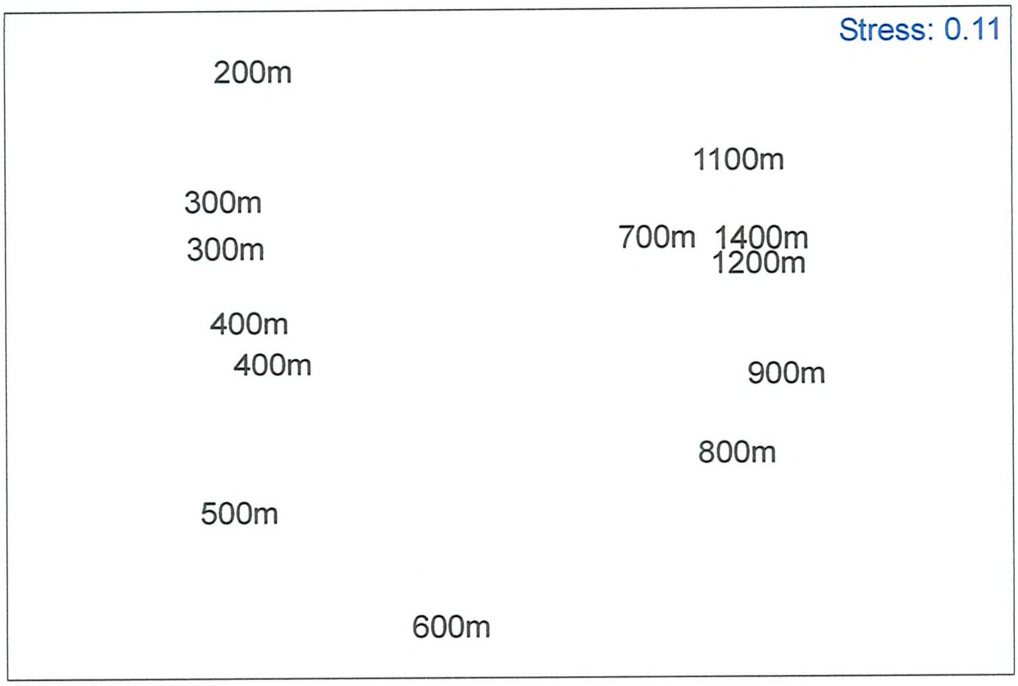


Figure 5.13. Multi-dimensional scaling (MDS) of the megafauna along the bathymetric transect.

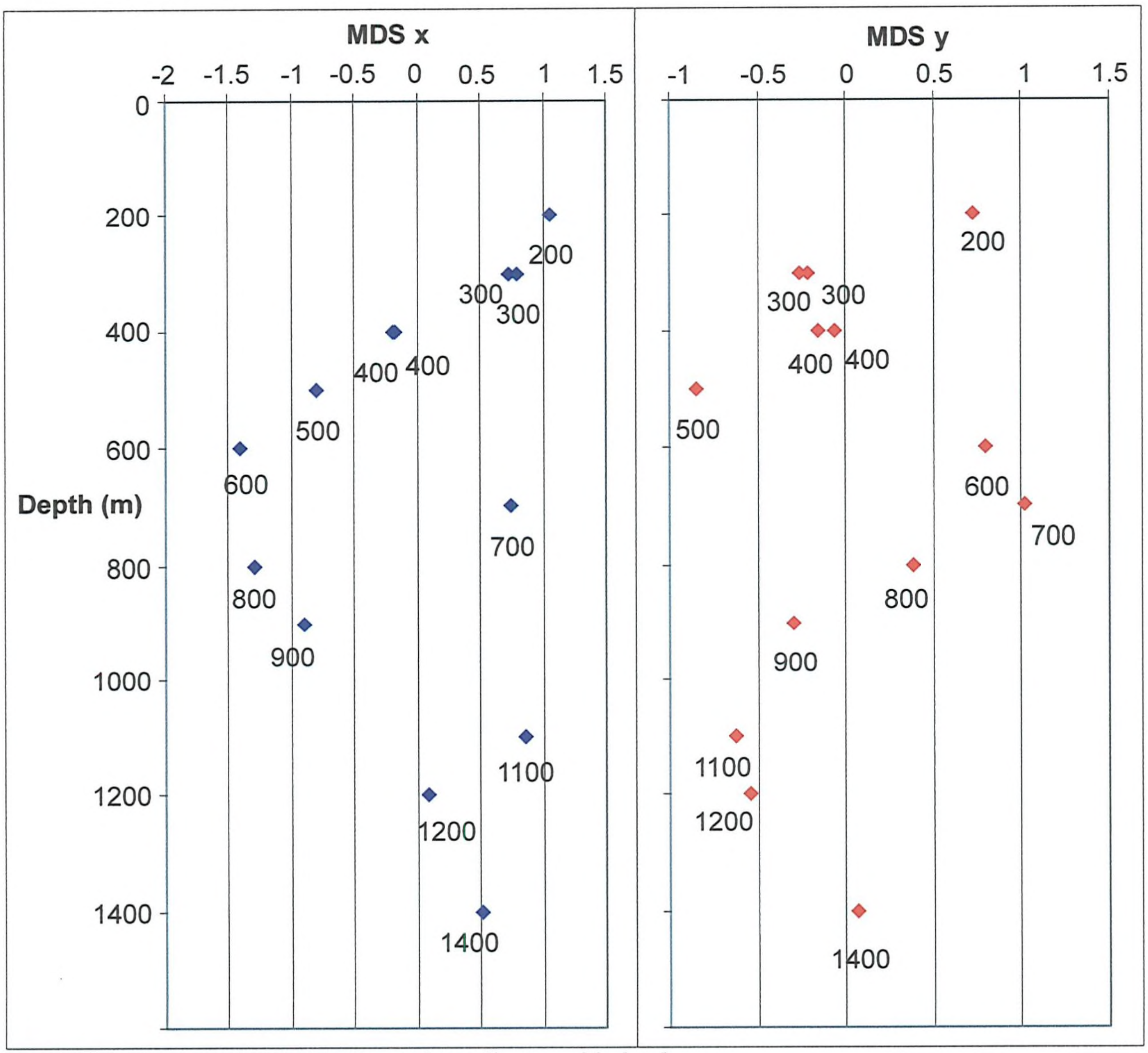


Figure 5.14. The variation in MDS x and y ordinates with depth.

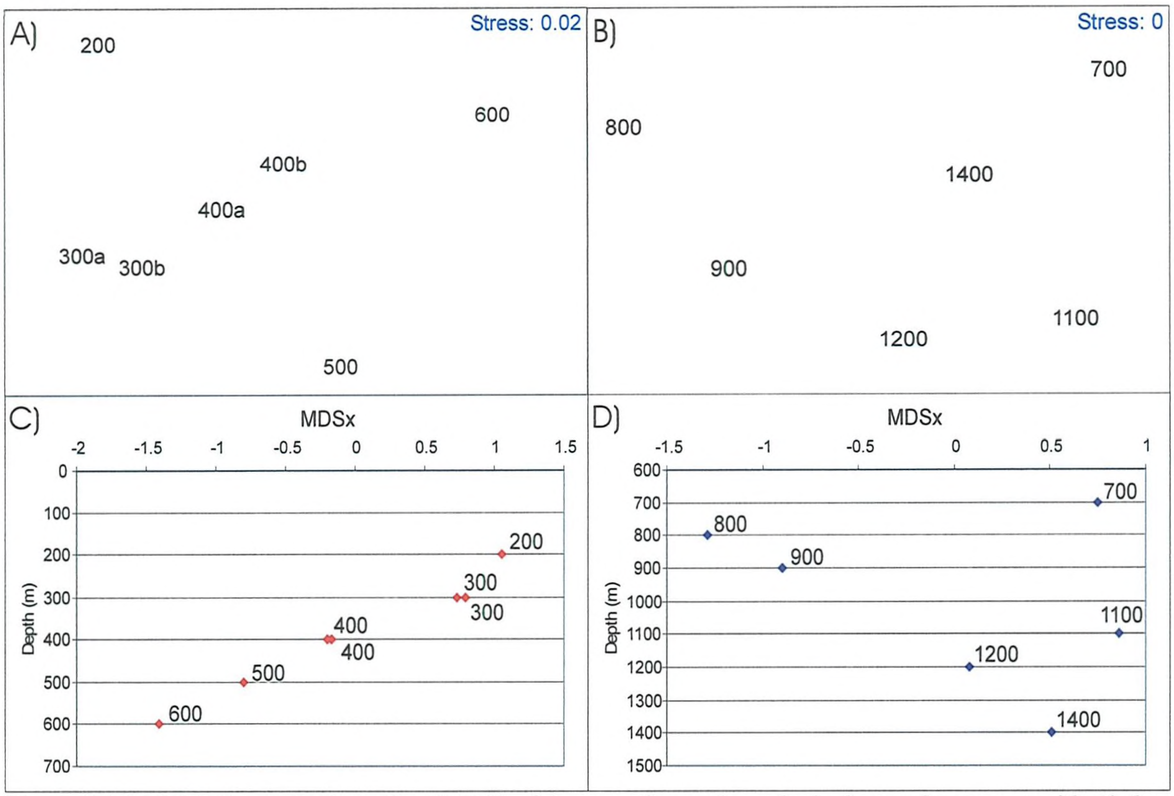


Figure 5.15. Multi-dimensional scaling (MDS) of the megafauna along the bathymetric transect with A) the shallow sites; B) the deep sites; C) MDS x ordinates for the shallow-water sites plotted against depth; D) MDS x ordinates for the deep-water sites against depth.

The results from the additional MDS analysis (figure 5.14 and 5.15) illustrate a depth trend within the shallow-water sites (figure 5.15 a) from left to right and c) a decrease in MDS x with depth), but a similar trend is not obvious within the deep-water sites (figure 5.15 b and d). Note that the stress levels of both the analyses (figure 5.15 a and b) are low, giving results that are 'excellent representations with no prospect of misinterpretation' (Clarke and Warwick, 1994). Within the shallow sites in figure 5.15a, the site at 200 m and that of 500 m are slightly outside the main trend line, but whilst the 200 m site is most likely as a result of distinct fauna, the 500 m site may be influenced by the lack of quantified sponges within the data, a faunal group known from photographic observations to be important at this depth. Within the deeper sites, where no obvious depth trend can be seen, some of the sites have been clustered (figure 5.12) and grouped (figure 5.13) together (800 m and 900m forming one group and the photographic runs at 1100 m, 1200 m and 1400 m forming the other). These groups are less obvious in figure 5.15 and perhaps the detailed aspects of clustering and ordination ought to be treated with some caution.

Spearman's rank correlation coefficient calculations have been carried out for the MDS x and y ordinates (from figure 5.15) and the results (shallow sites $r_s = -0.964$ and deep-water sites $r_s = 0.14$) are consistent with the initial analysis (figures 5.13) confirming a significant correlation between MDS x and depth within the shallow-water sites ($p<0.02$) but no significant correlation with depth was found within the deep-water sites (for neither MDS x nor y ordinates). When compared to other environmental data, temperature ($r_s = 1.0$) was the only parameter (apart from depth) significantly correlated with the MDS x ordinate (MDS y was not significant) within the shallower sites while WASP sediment grading ($r_s = -0.979$) was the only parameter significantly ($p<0.02$) correlated with MDS x ordinate (but not with MDS y) within the deeper sites. The variation in temperature with depth is given in figure 5.16 with a nearly uniform rate of decrease in maximum temperature with depth from the surface down to 700 m, a trend similar to that seen in MDS x ordinates.

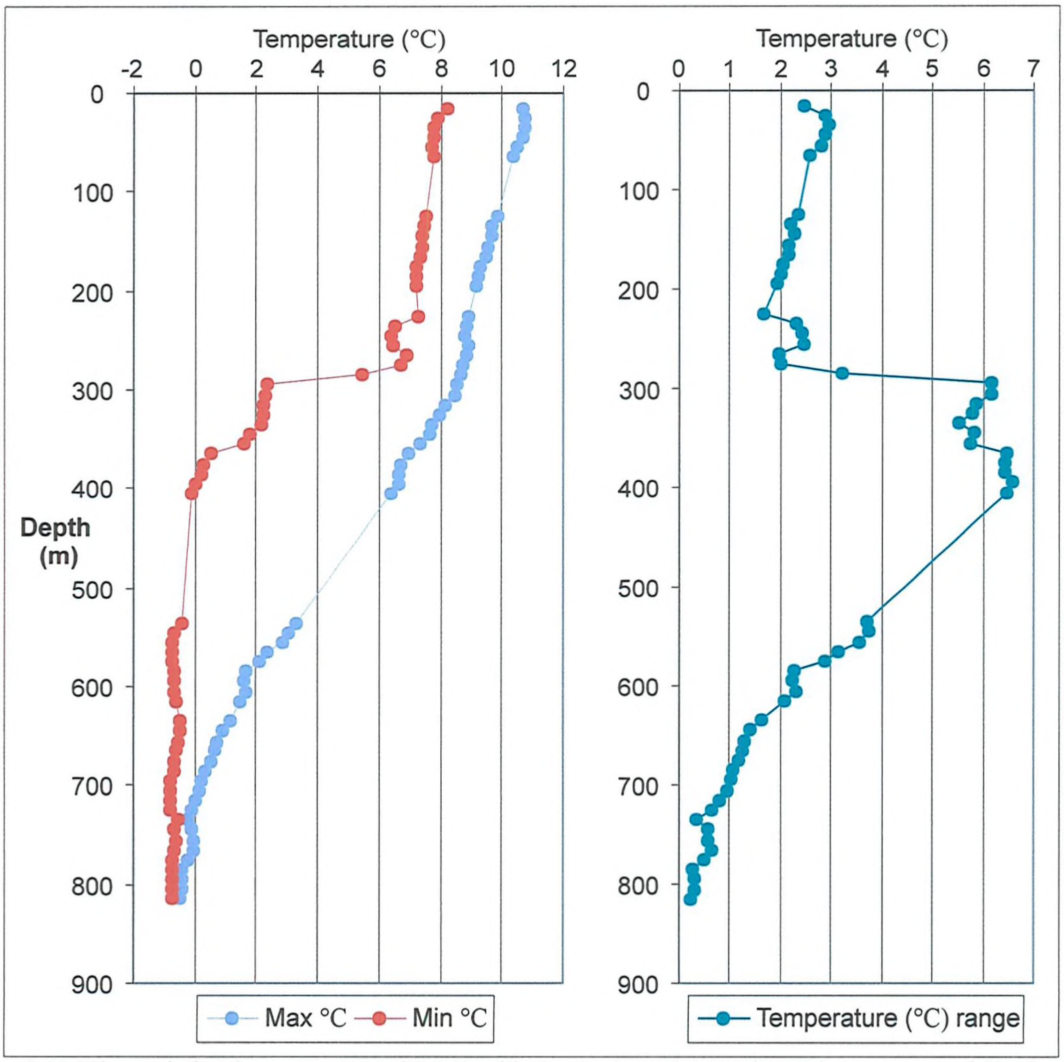


Figure 5.16. The variation in temperature (T, °C) with depth along the continental slope west of Shetland (note the difference in depth range compared to previous plots).

5.3.4 Analysis of the physical parameter– current flow

As determined from photographs, the apparent direction of the current flow is towards the northeast on the upper continental slope (≤900 m) but towards the south-southwest at depth (>900 m), see table 5.12. The indicators consist of sand ripples, scouring behind rocks and deposition of finer material on one side of a rock and the directions have been derived as described in chapter 3.

Station	Depth	Indicator	Current direction
55456	204 – 209 m	Sand ripples, sand streaks and scouring behind rocks	Towards northeast
53913	290 – 275 m	Sand ripples and scouring	Towards N – NE
53926	294 – 278 m	Scouring behind rocks	Towards N – NE
53928	390 – 370 m	Scouring behind rocks	Towards northeast
53914	410 – 397 m	Scouring behind rocks	Towards northeast
53925	507 – 496 m	Scouring and deposition	Direction unknown*
53916	595 – 580 m	Deposition (most), scouring and sand ripples	Direction unknown*
53985	685 – 672 m	Scouring behind rocks and some sand ripples/streaks	Towards northeast
53924	798 – 781 m	Sand ripples	Towards north/south
53984	912 – 881 m	Asymmetrical ripples	Towards northeast
53923	1088 m	Scouring behind rocks	Towards south
53981	1209 – 1203 m	Small scour marks behind rocks	Towards south-SW
53980	1408 – 1401 m	Scouring behind rocks	Towards south-SW

Table 5.12. Indicators and current directions along the bathymetric transect west of Shetland (* = no overlaps of succeeding frames were available – direction of current flows can therefore not be determined).

The size of sand ripples can be seen in table 5.13. The overall range is 15 cm to the maximum of 57 cm.

Station	Depth	Wavelength range
55456	204 – 209 m	15 – 25 cm
53926	294 – 278 m	21 – 22 cm
53924	798 – 781 m	27 – 57 cm
53984	912 – 881 m	18 – 45 cm

Table 5.13. Sand ripple wavelengths at stations along the bathymetric transect west of Shetland.

5.3.5 Assessment of other features

Only two artificial items have been observed along the bathymetric transect. The first was observed at 500 m (53925#1), where a cable (approximately 2-3 cm wide) was found. It was straight and stretched across the frame from one corner to the next. The second item was observed at 1400 m (53980#1) and it is believed to be a metal object but it was not possible to identify the item with any certainty.

5.3.5.1 Trawling

Trawl marks were recorded down to depths of 600 m west of Shetland (table 5.14). There appear to be more marks observed at the shallowest depths (≤ 300 m), a suggestion supported by both the absolute numbers and the density values. The scales of the trawl marks remain unknown, as it has not been possible to take any measurements, as the marks are wider than the width of the seafloor coverage of the photographs.

Station	**Depth**	**Mark**	**Number of marks**	**Density (trawl marks/100m^2)**
55456	204 – 209 m	None observed		
53913	290 – 275 m	Trawl marks (otter-board marks and marks from trawl nets)	13 marks	1.6
53926	294 – 278 m	Trawl marks (from trawl nets)	12 marks	0.8
53928	390 – 370 m	None observed		
53914	410 – 397 m	Trawl marks (from trawl nets)	2 marks	0.2
53925	507 – 496 m	None observed		
53916	595 – 580 m	Trawl marks (from trawl nets)	5 marks	0.1
53985	685 – 672 m	None observed		
53924	798 – 781 m	None observed		
53984	912 – 881 m	None observed		
53923	1088 m	None observed		
53981	1209 – 1203 m	None observed		
53980	1408 – 1401 m	None observed		

Table 5.14. Trawl marks observed at different depths along the bathymetric transect west of Shetland. The density values are based on the entire photographic transects rather than using those available after frame selection (frames < 6 m altitude).

5.3.5.2 *Lebensspuren*

Evidence of megafaunal activity as observed from ‘lebensspuren’ (trails and burrows), was widespread along the bathymetric transect and these are described in detail in chapter 6.

5.4 DISCUSSION

5.4.1 Seabed analysis

As a rule the mean sediment size decreases with depth (Tyler, 1995) and overall the sediment west of Shetland follows this pattern (see figure 5.3 and tables 5.2 and 5.5). However, the sedimentary environment is more complex and the results from the photographic analysis of the seabed environment largely conform to the results presented from the sidescan sonar analyses (Masson *et al.*, 1996, 1997; AFEN, 2000; Masson, 2001). The seafloor environment along the bathymetric transect can be described in a number of zones: 1) iceberg plough mark zone, 2) the sand wave zone, 3) the sand contourite, and 4) the basin floor (figure 5.17 and 5.18). These zones have all been identified through the integration of sidescan sonar data (Masson *et al.*, 1996, 1997; AFEN, 2000, Masson, 2001) and photographic images.

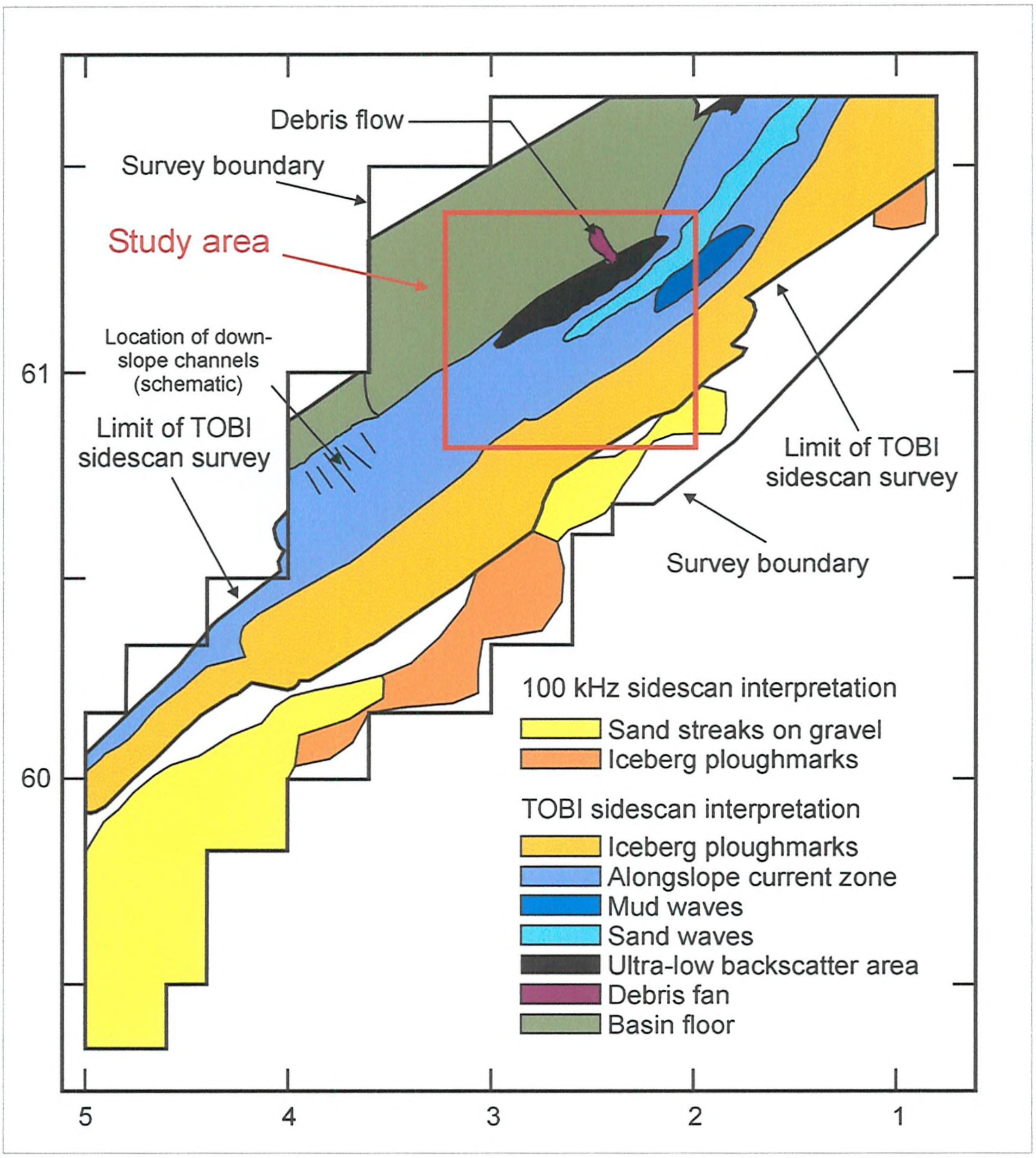


Figure 5.17. Interpretation of TOBI sidescan sonar imagery from the continental slope west of Shetland with the bathymetric transect study area superimposed (from Masson, 2001).

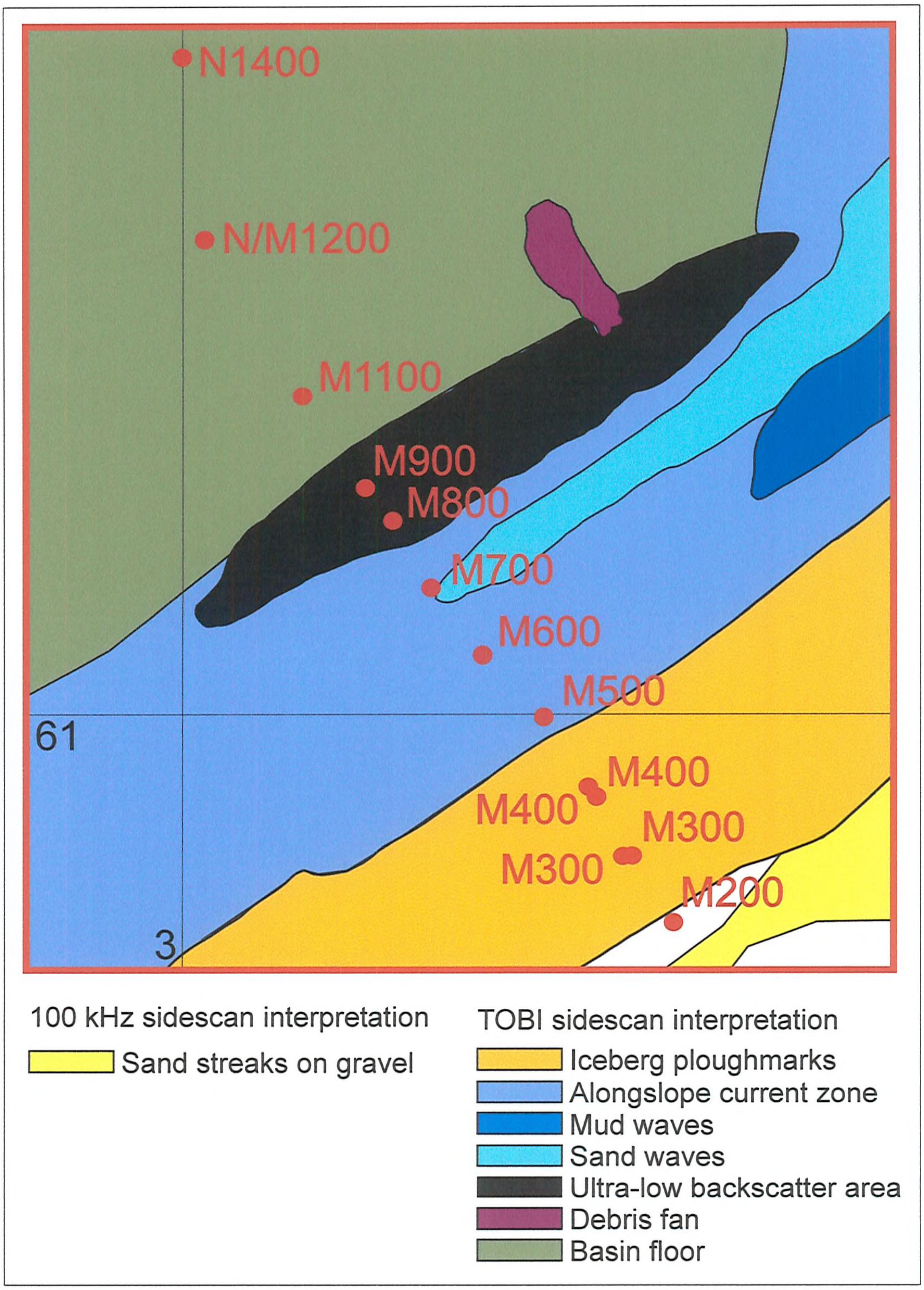


Figure 5.18. Sidescan sonar (TOBI) interpretation with the locations of the WASP sites (see table 5.1 for site identification) (adapted from Masson, 2001).

5.4.1.1 Iceberg plough mark zone

Between 200 and 500 m, the seabed is dominated by iceberg plough marks (see chapter 2; discussed further in chapter 8). The characteristic criss-cross pattern produced by iceberg plough marks (Belderson *et al.*, 1973, Masson *et al.*, 1996; Masson, 2001) can be seen on the sidescan images of this region. The dark areas of low backscatter relate to areas of finer material while the lighter areas of high backscatter relate to coarse material (see chapter 8). The general pattern is produced by the ploughing action of grounded icebergs creating deep furrows where the coarse material has been pushed to the margins of the furrows (Belderson *et al.*, 1973; Drewry, 1986; Stoker *et al.*, 1993; Masson, 2001). Finer material has subsequently been added through deposition and reworking of the surrounding sediment.

The photographic analyses indicate that these plough marks are apparent on the seabed and there seems to be some correlation between the results from the two survey techniques (see chapter 8 for a detailed study). There appears, from overall photographic observations, to be a degree of sediment size increase with depth within the iceberg plough mark zone with an increase both in cobble and boulder sizes and numbers with depth within this zone, a pattern which is not obvious from the WASP sediment grading and needs further investigation. In addition, at 200 m three different types of seafloor ('fine', 'medium' and 'coarse') have been identified while only two types ('medium' and 'coarse') have been observed between 300 m and 500 m, but the evidence of the two types becomes less obvious with depth. The 'coarse' and 'medium' sediment types are believed to be characteristic of iceberg plough marks. The 'fine' sediment consists of sand, often with ripples, and is potentially a feature classified as facies 1 or 3 by Masson (2001), features reportedly occurring on the inner and outer continental shelf, or as one of the four morphological types within the iceberg plough mark zone (Masson, 2001). The former facies both consist of sand, often forming patches and streaks overlying other sediments, factors consistent with the features observed on the photographs. However, sand is also present in some of the morphological types within the plough mark zone (Masson, 2001) and it is also possible that the rippled sand seen in the photographs at 200 m could be classified as one of these four morphological types. The sand ripples and scouring behind rocks observed in this study (see table 5.12), together with other evidence of comet marks and barchan dunes seen in studies from the same region (see chapter 2; Kenyon, 1986, 1987; Stoker *et al.*, 1993), indicate a net sediment transport towards the northeast.

The photographic analysis revealed a lack of evidence of plough marks towards the deeper end (~500 m) of the zone. A similar result has been reported by Masson (2001), and others (Masson *et al.*, 1996, 1997), showing that the plough marks become fewer but larger and more continuous towards the deeper part of the zone. Only a few plough marks extend deeper than 450 m with the deepest recorded mark being at approximately 500 m (Masson *et al.*, 1996, 1997; Masson, 2001) and this is likely to account for the lack of plough marks visible on the photographs at 500 m.

5.4.1.2 Sand wave zone

Between 500 m and 1000 m there is a broad region classified from sidescan sonar images as an along-slope current zone. It consists of a number of sub-zones including the sand and mud wave zones as well as the ultra-low backscatter zone (see below), but although these three regions have been described as separate facies, it should be noted that the boundaries between them are gradational (Masson *et al.*, 1996, 1997; Masson, 2001). The 'sand wave zone' forms part of the bathymetric transect at a depth of approximately 600 – 750 m (Masson, 2001) but the mud zone is slightly to the north of the bathymetric transect (figure 5.17 and 5.18). Little sub-bottom penetration of 3.5 kHz energy is apparent in the 'sand wave zone', suggesting a coarser grained, sand-rich sequence (Masson, 2001). The seabed photographs from the 'sand wave zone' (as identified from sidescan sonar; Masson *et al.*, 1996), show a sediment dominated by a thin layer of sand overlying coarser material (gravel and cobbles) but boulders (drop stones) are also present in large quantities. The seabed sampling confirms a mixed sand/gravel substrate, which typically is 5 – 15 cm thick (Graham *et al.*, 1996) but the larger sized sediment has not been sampled (see table 5.2), indicating that photography is good additional tool to sample the seafloor to 'ground truth' the features present. The sidescan sonar interpretations (Masson, 2001) showed large-scale 'sand' waves in this region but these are far too large to be visible on the photographs and an integrated approach is therefore needed to obtain as much information about the area as possible.

5.4.1.3 The contourite zone

One of the main discoveries of the AFEN 1996 survey was the ultra-low backscatter sediment feature at the base of the West Shetland Slope at a depth of approximately 750-950 m (Masson *et al.*, 1996, 1997; AFEN, 2000; Bett, 2001a; Masson, 2001), although the presence of sand contourites had previously been noted at the base of the slope (Stoker *et* *al.*, 1998). This feature was initially seen on the TOBI sidescan sonar, appearing as a large, dark 'patch' of low backscatter approximately 100 km long and 15-20 km wide, and it was first interpreted as an area of fine sediment. However, cores indicated that the seabed was covered by a layer of well-sorted fine sand or muddy sand (Masson *et al.*, 1996; Masson, 2001). Analysis of the photographs reveals the presence of a rippled sandy seafloor (table 5.5) with the ripples having an approximately 40 cm wavelength (table 5.13), indicating a current towards the northeast (table 5.12) with current speeds of up to 30-40 cm/s (Masson, 2001). After consulting the photographic material, the initial interpretations were extended and this sediment feature was identified as a sand contourite with a Holocene age for its deposition (Masson, 2001), a contourite generally being described as a feature produced by the deposition of material, in this case mainly sand, from a bottom current (Leeder, 1982; Stow, 1995). The photographs furthermore revealed a distinct and unique megafauna (see below) at high densities (figure 5.5 and table 5.9) at this site compared to the other sites, an aspect that may be linked to the fact that sand contourites are not entirely stationary as well as the fact that sand does not allow burrows to remain, potentially favouring some groups while preventing other groups of fauna from inhabiting the area.

5.4.1.4 The channel basin floor

The channel floor, at depths below 1000 m, is a fairly flat and featureless domain, a fact also observed on sidescan sonar imagery (Masson *et al.*, 1996, 1997; Masson, 2001). The photographs reveal a sediment that is getting finer towards the northwest, where coarse sediment (gravel, pebbles and cobbles) is overlaid by finer material (fine sand and or mud) at the 1100 m depth interval while sand and mud appear to be dominant at 1200 m and 1400 m. The featureless character of the seabed is attributed to the weak current towards the south (Stoker *et al.*, 1991; Stoker *et al.*, 1998), a fact deduced from the low levels of sorting of the sand/mud fraction of the surficial sediment (Masson, 2001), furthermore suggesting that low sediment supply is the reason for the low Holocene sediment rates rather than erosion or non-deposition (Masson, 2001).

5.4.2 Physical parameters

The presence of two layers, one shallow and one deep, with the direction of the current flow, towards the northeast at shallower depths (<900 m) and towards the south-southwest at depth (>900 m), follows largely the current directions described in previous hydrographic studies (e.g. Turrell *et al.*, 1999 and section 2.3.1) where the boundary is generally considered to occur at around 600 - 700 m depth. In this study there is evidence of a boundary at 900 m, with sand ripples being present at both 800 m and 900 m, showing consistent orientation indicating transport towards the northeast. There are a number of possible explanations for the reported difference in the depth at which the flows reverse include: 1) a vertical movement of the water masses within the channel, and/or 2) a decreased thickness of the deeper (the volume of FSCDW has been shown to vary decadally, a fact that may alter the relative positions of the water masses), cold water masses as described by Turrell *et al.* (1999). This could lead to the warmer, northeast-flowing water masses being present at increased water depths to those typically described. 3) These are relict features from the last glacial, when deep currents flowed towards the northeast (Masson, 2001). A fourth alternative is also possible, where the sand ripples are transient features reflecting only the last sediment transport events and not the residual current direction (Masson, 2001). The latter may refer to all the indicators used (sand ripples, scouring and deposition) in this study and it is possible that these do not always show the direction of the residual current. However, there are a number of studies over several decades indicating similar *overall* results to those of this study but in order to resolve the question of where the boundary actually is, more photographic and hydrographic data are required from this area.

The current speeds on the upper part of the slope (down to 600 m) have been estimated to be 0.3 – 0.6 m/s with peak currents reaching 0.7 – 0.8 m/s, the latter speeds being deduced from the presence of features such as barchan-type sand dunes and comet marks (see chapter 2; Kenyon, 1986, Stoker *et al.*, 1993; Masson, 2001). The lack of fine material, the large number of scouring marks (comet marks) and preferential deposition of sand behind boulders seen on the photographs from the upper continental slope in this study indicate strong current flows (Kenyon, 1986; Masson, 2001). Scour marks were also observed on the channel floor (1100 – 1400 m), indicating current activity at these depths. Estimates of the current speeds have been given in other studies (Saunders, 1990; Stoker *et al.*, 1993) of approximately 0.1 – 0.6 m/s but it is difficult to confirm these speeds in this study.

The current speeds on the lower continental slope are even more difficult to estimate. The majority of the sand ripples observed at these depths in this study are within the wavelengths typical (5 – 40 cm) for sand ripples (Leeder, 1982) but some are larger (approximately 15 ripples are > 40 cm, one from 900 m and the remaining were observed at 800 m). The reason for these being larger and outside the typical range may be as a result of mistakes made during the analysis and measurement of these bedforms, mainly as a result of the small sizes as seen on the photographs (a few millimetres). It is also possible that the grain size is large, a fact known to increase the wavelength of the ripples (Leeder, 1982), and that the recorded sizes are at the very upper range of the ripple range. However, the sample data (table 5.2) indicate that the sediment is dominated by fine sand and not towards the coarser limit of the range. The current speeds required to produce sand ripples are between 0.2 to 0.6 m/s (Open, 1989), although these values are highly dependent on the grain size. For the sites at 900 m and 800 m (in particular), where the wavelengths are larger, the peak current speeds may be in the middle to the upper part of the range but this is difficult to determine with any great certainty. Kenyon (1986) suggested that 'weaker' currents were present at these depths while Masson (2001) estimated current speeds from sand-ripple bedforms on the lower part of the continental slope (750 –950 m) to be between 0.3 and 0.4 m/s. These current speeds seem likely to be representative for the sand ripples observed in the photographs in this study. It was, however, speculated that the bedforms observed at these depths were transient features, only reflecting the last sediment transport event (a fact that may explain the apparent evidence on the photographs of flow both towards the NE and SW) or, relict features rather than indicators of present-day current speeds (Masson, 2001).

5.4.3 Other features

5.4.3.1 Trawling

This study has shown that trawl marks are present down to 600 m along the bathymetric transect west of Shetland but other studies have shown deep-sea trawling to occur down to approximately 1000 m in the UK Atlantic Margin (Aikman, 1997) and the northeast corner of the Rockall Trough (Bett, 2000b, c; Roberts *et al.*, 2000; chapter 9). Trawling is therefore believed to be a regular activity on the upper continental slope of the AFEN 1996 survey area (Bett, 2000c) and surrounding continental slope and shelf areas (Roberts *et al.*, 2000). The majority of observations of trawl marks in this study were made on the upper section of the bathymetric transect, an observation also reported by Bett (2000c). Trawl marks are also believed to be more frequent at shallower depths on the Hebrides continental slope but the evidence may not persist for as long as in the deep waters as a result of the strong Slope Current activities (Roberts *et al.*, 2000). The reason for trawl marks only being observed at shallower depths may be explained by the absence of commercially valuable species at depth, a suggestion that may be linked to the impoverished fish fauna present in the cold Norwegian Sea water below 600-700 m (Gordon, 2001). The effects of trawling on the fauna and ecology of an area are largely unknown but these are likely to be considerable with both indirect (e.g. loss of habitat and change in community structures) and direct lethal effects, matters further discussed in chapter 9.

5.4.4 Megafaunal analysis

5.4.4.1 General observations

The megafauna exhibit variation both in abundance and composition along the bathymetric transect west of Shetland illustrating a complex seabed environment. The megafauna can be described in terms of a large-scale pattern but there are also a number of small-scale patterns of localised faunal zones: the fauna associated with the iceberg plough marks, the ‘sponge-belt’ and the distinct fauna associated with the sand contourite. It should be noted that the deep-water coral *Lophelia pertusa*, a coral that has received a lot attention in recent years (see chapter 9 and e.g.; Rogers, 1999; Bett, 2000a, 2000b, 2001a; Bett *et al.*, 2001a; Masson *et al.*, 2001), has not been observed along the bathymetric transect west of Shetland, indeed it was rarely encountered during the AFEN surveys, being observed on seabed photographs at one site at 550 m (station 53801#1) and collected in two samples at site D3 (see figure 5.2) at 250 m (only dead fragments) and site G3 at 330 m (live and dead fragments) (Bett, 2000a), all northeast of the bathymetric transect west of Shetland (Bett, 1997). *Lophelia pertusa* has been collected around the Faroe Islands (Fredriksen *et al.*, 1992; Jensen and Fredriksen, 1992) and in the northern Rockall Trough (see chapter 9; Bett, 2000b; Bett *et al.*, 2001a; Masson *et al.*, 2001). *Lophelia pertusa* therefore appears to be a feature in some areas within and around the Faroe-Shetland Channel but rare on the continental slope west of Shetland.

5.4.4.1.1 Iceberg plough marks

The integrated analysis of sidescan sonar and photography has revealed a megafaunal distribution closely linked with the two 'types' of sediment present within the iceberg plough mark zone, where some faunal groups, the cidarids and squat lobsters, are observed mainly on the 'coarse' sediment, dominated by gravel and cobbles, while other groups, the irregular echinoids (possibly *Spatangus purpureus*) and *Stichopus tremulus*, are found mainly on the 'medium' sediment type, dominated by sand and gravel (see chapter 8 for a detailed study; Bett, 2000a; Bett and Axelsson, 2000). In addition, there appears to be a depth trend in the megafauna within the iceberg plough mark zone (figures 5.13, 5.14, 5.15 and the Spearman's rank correlation coefficient analyses), a pattern perhaps reflecting an apparent coarsening of the sediment with depth within the iceberg plough mark zone (see section 5.4.1.1). This pattern is not immediately apparent from the sediment grade analysis but the (personal) photographic observations indicate that the cobbles and boulders become larger towards the lower end of this zone. In addition, sandy patches are present at 200 m while sandy gravel and gravel become more dominant with depth rather than sand. Specifically this depth trend could be exemplified with regards to the genus *Munida*, where different species of this genus have been reported to have overlapping but distinct bathymetric ranges (Rice and de Saint Laurent, 1986). For example, while *Munida rugosa* has been identified at 200 m in this study, different species (e.g. *M. sarsi* or *M. tenuimana* with reported depth ranges of 200-800 m and >550-1400 m respectively: Rice and de Saint Laurent, 1986) may be present at mid-slope (500 – 600 m) depths. A similar pattern may be present in other taxa as well, where there may be different species present at different depths within the zone.

5.4.4.1.2 The 'sponge-belt'

The 'sponge-belt' is a feature where sponges are particularly widespread and dominant. The belt is not identifiable on the TOBI sidescan sonar images but the analysis of photographic material did reveal a well developed 'sponge-belt' in the depth range 500 – 600 m on the bathymetric transect with sponges being particularly dominant at 500 m becoming less important towards 600 m. The belt forms the lower end of the iceberg plough mark zone with some plough marks reaching into the 'sponge-belt' region and the sediment within the 'sponge-belt' is considered to be 'medium' to 'coarse', as it is dominated by sand and gravel but substantial additions of cobbles and boulders are also present, forming an important substratum for the sponges. The sponges are, as in other regions, of a wide variety of species including *Geodia* sp. and *Isops* sp. but many other sponge species, yet to be identified, are also common. The majority of the sponges are small but large (>10 cm) specimens are also common. The coarse nature of the seafloor sediments, as well as the sponges themselves, provide a large number of habitats for groups including squat lobsters (*Munida* sp.), sea stars and pencil-spined sea urchins (Cidaridae). There appears to be a change in the dominant megafaunal groups with depth within the 'sponge-belt', where for example *Munida* sp. is the most abundant megafaunal group at 500 m, but is absent towards 600 m. Conversely, cushion stars (asteroids) and echinoids are abundant at 600 m but rarely observed at 500 m.

The 'sponge-belt' feature has been recorded from other sites in the Faroe-Shetland Channel, including the Faroe Shelf and continental slope region where they are known as 'ostur' or 'ostebund' (Klitgaard *et al.*, 1997), with a rich associated fauna of over 200 different taxa (Klitgaard, 1995). As discussed in chapter 2, the presence of this 'sponge-belt' has been attributed to increased detrital flux caused by increased vertical mixing resulting from the internal tide (chapter 2; Fredriksen *et al.*, 1992; Klitgaard *et al.*, 1997). Temperature, another possible parameter, was shown from TOBI CTD data to be highly variable along the continental slope west of Shetland with a range of -0.5°C to 8.0°C (chapter 2; AFEN, 2000; Bett, 2001a; Masson, 2001) while approximately 5°C, or more, at the depths where the 'sponge-belt' is found around the Faroe Islands (Westerberg, 1990; Klitgaard *et al.*, 1997), indicating that local hydrodynamics rather than temperature may be more important in controlling the sponge distribution (Bett, 2000a). There is both theoretical and observational evidence of an internal tide within the Faroe-Shetland Channel (see chapter 2; Sherwin, 1991; 1995). The waves are believed to be generated at the Wyville Thomson Ridge, propagating up (northeast) into the Faroe-Shetland Channel at depths of approximately 500 - 600 m with an amplitude of around 40 m and expending their energy through mixing along the edges of the channel, leading to enhanced mixing of the water column and increased bottom friction (Sherwin, 1991; 1995). This may result in increased detrital flux as described by Klitgaard *et al.* (1997) (see chapter 2) and support the large number of sponges present between 500 m and 600 m west of Shetland.

5.4.4.1.3 The sand contourite

The sand contourite at the base of the slope (see above) has a distinct and unique megafauna (the sites at 800 m and 900 m were clustered together; figures 5.12 and 5.13), not only because of the high density values of the megafauna (figure 5.5 and tables 5.8 and

5.10) at this site compared to the other depth intervals but also because of the particular fauna present. The megafauna is dominated by sea spiders (Pycnogonida), anemones, sea pens and acorn-worms (enteropneusts). The presence of these surface-dwelling acorn-worms is one of the most novel discoveries at this site. Deep-sea enteropneusts typically lead a burrowing lifestyle and the burrows and the faecal casts produced are normally the only features seen on the seabed surface (Mauviel *et al.*, 1987; Tuck and Atkinson, 1995; Bett, 2000a). Multi-opening burrows believed to be produced by enteropneusts are common in deep-sea photographs (Mauviel *et al.*, 1987; Bett, 2000a) and burrows of this type have been seen on photographs from the deep slope sites and on the floor of the Faroe-Shetland Channel (Bett, 2000a). Surface-dwelling enteropneusts are known from the Galapagos hydrothermal vent sites (Grassle, 1986) but this habitat is considerably different to that of the contourite west of Shetland. In addition there is the 'Lopheneteropneust', a deep-sea, sediment surface-dwelling worm described by Lemche *et al.* (1976) and reported to be an enteropneust but no physical specimens have been examined (Tendal, 1998). The surface-dwelling specimens discovered on the contourite west of Shetland are typical enteropneusts, but the reason for their presence in such high numbers is still being debated, but the fact that sand may not support permanent burrow structures as well as the fact that sand contourites may not be entirely stationary, may potentially prevent the typical burrowing lifestyle of the enteropneust. These factors, as well as other factors (e.g. trophic amensalism; Rhoads and Young, 1970; Myers, 1977), may furthermore prevent other fauna from inhabiting the area and add to the distinctiveness of the fauna present. The abundance, estimated from the seabed photographs, of the animals is notable with approximately 100 individual/100m^2, with pycnogonids, sea pens and anemone B also found at higher densities (3-5, 2-21 and 11-75 individuals/100m^2 respectively) than at the other depth intervals. The total density is one order of magnitude higher than that of all other sites (apart from the 700 m site in the case of the pycnogonids which has a density of 1 individual/100m^2). Compared to a study of enteropneusts in deep-sea (1250-1400 m) sediments of the Vöring Plateau (Norway), with densities ranging from 800-1200 individuals/100m^2 (Romero-Wetzel, 1989), the densities west of Shetland are smaller, although a later study from the Vöring Plateau (Romero-Wetzel and Gerlach, 1991) recorded slightly lower densities of 400 individuals/100m^2. Compared to a deep-sea (1900 m) study in the Bay of Biscay (Mauviel and Sibuet, 1985; Mauviel *et al.*, 1987) with densities of c. 30 traces/100m^2, however, the result west of Shetland appears high. Note, however, that the enteropneusts from these studies have a burrowing life-style, while these surface dwelling acorn-worms west of Shetland seem to be a rather unique feature and not yet described elsewhere. Further studies of these animals would be of considerable interest but unfortunately they are difficult to collect as enteropneusts are known to be very fragile (Mauviel *et al.*, 1987).

5.4.4.2 Abundance

There is a general expectation of a decrease in megafaunal density and biomass with depth (Tait, 1981; Parsons *et al.*, 1984; Lampitt *et al.*, 1986; Gage and Tyler, 1991; Lalli and Parsons, 1993). This expectation does not appear to hold true for the megafauna west of Shetland, a result also reported in the macrofaunal studies from the same region (see chapter 2; Bett, 2000a, 2001a; Narayanaswamy, 2001). Overall, megafaunal densities (table 5.8 and figure 5.5) are lower at shallower depths compared to those deeper down the slope and on the channel floor. The overall pattern is similar to the macrofaunal data with relatively high abundance values at 200 m, values dropping sharply to 300 m and remaining fairly even down to 500 m. Approximately at this point the abundance values increase, however, whereas both size fractions of the macrofauna have mid-slope peaks in abundance, 550 – 600 m for the smaller size fraction (Narayanaswamy, 2001) and 700 m for the larger size fraction (Bett, 2000a), the maximum in megafaunal abundance is found at 900 m. After the peaks, the values again decrease with depth but these values are higher than those at the shallower sites (300 – 500 m), apart from the values at the shelf break (200 m). The low value at 800 m is slightly surprising considering the similarity in the type of sediment present at 800 and 900 m, but perhaps the 800 m site is found at the boundary between the sand contourite and the ‘sand-wave zone’, a fact that might restrict the type and number of taxa present. It should be noted that the value seen at 500 m is an underestimate (sponges are not fully enumerated).

Photography is likely to underestimate the abundance of fauna with a burrowing lifestyle or other cryptic habits. For example, it was clear from the photographs that taxa such as *Munida* sp. were frequently located beneath cobbles / boulders (claws remaining visible). Indeed, there was some indication of day / night variation in the habit of *Munida* sp., with cryptic behaviour during daylight hours. This observation may be coincidental, but as sunlight can penetrate to 200 m in clear coastal water and to approximately 1000 m in clear ocean water (Parsons *et al.*, 1984; Lalli and Parsons, 1993), it is possible that the fauna of upper levels of the bathymetric transect might respond to the day / night cycle.

In surveys where both photography and seabed sampling has been carried out there is often a difference between the results, where some taxa have higher densities when photographs are used rather than seabed sampling (e.g. Rice *et al.*, 1982; Rice and Collins, 1985; Thurston *et al.*, 1994; Nybakken *et al.*, 1998; Cailliet *et al.*, 1999) indicating that photography is a better tool for megafaunal abundance studies for at least some faunal groups. In addition, photography can provide information about the natural appearance (colour, size and orientation) and feeding methods of fauna, the spatial relationships of groups of organisms and the tracks and traces (see chapter 6) they leave (Barraclough Fell, 1967; Rice and Collins, 1985; Southward and Nicholson, 1985).

As was described in chapter 2, there is very little available biological data, such as faunal and *lebensspuren* densities, in the area northwest of Scotland and particularly west of Shetland. It is therefore difficult to compare the results from this study to similar work in the same region. Dyer *et al.* (1982) used a headline camera and trawls to study the North Sea benthos with some sites west of Shetland. There is no information about the altitudes of the headline camera apart from stating that "the height was not absolutely constant". Some faunal densities were, however, reported from the west of Shetland continental shelf (table 5.15). Examples of other studies that potentially could be used for comparison purposes are summarised in table 5.16. The comparative studies are from outside the present study (i.e. not along the continental slope west of Shetland) and the results may not be directly comparable. In addition, the fauna have not been identified to the same level and the photographs in the other studies have been taken using different instruments, a fact that may also influence the results to some extent. Assuming the data from the different studies are representative for the region and the fauna, the results from this study are within the density ranges for almost all the fauna at almost all depths, although the differences appear to increase when the deep-water sites are compared to the shelf sites.

Taxa (previous studies)	**Densities from photographs**	**Taxa (this study)**	**Densities from photographs**
Pennatula phosphorea *	0.14 ind./m^2	Pennatulacea	0.01 – 0.10 ind./m^2 (800 m) 0.12 – 0.32 ind./m^2 (900 m)
Munida rugosa +	0.03 ind./m^2	*Munida* sp.	0.03 – 0.14 ind./m^2 (300 m) 0.02 – 0.32 ind./m^2 (400 m) 0.08 – 0.38 ind./m^2 (500 m)
Cidaris cidaris *	0.09 – 0.22 ind./m^2	*Cidaris* sp	0.03 – 0.24 ind./m^2 (400 m) 0.01 – 0.02 ind./m^2 (500 m)
Echinus acutus *	0.07 – 1.68 ind./m^2	*Echinus* sp.	0.03 – 0.04 ind./m^2 (600 m)
Asterias rubens *	< 0.02 ind./m^2	Asteroid B sp *Ceramaster* sp.	0.01 – 0.04 ind./m^2 (500 m) 0.02 – 0.03 ind./m^2 (600 m)

Table 5.15. Population densities from photographic surveys of some species on the continental shelf west of Shetland (from Dyer *et al.* (1982), Cranmer *et al.* (1984) and the continental slope (this study – see table 4.6) respectively (* = Dyer *et al.* (1982) and + = Cranmer *et al.* (1984)).

Taxa (previous studies)	**Densities from photographs**	**Taxa (this study)**	**Densities from photographs**
Pennatulacea + (N. Rockall Trough)	0.11 ind./m^2 (1295 m)	Pennatulacea	0.01-0.10 ind./m^2 (800 m) 0.12-0.32 ind./m^2 (900 m)
Munida tenuimana + (N. Rockall Trough)	0.45 ind./m^2 (721 m) 0.40 ind./m^2 (885 m) 0.05 ind./m^2 (1108 m) 0.11 ind./m^2 (1295 m)	*Munida* sp.	0.03-0.14 ind./m^2 (300 m) 0.02-0.32 ind./m^2 (400 m) 0.08-0.38 ind./m^2 (500 m)
Echinus affinis * (Porcupine Sea bight)	0.08 ind./m^2 (980 m)	*Echinus* sp	0.03-0.04 ind./m^2 (600 m)

Table 5.16. Examples of faunal densities from two other studies with photographs from sleds (Rice *et al.*, 1982 = *) and oblique photographs (Roberts *et al.*, 2000 = +).

The analysis of the megafaunal density and environmental data showed significant correlations between mean density and sediment particle size (silt and clay content, $p<0.05$) mean and median, $p<0.05$), however, there was no apparent correlation with depth, temperature or total organic carbon. The abundance of both size fractions of the macrofauna was correlated with depth (see chapter 2; Bett, 2000a). Temperature and mean sediment grain size did also show significant correlations with the smaller size fraction of the macrofauna (Narayanaswamy, 2001). A suggested explanation for the peaks seen in the abundance of macrofauna west of Shetland was the presence of organically enriched sediments (Russell *et al.*, 1999) at intermediate depths (Bett, 2000a). Organic carbon input has been suggested as the major controlling factor for both macro- and megafauna in many deep-water Atlantic basins (Sibuet *et al.*, 1989) and this may also be the case west of Shetland. It is possible that the increased values of megafaunal abundance around 700 m are also as a result of these enriched sediments, although overall the megafaunal distribution is most strongly correlated with sediment size and not with total organic carbon (table 5.9). The reason for the peak abundance value at 900 m is somewhat enigmatic (see discussion about enteropneusts above). The faunal densities on the Faroe-Shetland Channel floor are, as on the sand contourite, higher than those of the shallower zones, and are potentially explained by the character of the sediment. Burrows and other 'lebensspuren' were frequently observed potentially indicating high biological activity (see chapter 6), although it could also indicate that conditions are more suitable to burrowing.

Improvements to this part of the study could include estimating the biomass of the megafauna present, although this is likely to be a difficult task. It has been argued that biomass is a more relevant measure in marine studies than abundance (Rowe, 1983), although others have argued the opposite (Gage and Tyler, 1991). A combination may, however, be the best alternative and therefore study of both patterns and this would most likely add to the ability of explaining the patterns seen in this study. In addition, improved identification of the megafauna is desirable as local-scale patterns within the different zones and groups of fauna may be further distinguishable. Identification is, however, a notoriously difficult task, not only because of the limited knowledge about deep-sea fauna but also because the limitations of using photographs where only a small number of specimens typically are photographed sufficiently close to the camera.

5.4.4.3 Species diversity

There have been a number of studies where a 'parabolic' diversity-depth relationship has been reported, with a diversity maximum at intermediate (bathyal) depths (Rex, 1981, 1983; Maciolek *et al.*, 1987; Paterson and Lambshead, 1995), a pattern believed to occur within the megafauna as well as the macrofauna (Rex, 1981, 1983; Gage and Tyler, 1991). This response was reported for both the large and small size fractions of the macrofauna west of Shetland with the diversity maximum found between 400-500 m and 450-550 m respectively (Bett, 2000a; Narayanaswamy, 2001). The main controlling factor for the large size fraction was believed to be temperature (Bett, 2000a) but in the small size fraction both temperature and sediment size were noted (Narayanaswamy, 2001). In this study the patterns are complex but the Shannon-Wiener diversity index decreases gradually with depth and a parabolic response is not apparent. Species richness is even more complex but a largely monotonic response with depth is evident (i.e. similar to that of the Shannon-Wiener index) although a mid-slope maximum is found at 600 m (with the exception of 200 m). In addition, there is something of a division of the sites into two groups, where the shallow-water (200-600 m) sites have similar richness values and the deep sites ($\geq$700 m) have similar values. Species richness was correlated (table 5.11) with both temperature (positive) and depth (negative) ($p<0.05$) but even more so ($p<0.02$) with sediment grain size (positive). Shannon-Wiener diversity was correlated (table 5.11) with depth (negative), temperature (positive), sediment grain size (positive) as well as organic (positive) and carbonate (negative) content. The strongest correlations were found with depth, temperature and sediment grain size (phi median) size ($p<0.02$). These parameters are all likely to have some influence on diversity but it is difficult to decide which one is most important. It should be noted that since the sponge species were not discriminated at the 500 m site, it is possible that diversity may have been appreciably higher at 500 m (perhaps even maximal) than is indicated in figures 5.6 and 5.7.

The results from the rarefaction curves are broadly similar to those of species richness but in the case of rarefaction a more obvious and significant (table 5.11) monotonic response to depth is evident on plotting $E(S_{500})$. In addition to these overall trends, there is the indication of deep- and shallow-water groups, where the sites of 600 m or less are grouped together and the deeper sites ($\geq$700 m) form the other group. The division is particularly evident in the species accumulation plot (figure 5.10) but also present in the majority of the diversity indices. This conforms well to the overall faunal composition analyses (see below) but also with the finding from the macrofauna where two layers have been identified (Bett, 2000a; Narayanaswamy, 2001).

The lower levels of species diversity found at depth within the Faroe-Shetland Channel could be linked to geographic isolation. The Norwegian/Arctic Seas have been reported to have low species richness (Gage and Tyler, 1991; Poore and Wilson, 1993; Rex *et al.*, 1993). Rex *et al.* (1993) attributed low species diversity in the deep Norwegian Sea to Quaternary glaciation (during which extensive sea ice covered the Norwegian Sea and the northern reaches of the Atlantic) and suggested that the poleward decline in species diversity might represent a recovery from the effects of glaciation. In agreement with this, Bett (2001a) showed an extreme (macrofaunal) diversity contrast between the deep Faroe-Shetland Channel and the deep Rockall Trough, and suggested a link to the presence of the

Wyville Thomson Ridge and a physical barrier separating the relatively species rich warm waters of the Rockall Trough from the species poor cold waters of Norwegian Sea waters. The presence of a thermal barrier was linked to the end of the transitional zone (1000-1800 m) in a study in the Rockall Trough, preventing species within the transitional zone from reaching the abyssal (>1800 m) zone (Gage, 1986). Similarly, the lack of a thermal barrier has been linked to a spread in species diversity (Grassle and Maciolek, 1992), a suggestion also made for sites at the Snorre Field in the northern North Sea (northeast of Shetland), where previous low species diversity had increased as a result of northward intrusion of warmer Atlantic Water (Pearson, *et al.*, 1996). The deep-, cold-water layer within the Faroe-Shetland Channel derives from the relatively species poor Norwegian/Arctic Sea, sharing few species with the North Atlantic (Gage and Tyler, 1991), while the shallow-, warm-water layer largely derives from the more species rich North Atlantic (see e.g. chapter 2; Turrell *et al.*, 1999), potentially resulting in low megafaunal diversity at depth and higher megafaunal diversity within the upper layer along the continental slope west of Shetland.

5.4.4.4 Megafaunal composition

At the large-scale level, the photographic analysis suggests two biological zones along the bathymetric transect of the continental slope west of Shetland. The results appear to indicate an upper, or shallow, layer and a lower, or deeper, layer. The boundary between the two zones appears to be at approximately 500-600 m. The multi-variate results cluster the data into the deep-water and the shallow-layer fauna and the univariate measures (particularly species richness, species equitability, Simpson's dominance and species accumulation) also suggest the division of the megafauna into these two layers but the division is less clear in the megafaunal density and Shannon-Wiener diversity data, although the lack of sponge data at 500 m may affect the results to some extent. The presence of the 'sponge-belt' is, however, obvious from the photographs and considering the description of a rich megafaunal association with the 'sponge-belt' around the Faroe Islands (Klitgaard *et al.*, 1997; Klitgaard, 1995), it furthermore indicates the presence of a zone of very particular characteristics west of Shetland.

The first suggestion of two biological zones in the Faroe-Shetland Channel was made during the '*Lightning*' and '*Porcupine*' cruises (Thomson, 1873, Gage and Tyler, 1991). A characteristic deep-water fauna comprising pycnogonids, echinoderms and asteroids was found in the cold, deep layer. Aspinall *et al.* (1992) have also reported the presence of a two-layer feature with a boundary between 400 m and 500 m.

Bett (2000a, 2001a) identified three layers when describing the macrofauna in this area, where the identified depth zones were <300 m, 300-600 m and >600 m. A warm, shallow layer was found to overlie a deep, cold layer with an intermediate layer at approximately 300-600 m with hydrographic parameters, particularly temperature, being considered to be the main factor controlling the distribution of the macrofauna, although depth and sediment grain size were also believed to be important. Although describing a macrofauna where the distribution varied substantially between species, Bett (2000a) gave examples of where bivalves and gastropods were most frequent in the warm and intermediate waters whereas isopods and tanaid crustaceans were particularly well represented in the intermediate and/or deep layers. One suggestion was that the enhanced diversity corresponded with the depth range having a well developed epifauna and a potential increase in habitat complexity, and other mechanisms, could explain the enhanced diversity (Bett, 2000a). Another possible explanation was the presence of an ecotone. The ecotone represents a mixture of the fauna from the upper, warmer, layer and the deeper, colder layer. A similar form of "bathyal transitional zone" has been identified by others, consisting of distinct faunal assemblages and forming a boundary between shallow and deep-water fauna (e.g. Belyayev *et al.*, 1973; Menzies *et al.*, 1973; Parsons *et al.* 1984; Gage, 1986; Gage and Tyler, 1991). The results from the ordination analysis (figures 5.13, 5.14 and 5.15) in this study indicate a depth trend within the shallower sites (200 m – 600 m), a result that may reflect the change in the fauna within the transitional zone, and therefore represent the 'ecotone' between the shallow and the deep-water fauna along the bathymetric transect west of Shetland, although the environmental parameters influencing the results the most are depth and temperature.

There may be a division of the megafaunal distribution into three layers, the shelf fauna, the transitional fauna (or 'ecotone') and the deep fauna. The evidence for the two layers with a boundary at approximately 600 m is apparent but when the fauna is considered there appears to be an additional division between 200 and 300 m, indicating the presence of a shallow layer (<300 m), a transitional zone (300 – 600 m) and a deep layer (>600 m). This is based partly on the species richness, Shannon-Wiener diversity and rarefaction analyses, all of which are indicating that there is a difference between the 200 m site and all the others apart from the 600 m site (where the other boundary is found), but also on the presence of particular fauna and particularly the scaphopods, species believed to be *Antalis entalis*, *Munida rugosa*, *Echinus acutus* (or *E. esculentus*), *Porania pulvillus* and *Hyalinoecia tubicola*. *Antalis entails* have been observed on the continental shelf (Künster *et al.*, 1992) but it has not been observed anywhere else along the bathymetric transect, or along the continental slope (see chapter 7). The other species have been identified as characteristic of the west of Shetland shelf areas (see chapter 2; Dyer *et al.*, 1982, 1983; Cranmer *et al.*, 1984). Some of the species identified as characteristic of the shelf area (e.g. *Echinus elegans and Echinus tenuispinus*) have not been identified in this study, although as identification is difficult, these taxa may still be present. The faunal densities of these taxa observed in this study (see table 5.8) are generally slightly lower than those from the other studies (see chapter 2; Dyer *et al.*, 1982, 1983; Basford *et al.*, 1989). The only species with a higher density value in this study compared to another (Cranmer *et al.*, 1984) is *Munida* sp. while the value for the Spatangidae (*Spatangus purpureus*) is similar (Basford *et al.*, 1989), although the latter value is from an Agassiz trawl and not from photography. The cluster analysis and ordination do not reveal a separate grouping for the 200 m megafauna but in the ordination there is an obvious trend with depth (figure 5.13) and the 200 m depth interval is placed a short distance away from the other shallow-water sites. The depth trend is most likely reflecting the change in fauna within the transitional zone ('ecotone') between the shallow and deep-water areas but it is still possible that the 200 m faunal assemblage is different to that of the fauna within the remaining shallower sites. As mentioned above, Bett (2000a) suggested a third layer within the macrofauna at depths of less than 300 m but analysis of additional photographic sites at depths of approximately 200 m will be required to establish the full extent of the division within the megafauna but it is possible that a third layer is present. It should be noted that the identification of the scaphopods is difficult to carry out and it is possible that the observed fauna are of the genus *Ditrupa*, a polychaete that is tusk-shaped. However, the size range (3.2 – 8.0 cm) of the animals seen in this study is larger than those reported for *Ditrupa* (1.5 cm) by for example Hayward and Ryland (1995) and the identification of the fauna seen here as Scaphopoda is therefore more likely correct.

5.5 CONCLUSIONS

The analysis of the photographic data has revealed what appears to be the presence of two main biological zones of megafaunal distribution along the bathymetric transect west of Shetland, an upper layer (200-600 m), and a lower layer (>600 m). There may be an additional boundary between 200 m and 300 m but additional sites at 200 m will have to be analysed to verify this suggestion. The two megafaunal layers with a boundary at 600 m largely reflects the distribution of water masses within the channel but within this large-scale distribution in the megafauna, there are also a number of local-scale features (iceberg plough marks, 'sponge-belt' and the sand contourite with its associated fauna) as well as bathymetric trends where there is an increase in megafaunal density with depth while species diversity decreases with depth. Although the hydrography and temperature are believed to be important factors controlling the megafaunal distributions, depth and sediment grain size have also be shown to be significant. The low species diversity at depth within the Faroe-Shetland Channel may be explained by the presence of physical (Wyville Thomson Ridge) and thermal barriers preventing waters rich in species from reaching the depths of the Faroe-Shetland Channel. It has been speculated that the reason for the low species diversity within the Faroe-Shetland Channel and the Norwegian Sea is linked to a slow recovery from the last glaciation, when the area was covered in sea ice (Rex *et al.*, 1993; Bett, 2001a).

In addition, the integration of sidescan sonar and photographic material has identified a number of seabed type zones along the continental slope west of Shetland: 1) iceberg plough mark zone, 2) the 'sponge-belt', 3) the sand wave zone, 4) the sand contourite, and 5) the basin floor. These zones have characteristic faunal and sedimentary features, but there is also considerable variation within each zone revealing the presence of a complex seafloor environment in the Atlantic Margin. An integrated approach has been used in shallow water habitat mapping in several studies and locations (e.g. Todd, *et al.*, 2000; Kostylev *et al.*, in press) but until the AFEN surveys it has been rare in deep waters. The results and success of the AFEN projects illustrate the great potential of an integrated approach to deep-sea habitat mapping, techniques that most likely will be an important part of future deep-water environmental surveys.

6 THE DISTRIBUTION AND VARIATION IN THE MAIN TYPES OF *LEBENSSPUREN* ALONG A BATHYMETRIC TRANSECT WEST OF SHETLAND

6.1 INTRODUCTION

The visible evidence of faunal activity is known as *lebensspuren.* The term *Lebensspur* is German for life trace and was coined in the early 1900s to designate any sedimentary structure produced by a living organism (Ewing and Davis, 1967). The German plural *Lebensspuren* is the term now generally used to describe the physical manifestation of benthic animals in sediments, although they are also known simply as traces (Gage and Tyler, 1991). Tracks, trails, burrows, faecal casts, body imprints and other sedimentary structures produced by such animal activity are all examples of *Lebensspuren* (Young *et al*., 1985). All of these different burrowing and feeding activities continually disturb and rework the sediments, a process known as bioturbation (Libes, 1992; Lalli and Parsons, 1993), and have different effects on the physical characteristics of the sediment (Gray, 1974; Leeder, 1982; Gage and Tyler, 1991; Libes, 1992).

The importance of burrowing and bioturbation on land was first established by Darwin in the 1880s whilst studying the effects of earthworms on the mixing of the uppermost layer of the soil (Gage and Tyler, 1991). One of the earliest studies in the marine environment was carried out by Davison in the 1890s, where the effects of *Arenicola marina* was investigated (Cadée, 1976). In more recent years many studies have been carried out showing that the activities of the benthos of shallow soft bottoms profoundly affect the sediment properties and processes (e.g. Rhoads and Young, 1970; Rhoads and Young, 1971; Aller and Dodge, 1974; Gray, 1974; Cadée, 1976; Myers, 1977; Pearson and Rosenberg, 1978 and Aller, 1978 and Brey, 1991). Rhoads and Young (1971), Aller and Dodge (1974) and Cadée (1976) showed that animal reworking of the sediment can change the particle distribution in the sediment where the coarser sediment, not available for ingestion by the animals, accumulates at depth of feeding, while the finer material is displaced upwards (often at the surface of the seabed) and therefore grade the sediment. These activities furthermore change the water content and oxygen levels within the sediment (Rhoads and Young, 1971, Aller, 1978) and also affect faunal distributions (Rhoads and Young, 1970; Gray, 1981; Brey, 1991), trophic structures (Myers, 1977) and the general chemistry of the reworked sediment layer (Aller, 1978; Libes, 1992). Bioturbation can occur as deep as 1 m below the sediment surface but it is most intense in the upper 10 cm (Libes, 1992), and the uppermost 2 cm in particular (Myers, 1977). The thickness of the reworked layer depends on the type and size of fauna present, their feeding behaviour, life habit and population density (Piper and Marshall, 1969; Aller, 1978; Wheatcroft *et al.*, 1989) and also on the season (e.g. Myers, 1977; Brey, 1991), particle size (Aller, 1978) and the level of disturbance, either natural (e.g. currents) or artificial (e.g. organic pollution) (Pearson and Rosenberg, 1978).

In the deep sea, where standing stock and the rates of biological processes may be lower and the benthic animals generally are smaller, it might seem that the effects caused by bioturbation are much lower (Gage and Tyler, 1991). It has also been argued that the generally lower levels of hydrodynamic energy and sedimentation rates (Leeder, 1982) in the deep sea leads to less disruption of biogenic structures such that biogenic structures may persist for long periods (Gage and Tyler, 1991). However, visual evidence from the ocean floor suggests that bottom organisms are important in restructuring and altering the sediment in the deep sea (Gage and Tyler, 1991). Photographic results from *in situ* studies at bathyal depths (1240 m) in the east Pacific by Smith *et al.* (1986) indicated a rapid sediment mixing and it was suggested that this mixing was important in controlling sediment properties and chemistry and benthic community structure at the deep-sea floor. Richardsson (1983) also demonstrated that bioturbation alters sediment properties in the abyssal deep sea (Caribbean Sea), where burrows and tubes were found to reach 10-12 cm into the sediment. It has even been suggested that 'bioturbation of pelagic abyssal deposits in the Atlantic Ocean is intense and total….regardless of latitude, water depth and sediment type' (Ekdale *et al.*, 1984), although differences in *lebensspuren* types and densities have been observed for different latitudes and different sediment types. For example, Kitchell *et al.* (1978) found high *lebensspuren* densities in abyssal deposits in the Arctic while these values were lower in the Antarctic, and Huggett (1987) found different types of traces in different types of sediments.

Photography has been shown to be an important tool in the study of *lebensspuren* and photographs of the ocean floor are an important source of information as to the identity of organisms responsible for the various traces (Ewing and Davis, 1967), although identification of the fauna, as well as determining the origin of the traces, often is a difficult task. Since the beginning of deep-sea photography in the 1940s (Ewing and Davis, 1967, Holme, 1985), the prevalence of *lebensspuren* in the photographs, rather than the animals themselves, has often been remarked upon (Bett *et al.*, 1995), a fact partly explaining the difficulty in identifying the origin of the traces. Up to 7 % of the sediment surface in seabed photographs from the continental slope have been estimated to be visibly disturbed by traces and about half this value in the abyss, although these values may be even greater if close-up photographs are used (Gage and Tyler, 1991). Furthermore, *lebensspuren* and the presence of bioturbation are easily identified in well laminated sediments, but these are likely to be underestimated in homogenous sediments or where substantial burrowing has taken place (Ekdale *et al.*, 1978; Leeder, 1982).

Although there are many studies (e.g. Ewing and Davis, 1967; Heezen and Hollister, 1971; Mauviel and Sibuet, 1985; Young *et al.*, 1985; Bett *et al.*, 1995) of the large amount of photographically recorded *lebensspuren* available throughout the world few seem to have assessed the variation in the type of traces with depth (studies of the variation in fossil traces with depth do exist; e.g. Seilacher, 1953). In this study, the *lebensspuren* present along a bathymetric transect have been studied using photographs. The photographic survey was part of the Atlantic Margin Environmental Survey (AMES) of 1996 funded by the Atlantic Frontier Environmental Network (AFEN) and the study area is located (figure 6.1) along the continental slope west of the Shetland Isles (Masson *et al.*, 1996, 1997; AFEN, 2000). The aims of the study are to identify and describe the main *lebensspuren* present along the bathymetric transect west of Shetland and to investigate whether there are any variations in type and number of traces with depth, using the relative frequency as well as the densities of traces observed on photographs and use these parameters for comparisons with the variations in megafaunal densities, sediment grain size, carbon content and other environmental parameters along the bathymetric transect.

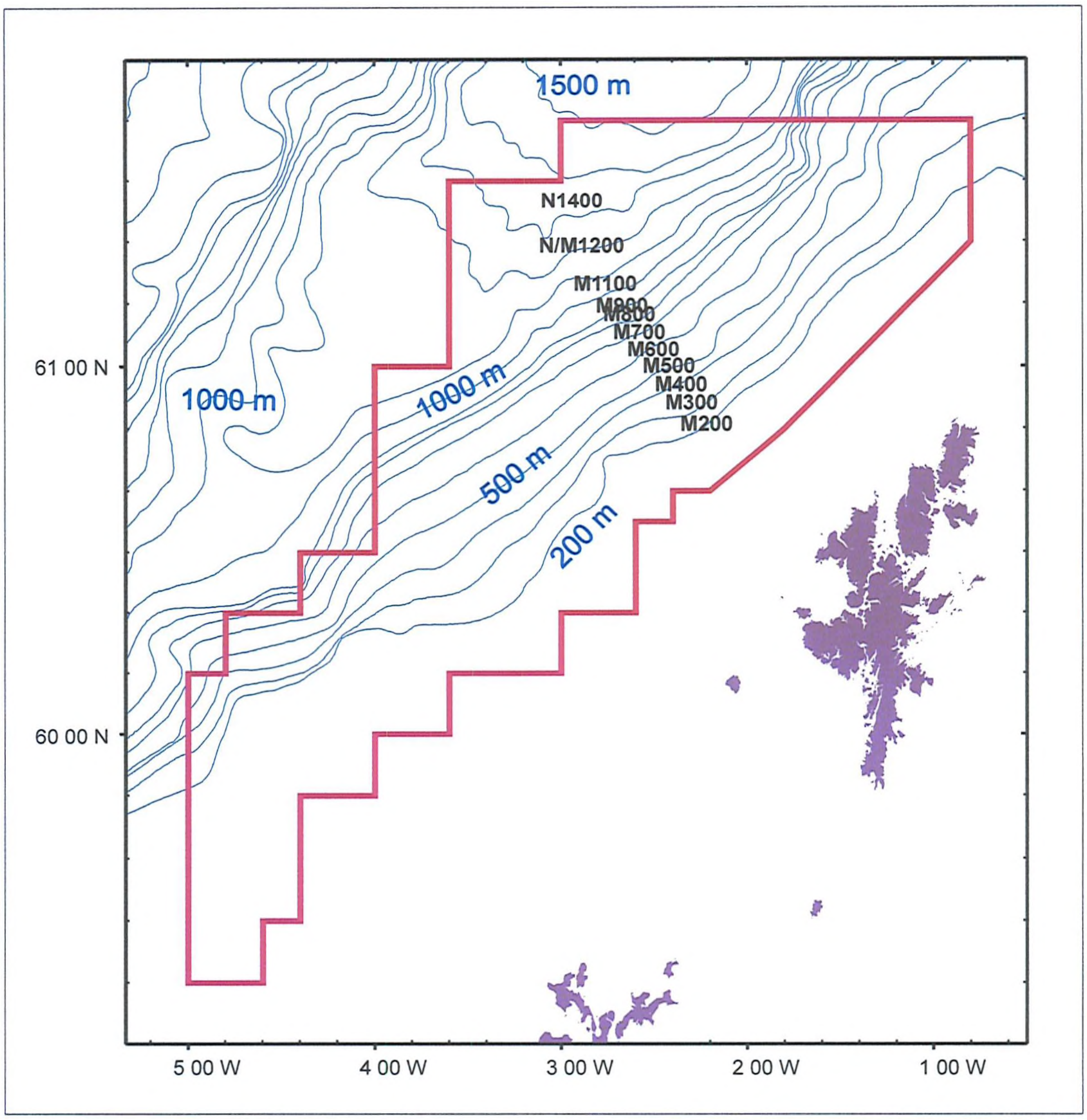


Figure 6.1. Photographic sites along the bathymetric transect west of Shetland.

6.2 METHODS

The photographic survey was carried out using the Wide Angle Seabed Photography (WASP) system (see chapter 3 and 4). Deep-sea photographs from 13 sites along a bathymetric transect west of Shetland at depths ranging from 200 m to 1400 m have been analysed for the presence of *lebensspuren* (figure 6.1 and table 6.1). While the vast majority of WASP runs are from AMES 1996, the 200 m site included in this study is from the White Zone Environmental Survey cruise, a Department of Trade and Industry survey, in 2000 (Bett, 2001b). Two photographic runs were completed at 300 m and 400 m (i.e. two films per depth) and the results from these films have been calculated and described together for those two depths.

Station (site)	**Location**	**Depth**	**Frame identification**	**Film run**	**Number of frames**
55456#1 (M200)	60° 52.80 N 02° 19.13 W	209-204 m	027 - 341	15 m colour	315
53913#1 (M300a)	60° 53.96 N 02° 22.07 W	290 – 275 m	435-543	5 m colour	109
53928#1 (M400b)	60° 56.70 N 02° 25.91 W	390 – 370 m	2506 - 2725	7 m colour	221
53926#1 (M300b)	60° 53.96 N 02° 22.15 W	294 – 278 m	2140 - 2249	4 m colour	110
53914#1 (M400a)	60° 57.74 N 02° 24.98 W	410 – 397 m	560 – 665	7 m colour	106
53925#1 (M500)	60° 59.54 N 02° 29.79 W	507 – 496 m	1780 - 2103	12 m colour	324
53916#1 (M600)	61° 02.49 N 02° 33.95 W	595 – 580 m	019 - 317	11 m colour	299
53985#1 (M700)	61° 05.40 N 02° 38.12 W	685 – 672 m	014 – 128	5 m colour	115
53924#1 (M800)	61° 07.99 N 02° 42.00 W	798 – 781 m	1545 – 1762	10 m colour	218
53984#1 (M900)	61° 09.57 N 02° 43.90 W	912 – 881 m	012 – 356	12 m colour	344
53923#1 (M1100)	61° 12.85 N 02° 49.41 W	1088 m	1164 – 1495	12 m colour	332
53981#1 (N/M1200)	61° 19.20 N 02° 58.23 W	1209 – 1203 m	371 – 690	10 m colour	320
53980#1 (N1400)	61° 26.65 N 03° 00.07 W	1408 – 1401 m	011 - 346	12 m colour	336

Table 6.1. Locations, depths and details of the photographs taken at stations along the bathymetric transect west of Shetland (the locations refer to the positions at the beginning of the transects and frame identification refers to the number printed on the frame at the time of exposure).

A total of 3149 seabed photographs were available for analysis (for the general methods of processing of films and analysis see chapter 3 and 4) from the 13 films (table 6.1). All the photographs were used during the initial processing of the films and subsequently rejected from the study if they were over- or underexposed or the altitude was in excess of 6 m.

During the photographic analysis all *lebensspuren* were recorded, briefly described and drawings produced of the main forms. All the traces were subsequently classified into a number of categories as follows.

6.2.1 Classification of lebensspuren

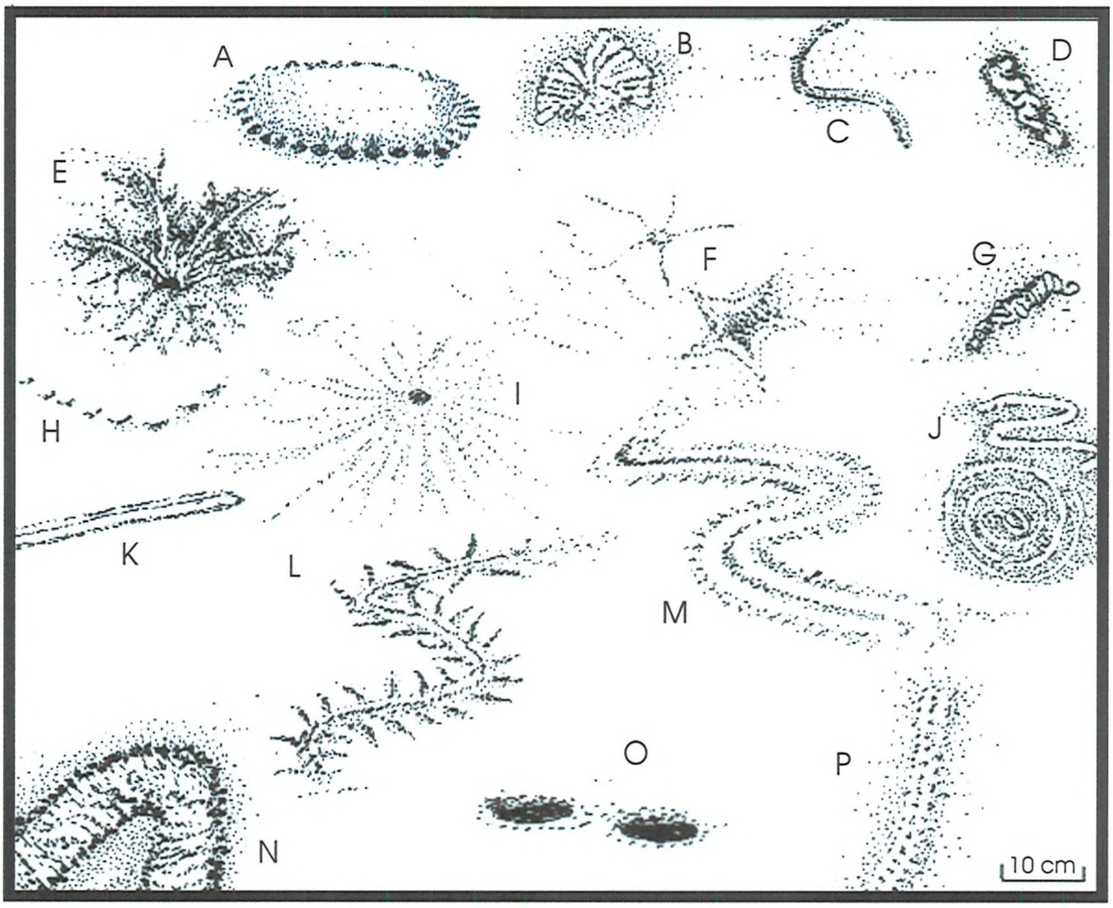


Figure 6.2. Examples of different types of traces (and the probable origin): A) ring of burrows, 'fairy rings' (unknown origin), B) rosette or spoke burrow surrounding a burrow (polychaete or echiuran), C) simple groove (actinian or mollusc?), D) faecal coil (holothurian cast), E) branched rosette burrow (bivalve, sipunculid, polychaete?), F) brittle star (above) and sea star resting traces, G) faecal coil (holothurian cast), H) discontinuous groove (fish, decapod crustacean?), I) fine-rayed rosette or spoke surrounding a burrow (polychaete?), J) coil and loops (lophenteropneust?), K) double furrow-two ridges separated by a groove (holothurian), L) pinnate ('herringbone') trail ((fish?), M) double plough furrows (irregular echinoids), N) 'tread track' straight or sinuous (sea star track?), O) simple large burrows (polychaete, crustacean?), P) four-row treaded (holothurian) track (from Gage and Tyler, 1991 – adapted from Ewing and Davis, 1967; Heezen and Hollister, 1971 and Mauviel and Sibuet, 1985).

The classification system suggested by Seilacher in 1953 has been used, where several categories of *lebensspuren* may be separated in terms of behaviour of the animal (Gage and Tyler, 1991):

a) *Resting traces*: imprints of animals that were stationary (e.g. the star-shaped traces left by asteroids and ophiuroids) (figure 6.2: F).

b) *Crawling traces*: characterised by a displaced 'bow-wave' of the sediment and sometimes also decorated with the imprints of locomotory organs (e.g. tracks and trails produced by gastropods and echinoids) (figure 6.2: C, H, K, L, M, N, P).

c) *Feeding structures*: examples are pellets from faeces or pseudofaeces by deposit-ingesters (figure 6.2: D, G).

d) *Grazing traces*: delicate marks on the sediment surface (e.g. spoke-burrows produced by echiurans and polychaetes) (figure 6.2: B, E, I, J).

e) *Dwellings*: habitats such as burrows and tubes (figure 6.2: A, O)

6.2.2 The analyses

In addition to the general description of the *lebensspuren* present, the relative frequency of photographs, i.e. the number of frames containing *lebensspuren* in relation to the total number of frames, was recorded and the percentage of frames containing *lebensspuren* at each depth was calculated. Confidence limits have been calculated using bootstrapping (see e.g. Cressie, 1993; Sokal and Rohlf, 1995; Krebs, 1999) and 'the first percentile method' in particular, where bootstrap resampling (with replacement) of the original data is carried out 1000 times to generate the bootstrap distribution (Manly, 1991). The 95% confidence interval is given by the values that are less than 2.5% and exceed 97.5% of the generated distributions (Manly, 1991). After the classification, the density of *lebensspuren* at each depth was calculated for each trace group. Confidence limits were calculated in a similar manner to those of the relative frequency. Based on the *lebensspuren* density values, the percentages of mobile and sedentary *lebensspuren* were then calculated for each site to investigate any variation with depth, relations to environmental variables, megafaunal data and other parameters of the *lebensspuren.*

The variation in the composition of *lebensspuren* with depth was also analysed by calculating the proportions of the five groups (according to the classification above) for each site. These were then plotted on a bar chart and the variation with depth analysed. Further analysis of this data was carried out using multi-variate analysis to assess the similarity of trace composition at different depths. The data were transformed (fourth root) to down-weigh the importance of common types of traces in relation to rarer types (Clarke and Warwick, 1994). The data were then analysed using the Bray-Curtis similarity coefficient (using Primer version 5) followed by a cluster analysis where the data were group averaged and linked to produce a dendrogram Clarke and Warwick, 1994). Non-metric Multi-Dimensional Scaling (MDS) was also carried out to further assess the presence of any similarities between the different depth intervals or depth trends along the transect (Clarke and Warwick, 1994).

The results from the above analyses were then compared to the environmental variables west of Shetland. The results were compared to the distribution of megafauna, the variation in temperature with depth as well as a number of sedimentary and other variables to assess which, if any, variable had the largest influence on the distribution and composition of *lebensspuren* along the bathymetric transect west of Shetland. These comparisons were carried out using Spearman rank correlation coefficient (r_S):

$$r_S = 1 - ((6\Sigma d^2)/(n^3 - n))$$

where *n* is the number of units in a sample, *d* is the difference between ranks, Σ is the 'sum of' and 6 is a constant peculiar to this formula (from Fowler and Cohen, 1992).

The correlation analyses were carried out comparing the relative frequency and density results as well as the percentage of mobile traces with the environmental variables available from the area west of Shetland (AFEN, 2000). The WASP sediment data are from the photographic interpretation of the bathymetric transect data (see chapter 5) where a scale was created to describe the sediment distribution with depth (a scale from 1 to 5 where 'very coarse' = 1 and 'very fine' = 5). The remaining environmental data were also collected during AFEN 1996 (see chapter 5) and subsequently analysed and reported (AFEN, 2000). This includes the sediment data (particle size and chemical analysis) and also the temperature data. The latter were collected using the TOBI instrument, however, it only covers the depth range 200 – 800 m within the bathymetric transect. For the correlation analyses the temperature at 800 m (-0.44 °C) has been extrapolated to all the deeper sites (900 – 1400 m) based on the information described in chapter 2.3, where it has been shown that the temperature is fairly constant at < - 0.5 °C for depths below 800 m. To enable correlation analyses using the vast amount of sediment data available, three seabed sampling sites were selected around each WASP site (figure 6.3). The distance between the WASP site and seabed sampling sites varied but the sites closest (both in distance and depth) to the WASP runs were selected. From these three sites, the mean values of the various environmental variables were calculated and used in the correlation analyses.

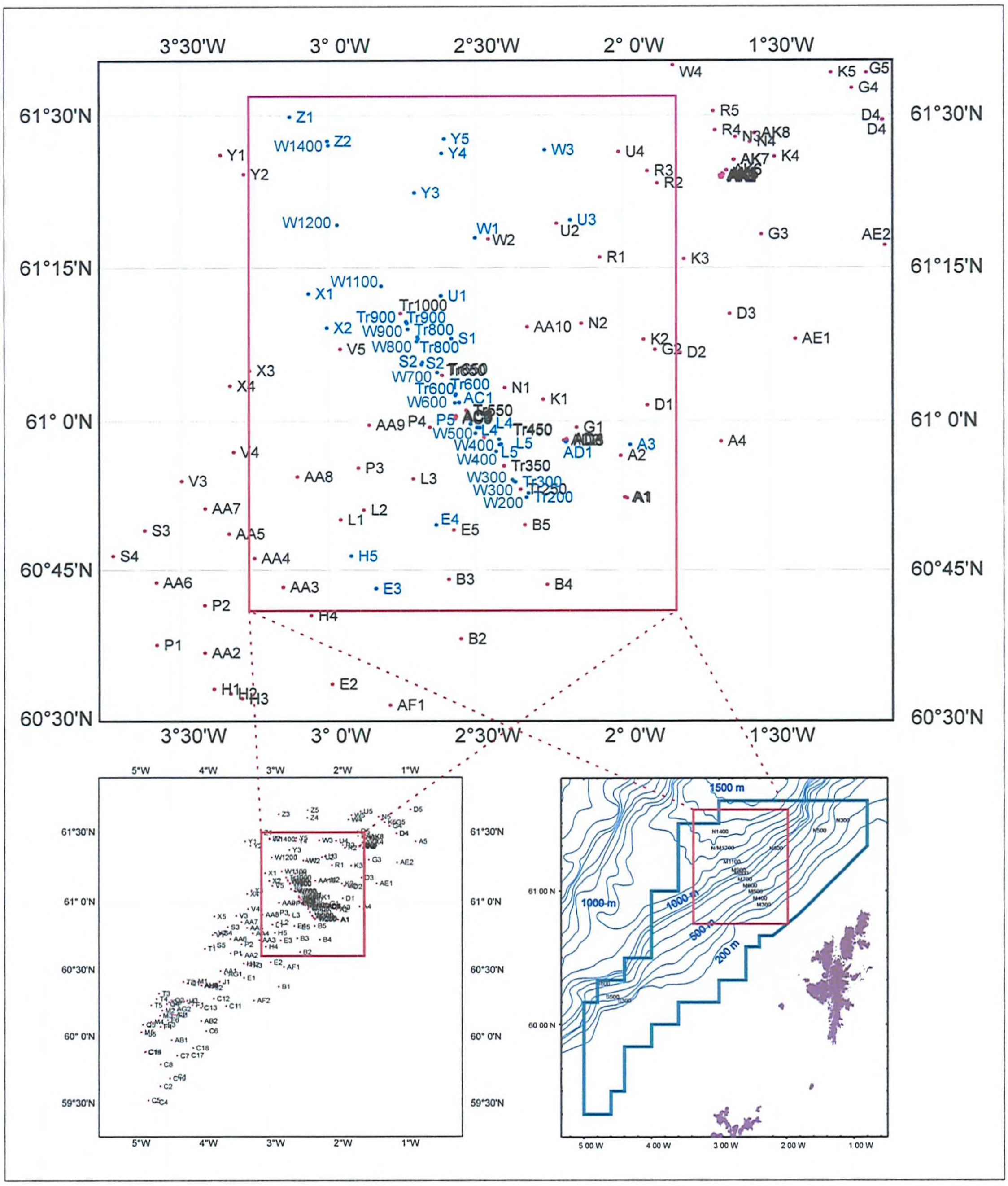


Figure 6.3. The selected seabed sample (blue) sites and the WASP run sites (green) in relation to the remaining seabed sample sites. The total number of sampling sites (lower left) and the position of the area in comparison to the AFEN 1996 survey (lower right) can also be seen.

Site	Depth	Phi	Wentworth scale	Org	S and C	TOC	TON	C/N
A3	160	1.12	Medium sand	0.31	0.26	0.18	<0.01	
Tr200	200	1.33	Medium sand	0.59	0.95	0.07	<0.01	
E3	222	0.70	Coarse sand	0.99	0.82	0.37	0.03	14.8
Tr300	286	1.18	Medium sand	0.63	0.70	0.07	<0.01	
E4	296	0.95	Coarse sand	0.63	4.61	0.58	0.07	0.80
AD1	324	1.84	Medium sand	0.34	1.75	0.14	<0.01	
H5	390	0.33	Coarse sand	1.49	2.86	1.43	0.10	14.0
L5	407	1.53	Medium sand	0.66	1.87	0.06	<0.01	
L5	408	1.38	Medium sand	1.25	1.22	0.10	<0.01	
L4	490	1.06	Medium sand	1.42	4.06	0.25	<0.01	
L4	494	1.44	Medium sand	1.23	2.53	0.14	0.01	17.0
P5	510	0.16	Coarse sand	1.45	1.96	0.31	0.01	37.0
Tr600	591	1.63	Medium sand	1.48	3.95	0.16	0.01	19.0
Tr600	591	1.74	Medium sand	1.42	6.63	0.31	<0.01	
AC1	575	1.13	Medium sand	3.82	1.65	1.00	0.11	9.0
S2	697	3.39	Very fine sand	1.39	14.40	0.42	0.03	12.2
S2	698	3.41	Very fine sand	1.48	13.44	0.48	0.03	15.6
S1	716	2.98	Fine sand	1.38	8.40	0.40	0.03	15.7
Tr800	789	3.48	Very fine sand	1.37	11.11	0.36	0.02	14.7
Tr800	792	3.50	Very fine sand	1.35	11.29	0.23	0.02	14.0
U3	825	2.25	Fine sand	1.19	4.98	0.74	0.07	10.5
Tr900	898	2.87	Fine sand	1.40	3.99	0.15	<0.01	
Tr900	899	3.05	Very fine sand	1.07	5.47	0.20	<0.01	
U1	922	2.88	Fine sand	1.06	4.33	0.66	0.06	10.3
X2	1046	2.49	Fine sand	1.61	9.70	0.40	0.05	8.17
W1	1069	3.20	Very fine sand	2.49	28.56	0.56	0.05	10.8
X1	1116	5.03	Medium silt	0.95	59.92	0.40	0.04	10.4
W3	1168	2.30	Fine sand	1.69	8.86	0.82	0.09	9.0
Y3	1213	2.90	Fine sand	1.73	25.60	0.52	0.05	10.7
Y4	1325	3.21	Very fine sand	2.46	19.62	0.82	0.09	9.0
Y5	1362	3.99	Very fine sand	2.66	38.40	0.56	0.06	8.75
Z2	1388	4.21	Coarse silt	3.03	44.90	0.65	0.07	9.00
Z1	1411	4.37	Coarse silt	2.36	40.32	0.63	0.07	9.44

Table 6.2. Sediment stations from AFEN 1996 used for correlation analysis studies with the WASP sites. Depth in m, Phi is the mean Phi value, Carb = carbonate content (% dry weight), Org = organics (% dry weight), S and C = silt and clay content (% dry weight), TOC = total organic carbon (% dry weight), TON = total organic nitrogen (% dry weight), C/N = carbon to nitrogen ratio.

6.3 RESULTS

Out of the original 3149 frames available from all the films, a total of 1757 usable photographs (with an area coverage of 23,311 m^2) were available for analysis after frame selection. Out of the 1757 analysed frames, 917 were found to contain *lebensspuren* with some frames containing more than one trace (see table 6.3 below). The analysis of the films revealed a total of 4282 *lebensspuren*, with a total of some 26 different types of traces, which in turn were recorded and re-classified according to Seilacher (1953) (table 6.3). Some of the most common traces have been redrawn and briefly described (figure 6.4), see also the photographs in figures 6.5 to 6.8.

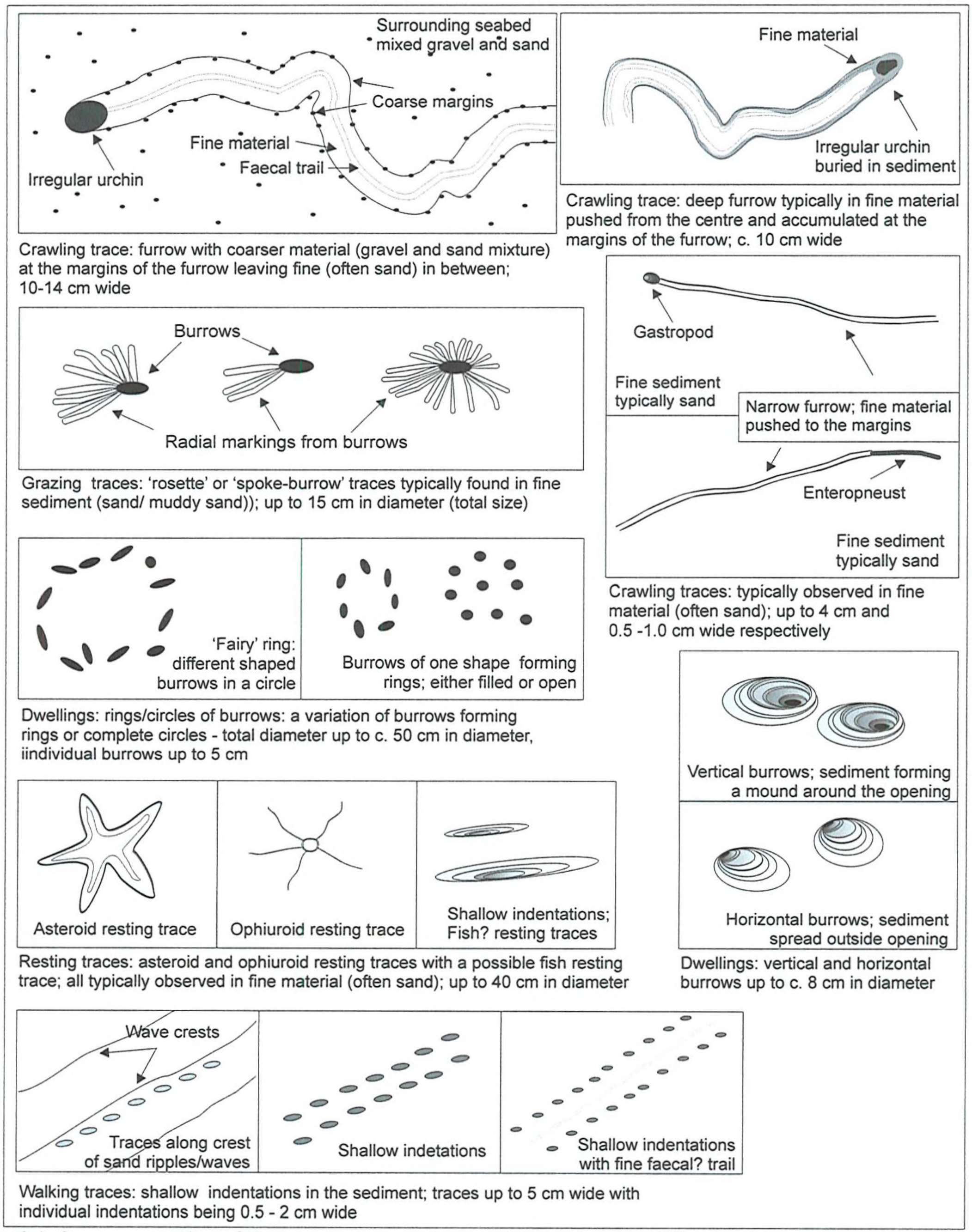


Figure 6.4. Some examples of the most common traces observed west of Shetland.

Initial identification of *lebensspuren* west of Shetland	***Lebensspuren* classification**
Deep furrow (urchin?), walking traces (single row, double row and double row with faecal trail), narrow furrow, furrow (spatangid), furrow, scallop (?) trail, large furrow (irregular urchin?), acorn worm, wide furrow, narrow furrow (gastropod)	Crawling traces
Horizontal burrow, small vertical burrow, large vertical burrow, circle of burrows/fairy ring, mounds, small mounds	Dwellings
Ophioroid feeding pit (f.p.), Asteroid f.p., asteroid/ophiuroid f.p., cephalopod (?) resting trace, fish (?) resting trace, shallow indentation	Resting traces
Rosette/spoke burrow	Grazing traces
Faecal cast?	Feeding structures

Table 6.3. Traces identified during the analysis and the five *lebensspuren* classification groups into which the initial traces have been categorized.

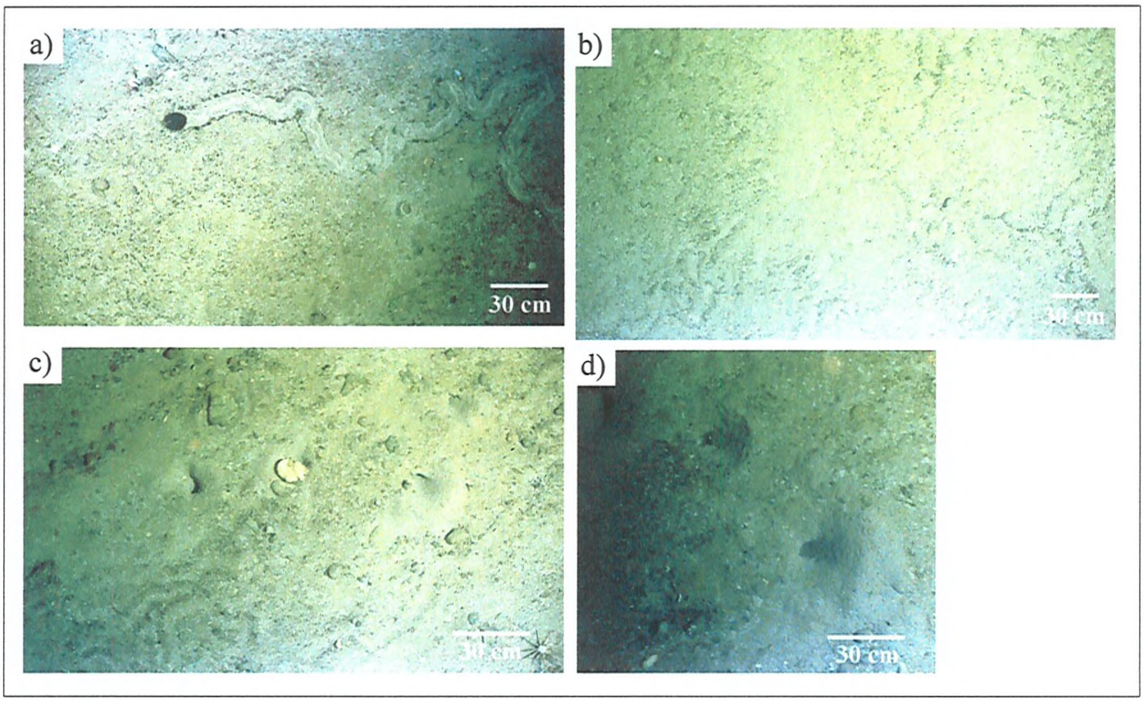


Figure 6.5: Examples of *lebensspuren* present at 300 - 500 m. a) A furrow produced by a heart urchin. Width of track c. 13-14 cm. b) Furrows (probably produced by sea urchins) with track widths of c. 10-12 cm. c) Burrows with opening diameters of c. 7 cm (crustaceans?). d) Burrows with opening diameters of c. 7 cm (origin unknown).

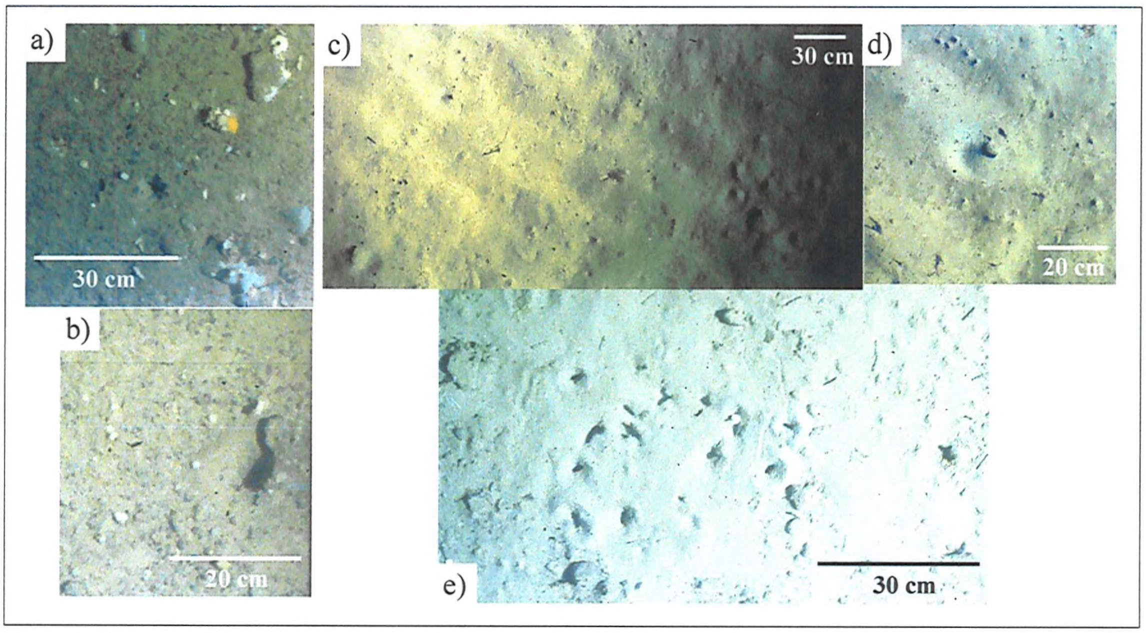


Figure 6.6: Examples of *lebensspuren* present at 600 m, 800 m and 1100 m. A) 600 m: burrow 2 - 3 cm in diameter (origin unknown). b) 600 m: burrow c. 6 cm in diameter (origin unknown). c) 800 m: a number of burrows of different sizes from 2 cm to 5 cm in diameter (origin unknown). d) 800 m: burrow c. 4 - 5 cm in diameter (origin unknown). e) 1100 m: a number of burrows in a 'fairy ring' formation (origin unknown). Sizes range from 2 cm by 1 cm to 4 cm by 2 cm.

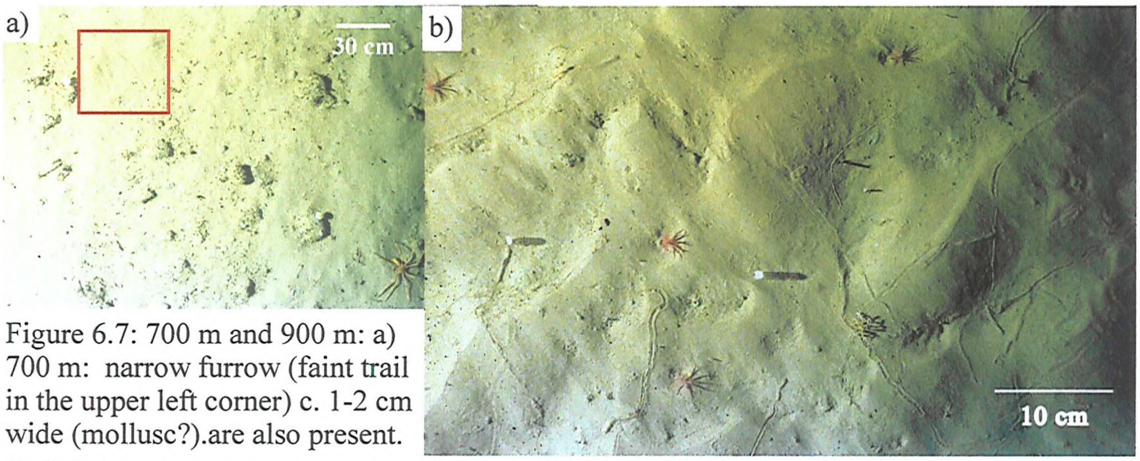


Figure 6.7: 700 m and 900 m: a) 700 m: narrow furrow (faint trail in the upper left corner) c. 1-2 cm wide (mollusc?).are also present. b) 900 m: crawling traces produced by enteropneusts (acorn-worms). The grooves are approximately 0.5-1.0 cm in diameter. Traces of other fauna are of unknown origin

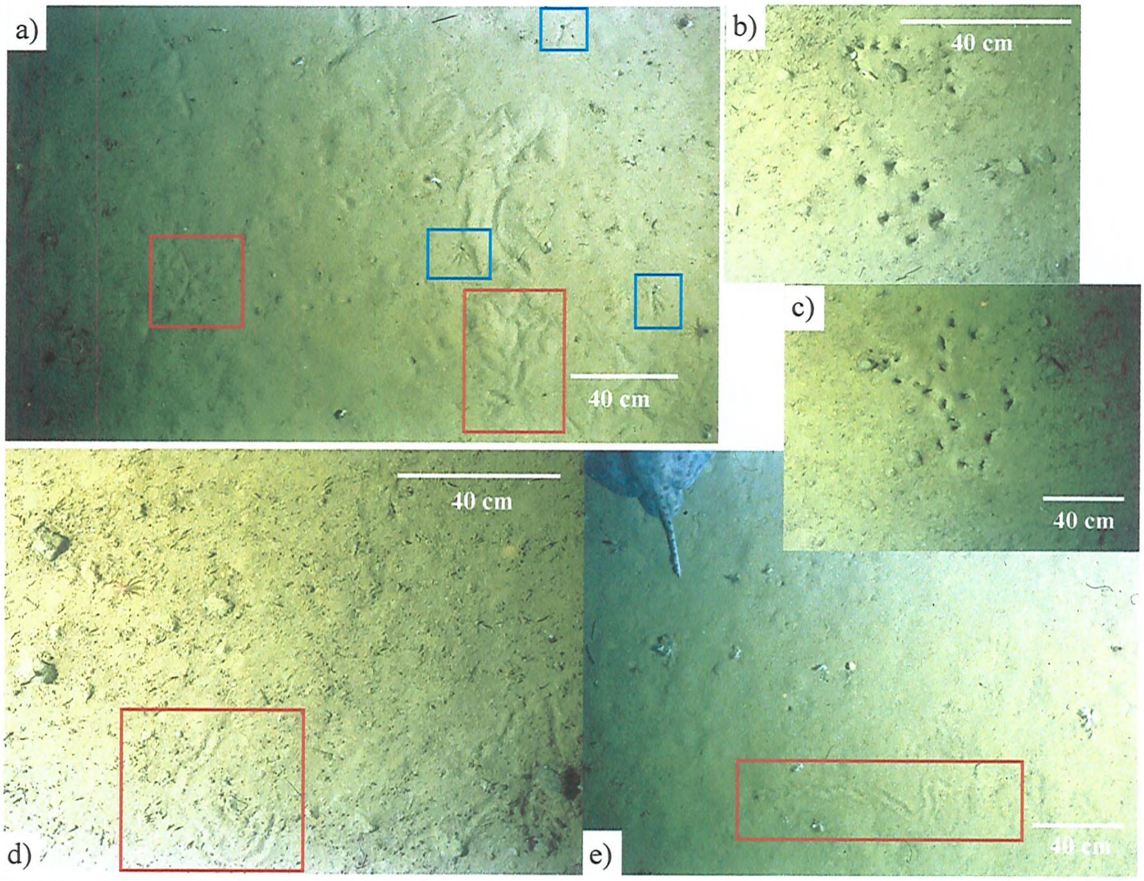


Figure 6.8: Examples of *lebensspuren* at 1200 and 1400 m. a) 1400 m: resting (asteroid feeding/resting pits) and grazing (rosette or 'spoke' burrows - origin unknown) traces. The resting traces (red rectangles) are c. 20 cm in diameter and the grazing traces (blue rectangles) are c. 10-12 cm in diameter. b) 1200 m: burrows; opening 2-3 cm in diameter (origin unknown). c) 1200 m: burrows; openings range from 3 by 1 cm to 6 by 1 cm (origin unknown). d) 1200 m: furrows 3-4 cm wide (sea urchins?). e) 1400 m: furrow c. 5 cm wide (sea urchin?).

6.3.1 *The relative frequency of lebensspuren present west of Shetland*

In table 6.4 and figure 6.9 the relative frequency (the percentage of frames containing traces) of *lebensspuren* present at the different depths along the bathymetric transect can be seen. In addition, the absolute numbers can also be seen in table 6.4.

	M200	M300	M400	M500	M600	M700	M800	M900	M1100	N/M1200	N1400
Total number of frames	315	46/105	102/52	191	257	42	113	201	81	151	101
Frames with *lebensspuren*	174	10/36	58/17	48	5	12	112	199	47	109	90
Relative frequency (%)	**55.2**	**28.0***	**44.8***	**25.1**	**1.9**	**28.6**	**99.11**	**99.0**	**58.0**	**72.2**	**89.1**

Table 6.4. The absolute numbers and the relative frequency of *lebensspuren* present in the photographs at different depths along the bathymetric transect west of Shetland (*=average value for the depth interval).

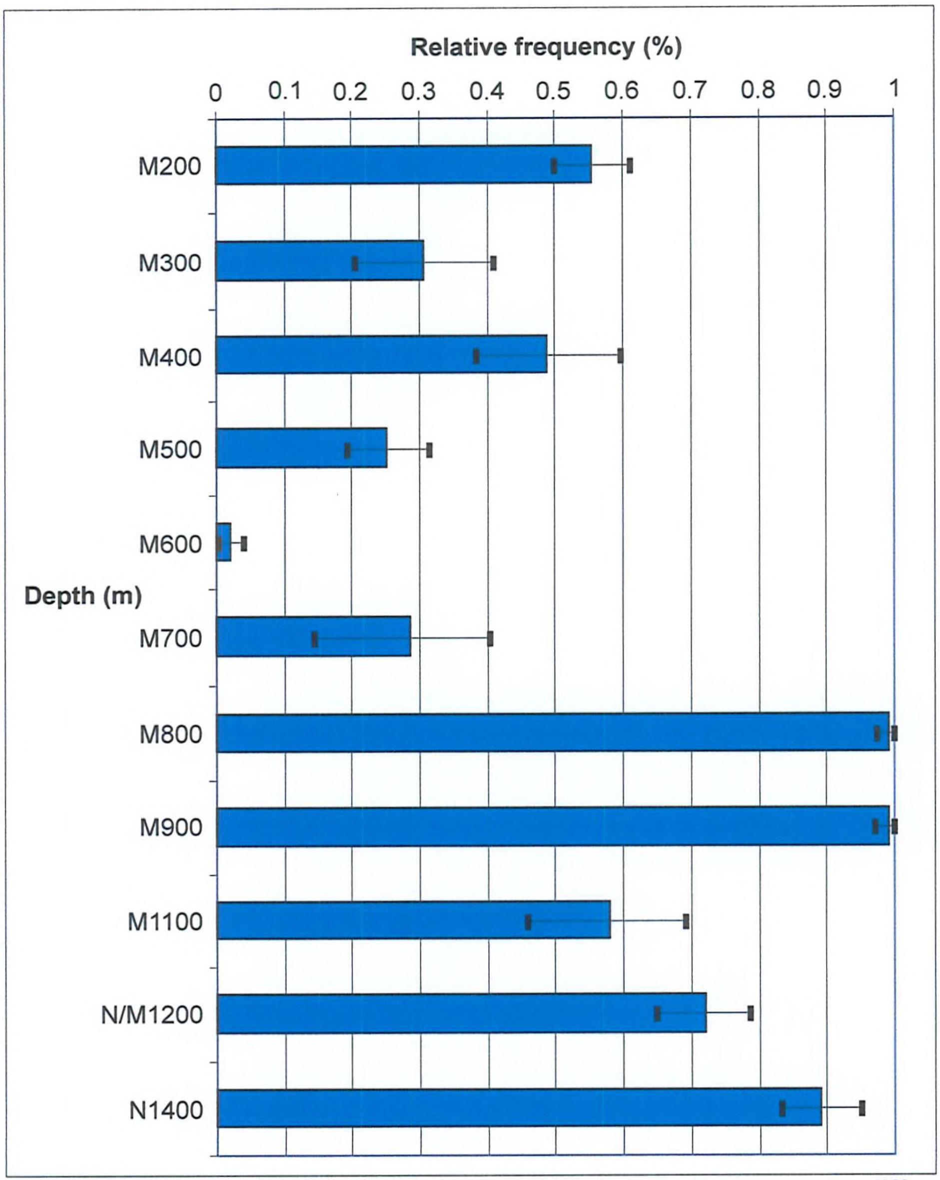


Figure 6.9. The relative frequency (with 95% confidence limits) of *lebensspuren* present at different depths along the bathymetric transect west of Shetland.

The overall pattern suggests a minimum at 600 m with relative frequencies being higher both a shallower (<500 m) and deeper (>700 m) sites, a pattern also (largely) supported by the confidence limits. The percentage of frames with *lebensspuren* is on the upper parts of the transect (200 – 500 m) approximately 25 - 55 % with values decreasing with depth to a minimum of approximately 2 % at 600 m, only to increase to 28 % at 700 m. Below 700 m, the percentage values are higher than those in the upper and middle sections of the transect with all sites containing relative frequencies in excess of 50 %. There is a maximum close to 100 % at both 800 m and 900 m with an additionally high value of nearly 90 % at 1400 m.

6.3.2 Lebensspuren densities recorded along the transect west of Shetland

After the classification of the 26 different types of *lebensspuren* into the five categories, the densities were calculated for each category at the different depth intervals and these can be seen in table 6.5 and figure 6.10.

Trace	M200	M300	M400	M500	M600	M700	M800	M900	M1100	N/M1200	N1400
Crawling traces	0.161	0.019	0.032	0.016	0.00	0.016	0.002	1.012	0.012	0.038	0.037
Dwellings	0.014	0.002	0.002	0.002	0.002	0.001	0.123		0.139	0.051	0.002
Resting traces	0.027	0.004				0.003	0.001	0.003	0.005	0.011	0.025
Grazing traces			0.00						0.002	0.00	0.032
Feeding structures	0.001	0.00	0.00								
Total densities (a)	0.203	0.025	0.034	0.018	0.002	0.020	0.126	1.015	0.158	0.100	0.097
Total densities (b)	0.239	0.025	0.035	0.020	0.003	0.025	0.141	1.068	0.139	0.113	0.112
95 % confidence limits	0.20-0.28	0.01-0.04	0.02-0.05	0.01-0.03	0.00-0.006	0.01-0.04	0.12-0.15	0.97-1.18	0.09-0.19	0.08-0.10	0.09-0.13

Table 6.5. *Lebensspuren* (mean) densities (traces/m^2) along the bathymetric transect west of Shetland (where a) is the arithmetic mean, b) is the geometric mean and 0.00 means that there are traces present but at very low densities).

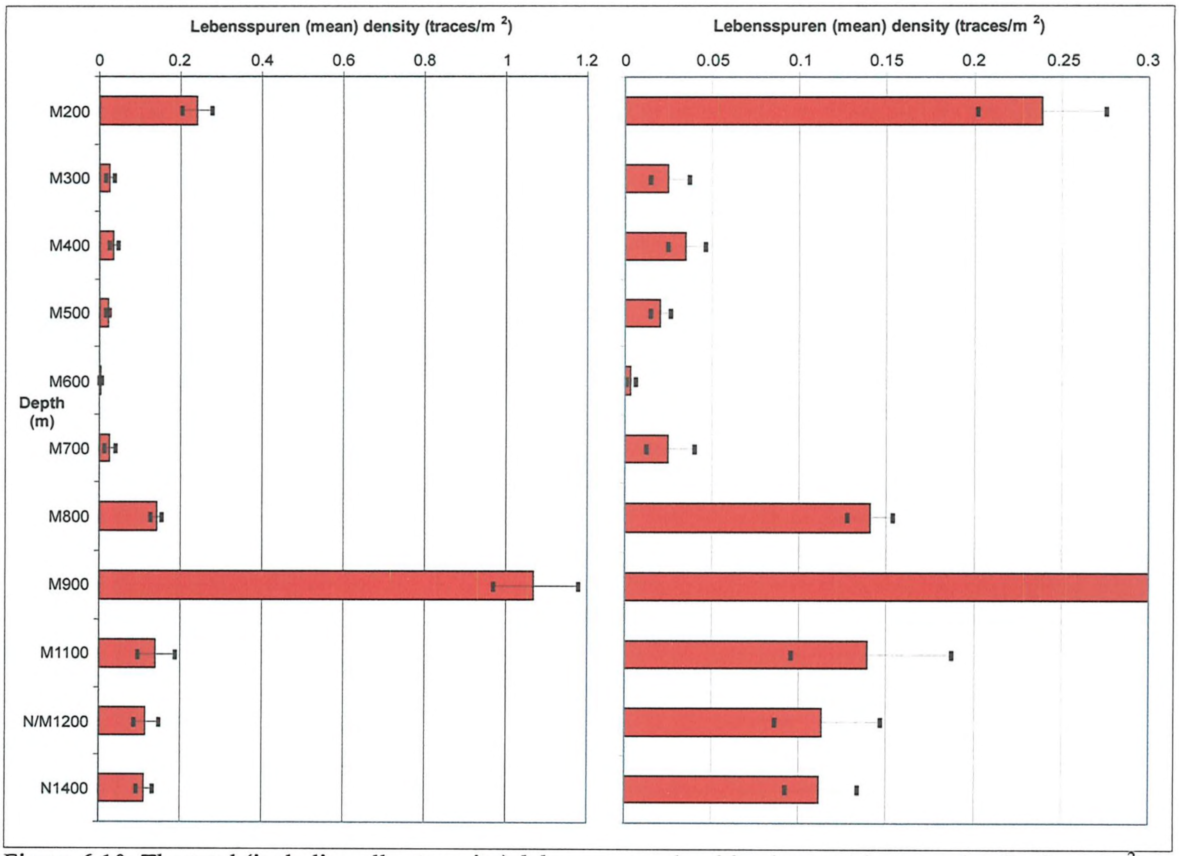


Figure 6.10. The total (including all categories) *lebensspuren* densities (geometric mean density (trace/m^2) with 95% confidence limits) at each depth interval along the bathymetric transect west of Shetland (the plot on right is a close-up of the plot on the left).

The overall pattern of the density values indicates a decrease in trace density with depth from 200 m down to a minimum at 600 m. Below 600 m the density values increase to reach a maximum in excess of 1 trace/m^2 recorded at 900 m (a value at least one order of magnitude higher than those recorded at any of the other depth intervals) only to yet again decrease with depth down to 1400 m. Within this overall pattern an additional pattern can be seen, where the densities observed at the shallower sites (300 m – 700 m) are one order of magnitude lower (range: 0.002-0.034 traces/m^2) than those recorded at depth (below 700 m; with a range between 0.097-1.015 traces/m^2). This pattern is furthermore supported by the confidence limits, which indicate a difference between the shallower sites (300 m – 700 m) and those at depth (>700 m). The only exception is the density calculated at the 200 m depth interval, where values are similar to those found below 700 m.

6.3.3 The percentage of mobile and sedentary lebensspuren with depth

The variations in the percentage of mobile to sedentary traces with depth are given in figure 6.11.

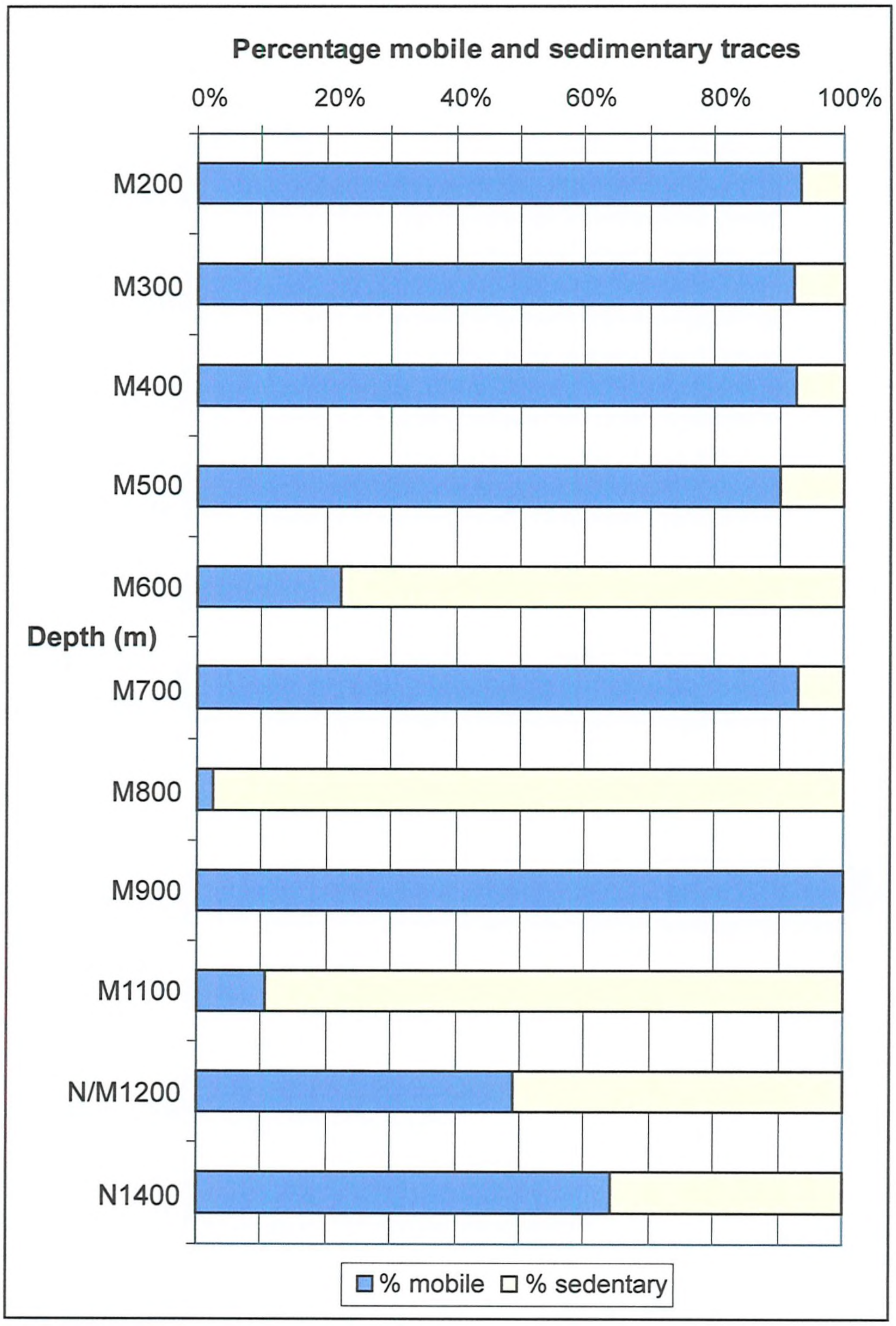


Figure 6.11. The variation in the ratios of mobile to sedentary traces with depth.

The results show high percentage of mobile traces on the upper part of the transect from 200 m to 500 m (≥90%), with similarly high values seen further down the slope at 700 m and the maximum at 900 m (100%). High sedentary trace percentages (>77%) are found at 600, 800 and 1100 m. In the deepest intervals (1100, 1200 and 1400 m), there appears to be a slight increase in the mobile percentage values with depth but the values do not reach the same level as those on the upper parts of the slope. The value seen at 900 m is largely attributed to the presence of high abundance of acorn-worms at this depth.

6.3.4 The composition of lebensspuren west of Shetland

In addition to the density values recorded for each classification category, the variation in the composition of *lebensspuren* along the bathymetric transect was investigated and these results can be seen in tables 6.6 and 6.7, with the results further illustrated in figure 6.12.

Trace	M200	M300	M400	M500	M600	M700	M800	M900	M1100	N/M1200	N1400
Crawling traces	79.32	76.71	91.96	90.00	22.22	78.57	1.89	99.73	7.66	37.56	38.46
Dwellings	6.75	7.60	6.65	10.00	77.78	7.14	97.64		88.04	50.68	2.56
Resting traces	13.50	14.38				14.29	0.47	0.27	2.87	11.31	25.64
Grazing traces			0.83						1.44	0.45	33.33
Feeding structures	0.42	1.31	0.83								

Table 6.6. Types of *lebensspuren*, expressed as percentage (%), present at different depths along the bathymetric transect west of Shetland (the calculated values at 300 m and 400 m are mean values for the two sampling runs carried out at those two depth intervals).

Trace	M200	M300	M400	M500	M600	M700	M800	M900	M1100	N/M1200	N1400
Crawling traces	188	23	42.5	45	2	11	4	3009	16	83	60
Dwellings	16	2	4	5	7	1	207		184	112	4
Resting traces	32	5.5				2	1	8	6	25	40
Grazing traces			0.5						3	1	52
Feeding structures	1	0.5	0.5								
Total	237	31.0	47.5	50	9	14	212	3017	209	221	156

Table 6.7. Types of *lebensspuren*, expressed in absolute numbers, present at different depths along the bathymetric transect west of Shetland (the calculated values at 300 m and 400 m are mean values for the two sampling runs carried out at those two depth intervals).

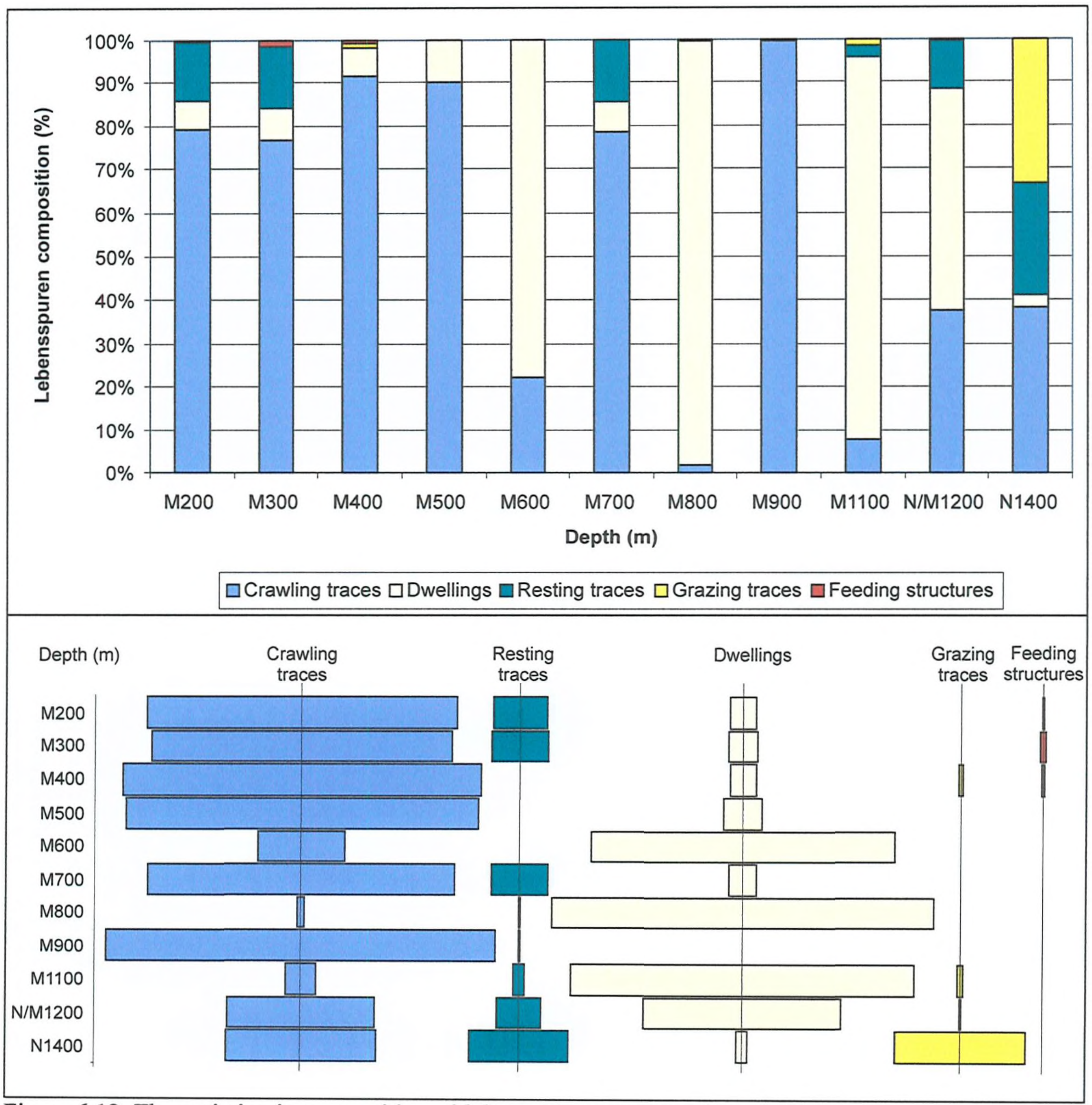


Figure 6.12. The variation in composition of *lebensspuren,* expressed in relative terms, with depth along the bathymetric transect west of Shetland (the bars indicate 100 % of the *lebensspuren* observed at each depth interval).

The tables and graphs illustrating the variation of type of *lebensspuren* with depth indicate a division of the continental slope into a number of zones containing particular types of *lebensspuren*. Crawling traces, predominantly furrows (figure 6.5), are the most common types of *lebensspuren* on the upper part of the transect (200 – 500 m) contributing over 75 % of the total types of observed traces. These traces are primarily produced by gastropods and irregular urchins (echinoids), fauna frequently observed on the photographs. The diameters of the furrows were typically 1 – 2 cm and 10 – 14 cm wide for the gastropods and urchins respectively. Dwellings, particularly different types of burrows, are also present (approximately 7 %) in this depth interval while grazing traces were hardly observed at all. The size of the burrows reached up to approximately 7 cm in diameter but their origins are unknown. Resting traces, produced predominantly by asteroids, were identified at 200 m and 300 m but were not observed at 400 m or 500 m.

At 600 m, 800 m, and again at 1100 m, dwellings, mainly burrows, are the most frequently (>77 % of recorded traces) encountered type of trace (figure 6.5), although the actual number of traces observed at 600 m was very low (table 6.7). The size of the burrows ranged from approximately 2 cm to 5 cm where some were circular whilst others were oblong. Most burrows appeared to be singular but many were arranged as 'fairy' rings (see figure 6.4). The origins of these burrows, both singular and those arranged in patterns, are unknown. Crawling traces, mainly furrows with widths of a few (1 – 3 cm) centimetres, were also observed (2 – 22 % of the total number of different traces) in these depth intervals. Grazing traces were not observed between 600 and 800 m. At 1100 m, however, a small number of grazing traces, appearing as spoke burrows, were identified. Resting traces were observed but they contributed 3 % or less of the total while feeding traces were not observed at all at these depths.

At 700 m and 900 m, sites within the zone otherwise dominated by dwellings (600 – 1100 m), crawling traces are particularly frequent with percentage values in excess of 78 % and close to 100 % respectively (figure 6.7). The composition of traces present at these depths appears more similar to those observed at shallower depths (200 – 500 m) rather than those dominated by dwellings (600 – 1100 m). At 700 m the majority of the crawling traces (narrow furrows c. 2 cm wide) were produced by gastropods although it should be noted that there was only a small percentage of photographic frames which contained *lebensspuren* at this depth. At 900 m enteropneusts produced the great majority of the narrow furrows (0.5 -1.0 cm in diameter) identified in the photographs. Resting traces, although few in number, were also present at these two depths. Dwellings were observed at 700 m but no other types of traces were observed at either depth.

The composition of traces observed at 1200 m is similar to those recorded at 600 m, 800 m and 1100 m but the proportion of resting traces is higher at 1200 m than those recorded at the other depth intervals. There appears to be a change in the overall composition in traces with depth between 1100 m and 1400 m, where the proportions of resting and crawling traces increase with depth while the proportion of dwellings decrease with depth, a pattern also seen in the absolute counts (although the crawling counts are slightly higher at 1200 m than those recorded at 1400 m). The crawling traces (figure 6.8) at 1200 m and 1400 m contribute with over 37% of the observed traces. The majority of crawling traces are believed to be produced by gastropods (tracks c. 2 cm wide) but burrowing urchins (tracks c. 3 – 5 cm wide) have also been identified as creators of some of the traces. The resting traces are created by both asteroids and ophiuroids with some traces, particularly those produced by ophiuroids, being close to 40 cm in diameter.

In addition to the patterns just described, grazing traces, identified as spoke-burrows (figure 6.8), are also observed (c. 33 % of the identified traces at 1400 m), a type of trace virtually absent at all other depths along the bathymetric transect, although small numbers have been observed at 400 m, 1100 m and 1200 m. The spoke-burrow *lebensspuren* are typically associated with echiurans (Bett *et al*, 1995) but these west of Shetland examples are of unknown origin since no associated fauna was observed. These spoke-burrows typically appear as a central burrow with one or more grooves radiating out from the burrow (see figure 6.4 and 6.8). The sizes vary but they are often between 10 – 15 cm in total diameter (including the radiating grooves).

6.3.5 Multi-variate analysis

The cluster analysis of the *lebensspuren* data using the Bray-Curtis similarity coefficient (Primer version 5) gave results (figure 6.13) similar to those obtained through the other methods but dissimilarities were also observed, illustrating a complex environment present along the bathymetric transect west of Shetland.

Two main groups of the data can be distinguished with one group consisting of three sub-groups (figure 6.13). The 900 m site has been separated from all the others, presumably as a result of the high proportion (>99%) of crawling traces (produced predominantly by acorn-worms). Within the other large group, the 600 m has been clustered separately from the remaining sites, presumably as a result of the large proportion of dwellings (>77%) present while lacking any other trace categories. A further division has produced two clusters with 300, 400, 500 and 700 m in one group and 200 m, 800 m, 1100 m, 1200 m and 1400 m in the other. The former cluster includes sites with a large proportion of crawling traces (>76%), a fact that may have influenced the result. The latter group contains a variety of compositions of traces but dwellings are present in high proportions at 800 m, 1100 m and 1200 m. The clustering together with the 200 m and 1400 m sites are more difficult to explain as the 200 m site is dominated by crawling traces while the traces seen at 1400 m are fairly equally distributed on three different types of traces.

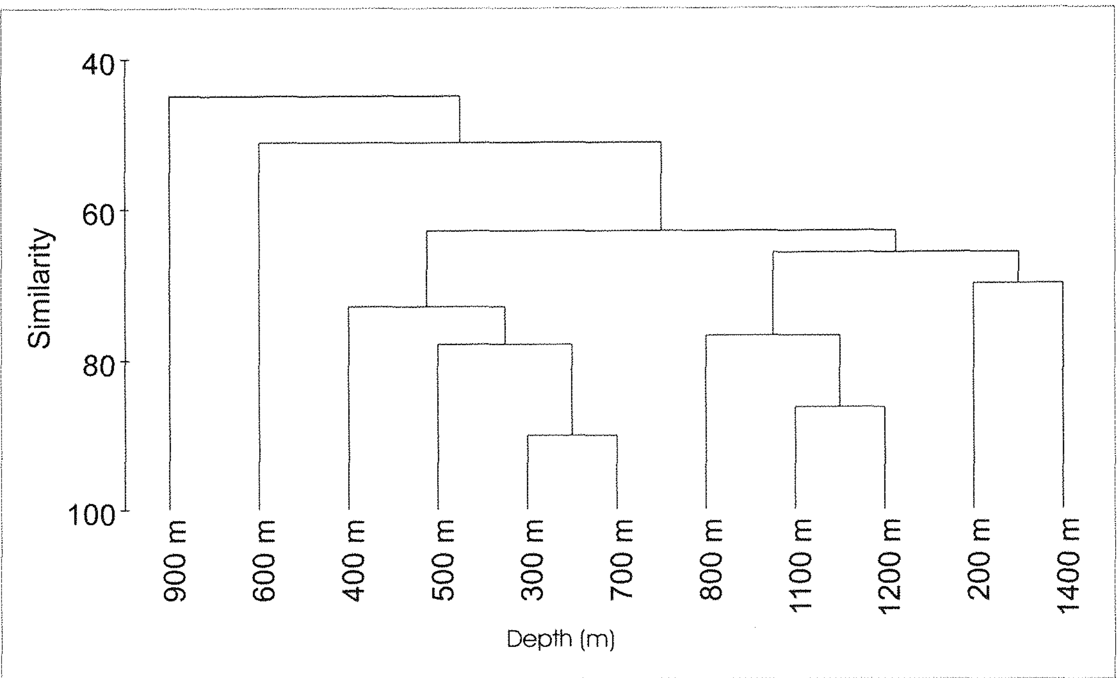


Figure 6.13. Cluster analysis (using the Bray-Curtis similarity index) of the *lebensspuren* observed along the bathymetric transect West of Shetland.

The multi-dimensional scaling (MDS) largely corresponds to the results seen in the cluster analysis with the 600 m and 900 m sites being located away and in opposite parts of the plot (figure 6.14), results most likely explained by the high proportions of dwellings and crawling traces respectively. The sites at 300 m, 400 m, 500 m and 700 m are again ordered close together, a pattern similar to the cluster analysis. The remaining sites are as in the dendrogram located relatively close together, particularly 800m, 1100 m, 1200 m and 1400 m, but again the overall result is complex and more difficult to explain as the compositions of the types of traces present at these sites are quite different. In addition to these overall groups, there appears to be a depth trend within the shallower sites (200 m to 600 m) and with a stress level of 0.09, which is just below the limit (< 0.1) indicating a 'good ordination with no real prospect of a misleading interpretation' (Clarke and Warwick, 1994), a further analysis was carried out investigating the shallow sites (figure 6.15). The results indicate a depth trend in both the MDS plot as well as in the MDS x ordinate variation with depth. The Spearman rank correlation coefficient result ($r_s = -1.0$) further strengthens ($p<0.05$) this observation (MDS y: $r_s = -0.3$, $p>0.10$). Note in addition that the stress levels of the MDS analysis (figure 6.15) is zero, giving results that are 'excellent representations with no prospect of misinterpretation' (Clarke and Warwick, 1994).

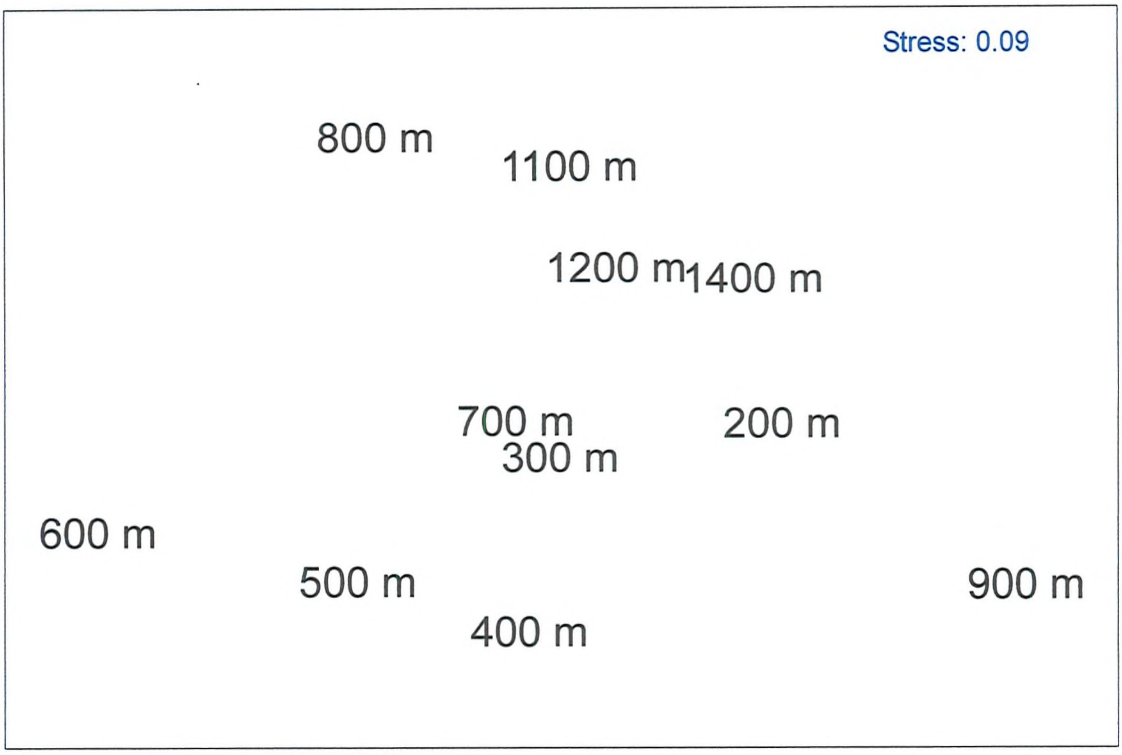


Figure 6.14. Multi-dimensional scaling (MDS) of the *lebensspuren* observed along the bathymetric transect west of Shetland.

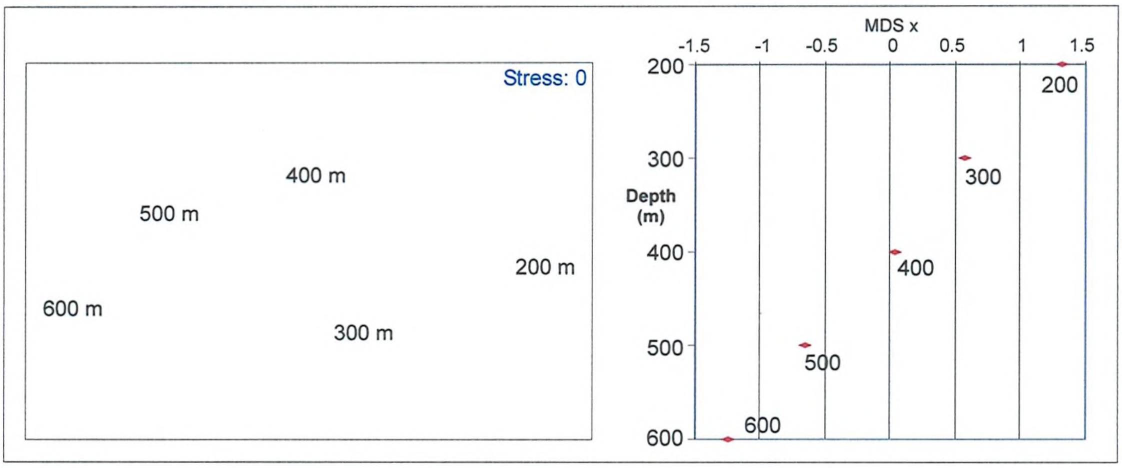


Figure 6.15. Multi-dimensional scaling (MDS) and the variation of MDS x ordinates of the *lebensspuren* observed at the shallow sites (200 m to 600 m) along the bathymetric transect west of Shetland.

6.3.6 Correlation analyses with environmental variables

The correlation analyses were carried out comparing the variation in the *lebensspuren* parameters along the bathymetric transect with the environmental variables in the same depth bands. The environmental parameters used and the results from the correlation analyses can be seen in table 6.8.

Environmental variables	**Relative frequency**	***Lebensspuren* density (traces/m^2)**	**Percentage of mobile traces**
Depth	0.609	0.264	-0.391
Temperature	-0.618	-0.291	0.482
Phi (mean)	0.555	0.255	-0.346
Phi (median)	0.500	0.209	-0.409
WASP sediment interpretation	**0.843**	0.570	-0.127
S/C	0.386	-0.273	-0.555
TOC (%)	0.261	-0.057	-0.330
Organic (%)	0.245	-0.100	-0.582
TON (%)	0.175	-0.102	0.430
C/N	0.011	-0.375	-0.521
Megafaunal density (ind./m^2)	0.518	0.600	0.164
Relative frequency		**0.809**	-0.109
Lebensspuren density	**0.809**		0.173
Significant levels (two-tailed test; from Fowler and Cohen, 1992)	*Tabulated value*	*Significance level*	*Description*
	0.818	*0.01*	*Highly significant*
	0.623	*0.05*	*Significant*

Table 6.8. Correlations (Spearman Rank correlation Coefficient) between environmental parameters and the *lebensspuren* parameters along the bathymetric transect west of Shetland (n = 11). Depth in m, Phi in mean and median Phi value, Org = organics (% dry weight), S and C = silt and clay content (% dry weight), TOC = total organic carbon (% dry weight), TON = total organic nitrogen (% dry weight), C/N = carbon to nitrogen ratio.

The vast majority of the correlation results show no significant correlations and that includes the analyses of MDS x and y ordinates against the environmental parameters. In fact, the only significant (highly) correlations, apart from the expected correlation between relative frequency and *lebensspuren* density, are found between the WASP sediment grading and relative frequency and between the MDS x ordinates and depth (as noted above).

6.4 DISCUSSION

Numerous *lebensspuren* from the ocean floor have since the 1940s been photographically recorded and they have been shown to occur in a wide variety of shapes and forms. There have been several attempts to classify these traces into different categories (e.g. Ewing and Davis, 1967; Heezen and Hollister, 1971; Mauviel and Sibuet, 1985) but most are very detailed and the classification by Seilacher (1953) was therefore used in preference. There may be some loss of information and perhaps more data could be extracted from the photographs and it should furthermore be mentioned that some traces might not have been identified correctly or observed at all during the analysis of the photographs. As Ewing and Davis (1967) noted, it is sometimes difficult to determine whether a feature seen in a photograph is a true *lebensspuren* or wholly inorganic. Rill marks, furrows produced by rolling pebbles or shells may all resemble *lebensspuren* and mounds that initially may appear as biologically produced features may simply be features produced by pebbles or stones buried in a thin veneer of sediment (Ewing and Davis, 1967). In addition, the height of the camera above the seabed is important. If the instrument is at a high altitude, features are difficult to identify and some may not even be observed at all. Furthermore, the photographs were taken vertically above the seafloor making any relief at the seabed difficult to identify. In the photographs from the bathymetric transect west of Shetland some features may therefore not have been recorded and some of the values may be underestimated. The process of frame selection (see chapter 4) is likely to reduce these effects but there may be some underestimates all the same. For example, at the 700 m site (53985#1), where frame selection was carried out (leaving 37 % of frames being equal to, or closer than, 6 m in altitude; table 6.9), the majority (22 %) of the frames left after frame selection are between 5 and 6 m off the seafloor, a fact that is likely add to the difficulty in identifying and counting the traces. In addition, the quality of the photographs was, for some unknown reason (perhaps poor light levels or incorrect focus), inferior to some of the other runs and the number of observed and identified *lebensspuren* may therefore be underestimated, results believed to be associated with the lack of data from this photographic run. The 700 m interval may be dominated by dwellings as is the case with most of the sites in the mid-slope region but additional photographs, closer to the seabed, from this site will be required to assess this fully. Equally, at 900 m (53984#1) the values are also believed to be underestimated, for the same reason (lack of frames close to the seabed) as at 700 m, but not to the same extent. The main reason being that the majority of traces here were produced by the acorn worms (see chapter 5) and as these are very small (c. 0.5-1.0 cm wide), some traces may not be visible at higher altitudes. At 600 m (53916#1), however, although the relative frequency value is low (see table 6.4 and figure 6.9 above), the photographs from this WASP run were of satisfactory quality with the vast majority (>85 %) having an altitude of 6 m, or less, and even 37 % of frames (the third highest proportion) being available at altitudes <5 m, throughout the run, giving a value not considered to be an underestimate.

Depth (m)	**Station**	**Total number of available frames**	**Altitude**			
			≤ 6 m	**≤ 5 m**	**≤ 4 m**	**≤ 2.5 m**
200	55456#1	315	1.00	1.00	0.98	0.56
300	53913#1	109	0.42	0.09	0.00	0.00
300	53926#1	109	0.96	0.49	0.00	0.00
400	53914#1	106	0.49	0.08	0.00	0.00
400	53928#1	221	0.47	0.12	0.01	0.00
500	53925#1	314	0.61	0.28	0.07	0.00
600	**53916#1**	**298**	**0.86**	**0.37**	**0.04**	**0.00**
700	**53985#1**	**114**	**0.37**	**0.15**	**0.03**	**0.00**
800	53924#1	215	0.52	0.24	0.07	0.00
900	**53984#1**	**340**	**0.59**	**0.27**	**0.06**	**0.00**
1100	53923#1	330	0.25	0.09	0.02	0.00
1200	53981#1	312	0.48	0.20	0.08	0.01
1400	53980#1	208	0.49	0.16	0.04	0.00

Table 6.9. The variation in the proportion of frames available for analysis at different altitudes at different depths west of Shetland (from chapter 4)

6.4.1 Combined analysis of the results

Crawling traces, dominated by gastropod and irregular echinoid furrows mainly in the uppermost surface layer of the sediment, are the most frequently observed and the dominant *lebensspuren* features at the upper part (200 – 500 m) of the transect. Dwellings, particularly different types of burrows (mostly of unknown origin), appear to be the most frequently encountered trace feature in the middle and lower part of the transect (> 600 m). Dwellings become less important proportionally while crawling as well as grazing traces become more important (figure 6.12 and tables 6.5 and 6.6) at the deepest sites (1100 m, 1200 m and 1400 m) but dwellings are still present down to 1400 m. These overall observations together with the minima in relative frequency and *lebensspuren* density seen at 600 m as well as the apparent change in the percentage of mobile traces and the composition of traces seen at this depth along the bathymetric transect west of Shetland all appear to indicate a division of the distribution of *lebensspuren* into two layers with a boundary at intermediate depths of approximately 600 – 700 m. The relative frequency and the *lebensspuren* density results are particularly similar, both showing minimum values at 600 m, with relatively high densities and relative frequency values at depth (>700 m) compared to the values for both parameters at the shallower sites, apart from the site at 200 m. The confidence limits also appear to support these observations and together with the case of the trace density values, where there is an order of magnitude difference (apart from station 55456#1 at 200 m) between the deep and shallow sites, these results further indicate that there is a difference of some significance between the shallow- and deep-water sites. The percentages of mobile (compared to sedentary) traces show (figure 6.11) a dominance of mobile traces down to

500 m (mainly furrows produced by gastropods and irregular echinoids) and a dominance of sedentary traces at 1100 m and below. Between 600 m and 1100 m the picture is more complex with mobile traces being dominant at 700 m and 900 m (no sedentary traces at all at 900 m) while sedentary traces are dominant at 600 m, 800 m and 1100 m. This pattern is further supported by the variation in the composition of traces (figure 6.12), where a fairly clear dominance of mobile traces is evident at shallower depths while sedentary traces dominate at depth with a complex variation in dominance apparent at the intermediate depths (600 m to 900 m). The cluster (figure 6.13) and MDS analyses (figure 6.14) also show complex results but largely support the other findings. The site at 600 m (and 900 m) clustered and grouped separately from the other sites, illustrating further that it is different to the other sites. This overall pattern with a boundary at approximately 600 m was also seen in the megafaunal (see chapter 5) and the macrofaunal distributions but while the boundary within the megafaunal distributions was identified at 600 m (see chapter 5), the boundaries within the macrofaunal distributions were found at the slightly shallower depth of approximately 500 m (Bett, 2000; Narayanaswamy, 2001).

Within this overall bathymetric pattern, there are a number of small-scale features and particularly notable is the site at 900 m. The results from the cluster and MDS analyses, grouping the 900 m site separately from all the other sites, together with the large percentage and density of crawling traces observed at this depth are believed to be related to a very particular feature, the sand contourite (see figure 6.16; chapter 2 and 5; Masson *et al.*, 1996; Masson, 2001) with its associated fauna, at this depth. This feature does not appear to be 'representative' of the seabed environment in all locations at this depth within the Faroe-Shetland Channel (see chapter 7; Stoker *et al.*, 1993; Masson 2001), but a similar feature has been observed at similar depths north of this transect (see chapter 7) and although this feature was also identified at 800 m along the bathymetric transect, both in terms of the fauna and sediment type present (see chapter 5), only a small number of crawling traces were observed at 800 m in this study. Large densities of acorn-worms (enteropneusts) and their traces (c.1 trace/m^2; see figure 6.7b) dominate (see figures 6.10 and 6.12 and tables 6.5, 6.6 and 6.7) the site at 900 m. The reasons for the large densities of these fauna being present remains unclear but the type of sediment is likely to have some effects as the acorn-worms are only present on this type of sediment in other parts of the channel (see chapter 5 and 7). Acorn-worms typically live in burrows (Mauviel *et al.*, 1987; Romero-Wetzel, 1989; Tuck and Atkinson, 1995) but here they are only seen at the surface of the sediment, producing a large amount of narrow furrows (c. 0.5-1.0 cm wide). It is possible that the type of sediment present makes burrows unstable and potentially prevents many other species from inhabiting this area. Anemones and sea spiders are present at high densities (see chapter 5) but perhaps the acorn-worms have developed a specialised feeding niche and perhaps their large numbers together with their feeding mode prevent other taxonomic groups from flourishing here. Little is known about deep-water acorn worms and perhaps the fauna discovered here is present in other, yet undiscovered, locations but further studies are required to understand more about their distribution patterns, ecology and biology.

In addition to the particular feature seen at 900 m, there also appears to be a depth trend (significant correlation, $p<0.05$, between the MDS x ordinates and depth) within the shallower sites (200 m to 600 m). A similar depth trend was found within the megafaunal distributions (see chapter 5) and as these sites lie within the iceberg plough mark zone (see figure 6.16; chapter 5, 7 and 8; Masson *et al.*, 1996, 1997; Bett, 2000; Masson, 2001), it was suggested that the variation in sediment (coarser with depth) within this zone (see chapter 5) may have an influence on the distribution of the megafauna. Another possibility is that it reflects the presence of an 'ecotone' as suggested in chapter 5, where the megafauna reflects a mixture of shallow- and deep-water species. It is possible that there are similar effects on the distribution of *lebensspuren* but as no significant correlations could be found with the environmental variables, apart from depth, it is not apparent what factors control the trend seen within these shallow sites.

Within the deeper sites there also appears to be some variation, particularly with regards to the composition of traces present. Resting and grazing traces increase from 1100 m to 1400 m and this is potentially linked to the sediment present. Although correlation analyses are difficult as a result of the lack of sampling units (only 3 sites), photographic observations and the WASP sediment grading analysis in particular, indicate a decrease in sediment size within these sites. The sediment appears appreciably coarser at 1100 m compared to both 1200 m and 1400 m and this may have some influence on the fauna, increasing the number of spoke-burrows and resting traces present.

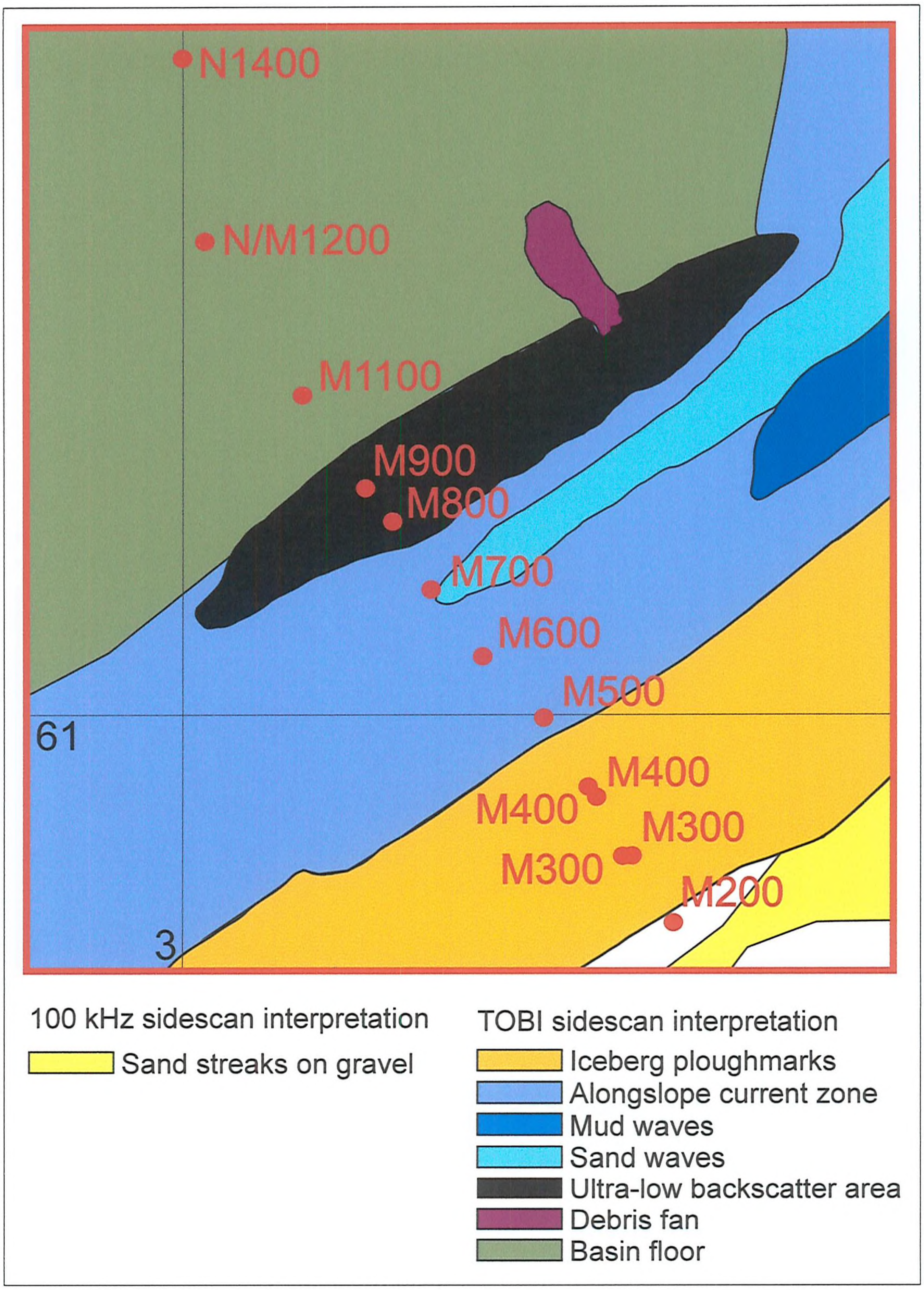


Figure 6.16. Sidescan sonar (TOBI) interpretation with the locations of the WASP sites (see table 6.1 for site identification).

6.4.2 Interpretation and correlation of results with environmental variables

The sediment along the bathymetric transect is in general terms getting finer with depth (see chapter 2 and 5; Stoker *et al.*, 1993; Masson *et al.*, 1996; Masson, 2001). The correlation analyses show a positive correlation between *lebensspuren* frequency and the sediment type (table 6.8) and particularly with the WASP sediment analysis (highly significant), although no other significant correlations were found. Perhaps the explanation lies in a combination of sedimentary features including superficial sediment thickness, sediment grain size and silt and clay content as other studies (Aller, 1978; Huggett, 1987) have also shown that the type of sediment is important in determining the type and density of traces present. The reason for the WASP data showing a significant correlation and not, for example, the phi values may be explained by the fact that the seabed samplers (Megacorer, box core and Day grab) used to collect the particle size data are less likely to sample all the sediment types present. These samplers are very good at collecting fine material such as silt and clay but less so with regards to the coarser material (cobbles, boulders and solid rock surfaces) where the samplers may fail (Tait, 1981), while the photographs will show all the different types of sediment present. In addition, the use of photography has also been shown to reveal higher and, it was argued, perhaps better estimates of megafauna densities compared to trawls (e.g. Dyer *et al.*, 1982; Cranmer *et al.*, 1984; Rosman and Boland, 1986; Cailliet *et al.*, 1999) and sledges (Rice *et al.*, 1982), although Dyer *et al.* (1984) also recorded higher densities of some burying fauna using the trawls compared to photography while Rice *et al.* (1982) recorded 'quite reliable quantitative samples of at least some species' (Rice and Collins, 1985). Therefore, in the case of megafauna and their traces, photography may be more representative of the sediment affecting their distribution, particularly when a mixed seafloor is being sampled, but despite the clear significant correlation between the *lebensspuren* frequency and the WASP sediment distributions, it should, however, be noted that the WASP sediment analysis is a subjective process and integrating different techniques will most likely provide the best results. In addition, the minimum values observed at 600 m and the complexity in the *lebensspuren* distribution at the intermediate depths is not completely explained by these results.

Wheatcroft *et al.* (1989) suggested three main mechanisms for destruction of *lebensspuren*: tracking over by epifaunal organisms, grain-by-grain collapse due to subsurface mixing by the infauna and physical erosion and deposition. The first two mechanisms are believed to affect the results west of Shetland but the impact of these mechanisms is difficult to assess. Destruction of parts of traces has been observed (e.g. a newly created trace crossing over old) but parts of the original traces are also often seen. The subsurface mixing may be important in the finer sediment on the channel floor but is less likely to affect the number and types of *lebensspuren* present on the continental slope west of Shetland as most of the seabed appears to be covered only by a thin veneer of finer sediment (Masson, 2001). These effects are therefore believed to be of minor importance. The physical erosion and deposition may therefore be most important.

The sedimentary regime beyond the shelf edge west of Shetland is dominated by erosion or non-deposition (Masson, 2001). Sedimentation rates are low, a fact mainly attributed to the low sediment supply to the channel (Masson, 2001). The fine sediment still present on the channel floor (<1000 m) is attributed to the weak bottom currents present (Masson, 2001) causing little re-suspension and movement of the sediment and therefore little, or no, destruction to any traces present. The continental slope west of Shetland is on the other hand dominated by erosion caused by strong bottom currents flowing towards the north-east leaving a sediment with a 10-15 cm thick layer of sand and gravel (Masson, 2001). The currents have been shown to be particularly strong (approximately 0.7 m/s) on the upper part of the slope (see chapter 2.3) removing the finest sediment material. The current regime at depths between 500 and 900 m is less well understood, although the currents are believed to be weaker (possibly 0.3-0.4 m/s; Masson, 2001) than those recorded on the upper slope. The coarse nature of sediments on the upper parts of the slope (300 – 600 m) will most likely restrict the amount of visible traces produced, although biological activity may despite this be high, not only because the sediment may be more difficult to penetrate but also as any traces, particularly burrows are more likely to collapse in coarser sediment. In addition, any traces created by the fauna are likely to become erased by strong bottom currents (Owen *et al.*, 1967; Wheatcroft *et al.*, 1989). This is to some extent reflected in the medium frequency values (traces occur on less than c. 50 % of the frames) and density values observed on this part of the transect, although at 200 m the relative frequency and the density values are higher than the others in the interval, a fact potentially attributed to the presence of large patches of sandy bedforms as identified by Masson (2001). Lower down the slope (deeper than 700 m) the frequency (and density) of observed traces increases and the values at all sites exceed 50 %, with the added possibility that the lowest recorded value at 700 m may be an underestimate (c. 29

%). The sediment at the lower part of the slope is finer (traces are known to easily form in soft sediment; Gage and Tyler, 1991), particularly at the deepest sites, and the current speeds are low (little destruction of traces), factors likely to lead to the persistence of visible traces. Therefore, the results show a higher relative frequency of *lebensspuren*, and therefore indicate a higher activity of the fauna, on the channel floor compared to the values seen on the upper slope. This may partly be explained by higher erosion, and therefore destruction of *lebensspuren* at the shallower depths. At 600 m, however, where the sediment is relatively coarse, but not appreciably more so than within the 300 – 500 m interval, the number of frames containing traces is at a minimum (around 2 %). It is possible that the majority of fauna may be attached to boulders, cobbles and other sedimentary features (sedentary suspension feeders rather than motile carnivores or deposit feeders) but there appears to be little difference between 500 m and 600 m with regards to the general sediment environment, as well as the fact that the change in sediment appears to be gradational along the slope (see chapter 5, Stoker *et al.*, 1993; Masson *et al.*, 1996; Masson 2001). In addition, current speeds are believed to be weaker than those on the upper slope (Masson, 2001) and the effects of erosion should therefore be smaller. On this basis, the number and the density of *lebensspuren* should therefore be the same as those further up the slope, but with values at a minimum, another factor controlling the observed features must be sought.

The hydrographic setting consists of a warm, shallow layer overlying a cold, deeper layer forming a boundary at about 500-600 m (see chapter 2.3; Turrell *et al.*, 1999). The temperature difference between the two layers is considerable and the boundary furthermore moves vertically leading to an extremely variable environment (see section 2.3.2.2 regarding the tidal oscillations and changes in temperature). Two layers in the distribution of the macrofauna, closely associated with the hydrographic structure, have furthermore been identified and the boundary between the two layers has been found to occur at approximately 500 - 600 m (Aspinall *et al*, 1992; Bett, 2000a; Narayanaswamy, 2001). Bett (2000a) considered the temperature to be the main factor controlling the distribution of the larger size-fraction (>500μm) of macrofauna and, as can be seen in chapter 5, the distribution of megafauna is also related to this parameter. Bett (2000a) described the presence of an ecotone at about 600 m, where there was an overlap of the fauna from the shallower and deeper depths with some of the fauna reaching the limit of their distribution. Narayanaswamy (2001) also suggested that the distribution of the smaller size-fraction of macrofauna (250-500μm) was significantly influenced by the variation in temperature with depth. The results from the correlation analyses in this study show no significant correlation with temperature (table 6.8) but nor did the correlation analysis with megafaunal density in chapter 5. Megafaunal species diversity and richness were, however, significantly correlated with temperature (see chapter 5) and temperature may therefore have some influence on the distribution of traces. Note in addition that the results in this study could be affected by the fact that the temperature data had to be extrapolated to all the deeper sites (900-1400 m) from 800 m (see methods) and this may have altered the correlation results.

It has been shown that the type of fauna present and their activities may influence the faunal composition as well as the traces present in an area (Rhoads and Young, 1970; Aller, 1978; Gray, 1981; Brey, 1991) as the presence and abundance of for example foraging traces is largely species specific (Gage and Tyler, 1991). The results from this study show no significant correlation between megafaunal and *lebensspuren* densities (table 6.8). The result is despite this interesting, as it is different to some other studies (e.g. Kitchell *et al.*, 1978; Young *et al.*, 1985) where inverse relationships between trace and megafaunal densities were found, despite the fact a positive correlation was expected. Their results furthermore showed a greater proportion of mobile to sedentary types of traces when food resources were low (Young *et al.*, 1985). A general observation partly supporting this finding was made by Seilacher (1967), suggesting a change with depth in the fossil traces as a behaviour response to a bathymetric gradient in food supply. The results from this study support both these findings, where the organic content and the density of sedentary traces increase with depth while mobile traces decrease with depth.

6.4.3 Lebensspuren densities and sizes

The lack of available information about the faunal distributions west of Shetland has already been remarked upon (chapter 2) but there is even less information with regards to *lebensspuren*. It is therefore extremely difficult to compare any size and density values with areas nearby. There are, however, studies from other parts of the world (see table 6.10) and the density values from this study compare reasonably well with the other studies, although the sites west of Shetland are shallower than those of the other studies and as the range of density values west of Shetland is wider than those given for many of the other studies.

Trace density (trace/m2)	Study site	Depth (m)	Reference
0.35 - 1.0 0 - 0.35	Canadian Basin, the Arctic Sea Bellinghausen Basin, the Antarctic Sea	3700-3840m 4000-5000m	Kitchell *et al.*, 1978
0.265	Bay of Biscay, France	1900m	Mauviel and Sibuet, 1985
3.2	Venezuela Basin	3450m	Young *et al.*, 1985
0.0097	Santa Catalina Basin, East Pacific	1300m	Wheatcroft *et al.*, 1989
0.002-1.015	West of Shetland	200-1400m	This study

Table 6.10 Examples of *lebensspuren* densities from photographic studies at different locations.

The sizes of *lebensspuren* observed on photographs vary enormously depending on the type of trace, ranging from less than a centimetre to over 200 cm in diameter as observed on the Madeira Abyssal Plain (Huggett, 1987). West of Shetland, the largest observed trace was close to 40 cm in diameter (ophiuroids) while the smallest visible trace was approximately 0.5 cm (acorn worms) in diameter and a few centimetres long. Comparisons are therefore difficult to carry out unless the same, or at least very similar, traces are present. One such feature is the meandering traces of 15 cm width attributed to the irregular echinoids found on the Madeira Abyssal Plain (Huggett, 1987). These are very similar in both size and structure to those observed west of Shetland (see figure 6.4). The densities of these traces are, however, difficult to compare as these values vary enormously depending on the type of sediment present, but also because traces often are summarised or classified into groups such as crawling traces as seen in other studies (Gage and Tyler, 1991).

6.4.4 Features of particular interest

Of additional interest is the presence of grazing traces, appearing as spoke-burrows, at the three deepest sites (1100, 1200 and 1400 m), a feature making the deepest part of the transect particularly distinctive. These burrows appear to become more important proportionally with depth and this is also reflected in the density values. At 1100 m and 1200 m the densities are <0.002 burrows/m^2, while at 1400 m the densities were found to be approximately 0.03 burrows/m^2, but additional sites are, however, required to assess this apparent density increase fully. The observed spoke burrows west of Shetland looks very similar to those seen in figure 6.2 (b) and 6.4, and they are up to about 15 cm in diameter but larger burrows may be present. It should be noted that one additional trace was also recorded at 400 m but this may be incorrectly identified as only one trace was recorded for the whole upper continental slope. The burrows are potentially produced by echiuran or polychaete worms but since no actual fauna has been observed in association with the burrows, their origin remains unknown. Similar burrows have been observed in the northern Rockall Trough (Roberts *et al.*, 2000) but the sizes, densities and the variations in traces with depth were not reported. The origin of these was also unknown, although echiurans or polychaete worms were believed to have created them. Bett and Rice (1993) described echiuran feeding behaviour on the Porcupine Abyssal Plain and discussed two different types of feeding behaviour, one of which, the 'conveyor-belt' mode, creates the characteristic spoke-burrow traces, a suggestion supporting the theory that the traces observed west of Shetland are produced by echiurans rather than polychaetes. Other spoke burrows have been observed on the Cape Verde Abyssal Plain (Bett *et al.*, 1995) and on the Madeira Abyssal Plain (Huggett, 1987). Both reported high densities of large spoke burrows (>200 cm in diameter; Huggett. 1987) but these appeared to be much larger and occurred at higher densities (c. 9 spokes/m^2, Bett *et al.*, 1995; c. 0.3 spokes/m^2, Huggett, 1987) than those found west of Shetland and although the origin was unknown, echiurans were also believed to have created them.

6.5 CONCLUSIONS

The combination of the results from all the analyses appears to indicate the presence of two main layers with a boundary at approximately 600 m, where few *lebensspuren* are observed. On the upper part of the slope (200 – 500 m) crawling traces are the dominant types of *lebensspuren*. Between 600 m and 1100 m dwellings are the most frequently observed types of *lebensspuren*, with one exception observed at 900 m where crawling traces dominate, a feature attributed to the particular sediment found there, namely the sand contourite. The depth interval 1200 m to 1400 m is dominated by a combination of crawling, resting and grazing traces, the latter referring mainly to spoke (or rosette) burrows. A depth trend is also found within the shallower sites (200-600 m), a feature that may be a result of the 'ecotone' as described in chapter 5. The largest influence on the distribution of type and density of *lebensspuren* present along the bathymetric transect west of Shetland as a whole is believed to be the type of sediment present (e.g. sediment grain size and superficial sediment thickness), but a combination of factors including the temperature, the current regime and the food resources present are also believed to be important factors, particularly in the division of the *lebensspuren* distribution into two layers and the position of the *lebensspuren* density and relative frequency minimum values observed at 600 m depth.

7 AN ANALYSIS OF THE SEAFLOOR ENVIRONMENT ALONG THE CONTINENTAL SLOPE WEST OF SHETLAND USING THE PHOTOGRAPHIC INSTRUMENT WASP (WIDE-ANGLE SEAFLOOR PHOTOGRAPHY)

7.1 INTRODUCTION

There are variations in faunal distributions (both macro- and megafauna) with latitude (Belyayev *et al.*, 1973; Gage and Tyler, 1991; Rex *et al.*, 1993; Vinogradova, 1997; Zezina, 1997) and it has been suggested that within the bathyal zone there are a number of different latitudinal belts (Zezina, 1997), although the latitudinal variations are believed to be smaller than the variations with depth (Carney *et al.*, 1983; Gage and Tyler, 1991; Grassle and Maciolek, 1992). The lowest faunal abundance and biomass is believed to be found in the central ocean gyres while maximum values are found on the continental shelves (at high latitudes) and in areas of upwelling in particular, regional differences believed to be linked to the distribution of phytoplankton production (Parsons *et al.*, 1984; Lampitt *et al.*, 1986; Gage and Tyler, 1991; Zezina, 1997). It has also been suggested that deep-sea species diversity varies geographically with an overall apparent decrease in diversity from the equator towards the poles, although interregional variation in this general pattern is known (Gage and Tyler, 1991; Rex *et al.* 1993). This includes a decrease in diversity with latitude in the eastern North Atlantic with low diversity values in the Norwegian and Arctic Seas. In a recent study, Bett (2001a) reported stark differences in macrofaunal species diversity between the northern Rockall Trough and the Faroe-Shetland Channel.

In this study the megafauna, sediments and other seabed parameters are analysed to study and examine any variations along the continental slope west of Shetland. The seafloor environment west of Shetland, particularly with regards to the fauna has, as noted in chapter 5, until recently been relatively unknown (see chapter 2). Recent studies, part of the AFEN 1996 and 1998 surveys (e.g. Masson *et al.*, 1996, 1997; AFEN, 2000, 2001; Bett, 2000a, 2001a; Narayanaswamy, 2000; Masson, 2001) have increased the knowledge and understanding of faunal and sedimentary distributions, with particular reference to the bathymetric variations, in this region. Little is, however, known about the along-slope variations west of Shetland and this study aims to investigate the environmental features found on the Atlantic Margin including the variation in megafaunal abundance and species diversity, sediment and other features along the continental slope west of Shetland using photographs. Photographic sites at three different depth intervals were surveyed during AFEN 1996 (Bett, 1997) to the southwest, west and northwest of the Shetland Islands (figure 7.1).

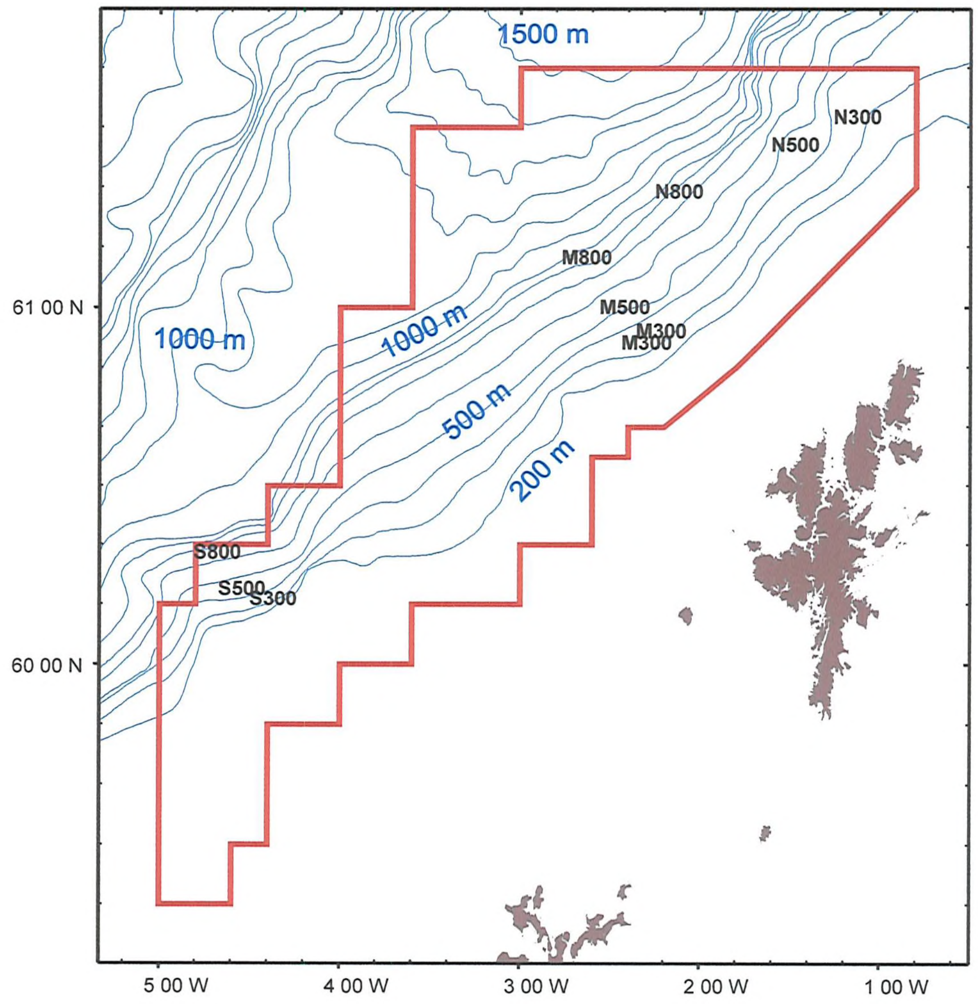


Figure 7.1. The photographic (WASP) sampling sites part of the along-slope study from AMES 1996.

7.2 METHODS

Ten photographic sites were located at depths of approximately 300 m, 500 m and 800 m in three regions, the south- (southwest), mid- (west) and north (northwest) areas (figure 7.1 and table 7.1). There are two photographic runs at 300 m in the mid-region (stations 53913#1 and 53926#1), with one photographic run at each of the other sites. Note that station 53810#1 has no altitude data as the imprinting of this information failed during the deployment of WASP at this site. All calculations, such as faunal densities, have therefore been carried out assuming an altitude of 5.65 m, the average altitude value for the 18 WASP runs studied during this project.

Station (site)	**Location**	**Depth**	**Frame identification**	**Film run**	**Number of frames**
53810#1 (N300)	61° 31.45 N 01° 10.72 W	300 – 303 m	012 – 313	12 m colour	302
53913#1 (M300a)	60° 53.96 N 02° 22.07 W	290 – 275 m	435-543	5 m colour	109
53926#1 (M300b)	60° 53.96 N 02° 22.15 W	294 – 278 m	2140 - 2249	4 m colour	110
53948#1 (S300)	60° 10.57 N 04° 25.64 W	304 – 324 m	3130 – 3357	9 m colour	228
53921#1 (N500)	61° 15.97 N 01° 48.01 W	496 – 486 m	680 – 788	5 m colour	109
53925#1 (M500)	60° 59.54 N 02° 29.79 W	507 – 496 m	1780 - 2103	12 m colour	324
53949#1 (S500)	60° 12.16 N 04° 36.71 W	512 – 504 m	007 – 113	3 m colour	107
53922#1 (N800)	61° 19.05 N 02° 10.85 W	812 – 787 m	815 – 1118	12 m colour	304
53924#1 (M800)	61° 07.99 N 02° 42.00 W	798 – 781 m	1545 – 1762	10 m colour	218
53950#1 (S800)	60° 18.41 N 04° 44.11 W	816 – 829 m	009 – 346	13 m colour	338

Table 7.1. Station data of the photographic (WASP) sites for the along-slope study west of Shetland, where N refers to the north-, M to the mid- and S refers to the south regions (the locations refer to the positions at the beginning of the transects and frame identification refers to the number printed on the frame at the time of exposure).

All sites have been surveyed using the photographic instrument WASP (Wide-Angle Seafloor Photography). In general there were approximately 200 to 300 frames for each run, the equivalent of 10 to 12 m of film (table 7.1). All frames were processed and analysed for the fauna, the sediment and any other visible features on the seabed (as described in chapter 3 and 4), after which they were examined for suitability of use in the study. Frames were rejected during the first stage of frame selection if they were considered to be inferior in quality and in the second stage of frame selection all photographs with altitudes in excess of 6 m were excluded from the final analysis (see chapter 3, 4 and 5).

7.2.1 Seabed analysis

The seabed analysis was carried out by taking notes of the general seafloor environment with descriptions of the type of sediment present but also including large and unusual features such as boulders or particular patterns on the seabed (e.g. sand streaks). To aid the description of the sediment type observed on the WASP photographs, a scale for the overall sediment type present in an area was created. The scale ranges from 1 to 5, where

5 refers to very fine sediment and 1 refers to very coarse sediment. Sites where a mixture of different sediments are observed were given a value reflecting the main, or most common type of seafloor present while taking all sediment types into account as far as possible. The analysis is subjective but every effort was made to achieve an objective result. To enable correlation analyses to be carried out, the environmental data from AFEN 1996 (AFEN, 2000) was used (see sampling methods in chapter 3). These data included particle size analysis data (Phi), silt and clay content as well as the carbon and nitrogen content (table 7.2). As in chapter 5, the selection of seabed sampling stations was made such that the three seabed sampling stations closest in depth and distances to each of the WASP sites were assessed (see table 7.2 and figure 7.2). As in chapter 5, the mean values were then calculated for each depth interval and used in the correlation analysis studies. Note, however, that in this study where there is a limited number of sampling units (n=3) along the slope, only comparative correlations can be carried out (i.e. levels of significance can not be obtained).

WASP	Site	Depth	Phi	Wentworth	Carb	Org	S and C	TOC	TON	C/N
N300	D5	244	1.56	Medium sand	19.59	0.54	0.68	0.35	0.01	43.0
	G5	346	1.47	Medium sand	34.85	0.90	2.50	0.53	0.07	8.1
	G4	356	1.10	Medium sand	44.62	1.07	1.56	0.47	0.06	8.5
M300	Tr300	286	1.18	Medium sand	22.06	0.63	0.70	0.07		
	E4	296	0.95	Coarse sand	27.43	0.63	4.61	0.58	0.07	0.80
	AD1	324	1.84	Medium sand	12.81	0.34	1.75	0.14		
S300	AJ1	294	-0.07	Coarse sand	75.85	1	1.33	0.4		
	J2	328	0.78	Medium sand	42.6	1.57	3.24	0.4	0.05	8.75
	J5	337	0.89	Medium sand	41.74	1.25	5.30	0.70	0.08	8.57
N500	K3	482	2.09	Fine sand	22.47	1.64	3.33	0.40	0.01	51.0
	N2	554	2.89	Fine sand	14.91	1.79	15.65	0.43	0.01	51.0
	AK9	550	1.4	Medium sand	16.65	2.55	4.4	0.67	0.06	11.4
M500	L4	490	1.06	Medium sand	18.39	1.42	4.06	0.25		
	L4	494	1.44	Medium sand	20.31	1.23	2.53	0.14	0.01	17.0
	P5	510	0.16	Coarse sand	16.01	1.45	1.96	0.31	0.01	37.0
S500	M4	460	1.30	Medium sand	25.13	0.98	1.24	0.43	0.03	14.5
	M2	488	-0.27	V. coarse sand	24.05	1.13	1.51	0.55	0.04	14.6
	Q4	533	0.84	Coarse sand	13.5	0.91	1.8	0.43	0.05	8.33
N800	R3	725	2.37	Fine sand	15.32	0.52	14.42	0.88	0.09	9.45
	U3	825	2.25	Fine sand	11.97	1.19	4.98	0.74	0.07	10.5
	U2	860	2.91	Fine sand	9.28	1.41	15.35	0.75	0.07	10.3
M800	Tr800	789	3.48	V. fine sand	18.93	1.37	11.11	0.36	0.02	14.7
	Tr800	792	3.50	V. fine sand	16.71	1.35	11.29	0.23	0.02	14.0
	U3	825	2.25	Fine sand	11.97	1.19	4.98	0.74	0.07	10.5
S800	T4	709	1.57	Medium sand	7.09	1.03	2.87	0.33	0.01	35
	T3	773	1.21	Medium sand	10.68	1.62	8.18	0.6	0.06	9.57
	T5	675	2.05	Fine sand	11.9	1.08	9.37	0.53	0.08	6.67

Table 7.2. Sediment sampling stations from AFEN 1996 used for correlation studies with the WASP sites. WASP is WASP (photographic run) site, depth in m, phi is the mean phi value, Wentworth is Wentworth Scale (V. = very), Carb = carbonate (% dry weight), Org = organics (% dry weight), S and C = silt and clay content (% dry weight), TOC = total organic carbon (% dry weight), TON = total organic nitrogen (% value), C/N = ratio carbon to nitrogen.

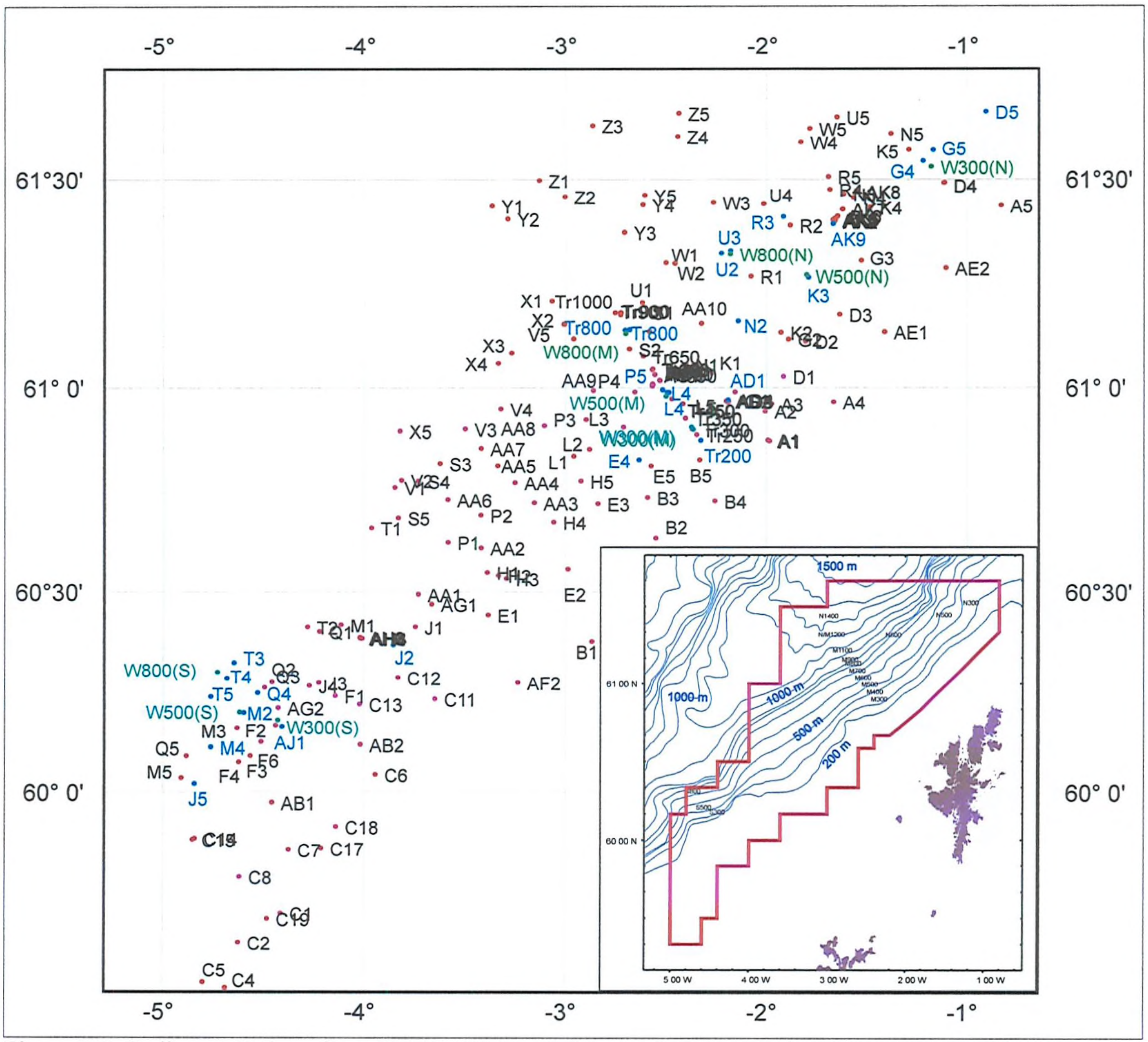


Figure 7.2. Sediment stations from AFEN 1996 used for correlation analysis studies with the WASP sites. All sampling stations (large map) can be seen in relation to the AFEN 1996 survey area as well as the WASP sites (lower right). The relative positions of WASP sites (green), the selected seabed sampling stations (blue) and all the remaining stations (black) not used for the correlation analyses can all be seen.

7.2.2 The faunal analysis

As described in chapter 5, the selected approach to study multi-species data is that of Field *et al.* (1982), preferring to 'let the species tell their story' and search for patterns amongst the biological variables with an aim to interpret these in terms of environmental data. The megafauna present at the different sites will first be described in general terms with a brief description of the fauna present at each depth interval. The notoriously difficult process of identifying the megafauna (Barraclough-Fell. 1967; Holme, 1985; Southward and Nicholson, 1985) in the photographs has been carried out using a number of different sources as described in chapter 5. The megafaunal dataset was then analysed using univariate (abundance, species diversity, species richness and equitability) and multivariate (cluster analysis and ordination) methods as described in chapter 5.

7.2.3 Analysis of physical parameters

The occurrence of any physical features was first recorded during the processing and analysis of the photographs. The positions of any scouring around rocks or other sedimentary features were recorded. In addition, the directions and sizes of sand ripples were established and measured to enable estimates about current speeds to be made. The direction of the currents was made by first establishing the direction of travel along the photographic run as described in chapter 3 and 5. From this information the direction of the current flow was established (Leeder, 1982; Open, 1989).

7.2.4 Assessment of other features

The photographs were assessed for the presence of any artificial artefacts, any slumps or failures of the sediment and any other features observed on the photographs.

7.2.4.1 Lebensspuren

Lebensspuren are the imprints and visual evidence of faunal activity on the sediment surface and include for example tracks, trails and burrows (see chapter 6 for a detailed study of the bathymetric transect). During the processing and analysis of the photographs notes were taken about the type of traces present, their sizes and the numbers observed. The information was subsequently used to calculate relative frequency (the proportion of frames containing traces) and trace density.

7.2.4.2 Trawling

Marks believed to have been created by trawling have been recorded. The total number and the density values for each depth interval and sampling site have been calculated using all the photographs available for the entire runs rather than those left after frame selection as many marks are only visible on the higher altitude frames. The sizes of these marks are not possible to estimate as their physical scales are larger than the width of the seafloor coverage of the photographs.

7.3 RESULTS: PHOTOGRAPHIC ANALYSIS OF THE ALONG-SLOPE SITES

A total of 2149 photographs were obtained in the along-slope study with 2124 frames (equivalent of 39,479 m^2, excluding station 53810#1) being left after the first stage of frame selection and 1209 frames (equivalent of 14,425 m^2, excluding station 53810#1) after stage two of frame selection (see chapter 3 and 4). Over 90% of all these frames contained megafaunal data for analysis (table 7.3).

Site	N300	M300	S300	N500	M500	S500	N800	M800	S800
Percentage	n/a	98.1	97.7	100	91.6	100	100	97.3	90.7

Table 7.3. Proportion (percentage) of frames containing observed and recorded megafaunal data (M300 m is the mean value for the two sampling runs at this depth and N300 has no data as the imprinting of altitude failed during the operation of WASP at this site).

7.3.1 Seabed analysis

The photographic analysis of the seabed along the continental slope revealed a general pattern both within the overall sediment descriptions (table 7.2) and the WASP sediment grading where there is a variation along the slope (table 7.4) but also that the sediment becomes finer with depth, generally following that seen along the bathymetric transect in chapter 5. At the shallower sites the sediment has a large proportion of gravel with cobbles and boulders while at the deeper sites sand is the dominant sediment type. At 300 m, two types of seafloor have been identified in all three regions. Within these photographic runs, there is a repeated change in the type of sediment with segments of variable lengths consisting of 'medium' and 'coarse' sediment areas. The boundaries between these types are sometimes transitional in character but overall these two types are apparent. At 500 m the sediment is predominantly coarse in the north- and mid-regions with gravel and high concentrations of cobbles while the southern region has finer sediment with sand and gravel with only occasional cobbles and boulders. At 800 m sand is the dominant sediment type in the north- and mid-regions while coarser material appears more frequently in the south. Drop-stones of a variety of sizes are present throughout the photographic runs, a characteristic of the Faroe-Shetland Channel (Stoker *et al.*, 1998).

Station (site)	Depth	Sediment grading*	Sediment
53810 (N300)	300 - 303 m	2	Two types, 'medium' and coarse'. 'Medium' dominated by sand and gravel, 'coarse' dominated by gravel, pebbles, cobbles and boulders
53913 (M300)	290 – 275 m	2	Two types, 'medium' and coarse'. 'Medium' dominated by sand and gravel, 'coarse' dominated by gravel, pebbles, cobbles and boulders
53926 (M300)	294 – 278 m	2	Evidence of two types, 'medium' and 'coarse'. 'Medium' dominated by sand and gravel, 'coarse' dominated by gravel, pebbles and occasional boulders.
53948 (S300)	304 – 324 m	2	Two types, 'medium' and coarse'. 'Medium' is dominated by gravel and pebbles with sand; and 'coarse' is dominated by pebbles, cobbles and boulders
53921 (N500)	496 – 486 m	2-3	The sediment is dominated by gravel and pebbles, with small cobbles and boulders at fairly high concentrations throughout the run
53925 (M500)	507 – 496 m	2-3	The sediment is dominated by sand and gravel but pebbles, cobbles and boulders are also present at high concentrations throughout the run
53949 (S500)	512 – 504 m	3	The sediment is dominated by sand with gravel and the occasional cobbles and small boulders. A thin layer of sand appears to overlie a coarser sediment throughout the run
53922 (N800)	812 – 787 m	4	Sand dominates the sediment
53924 (M800)	798 – 781 m	4	Sand dominates the sediment
53950 (S800)	816 – 829 m	3-4	Evidence of two types, 'fine' and 'coarse'. 'Coarse' is the dominant type and consists of gravel and pebbles with occasional small boulders. 'Fine' dominated by sand and fine sand with gravel

Table 7.4. Sediment analysis from WASP photographs along the continental slope west of Shetland (* the WASP sediment grading as described in the methods sections 5.2.1 and 6.2).

7.3.2 Faunal analysis

The total number of megafauna observed and recorded prior to the two stages of frame selection was 11,424 individuals while the resultant number after frame selection is 7,337 individuals, leaving only frames with an altitude of 6 m, or less (see chapter 4). The number of individuals and taxa present at the sites in the along-slope study can be seen in figure 7.3.

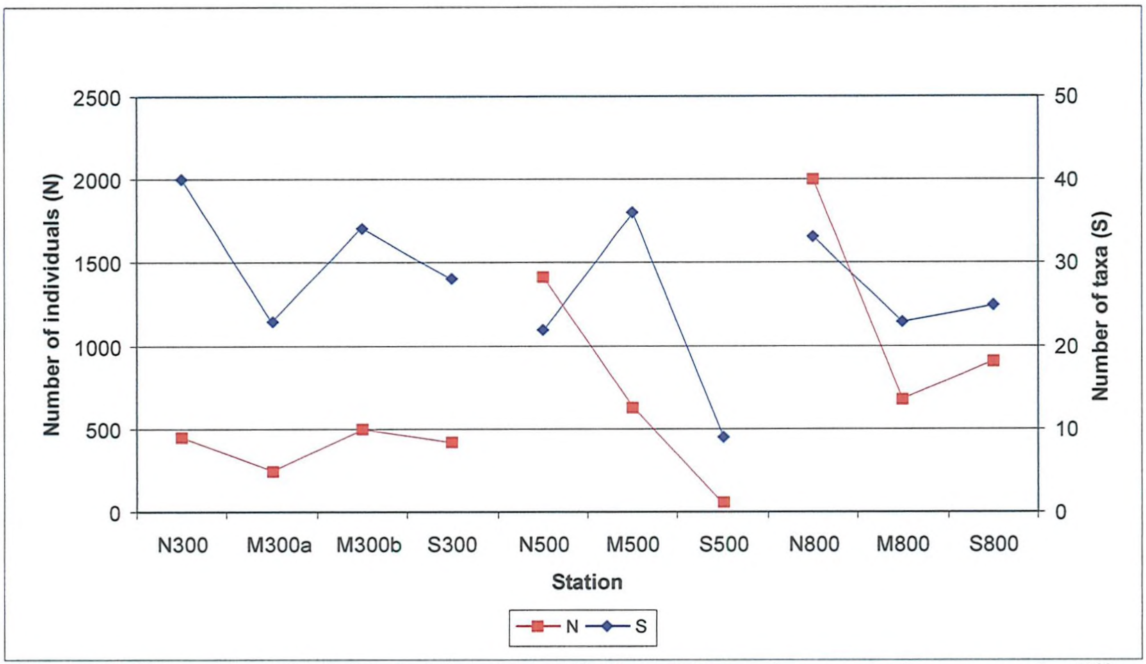


Figure 7.3. The number of individuals (N) and taxa (S) (from Primer using raw data) present at the different sites along the continental slope study.

Overall the fauna is dominated by Porifera (35.2 %), cnidarians (18.4 %), crustaceans (16.6 %), molluscs (6.5 %), polychaetes (5.7 %) and echinoids (4.3 %), the total of which represent nearly 87 % of the megafauna present. Enteropneusts, pycnogonids and the asteroids contribute with approximately 3 % each, while the fish contribute with about 2 %, while the remaining groups comprise approximately 1.3 % each. The unknown and unidentifiable group comprises approximately 1.3 % of the total megafauna observed. It should be noted that the proportion representing the Porifera at 500 m in the mid-region is an underestimate as these large numbers of sponges were not recorded or counted.

The photographic analysis (table 7.5) revealed some similarities between the sites in the different regions but also some differences. At the shallowest sites (300 m) in this study, sites within the iceberg plough mark zone, the megafaunal distribution appears to relate to the two 'types' of seafloor present with different megafaunal associations linked to the 'type' of sediment present. However, these associations appear to be somewhat different in the different regions (see below). The megafauna are similar in all three regions at 500 m, being dominated by sponges and crustaceans (mainly squat lobsters believed to be *Munida* sp.). The sponges are, however, more frequently observed and more individuals appear to be larger in the north- and mid-regions (the recorded values are underestimates at M500) compared to those observed in the south, a fact very much apparent when the photographs are observed. At 800 m cnidarians, polychaetes, molluscs and sea spiders are the dominant groups. Sponges are also present in all three regions, becoming more important towards the south. An additional group, the enteropneusts, are present in the northern and mid-regions but they are absent in the south.

Station	Depth	Sediment
53810 (N300)	300 - 303 m	Sponges, pencil-spined urchins (Cidaridae), squat lobsters (*Munida* sp.), purple heart urchins (Spatangidae) and molluscs are the dominant fauna. Squat lobsters are more abundant on the 'coarse' sediment type than on the 'medium' while the purple heart urchins are more abundant on 'medium' sediments.
53913 (M300a)	290 – 275 m	'Stalked' anemones (bringing the feeding tentacles above the seabed), squat lobsters (*Munida* sp.), bivalves (scallops) and gastropods dominate the fauna. Squat lobsters are more abundant on the 'coarse' sediment type than on the 'medium' while bivalves are more abundant on 'medium' sediments.
53926 (M300b)	294 – 278 m	'Stalked' anemones dominate the megafauna but bivalves (believed to be scallops), gastropods, brittle stars, asteroids, squat lobsters (*Munida* sp.) and a variety of fish species (e.g. ling and red fish) are also present.
53948 (S300)	304 – 324 m	Pencil-spined urchins (Cidaridae), squat lobsters (*Munida* sp.) and *Stichopus* sp. are the dominant megafauna. Gastropods and bivalves are also present. Squat lobsters and the cidarids are more abundant on the 'coarse' sediment type than on the 'medium' while *Stichopus* sp and molluscs are more abundant on 'medium' sediments.
53921 (N500)	496 – 486 m	The 'sponge-belt', where a large amount of sponges of a large variety of species dominate the fauna. Other megafaunal groups are *Munida* sp. (most likely *Munida sarsi*), cidarids, spatangids and asteroids.
53925 (M500)	507 – 496 m	The 'sponge-belt', where a large amount of sponges of a large variety of species dominate the fauna. Soft corals are also abundant. Other megafaunal groups are *Munida* sp. (most likely *Munida sarsi*), cidarids and asteroids.
53949 (S500)	512 – 504 m	Very sparse fauna dominated by squat lobsters with occasional sponges and gastropods.
53922 (N800)	812 – 787 m	Megafauna dominated by sea spiders, anemones, gastropods and acorn worms (enteropneusts).
53924 (M800)	798 – 781 m	Anemones (cerianthids), gastropods and pycnogonids dominate the megafauna. Polychaete tubes (sabellids) and a variety of fish species (e.g. rays and eel pouts) are also present.
53950 (S800)	816 – 829 m	Sparse fauna dominated by asteroids, anemones, soft coral, and to a lesser extent sea spiders.

Table 7.5. Megafaunal analysis from photographs at sites along the continental slope west of Shetland ('stalked' refers to anemones where the body extends above the seafloor, while the tentacles are only visible in the other anemones).

7.3.2.1 Abundance (faunal density)

The faunal densities of major megafaunal taxa along the continental slope are illustrated in figure 7.4 and table 7.6. The values appear to be fairly equal throughout the sites in the study with the exception of site N500, where the density value is double that of the other sites. Site N300 has an overall low faunal density, half that of any of the others. The latter is an estimate based on an altitude of 5.65 m (the average altitude of all photographs part of AMES 1996) for comparison purposes and to further illustrate that the faunal densities here appear to be lower than those seen at the other sites.

At 300 m, the highest density value is found in the mid-region. The opposite pattern is seen in the 500 m depth interval with the lowest values seen are in the mid-region, although the mid- and southern regions have similar density values and considering the underestimate of sponge density at M500, a value that may even be as high as that seen in the north (N500), it is possible that the actual pattern at 500 m may be an increase along the slope from the south towards the north. The 800 m depth interval shows a high median value in the north deceasing to a minimum in the mid-region and increasing again in the south, a pattern similar to that seen at 300 m. The mean densities at 800 m indicate an increase in density from the southern to the northern sites.

Site	**Mean density (ind/m^2)**	**Median density (ind/m^2)**	**Median 95 % confidence limits**
N300	0.08	0.05	0.05 – 0.05
M300	0.32	0.26	0.23 – 0.30
S300	0.32	0.12	0.10 – 0.15
N500	1.59	1.26	1.14 – 1.38
M500	0.22	0.10	0.07 – 0.12
S500	0.53	0.11	0.08 – 0.13
N800	0.74	0.47	0.42 – 0.52
M800	0.41	0.15	0.11 – 0.19
S800	0.36	0.19	0.17 – 0.22

Table 7.6. Megafaunal densities (individuals/m^2) along the continental slope west of Shetland (mean and median density with 95 % confidence intervals).

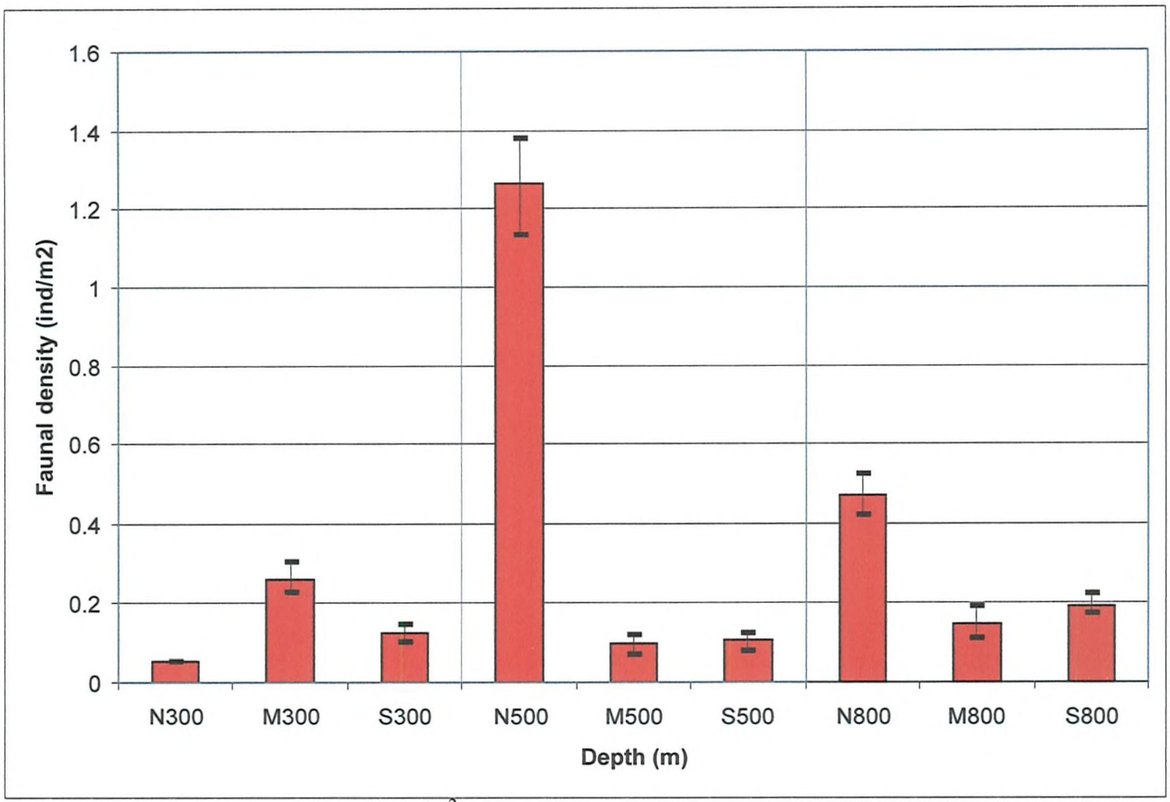


Figure 7.4. Megafaunal densities (ind. /m^2) along the continental slope west of Shetland, where N refers to the northern region, M the mid-region and S the southern region (median with 95 % confidence limits).

In addition to overall faunal densities for each site, the densities of some of the most important taxa have also been calculated (table 7.7). As noted in table 7.5, there are similarities but also some differences in the dominant megafauna present in the three regions. At the 300 m depth interval, for example, the *Stichopus* sp., *Munida* sp., scallops and spatangids are present in all regions but sponges are more frequently observed in the south and in the north compared to the mid-region and 'stalked' anemones are present in the mid-region, but absent in the other two regions. At 500 m in the northern and mid-regions, the 'sponge-belt' (see chapter 2 and 5) is the main feature with a large amount of sponges of a variety of species (not enumerated or identified but apparent from observing the photographs), a feature also reported from the Faroe Islands at similar depths (Klitgaard *et al.*, 1997). In the southern region, however, sponges are less dominant with regards to both density and physical size. In addition, *Munida* sp. and spatangids (possibly *Spatangus* sp.) were observed in all three regions at 500 m while the cidarids were only observed in the north and mid-regions. At 800 m, polychaetes, anemones and pycnogonids are present in all regions but densities of the latter are lower in the south than in the other two regions. In addition, there appear to be different species of anemones present in the south compared to those in the mid- and north regions; acorn worms are present in the northern and mid-regions but they are absent in the south; and the asteroid *Solaster* sp. is present in the south, but it is not observed in the other two regions. It therefore appears that there are subtle differences between the regions with regards to the megafaunal densities and distributions. The distributions are similar in all regions at the 300 m depth interval but at 500 m and 800 m, the northern and mid-regions appear to be somewhat different to those of the south.

Taxa	N300	M300a 53913#1	M300b 53926#1	S300	N500	M500	S500	N800	M800	S800	Descriptions
Fan-shaped sponges	0.2	0.2	0.1	0.2	43.9		1.8			0.8	
Massive sponge	1.1			0.3	6.4		3.5	0	0.1	5.4	
Branched sponge	0.9			0.9	81.8						
Globiferous sponge	0.1			0.2	0.1		5.3	0.2	0	4.4	
Stalked sponge								4.5	0.3	0	White, bell-like structure on top of a long thin stalk
Soft coral					0.1			1.7	0	3.3	
Sea pen			0.3			0.1		0	2.1	0	White, feather-like
'Stalked' anemone		10.6	11.5								Body/trunk visible above seabed
Anemone B								30.6	11.1		Orange colour, no body visible, tapering tentacles
Anemone D										6.8	Orange, flat, large central disc
Anemone E										2.0	Dark tentacles, could be Anemone B*
Ceriánthid B								0.3	4.0		Body above seabed, light tentacles with dark centre disc
Anemone sp.					0.1	0	2.6				
Polychaete sp.				3.1	1.2			6.5	10.8	9.3	Worm tubes believed to be Sabellids
Munida sp.	0.6	5.7	1.9	10.0	11.7	15.2	34.2				
Pycnogonid A								3.7	4.3		As B in size, but no white spots
Pycnogonid B								2.2	3.1		Small (10 cm) size, parasites (white spots) on leg joints
Scallop	0.6	4.1	5.9	0.5							
Gastropod sp.	0.2	3.1	2.3	1.9			2.6	3.5			
Stichopus sp.	0.3	0.4	0	0.2							*Stichopus ?tremulus*
Spatangidae sp	0.4		0.5	0.5	4.4	0.2					
Cidarid sp.	2.4			8.7	0.4	1.6					*?Cidaris cidaris*
Asteroid A	0		0.5	1.8							Small, orange colour but very hard to identify
Asteroid B		0.2			1.2	1.5					Strong orange colour, five arm
Cushion A			0	1.4							*?Porania pulvillus*
Solaster sp.										1.3	
Ophiuroid sp.	0	0.9	2.1	0		0.2					
Acorn worm								16.3	0.5		

Table 7.7. The megafaunal densities of some of the most dominant taxa/species at the sites in the along-slope study west of Shetland (values as individuals/100m^2) (* = low quality of specific frames made identification particularly difficult; 0 = low density of fauna present).

7.3.2.2 Diversity

The range of the Shannon-Wiener diversity index values (figure 7.5) is similar at 300 m and 800 m but the values are lowest at 500 m. Within the depth intervals, there is an increase in diversity from the southern sites towards northern sites along the slope at 300 m and 500 m while the opposite is seen at 800 m, where the southern site has the highest value.

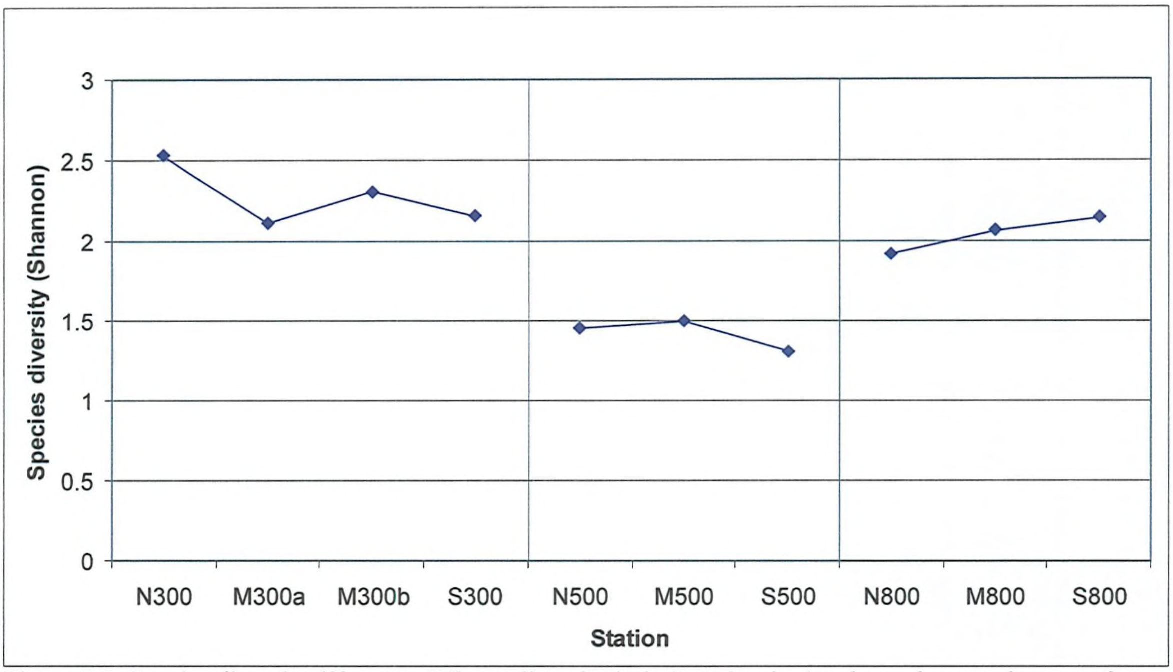


Figure 7.5. Species diversity (Shannon-Wiener diversity index) at sites in the along-slope study west of Shetland.

The species richness (figure 7.6) values overall appear to increase slightly from the southern sites towards the northern sites along the slope both at 300 m and 800 m with the highest values in north. At N500 the pattern is slightly different with the highest value in the mid-region and the lowest value in the south. The lowest value overall is seen at 500 m in the southern region and the highest at 300 m in the northern region.

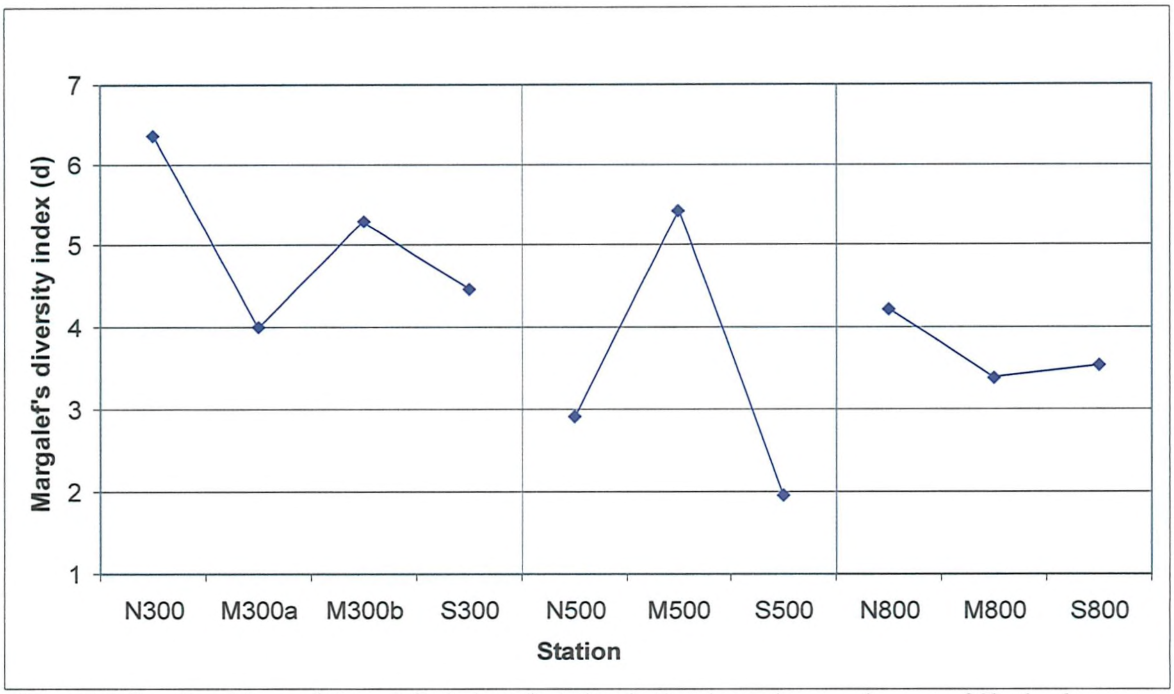


Figure 7.6. Species richness (Margalef's index, d) at sites in the along-slope study west of Shetland.

The evenness values calculated for the sites in the along-slope study (figure 7.7) are all within a similar range in the 300 m depth interval, with only a slight increase along the slope from the south towards the north. The opposite pattern is seen at 800 m with the highest value in the south. At 500 m the values are overall lower than at the other depth intervals and in the north and mid-regions the values indicate neither dominance nor evenness in the fauna present. The distribution of individuals among species is therefore more even at 300 m and 800 m than the 500 m sites. It should, however, again be noted that the lack of data with regards to the sponges at M500 m may affect the result and perhaps there is higher evenness at this site than is apparent from the present results.

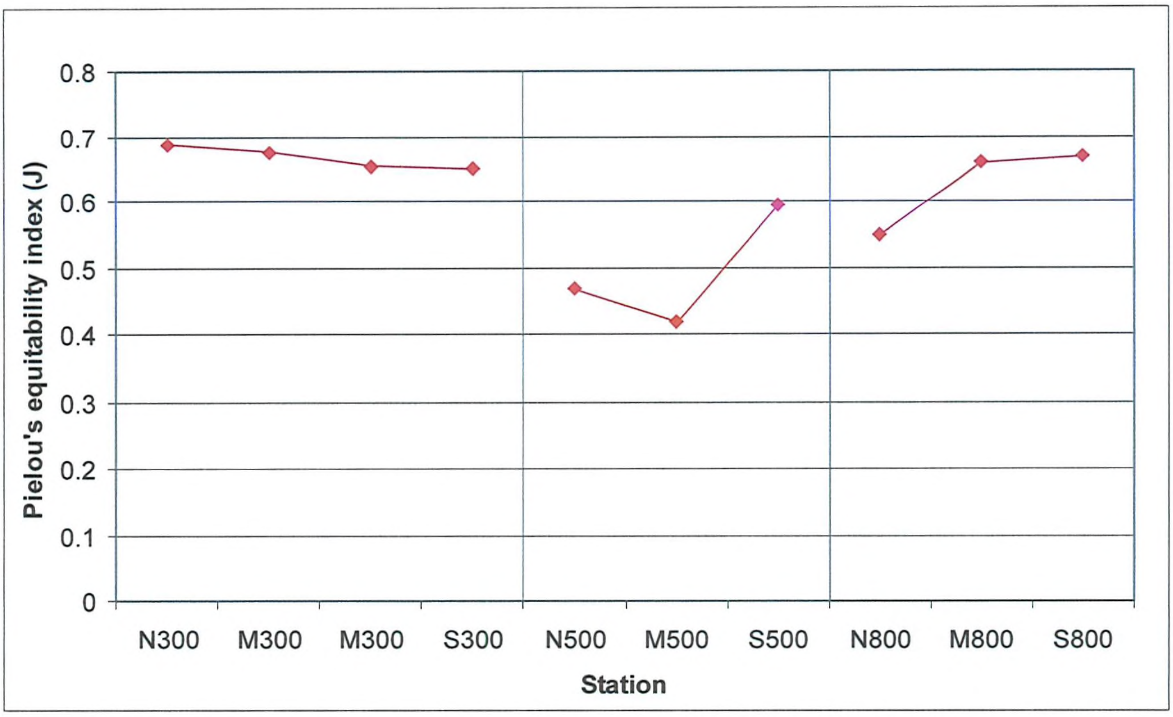


Figure 7.7. Species (Pielou's) equitability index at sites in the along-slope study west of Shetland.

The Simpson's dominance index values (figure 7.8) are largely a mirror image of the Pielou's equitability index (figure 7.7) results with the highest evenness found at the shallowest (300 m) and deepest sites while the mid-depths (500 m) are neither dominant nor evenly distributed with regards to the number of species in relation to the number of individuals.

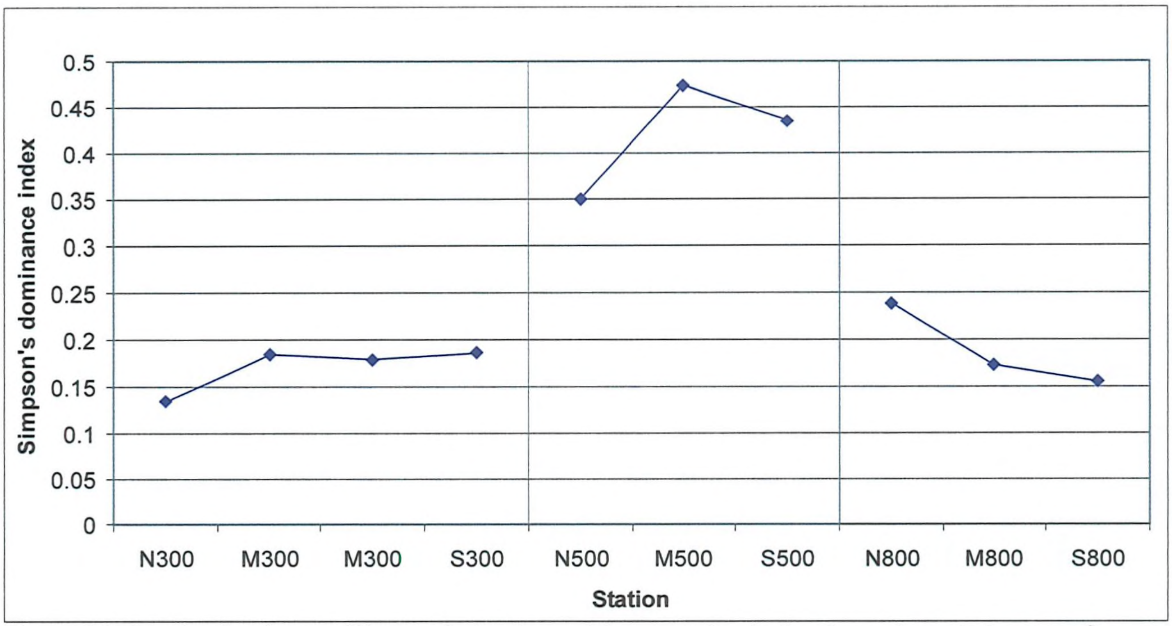


Figure 7.8. Species dominance (Simpson's dominance) index at sites in the along-slope study west of Shetland.

The results from the rarefaction analysis (figure 7.9), where high diversity is found when the curves are steep (referring to evenness) and more elevated (referring to species richness) (Gage and Tyler, 1991), show that overall the diversity is highest at N300, M500 and one of the M300 sites. The lowest diversity overall is found at S500, a value much lower relative to any of the others but note the low number of individuals observed. The rarefaction curves (figure 7.9) for the 300 m depth interval show the highest species diversity and the highest evenness at N300. One of the M300 has the lowest species diversity but also appears to be the lowest with regards to evenness but as the curves are short, samples containing low numbers of individuals, it is difficult to assess this fully. In the 500 m depth interval the highest species richness and evenness is found in the mid-region and the lowest both with regards to species richness and evenness is in the south. The values for the northern region are found somewhere in between those of the other regions. In the 800 m depth interval the curves are similar in all three regions with lower species diversity and evenness compared to the other depths. The evenness is similar in all regions but species richness appears to be highest in the north but the numbers of individuals present in all three sites are insufficient to establish this fully.

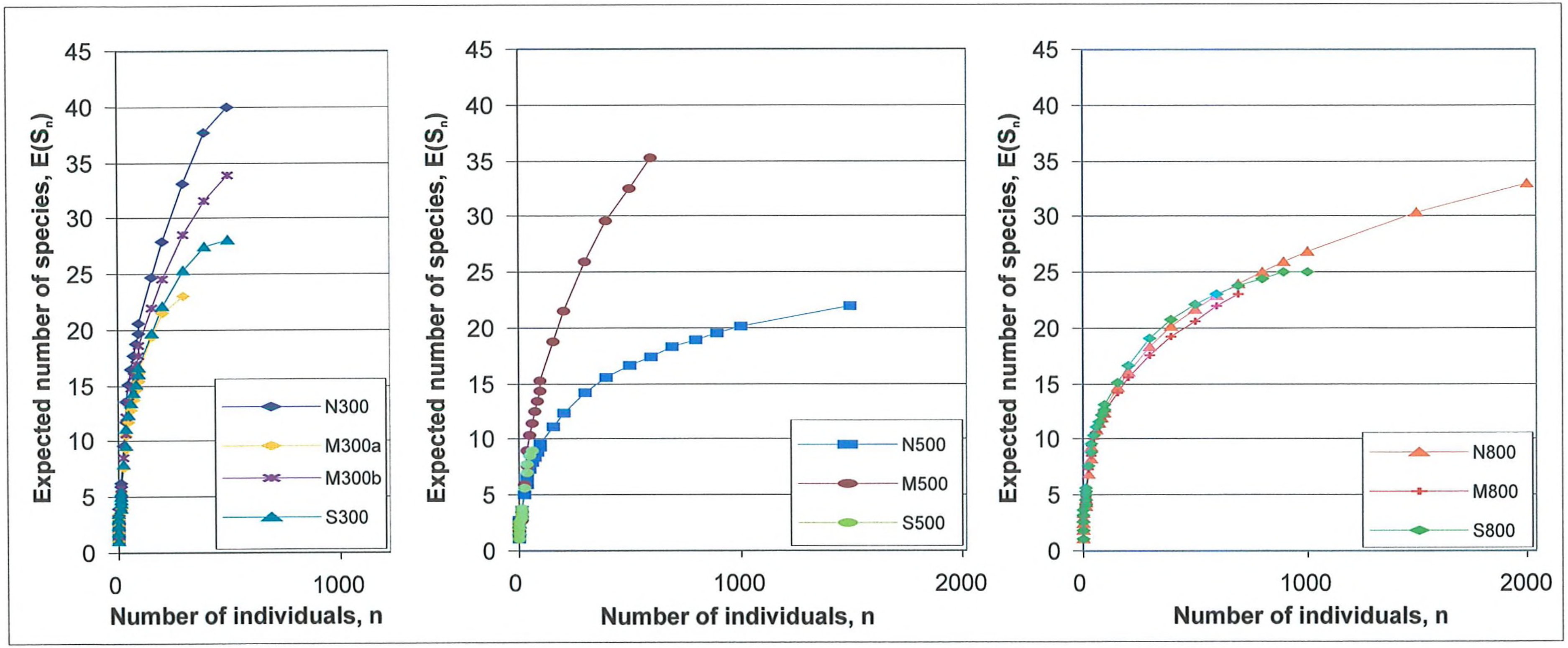


Figure 7.9. Rarefaction index curves at the sites in the along-slope study west of Shetland with the 300 m depth intervals to the left, the 500 m intervals in the middle and the 800 m depth intervals to the right (northern region: shades of blue; mid-region: shades of red; and southern region: shades of green).

7.3.2.3 Faunal composition

Variations in megafaunal composition appear to be present at all depth intervals along the continental slope. At 300 m there is a decrease in the proportion of crustaceans and asteroids from south to north, while the opposite pattern is seen for the holothurians. In many of the remaining taxa at 300 m, however, there is no apparent trend in megafaunal composition along the slope. At 500 m, the proportion of crustaceans, cnidarians and molluscs appears to decrease from south to north along the slope, while the proportion of sponges is believed to increase from south to north, although the latter is not obvious from figure 7.10. The value at M500 is an underestimate as the sponges at this site were not fully enumerated but the large quantities of sponges present (at least as abundant as those observed at N500) was apparent from viewing the photographs (personal observation). In addition to these two trends in megafaunal composition at 500 m, echinoids are present in the north- and mid-regions but not in the south, while molluscs are present in the southern and mid-regions but not in the north. At 800 m the most obvious examples of variations along the slope are the sponges and the polychaetes, taxonomic groups that decrease in proportion along the slope from the southern to the northern site, and the cnidarians and the enteropneusts, two groups that increase in proportion from south to north. A similar pattern as the latter is found in the distribution of molluscs, but to a slightly lesser extent. The higher proportions of sponges present at S800 is even more evident on the photographs (personal observation), while smaller proportions were seen at M800 and N800. In addition, there appears to be a difference in the fauna in the regions with similar sponges in the northern- and mid-regions (dominated by stalked sponges, see table 7.6) while different sponges are present in the south. The enteropneusts are known from the bathymetric transect study (see chapter 5), where they were observed at 800 m and 900 m (most abundant at 900 m) but it is clear from this study that this group also exists at 800 m in the northern region while apparently absent from any other depths within the study area. Anemones (cerianthids), gastropods and pycnogonids dominate the megafauna.

In addition to these variations it should also be noted that the most important taxonomic groups (proportionally) vary between the depth intervals. The dominant groups at 300 m are the sponges, cnidarians, crustaceans, molluscs and the echinoids and at 500 m the sponges and crustaceans are proportionally most important. At 800 m the most important groups are slightly different to those further up the slope and cnidarians, polychaetes, enteropneusts (acorn worms) and sea spiders are most important.

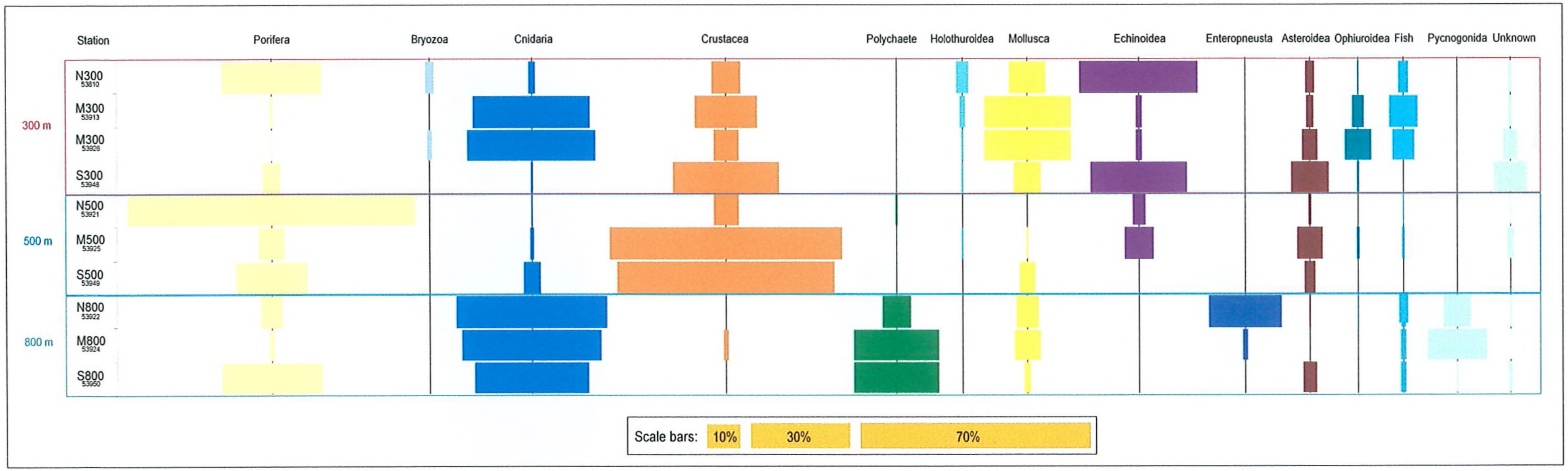


Figure 7.10. Faunal composition in the three regions part of the along-slope study west of Shetland (the scale bars represent 100 % for each site).

7.3.3 Further statistical analysis

7.3.3.1 Multi-variate analysis

7.3.3.1.1 Cluster analysis

The dendrogram (figure 7.11) reveals two main clusters, one containing sites on the upper part of the continental slope down to 500 m and one cluster forming the remaining sites at 800 m (stations 53950#1, 53924#1 and 53922#1). This agrees with the results seen in chapter 5, further supporting the suggestion that the megafauna is divided into at least two layers with a boundary occurring at mid-depths of approximately 600 m on the continental slope west of Shetland. Within these two main clusters additional groupings are present with N500 and M500 grouped separately from S500, while M300a and M300b are clustered separately from S300 and N300. At 800 m, the northern- and mid-regions are clustered together separately from S800. Note, however, that some caution may be necessary when interpreting the fine-scale cluster groupings and comparisons with the multi-dimensional scaling is necessary to establish the groups further.

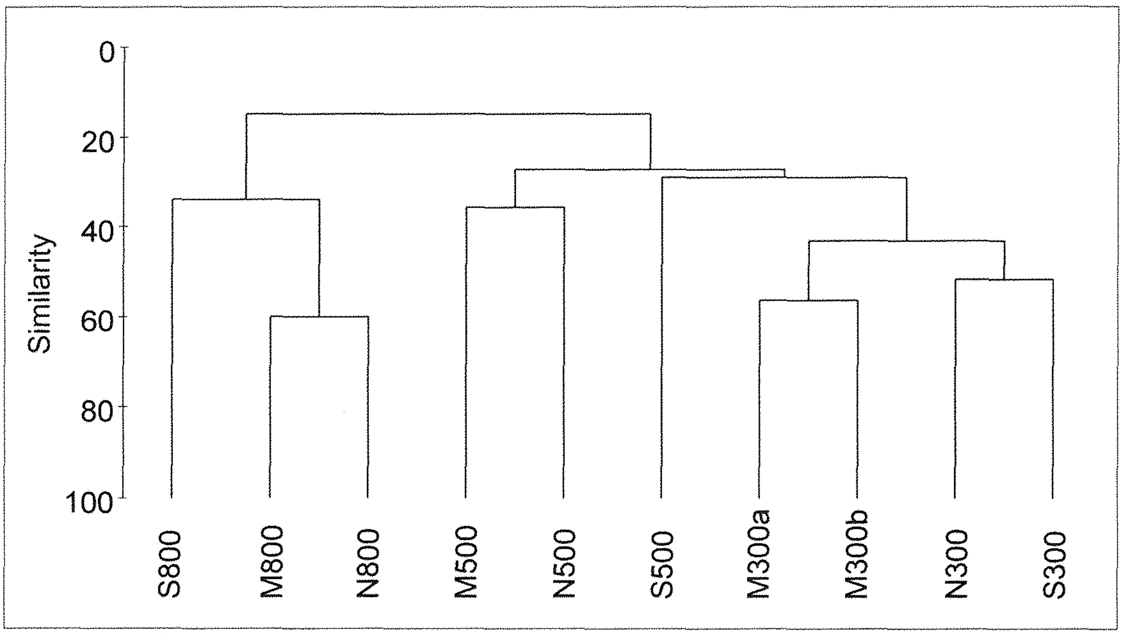


Figure 7.11. Cluster (dendrogram) analysis of the megafauna at the sites in the along-slope study west of Shetland

7.3.3.1.2 Ordination by Multi-Dimensional Scaling (MDS)

The results (figure 7.12) from the non-metric multi-dimensional scaling (MDS) illustrate a configuration largely in support of the cluster analysis. The deep-water sites have been grouped together and the shallower sites have been grouped together. The stress level of 0.08 is within the limit (<0.1) indicating a 'good ordination with no real prospect of a misleading interpretation' (Clarke and Warwick, 1994). It should, however, be noted that the divisions of the sites at 500 m where N500 and M500 are clustered together separately from S500 is not apparent in the MDS. The MDS does, however, agree with cluster results at 300 m, separating the mid-region from the north- and the south-regions. At 800 m there appears to be an along-slope trend from north to south (top to bottom in the plot), a result also seen in the cluster analysis (figure 7.11). To assess this further, the MDS x and y ordinates have been plotted against latitude (figure 7.13) and indicating further that there is a trend along the slope present, particularly with regards to the MDS y ordinates, although confirming any correlations statistically is difficult as there are only three data points.

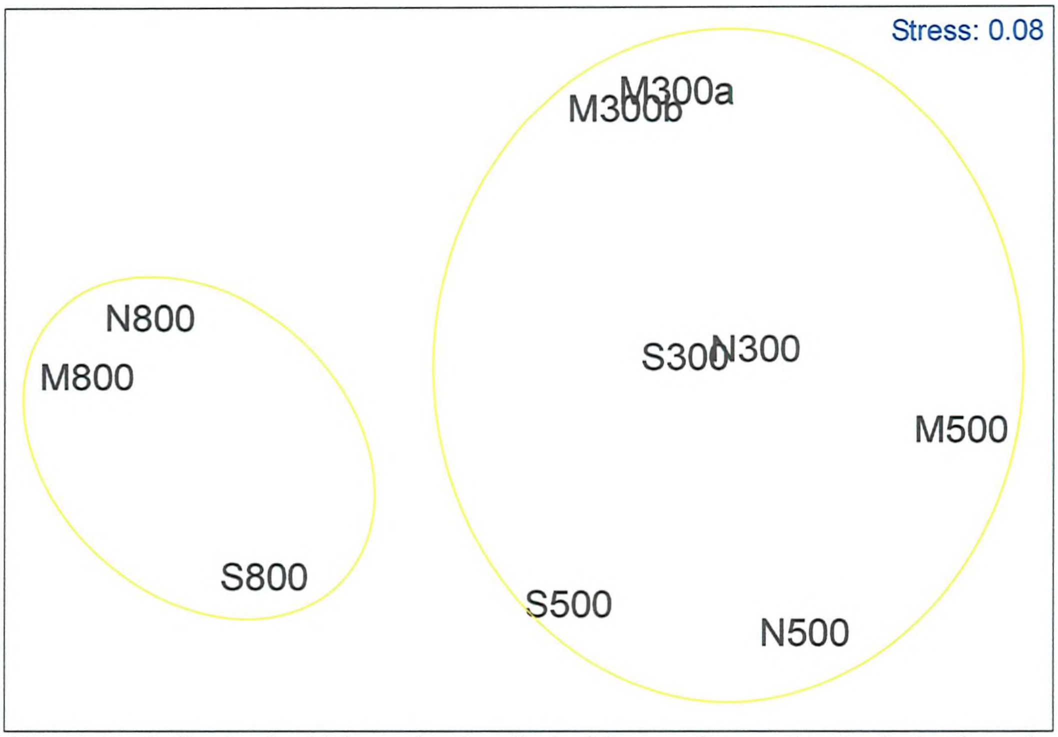


Figure 7.12. Ordination (multi-dimensional scaling) of the megafauna at the sites in the along-slope study west of Shetland

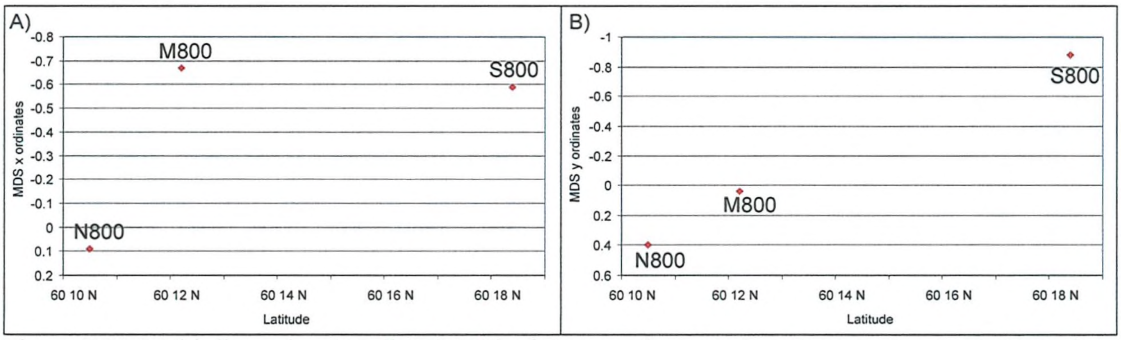


Figure 7.13. Multi-dimensional scaling (MDS) of the megafauna at sites along the lower continental slope west of Shetland; A) MDS x ordinates against latitude and B) MDS y ordinates plotted against latitude.

7.3.4 *Physical parameter analysis – current flow*

As determined from photographs, the apparent direction of the current flow (table 7.8) is towards the northeast on the upper continental slope (<500 m) but towards the south-south/southwest at depth (800 m). However, while the indicators on the upper continental slope clearly indicate a flow towards the northeast, the direction of the current flow at depth is somewhat less obvious, particularly in the mid- and southern regions, where the indicators show flow in both directions.

Site	Depth	Indicator	Current direction
N300	300 - 303 m	Scouring behind rocks	Towards N – NE
M300a	290 – 275 m	Sand ripples and scouring	Towards N – NE
M300b	294 – 278 m	Scouring behind rocks	Towards N – NE
S300	304 – 324 m	Scouring behind rocks	Towards northeast
N500	496 – 486 m	Scouring behind rocks	Towards E - NE
M500	507 – 496 m	Scouring and deposition	Direction unknown*
S500	512 – 504 m	Sand ripples and scouring	Towards N – NE
N800	812 – 787 m	Sand ripples	Towards the south
M800	798 – 781 m	Sand ripples	Towards north/south
S800	816 – 829 m	Scouring behind rocks	Towards NE/SW

Table 7.8. Indicators and current directions along the continental slope west of Shetland (* = no overlaps of succeeding frames were available – direction of current flows can therefore not be determined).

7.3.5 *Other features*

7.3.5.1 *Lebensspuren*

The observed *lebensspuren* consist of furrows, narrow furrows, burrows, circle of burrows (fairy rings), shallow burrows (possibly produced by fish), asteroid feeding pits and gastropod trails (fauna seen). These have all been reclassified according to Seilacher (1953), as described in chapter 6, and the results can be seen in table 7.9. The results show that crawling traces are most frequently observed and dominant at the shallowest depths (300-500 m) in all regions while dwellings are dominant at depth (800 m). The latter does, however, only refer to the mid- and northern regions as crawling traces are dominant at 800 m in the south. There is another difference between the regions with regards to the trace densities. At 300 m, there is little difference in trace density along the slope. At 500 m and 800 m, however, the trace densities are higher in the northern- and mid-regions compared to those of the southern region. A similar pattern is seen in the relative frequency, with similar values throughout the 300 m depth interval while higher values are seen in the northern- and mid-regions compared to the south at both 500 m and 800 m. These results therefore appear to suggest that there is a difference in the distribution and number of *lebensspuren* in the south of the along-slope study area compared to those in the mid- and northern regions, at least at 500 m and 800 m.

Parameter	**N300**	**M300a**	**M300b**	**S300**	**N500**	**M500**	**S500**	**N800**	**M800**	**S800**
Relative frequency	37.7%	21.7%	34.3%	25.9%	58.0%	25.1%	0%	51.4%	99.1%	29.5%
Trace density	2.0	2.0	3.0	1.8	3.2	1.8	0	11.2	12.6	4.0
Crawling traces	114	14	32	19	29	45		6	4	93
Dwellings		2	2	5		5		292	207	8
Resting traces			11					1	1	
Feeding structures			1							

Table 7.9. Lebensspuren data for the sites in the along-slope study west of Shetland (M300a refers to 53913#1 and M300b refers to 53926#1). Relative frequency and density data refer to the sites overall total values (density = individuals / $100m^2$).

7.3.5.2 Trawl marks

Trawl marks have been observed at depths down to 800 m but only in the southern region (table 7.10). None were observed in the northern region, while only four were seen in the south. A total of 25 were, however, recorded in the mid-region, indicating that fishing activity here is more frequent than in the other regions, but only at the shallower depths (300 m).

Site	**Depth**	**Mark**	**Number and size**	**Density (trawl marks/$100m^2$)**
N300	300 - 303 m	None observed		
M300a	290 – 275 m	Trawl marks (otter-board marks and marks from trawl nets)	13 marks	1.6
M300b	294 – 278 m	Trawl marks (from trawl nets)	12 marks	0.8
S300	304 – 324 m	Trawl mark (from trawl nets)	1 mark	0.02
N500	496 – 486 m	None observed		
M500	507 – 496 m	None observed		
S500	512 – 504 m	None observed		
N800	812 – 787 m	None observed		
M800	798 – 781 m	None observed		
S800	816 – 829 m	Trawl marks (from trawl nets)	3 marks	0.1

Table 7.10. Trawl marks observed at different sites in the along-slope study west of Shetland.

7.3.5.3 Other features

The only items found were observed at station 53922#1 (approximately 800 m) and consisted of some ropes, which might have been part of some kind of lost fishing gear.

7.4 DISCUSSION

7.4.1 Seabed analysis

The seabed analysis has revealed a sediment distribution pattern very similar to the results identified along the bathymetric transect west of Shetland (chapter 5) and those described by Masson (2001) and others (see chapter 2; Stoker *et al.*, 1991; Stoker *et al.*, 1993; Masson *et al.*, 1996, 1997; Stoker *et al.*, 1998). Several different sediment zones along the continental slope have been identified from sidescan sonar images (see figure 7.14) and the observations made from the photographs in this study confirm these patterns (see the superimposed photographic sites on figure 7.14). The presence of two main sediment types, 'coarse' and 'medium', is evident throughout the shallower sites (300 m) and there is repeated change in the segments, of various lengths, of these two sediment types throughout the runs, a pattern indicative of iceberg plough marks (see chapter 8 for a detailed study). Iceberg plough marks are evident on many polar and high latitude continental shelves and slopes (Belderson and Wilson, 1973; Belderson *et al.*, 1973; Miller and Barnes, 1985; Drewry, 1986; Bass and Woodworth-Lynas, 1988; Lien *et al.*, 1989) and while some are still being created (in the Arctic and Antarctic), the plough marks west of Shetland are relict features potentially produced during one of at least three glacial periods in the last 0.44 Ma (Stoker *et al.*, 1993). During these periods grounded ice-sheets extended to the shelf-edge, gouging the seabed and depositing coarse debris directly on to the slope (Stoker *et al.*, 1991). Considerable evidence of both is present at 300 m west of Shetland with plough marks being present between 200-500 m and coarse debris found throughout the west of Shetland region (Stoker *et al.*, 1998). The coarse sediment seen at 300 m is most likely linked to the coarse debris from the grounded ice sheets but also to strong currents transporting much of the finer material towards the northeast (see chapter 2; Kenyon, 1986; Stoker *et al.*, 1993; Masson, 2001). The overall sediment characteristics appear to be very similar all along the continental slope at this depth. These observations are also supported by the seabed sampling data (see table 7.2; AFEN 2000), illustrating further that there is little apparent difference in sediment composition between the three regions.

At 500 m the sediment overall is coarse, a fact that is likely to be associated with the strong currents on the upper part of the slope (see chapter 2; Kenyon, 1986; Stoker *et al.*, 1993; Masson, 2001), removing the majority of the finer material, but contrary to the results seen at 300 m, the sediment distribution at 500 m is not uniform throughout the three regions within the depth interval. In the northern and mid-regions the seabed is relatively coarse, with a large number of cobbles and boulders (drop-stones which are characteristic of the Faroe-Shetland Channel; Stoker *et al.*, 1998) spread within the sandy and gravely sediments, but much less so in the southern region. In the southern region sand and gravel dominate and although cobbles and boulders are present, the numbers are much lower than within the other two regions. At 500 m the sediment therefore appears to become coarser from south to north along the continental slope west of Shetland. The reason for this apparent variation along the slope is unknown but as the overall sediment is similar, with the number of cobbles and boulders being the main difference, perhaps it simply is because of a smaller supply of larger material (e.g. drop-stones) to the southern region of this along-slope study.

The iceberg plough mark zone, as identified from TOBI sidescan sonar, reaches down to 500 m (Masson *et al.*, 1996, 1997; Masson, 2001) but from the photographs used in this study there is little apparent visual evidence of two, or more, sediment types with distinct boundaries between them as identified at 300 m. The plough marks are known to become fewer and larger with depth with only a few reaching depths below 500 m (Masson *et al.*, 1996, 1997; Masson, 2001) and perhaps the lack of detectable plough marks at this depth in this study is related to the fact that they are rare. Additional photographs and perhaps a more refined method may be required to detect these marks using photography and to identify the boundaries between the different sediment types at this depth.

At 800 m the sediment distribution varies, as at 500 m, between the regions but overall the sediment is finer at 800 m than that observed on the upper parts of the slope. Sand dominates in the northern and mid-regions (see figure 7.14), a feature identified as a sand contourite with a unique associated fauna (see below), a feature also particularly apparent at 900 m along the bathymetric transect (see chapter 5). In the southern region, however, much coarser sediment is found and the sediment therefore becomes finer from south to north at 800 m, the reverse of that seen at 500 m. The coarse sediment at the S800 site, consisting of gravel with the occasional boulder appearing throughout the photographic run, is also interspersed with sections of fine material consisting of sand (or perhaps sandy mud). These overall observations are also noticeable in the AFEN sampling data (table 7.2) and although correlation analyses are not possible (n=3), the overall patterns identified from the photographs are also evident within the seabed sampling data both at 500 m and 800 m. Furthermore, the observations made by Masson (2001), including the report that erosional features predominate in the south (large-scale depositional bedforms are absent) while depositional features such as sand waves and sand sheets are dominant in the north (north of 61°05'N), are consistent with the result from this study. It has been suggested that the erosional features in the south are linked to stronger currents in that region compared to the northern- and mid-regions, a fact that may be linked to a narrowing of the channel, leading to a constriction of the flow (Masson, 2001).

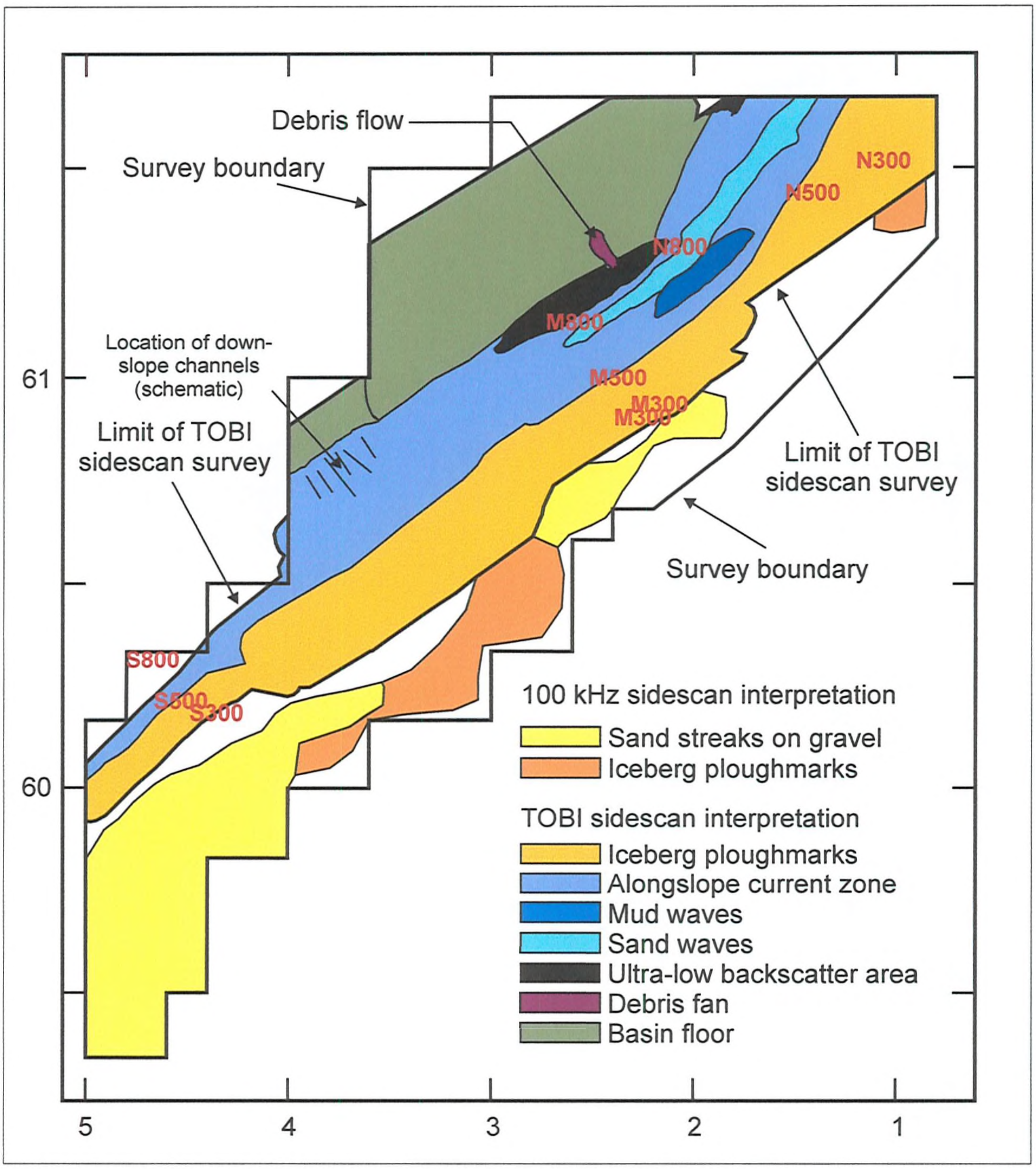


Figure 7.14: interpretation of TOBI sidescan sonar imagery from the continental slope west of Shetland with the sites from the along-slope study area superimposed.

7.4.2 *Faunal analysis*

7.4.2.1 General observations

The megafaunal distributions show evidence of along-slope variations within all three depth intervals. There are furthermore local-scale features within the regional variations as well as an additional large-scale pattern. The former refer to the iceberg plough marks at 300 m, the 'sponge-belt' apparent at 500 m and the sand contourite present at 800 m, while the latter refers to the division of the megafauna into two layers. There has been a lot of interest in the deep-sea coral *Lophelia pertusa* in recent years (Rogers, 1999; JNCC, 2002, 2003) and it has been collected around the Faroe Islands (Fredriksen *et al.*, 1992; Jensen and Fredriksen, 1992) as well as in the northern Rockall Trough (see chapter 9; Bett, 2000b; Bett *et al.*, 2001a; Masson *et al.*, 2003). *Lophelia pertusa* was, however, not observed anywhere in this along-slope study, or along the bathymetric transect (chapter 5) despite being seen on seabed photographs at one site at 550 m (station 53801#1) within the northern-region WASP sampling runs as well as collected in two samples (see figure 7.1) at site D3 (see figure 5.2 or 7.2) at 250 m (only dead fragments) and site G3 at 330 m (live and dead fragments) (Bett, 2000a). *Lophelia pertusa* therefore appears to be present in some areas within and around the Faroe-Shetland Channel but rare on the continental slope west of Shetland.

7.4.2.1.1 The iceberg plough marks

The presence of iceberg plough marks on the upper continental slope west of Shetland was noted in the seabed sediment analysis section (see above), where at least two types of sediment were identified, 'coarse' and 'medium' sediment types. The fauna appears to be closely linked to the sediment type with some faunal groups, the cidarids and squat lobsters, being observed mainly on the 'coarse' sediment, dominated by gravel, pebbles and cobbles, while other groups, the irregular echinoids (possibly *Spatangus purpureus*) and *Stichopus tremulus*, are found mainly on the 'medium' sediment type, dominated by sand and gravel (see chapter 8 for a detailed study; Bett, 2000a; Bett and Axelsson, 2000).

7.4.2.1.2 The 'sponge-belt'

The 'sponge-belt', a feature where sponges are particularly widespread, was identified in the bathymetric transect study (chapter 5), where it was found at depths between 500 m and 600 m (sites M500 and M600). A similar feature was found at N500 but in the south (S500) there was very little evidence of a 'sponge-belt'. In the north- and mid-regions sponges are the dominant megafaunal group but many other species (e.g. squat lobsters

(*Munida* sp.), sea stars, pencil-spined urchins (cidarids) as well as irregular urchins (spatangids)) are also present, presumably as a result of the large number of habitats created by the coarse nature of the sediment as well as the presence of the sponges themselves. As discussed in more detail in chapter 5, similar features to the 'sponge-belt' have been reported from other sites in the Faroe-Shetland Channel, including the Faroe Shelf and continental slope region where they are known as 'ostur' or 'ostebund' (Klitgaard *et al.*, 1997), with a rich associated fauna of over 200 different taxa (Klitgaard, 1995). The presence of these features has been attributed to some aspect of an internal tide (Sherwin, 1991; 1995), the effects of which are believed to increase the detrital flux, enabling the large number of sponges to flourish at these depths (Klitgaard *et al.*, 1997).

7.4.2.1.3 The sand contourite

The discovery of the sand contourite was initially made with the TOBI sidescan sonar (Masson *et al.*,1996, 1997; Masson, 2001*)* and also confirmed after the photographic analysis (as discussed in chapter 5) as well as the analysis of the seabed samples from this region (Masson, 2001). The novel discovery of the enteropneusts present on this sediment at both 800 m (M800) and 900 m (M900), together with high densities of both anemones and sea spiders, was noted in chapter 5. In this study this feature has also been shown to be present at 800 m (N800) in the northern region but while the densities (table 7.11) of the main megafauna are slightly lower than those seen at the 900 m site (higher than the 800 m values) along the bathymetric transect, these results further support the sidescan sonar results illustrating that the sand contourite stretches several kilometres up the Faroe-Shetland Channel (see figure 7.14; Masson *et al.*, 1996, 1997; Masson, 2001).

Taxa	N800	M800	M900
Acorn-worms	16.3	0.5	101.2
Anemone B	30.6	11.1	75.4
Sea spider A	3.7	4.3	5.1
Sea spider B	2.2	3.1	2.6

Table 7.11. Faunal densities (individuals/100m^2) of the main taxa found associated with West of Shetland sand contourite (M900 is from the bathymetric transect study, chapter 5; see table 7.7 for brief descriptions of the fauna).

7.4.2.2 Abundance

The analysis of the abundance data in this study is made more difficult by the fact that site N300 was sampled without the altitude recordings being made on the film at exposure and the density values at site M500 are likely to be underestimates as the sponges were not fully enumerated. In the case of site N300, true abundance values are therefore difficult to estimate and even though the average value (5.65 m) for all the sites available was used, the values may be incorrect. In addition, it was not possible to carry out the second stage of frame selection and some (or several) frames might have been included in the analysis despite the fact that the altitude was in excess of 6 m. To assess any variations along the slope is therefore difficult but taking these aspects into account, there appears to be little evidence for an overall change in faunal density along the slope at 300 m, while more apparent changes are present at 500 m and 800 m. At 500 m there is a considerable difference in the abundance of sponges present in the north- and mid-regions compared to the south (M500 is an underestimate). Acorn-worms are an obvious feature at 800 m in the north- and mid-regions, i.e. the contourite, but were not observed in the south. Although there is no overall along-slope density trend at 300 m, there are, however, some variations in the most abundant megafauna present. This is particularly evident in the squat lobsters (*Munida* sp.) but also seen in the Asteroid A, both showing a decrease in density from the southern towards the northern sites. In addition, polychaetes, Cushion star A (believed to be *Porania pulvillus*) and cidarids (?*Cidaris* cidaris) are most abundant in the southern region while numbers are lower in the other two regions and even absent completely from the north- and mid-regions with reference to the Cushion A and polychaetes (see table 7.7). Sponges are present in all three regions, but the densities are higher in the north and south compared to the mid-region, while the 'stalked anemones' are present in the mid-region but absent in the other two regions. Considering the apparent lack of any differences in the sediment and hydrographic environments from the photographic analysis (see above), the ecological observations are difficult to explain. There could be some small-scale sedimentary variations not visible on the photographs or notable in the seabed samples that could explain these differences. In fact, Bett (2001a) noted an increase in silt and clay content along the continental slope (south to north), a fact suggested to be linked to the widening of the channel in the north, leading to a settling out of finer material. This is seen in the mean sediment grain size (Phi) in this study (table 7.2) and this may affect the faunal distribution the most. Another possibility is trawling as trawling activity was observed in the mid-region but not in the other two regions (table 7.10). Trawling may of course be present in the other regions as well and in addition any effects on the density values are difficult to assess.

Comparing the density values obtained in this study is difficult as there are no comparable megafaunal studies on the continental slope west of Shetland. There are some studies where the continental shelf west of Shetland was sampled (see table 7.12) using photographic instruments (Dyer *et al.*, 1982; Cranmer *et al.*, 1984) and trawls (Basford *et al.*, 1989). Some other examples from the northern Rockall Trough are also given (table 7.12). The results from these studies show ranges of faunal density similar to those seen in this study despite the suggestion that megafaunal abundance between areas may be large in comparison with differences resulting from the method of sampling alone (Lampitt *et al.*, 1986).

Taxa (previous studies)	**Densities from photographs**	**Taxa (this study)**	**Densities from photographs**
Pennatula phosphorea * Pennatulacea #	0.14 ind./m^2 (shelf) 0.11 ind./m^2 (1295 m)	Pennatulacea	0.01 – 0.10 ind./m^2 (800 m)
Munida rugosa + *Munida tenuimana* #	0.03 ind./m^2 (shelf) 0.45 ind./m^2 (712 m)	*Munida* sp.	0.03 – 0.14 ind./m^2 (300 m) 0.08 – 0.38 ind./m^2 (500 m)
Asterias rubens *	< 0.02 ind./m^2 (shelf)	Asteroid B sp	0.01 – 0.04 ind./m^2 (500 m)
Spatangus purpureus ^	0.001 – 0.004 ind./m^2	*Spatangus* sp.	0.05 ind./m^2 (300 m)
Cidaris cidaris *	0.09 – 0.22 ind./m^2 (shelf)	*Cidaris* sp	0.01 – 0.02 ind./m^2 (500 m)
Echinus acutus * Echinoidea #	0.07 – 1.68 ind./m^2 (shelf) 0.10 ind./m^2 (721 m)	*Echinus* sp.	0.002 ind./m^2 (300 m)

Table 7.12. Examples of faunal densities in some studies from the continental shelf west of Shetland (*=Dyer *et al.*, 1982; ^ = Cranmer *et al.*, 1984; + = Basford *et al.*, 1989) and northern Rockall Trough (# = Roberts *et al.*, 2000).

7.4.2.3 Species diversity

Species diversity has been shown to vary geographically with several different trends and overall diversity is believed to decrease towards the poles (Zezina, 1997), a trend exemplified in the northeastern Atlantic, where it has been suggested to be a decrease in species diversity with latitude with low species diversity in the Greenland and Norwegian Seas (Gage and Tyler, 1991; Rex *et al.*, 1993). More specifically, a sharp contrast has been reported between species (macrofauna) diversity in the northern Rockall Trough (high diversity) and the Faroe-Shetland Channel (low diversity) (Bett, 2001a). Suggestions for explaining the low diversity in the northern region include geographic isolation (Gage and Tyler, 1991) and extensive ice cover in the past. The Norwegian Sea and the northern reaches of the Atlantic were covered with ice during the Quaternary glaciation, and it has been suggested that the low diversity values seen in this region represent a recovery from the effects of glaciation (Menzies *et al.*, 1973; Tait, 1981; Rex *et al.*, 1993), a suggestion also made for the difference seen between the macrofauna in the Rockall Trough and Faroe-Shetland Channel (Bett, 2001a). In this study, some variations in diversity have been noted but the results are rather complex. There is an increase in Shannon-Wiener diversity and species richness from southern to northern sites at 300 m and 500 m but while there is an along-slope increase (south to north) in species richness at 800 m, the opposite is seen in Shannon-Wiener diversity at the same depth. Evenness increases from south to north at 300 m but an opposite trend is seen at both 500 m and 800 m (figures 7.7 and 7.8). The rarefaction analysis reveals little evidence of along-slope trends in species diversity, although differences between the sites can be seen. Overall there appears to be some evidence for an increase in species diversity along the slope south to north at 300 m, but at 500 m and 800 m the evidence is less convincing. In addition it should be noted that there appears to be a decrease in diversity with depth, a result also seen in the bathymetric transect (chapter 5). The potential increase in species diversity at 300 m may be related to the change in sediment (getting finer with latitude; Bett, 2001a) along the slope as was noted in the abundance analysis but as the difference in the values are small and the results overall in the study inconclusive, definite conclusions are difficult to make. It is possible that the distances between the sites are too small to record any clear evidence of along-slope change in diversity and further sampling, using additional sampling sites along the continental slope, is required to assess this further.

7.4.2.4 Faunal composition

The results of the faunal composition analysis largely reflect the results seen in the density study, essentially indicating variations at all depths along the continental slope west of Shetland. There are differences in both megafaunal and sedimentary distributions where the mid- and northern regions are different from those of the south at all three depths. The most obvious examples of the faunal variations are the sponge-belt at 500 m and the enteropneusts at 800 m but other examples are also present (see result section) and in many cases the southern region appears to be different to the other two. While fine-scale sedimentary differences have been seen in this (table 7.2) and other studies (Bett, 2001a) at 300 m (i.e not apparent in the photographs), more apparent differences in the sediment characteristics are present at both 500 m and 800 m in this (table 7.2 and 7.4) and other studies (Bett, 2000a, 2001a; Masson, 2001) and although significant correlation analyses are not possible (n=3), sediment appears to be the main controlling factor for these regional differences, a suggestion also made for the variations seen in the macrofauna (Bett, 2001a).

In addition to these regional variations along the slope, the multi-variate analyses have furthermore divided the sites into shallow-water sites (300 m and 500 m) and deep-water sites (800 m). The cluster analysis (figure 7.11) and ordination (figure 7.12) in this study grouped the deep-water sites together and the shallow-water sites together. The results of the faunal density and composition analyses in the along-slope study indicate that some megafauna are restricted to the upper part of the slope, while other groups are found only at the deeper sites. Polychaetes, pycnogonids (sea spiders) and enteropneusts (acorn worms) are only seen in the 800 m depth interval, while echinoids and holothurians are found at 300 and 500 m but not at 800 m. The boundary between the two zones is difficult to determine with sites at 300 m, 500 m and 800 m but considering the results in chapter 5, the boundary is most likely at approximately 600 m. The results from the other data are, however, somewhat more complex, although there appears to be a decrease in species richness (figure 7.6) and rarefaction (figure 7.9). For a more detailed study of these variations, see chapter 5.

7.4.3 Physical parameters

The prevailing currents were identified to flow towards the northeast on the upper continental slope both in this study and in the bathymetric transect study (chapter 5) a result also reported for many other studies (see chapter 2; Kenyon, 1986; Stoker *et al.*, 1993; Burrows *et al.*, 1999; Turrell *et al.*, 1999; Bett, 2001a; Masson, 2001). The flow at 800 m is, however, slightly more uncertain but the evidence in this study and the bathymetric study (chapter 5) suggests a flow towards the south-southwest, although it has been suggested that the sediment characteristics seen on the photographs are relict or potentially the result of a northeastward flowing current (Masson, 2001). Given the complex hydrography of the region, it is possible that significant flows in both directions may occur, further study will be required to assess the detailed hydrodynamics of the mid-slope depths.

7.4.4 Other observations

7.4.4.1 Trawling

Trawling has been shown to occur in many parts of the Atlantic Margin but west of Shetland, trawling appears to be largely restricted to the upper continental slope with some seen down to 600 m along the bathymetric transect (chapter 5). In this study, however, a few trawl marks were recorded at 800 m in the southern region, a result not reported elsewhere from this region. Bett (2000c) reported similar results to those seen in chapter 5, with the majority of trawl marks observed between 300-600 m. All these observations agree well with the limits (down to c. 500 m) of the established fisheries for commercially valuable species (e.g. *Lophius piscatorius* (anglerfish), *Molva dypterygia* (blue ling) and *Sebastes* spp. (redfish)) in this area (Gordon, 2001). The trawl marks seen at 800 m in the southern region, however, could potentially be linked to a relatively new fishery (from 1995) for *Reinhardtius hippoglossoides* (Greenland halibut) with some bycatch species, which has been reported to occur within the 'transitional zone' between the impoverished fish fauna found in the deep-, cold-water layer and that of the shallow-, warm-water layer within the Faroe-Shetland Channel (Gordon, 2001). This fishery is believed to occur at depths of approximately 500-700 m (Gordon, 2001) but perhaps it stretches down to 800 m which could explain the trawl marks seen at this depth in this study. Whether this fishery occurs in the other regions along the continental slope is unknown and further photographic sampling is required to assess this further.

7.5 CONCLUSIONS

This study has revealed a number of patterns along the continental slope west of Shetland. Differences in both megafaunal distributions and sediment type between the southern and the mid- and northern regions, particularly with regards to 500 m and 800 m. While the 'sponge-belt' is an obvious and dominant feature at 500 m in the mid- and northern regions, it is much weaker in the south. The sediment is less coarse and the sponge seabed cover is less with smaller sizes and lower numbers of individuals in the south. At 800 m, the sediment is fine in the mid- and northern regions but coarse in the south, a fact also reflected in the distribution of megafauna and *lebensspuren*. The densities of *lebensspuren,* polychaetes, anemones and sea spiders are higher in the mid- and northern regions compared to the south and while acorn worms are present in the mid- and northern regions, they are absent in the south. The distribution of both sediment and megafauna within the iceberg plough mark zone (300 m) is, however, similar in all three regions, although there appears to be some differences in some of the megafauna present. These differences may be linked to trawling, as this activity appears to be most widespread in the mid-region while only a few trawl marks were seen in the south and none in the northern region but further photographic sampling is required to assess this fully. Other factors (e.g. sediment grain size and current regime) may also be important and influence the differences between the regions.

In addition to the main along-slope variations identified in this study, a depth trend has also been identified. Two main biological zones of megafaunal distribution have been identified with an upper layer (300 m – 500 m) and a lower layer (800 m). These results support those from the bathymetric transect study (chapter 5) and others (Bett, 2000a, 2001a; Narayanaswamy, 2001), where the boundary between the two main zones was identified to be at approximately 600 m. It is likely that the boundary in the along-slope study area is found at a similar depth. The main factors controlling this distribution are believed to be depth, sediment grain size and temperature (see chapter 5), although hydrographic factors may also be important, exemplified by the stronger currents believed to be present in the southern region (800 m) as a result of a narrowing of the channel.

The integrated approach used in this study has until the AFEN surveys been rare in deep water surveys, although similar approaches have been used in shallow-water habitat mapping (e.g. Todd, *et al.*, 2000; Kostylev *et al.*, in press). The results and success of the AFEN projects illustrate the great potential of an integrated approach to deep-sea habitat mapping, techniques that are likely to become more important in of future deep-water environmental surveys.

8 AN INTEGRATED STUDY OF THE ICEBERG PLOUGH MARKS ON THE UPPER CONTINENTAL SLOPE WEST OF SHETLAND

8.1 INTRODUCTION

Iceberg plough marks are widespread and occur on almost all continental shelves and slopes at high latitudes around the world including the Arctic, Antarctic and the northeast Atlantic Ocean (e.g. Belderson and Wilson, 1973; Belderson *et al.*, 1973; Miller and Barnes, 1985; Drewry, 1986; Bass and Woodworth-Lynas, 1988; Lien *et al.*, 1989; Mortensen *et al.*, 2001). The plough marks are found on present-day polar continental shelves where they are currently being formed, and on shelves at lower latitudes where they are relict features from former glacial episodes (Drewry, 1986).

Gouging of the seafloor takes place when either sea-ice keels or the bottoms of icebergs run aground in shallow water and the ploughing action of these drifting icebergs produces deep furrows (Figure 8.1) in the sediment (Drewry, 1986). Marks made by ice-keels are restricted to continental shelf areas shallower than 100 m. The marks produced by icebergs are found on the outer shelf and continental slope at depths between 50 and 500 m (Drewry, 1986; Stoker *et al.*, 1993).

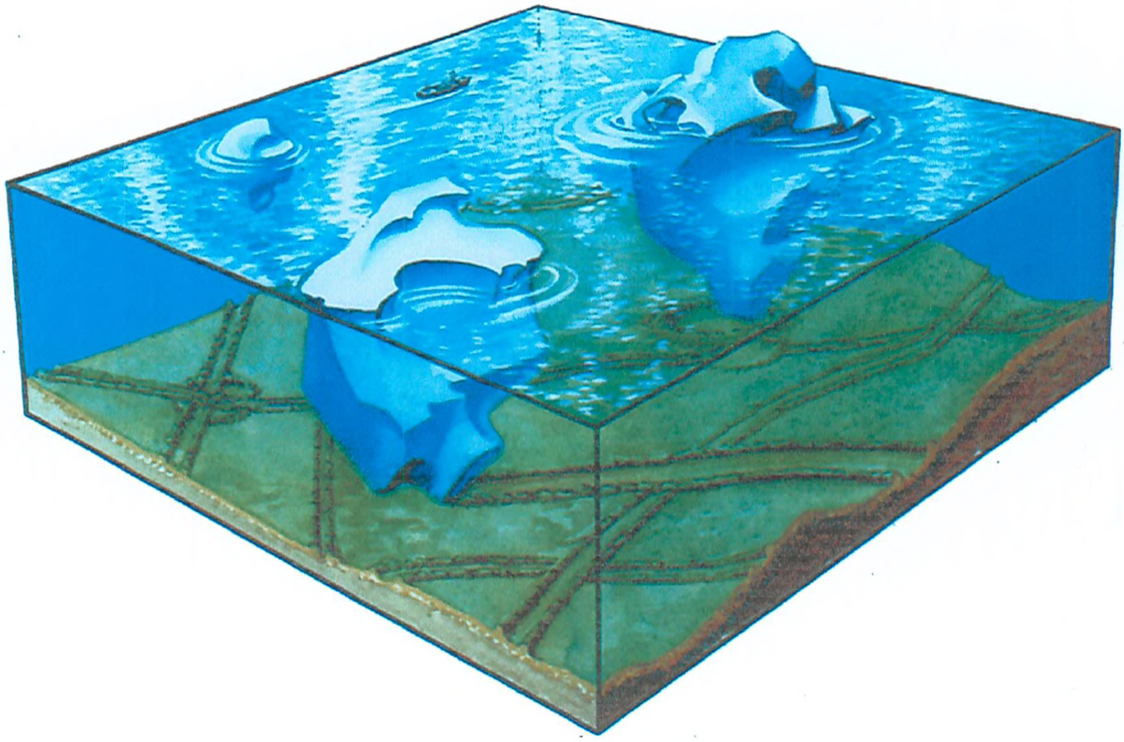


Figure 8.1. The creation of iceberg plough marks (from Drewry, 1986).

The morphology of plough marks varies considerably depending on the properties of the underlying sea floor, the geometry of the impacting ice keel, characteristics of the motion of the ice and the nature of the impelling forces (Drewry, 1986). In stiff, cohesive sediments, ice keels may create irregular, rough grooves and associated flanking ridges, features that are not readily modified by wave action. In less cohesive, soft sediments plough marks are more regular and continuous but are rapidly modified by currents and wave action (Drewry, 1986).

According to Bond *et al.* (1992) there is evidence of massive discharges of icebergs into the North Atlantic during the last glacial period and there is direct evidence for at least two glaciations in the area northwest of Britain, both of which are believed to have occurred during the Pleistocene period (Stoker and Holmes, 1991). During both events, continental ice-sheets are believed to have reached the shelf-edge, having been of a submarine character and resulted in ice-marginal sedimentation on the slope as well as the release of drifting icebergs (Stoker, 1988; Stoker and Holmes, 1991; Stoker *et al.*, 1993; Stoker, 1995). Further south the ice-sheet is also believed to have reached the shelf edge on the northern Hebrides shelf and it may even have reached the Wyville- Thomson Ridge, if only for a short period (Stoker, 1988).

On sidescan sonar imagery the plough marks appear as semi-parallel lines or as a 'criss-cross' pattern of short and long winding grooves and furrows along the seafloor consisting of alternating high and low backscatter (Belderson *et al.*, 1973; Belderson and Wilson. 1973). The processing of SOC TOBI sidescan sonar imagery from the Atlantic Margin Environmental Survey (AMES) of 1996 (Bett, 1997) revealed the presence of the characteristic pattern of iceberg plough marks (Masson *et al.*, 1996; Masson *et al.*, 1997; Masson, 2001). These patterns were found to dominate the seafloor at depths between 140 and 500 m (see chapter 2), results similar to earlier studies from the same region (Belderson *et al.*, 1973), and the extent of these plough marks can be seen on figure 8.2. The plough marks are typically 20 - 100 m wide, 2 - 10 m deep and can be several kilometres long (Belderson *et al.*, 1973; Masson, 2001), with the longest mark being some 5.5 km (Belderson *et al.*, 1973). The importance of the plough mark terrain in the deep waters around Shetland is currently being assessed and a portion of this zone may eventually be selected for protection under the EC Habitats Directive (92/43/EC) as a

'Special Area of Conservation' to represent 'reefs', one of the main habitat variants identified to occur in UK offshore waters (JNCC, 2002).

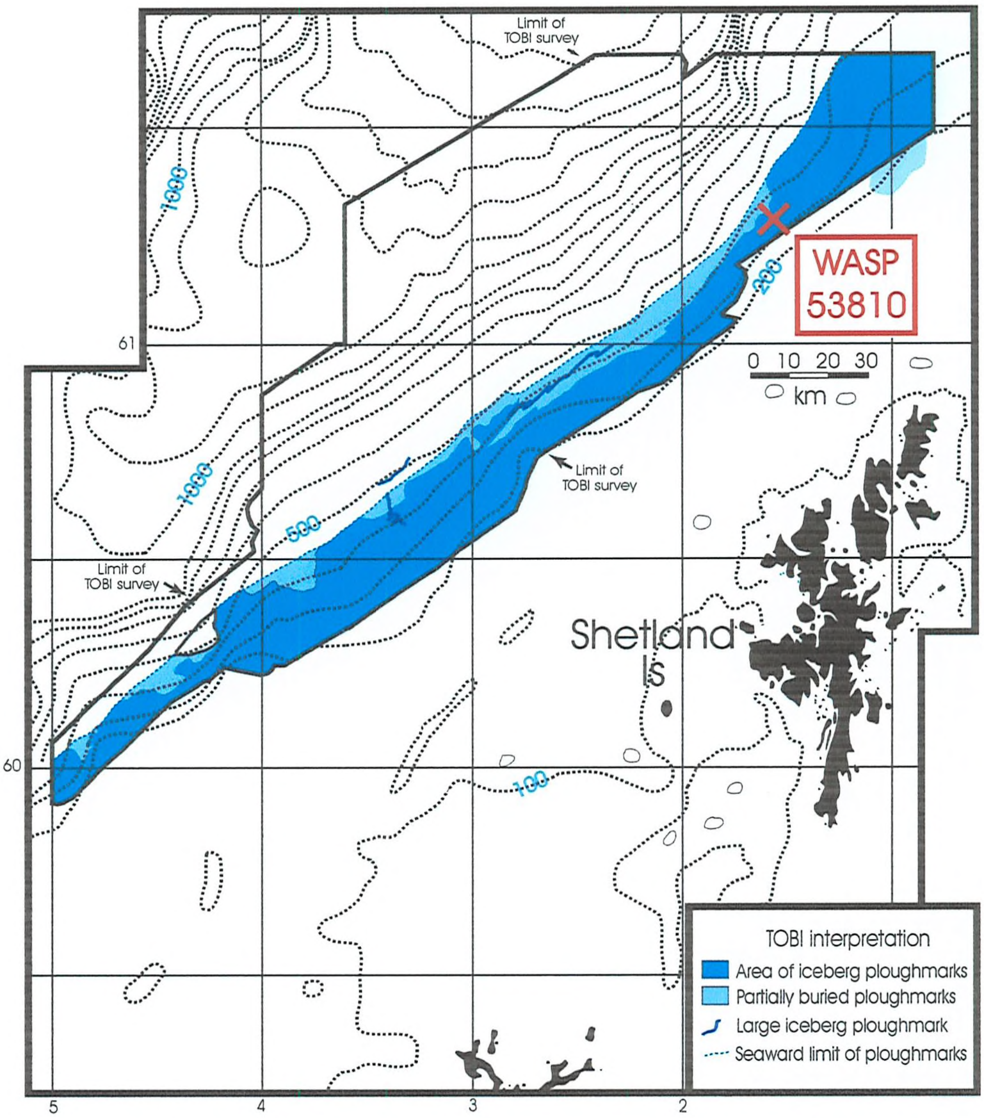


Figure 8.2. The extent of iceberg plough marks within the survey conducted using TOBI and the position of WASP station 53810#1 (adopted from Masson, 2001).

Samples and photography have shown that areas of high backscatter on the sidescan sonar imagery relate to areas of coarse material, i.e. cobbles, boulders and gravel (Belderson *et al*., 1973, Masson, 2001). The areas of low backscatter relate to finer material, mainly sand and mud (Belderson *et al*., 1973). The icebergs produce furrows, forcing coarser material towards the margins of these furrows. Subsequently, after the Late Glacial period, these furrows have been buried or filled with finer material through deposition and reworking of the surrounding sediment which has lead to a smoothing of the margin ridges (Belderson *et al*., 1973; Masson, 2001). On the continental shelf, where there is strong tidal and bottom current activity as well as wave action, a large proportion of plough marks have been buried or eroded (Masson *et al.*, 1996; Masson, 2001). On the continental slope, however, the plough marks are widespread and the frequency of plough marks is highest at the upper part of the slope. With increased depth the plough marks become fewer but larger, deeper and more continuous (Masson *et al.*, 1997; Masson, 2001).

The deepest occurrence of iceberg plough marks west of Shetland is at approximately 500 m (Masson, 2001). Considering that these marks were produced when the sea level was 100 m lower than present-day levels, this indicates that the maximum draft of the icebergs was 400 m. Large icebergs around Greenland were in the 1930s shown to be about 80 m high giving a draft of approximately 400 m (Belderson *et al.*, 1973). This suggests that icebergs during the last Ice Age were of a similar size to present day icebergs which in turn suggests that these features are still produced in certain areas around the world, including the shelf and upper slope off Antarctica, Greenland, Norway, Iceland and around the Labrador Sea (Belderson *et al.*, 1973). Present day, in geological terms, formation of these features has been confirmed by several authors (Belderson and Wilson, 1973; Miller and Barnes, 1985; Bass and Woodworth-Lynas, 1988; Lien *et al.* 1989).

Most of the discoveries of iceberg plough marks have involved surveys using sidescan sonar instruments, but little work has been carried out relating this sidescan sonar data to groundtruth observations. In this study, photographs from a site within the iceberg plough marks (figure 8.2) are analysed and assessed to: 1) establish the nature of the seabed expression of iceberg plough marks, 2) how the seabed expression may influence the local-scale ecology of the megabenthos, and 3) how seabed expression and megafaunal ecology relates to corresponding sidescan sonar imagery.

8.2 METHODS

The WASP station, number 53810#1 (part of AMES 1996), is located (figure 8.2) northwest of Shetland (61°31'N, 01°11'W) at a depth of 300 m (300 – 303 m depth range). The frames from this photographic run within the iceberg plough mark zone west of Shetland have been processed and analysed for all details, including fauna, sedimentary character and any other features present, as described in chapter 3. The results from the sediment analysis were then used to grade the sediment and assess any variation in sediment type along the run by plotting sediment grade against time. At the boundaries there was typically a transitional zone between the two sediment types and these zones have been marked on the plots. The fauna were identified as far as possible. The results from the faunal analysis were used to calculate faunal densities for the main phyla and also for individual species/taxa to assess any differences in distribution between different sediment types. The *lebensspuren* density has also been calculated. During the operation of WASP at this station (53810#1), the imprinting of altitude (see chapter 3) on to the frames during exposure failed and these data are therefore missing. The density estimates have therefore been calculated with an overall altitude of 5.65 m throughout this study, a value obtained by averaging the altitude of all frames for the 18 photographic runs undertaken during the AMES project. The calculation was carried out after stage one of frame selection (see chapter 4). In addition to the faunal density values, some univariate parameters were calculated to further assess any differences between sediment types. The univariate measures were calculated using PRIMER (version 5; Clarke and Warwick, 1994) and included the total number of individuals, total number of species, Shannon-Wiener diversity index, Pielou's evenness index and Margalef's species richness (see chapter 5). After these calculations, the results from the photographic analyses were integrated by plotting them against time to assess any similarities or differences between the faunal and sedimentary results. These results were further tested by carrying out a G-test (e.g. Fowler and Cohen, 1992; Sokal and Rohlf, 2001) to assess the distribution of the fauna between the two types of sediment.

Finally, the photographic results were then compared to the patterns on a sidescan sonar (SOC TOBI) image from the same area. The WASP run was superimposed on the sidescan sonar image and the patterns compared to assess whether there were any similarities or differences in these results. In addition, the results from sediment analyses of both the sidescan sonar and the photographs have been plotted against time and compared to further assess any similarities or differences in sediment type along the transect. A randomisation test was carried out, where the observed result was tested to assess whether the match between the photographic and sidescan sonar interpretations was better than random chance (see e.g. Sokal and Rohlf, 2001). First the numbers of observed matches were calculated. The photographic data were then reordered randomly, compared to the sidescan sonar data and the number of matches calculated. This was repeated 1000 times. The observed value was then compared to the distribution of these calculated values at the 95% confidence level.

8.3 RESULTS: COMPARISONS OF SIDESCAN SONAR IMAGERY AND PHOTOGRAPHIC MATERIAL

A total of 302 photographs were taken at station 53810#1. The assumed average height off the seafloor of 5.65 m gives a total seafloor coverage of 5,675 m^2.

8.3.1 Seabed analysis

The seabed analysis of the photographs along the run revealed the presence of two 'types' of seafloor: 'medium' and 'coarse' sediment areas. Gravel and sand dominate the 'medium' sediment type while gravel, cobbles and boulders dominate the 'coarse' sediment type (photographs a-d in figure 8.3). The 'medium' seafloor appears homogenous (gravel and sand without any particular features) in the majority of frames but *lebensspuren* are frequently observed and in some instances there is evidence of sand streaks or bands (see photographs a-b in figure 8.3). The 'coarse' sediment is covered with scattered gravel, cobbles and boulders (see photographs c-d in figure 8.3) and in some photographs *lebensspuren* can also be seen. Out of the 302 photographs, 183 frames (approximately 3,439 m^2) were identified as the 'medium' sediment type and 119 frames (approximately 2,236 m^2) within the 'coarse' sediment type. In figure 8.4, working from left to right, the sediment is initially dominated by the 'medium' sediment type but within about five to six minutes of the run the sediment changed to the 'coarse' type. The seafloor type then changes repeatedly throughout the run. The distinction between the two 'types' of seafloor is clear, although there is often a transitional zone where a mixture of the two types is found.

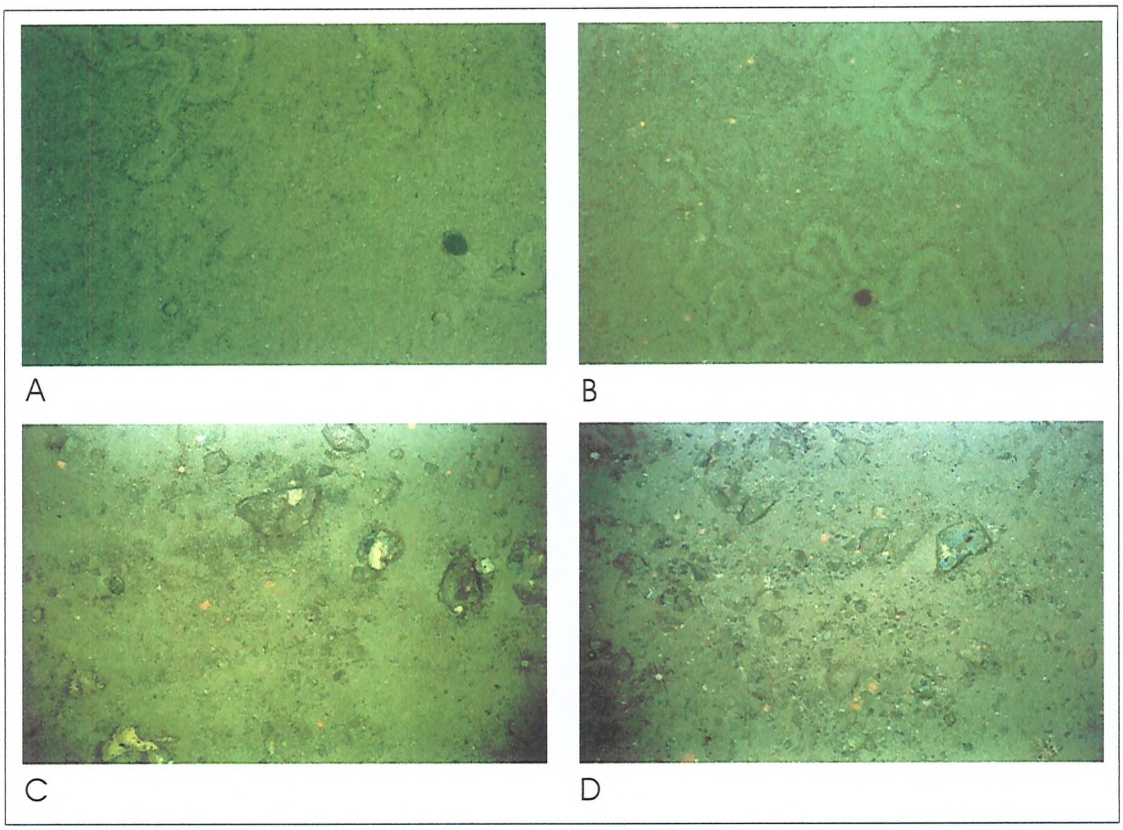


Figure 8.3. Photographs from station 53810#1 west of Shetland. Photographs a-b: 'medium' sediment dominated by sand and gravel; with purple heart urchins with their associated trails. Photographs c-d: 'coarse' sediment dominated by gravel, cobbles and boulders with pencil-spined sea urchins, squat lobsters, sponges and other fauna.

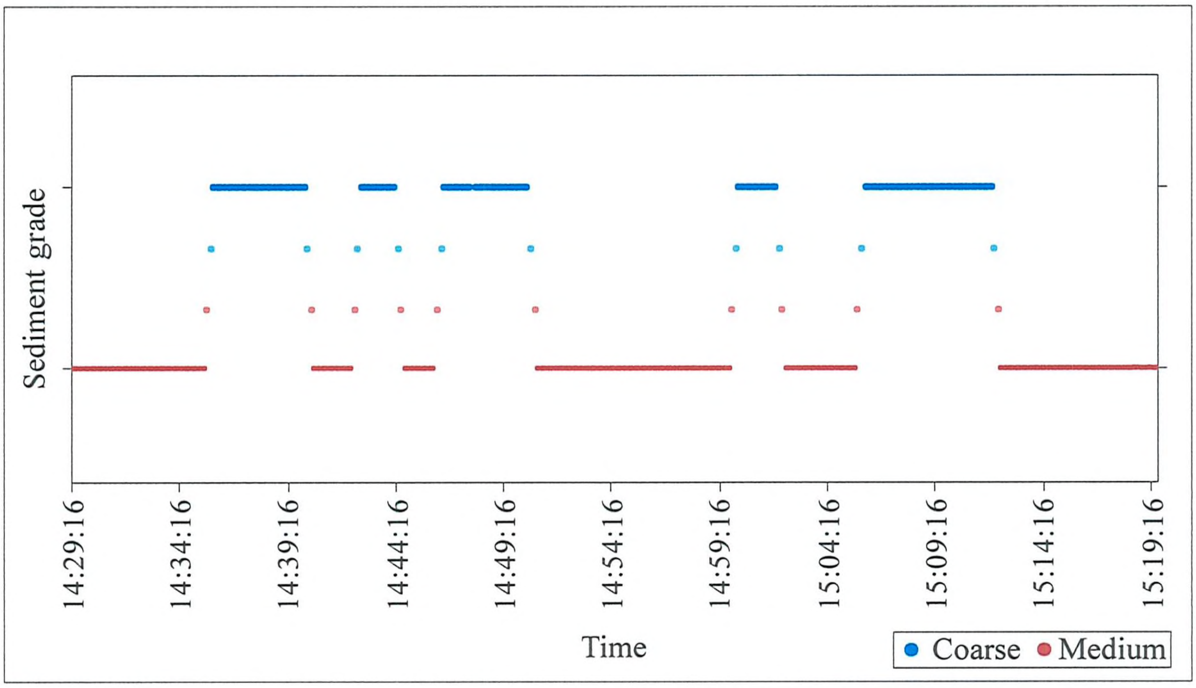


Figure 8.4. Results from the sediment analysis along the photographic run (53810#1), where blue coloured points represent 'coarse' sediment and red represent 'medium' sediment (each point represents one frame, intermediate points indicate areas of transition between sediment types).

8.3.2 Faunal analysis

The faunal analysis, referring to the megafauna (typically defined as animals visible on seabed photographs), of the photographic run revealed a seafloor dominated by echinoderms and sponges, although several other taxa were also observed (table 8.1).

Taxa	'Medium' sediment		'Coarse' sediment	
	Number of individuals	Faunal density (ind./100m^2)	Number of individuals	Faunal density (ind./100m^2)
Echinoidea	63	1.83	98	4.38
Porifera	22	0.64	116	5.19
Crustacea	2	0.06	36	1.61
Mollusca	28	0.81	24	1.07
Holothuroidea	13	0.38	3	0.13
Coelenterata	1	0.03	8	0.36
Asteroidea	3	0.09	10	0.45
Ophiuroidea	0	0	1	0.04
Fish	4	0.12	10	0.45
Bryozoa	0	0	12	0.54
Unknown	1	0.03	5	0.22
TOTAL	137	3.98	323	14.45

Table 8.1. Megafauna along the photographic run at 53810#1.

Overall, megafaunal density was almost four times higher on the coarse than the medium sediment. Some major taxa show substantial variations in density between sediment types (e.g. Porifera and Crustacea), while others are little influenced (e.g. Mollusca). The Holothuroidea are the only group that appear to be more abundant in medium rather than coarse sediment (table 8.1). Within these taxonomic groups, however, the distribution of specific fauna on the two types of sediment is more complex, where individual taxa show even more marked variations in density between sediment types (table 8.2), most notable in the case of *Munida* sp (coarse) and Spatangidae (medium), but also appreciable in the case of Cidaridae (coarse) and *Stichopus* sp. (medium). As might be expected, *lebensspuren* were more abundant on medium sediment.

Taxa	'Medium' sediment		'Coarse' sediment	
	Number of individuals	Faunal density (ind./100m^2)	Number of individuals	Faunal density (ind./100m^2)
Cidaridae sp.	38	1.10	97	4.34
Munida sp. (squat lobster)	1	0.03	35	1.57
Spatangidae sp.	22	0.64	1	0.05
Scallop	22	0.64	14	0.63
Stichopus sp.	12	0.35	3	0.13
Gastropoda sp.	5	0.15	9	0.40
Redfish	2	0.06	9	0.40
Rabbit fish	2	0.06	0	0
Lebensspuren	97	2.82	18	0.81

Table 8.2. Specific faunal groups and *lebensspuren* with the absolute numbers and their densities (individuals/m^2) along the photographic run at 53810#1.

In order to investigate this pattern further, a range of diversity measures were calculated for the total fauna recorded in the medium and coarse areas (table 8.3). Values from the coarse sediment type area generally higher, with Pielou's evenness index being the only one exception, indicating further that there is a difference in the megafauna present on the two types of sediment. The values for Shannon-Wiener diversity, species richness and equitability furthermore all compare well with those found at similar depths along the bathymetric transect (chapter 5).

Diversity measure	'Medium' sediment	'Coarse' sediment
Number of taxa, S	22	32
Shannon-Wiener diversity index, H' (log$_e$)	2.28	2.39
Pielou's evenness, J'	0.74	0.69
Margalef's species richness index, d	4.27	5.37

Table 8.3. Diversity measures for 'medium' and 'coarse' sediment types at station 53810#1 (total number of individuals are 137 on medium and 323 on coarse sediment).

8.3.3 Integration of megafaunal and sedimentary analyses

Figure 8.5 illustrates the occurrence of the four dominant taxa (as cumulative percentages) along the photographic run together with variations in sediment type (from figure 8.4). In three cases there appears to be a clear link between faunal and sediment distributions (*Munida* sp. – coarse; Cidaridae sp. – coarse (photographs c-d in figure 8.3); Spatangidae sp. – medium (photographs a-b in figure 8.3)). The *Stichopus* sp. distribution shows occurrence in both sediment types with 12 of the 15 identified individuals observed on the medium and 3 individuals on the coarse sediment. The results from the G-test analyses (table 8.4) support these observations and results (from figure 8.5) with highly significant results ($p<0.01$) with regards to *Munida* sp. (coarse), the Cidaridae sp. (coarse) and the Spatangidae sp. (medium) while no significance can be seen in the distribution of *Stichopus* sp. between the two types of sediment. There is therefore strong evidence in support of the pattern seen in the three main faunal distributions being closely linked to the repeated variation in the sediment distribution.

It should also be noted that it was difficult to identify the type of sediment present but also any distinct boundaries between the two types of sediment towards the end of the run. The former is particularly evident in the last section (the last few (c. 7) minutes) where the sediment has been identified as 'medium'. In contrast to the overall patterns identified above, 15 Cidaridae and one individual of *Munida* sp. have been observed together with the expected presence of *Stichopus* sp. and the Spatangidae on the 'medium' sediment. It therefore appears to be some local variation in this part of the run but the overall result indicates a close link between type of sediment and the megafauna present.

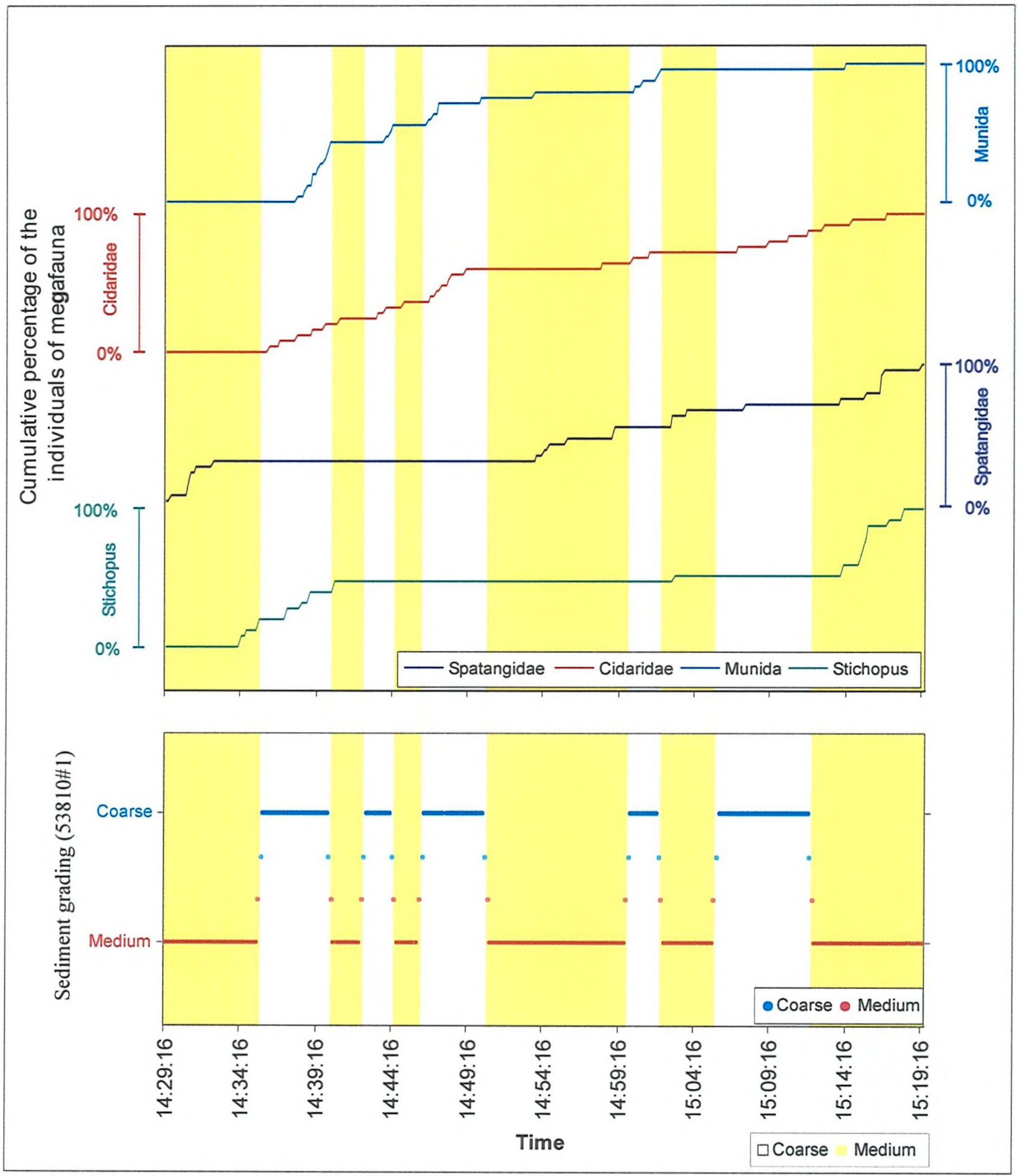


Figure 8.5. Megafaunal (cumulative percentage) and sediment grade variation along the photographic run (53810#1), running from left to right. For illustration purposes, yellow and white colours have been superimposed onto the two plots, where yellow represents the presence of 'medium' sediment and white represents 'coarse' sediment.

	Cidaridae sp.		Spatangidae sp.		*Munida* sp.		*Stichopus* sp.	
	Presence	Absence	Presence	Absence	Presence	Absence	Presence	Absence
Medium	22	161	12	171	1	182	34	149
Coarse	62	57	1	118	28	91	3	116
G_{adj}	36.96**		16.27**		47.87**		2.63	

Table 8.4. Presence and absence data on the two sediment types in the frames (183 on coarse and 119 on medium sediment) at station 53810#1, as well as the G_{adj} values, for the four main taxa (the critical values (** p<0.01) from Fowler and Cohen, 1992).

8.3.4 *Joint photographic and sidescan sonar analysis*

Figure 8.6 shows a TOBI sidescan sonar image from the area of the WASP site. The characteristic dark (low backscatter) and light (high backscatter) criss-cross pattern of iceberg plough marks, as described above, is readily seen on this image. Superimposed on the image is the photographic run from station 53810#1.

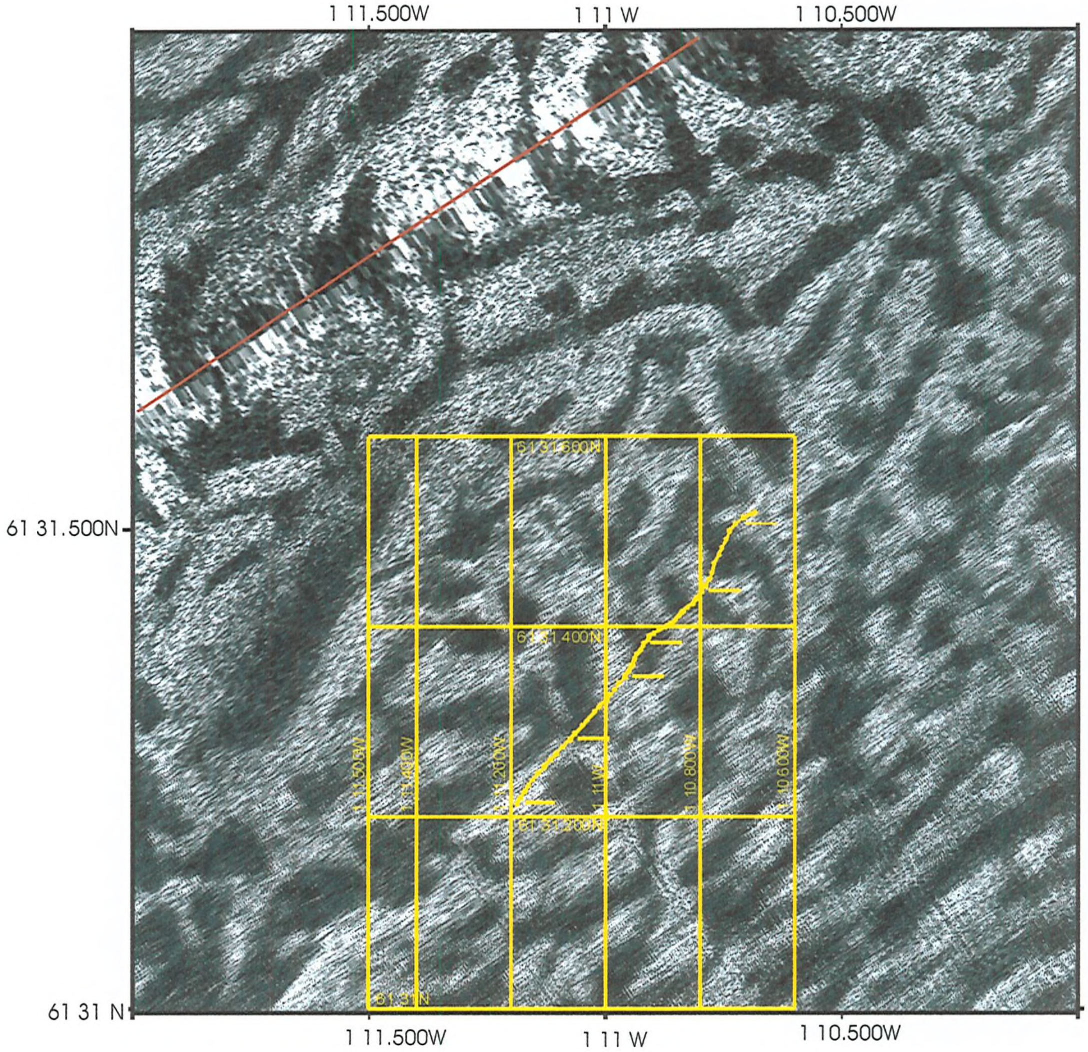


Figure 8.6. Sidescan sonar image and WASP track from station 53810#1 west of Shetland (the red line represents the TOBI vehicle track).

Figure 8.7 shows a simplified interpretation of the sidescan sonar image with white representing high backscatter and yellow representing low backscatter. In addition to the sidescan sonar image, two versions of the figures from the photographic (faunal and sedimentary) analyses have also been added (note these run from right to left, see figure 8.5). The pattern of repeated change in seafloor 'type' along the run on the sidescan sonar image can then be compared to the results from the photographic analyses.

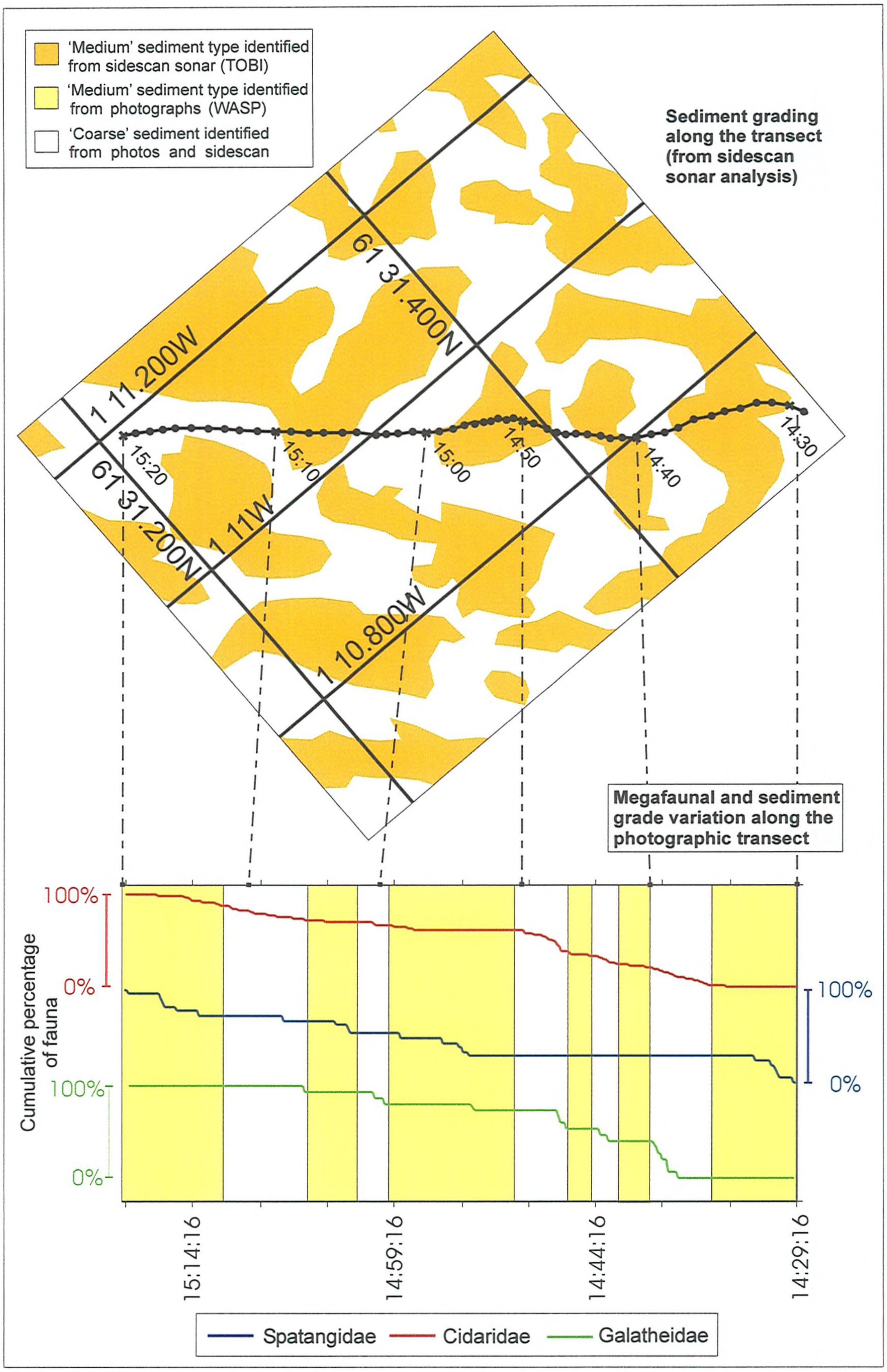


Figure 8.7. Joint analysis of sidescan sonar and photographic transects (WASP 53810#1)

An initial examination reveals similarities, the repeated change in sediment type is evident in both sets of data, and there are sections where the pattern is near identical. However, on closer inspection, several differences can also be seen (see figure 8.8). Overall there is a match between the two techniques in sections of the transect where the change in seafloor 'type' detected by the sidescan sonar corresponds with those of the photographic sediment and faunal analyses. However, some sections are clearly different, most obviously in the last fifteen to twenty minutes of the transect. The randomisation test gave a critical value of 171 at the 95 % confidence limit (range: 137 – 171) illustrating that the observed value of 159 matches in this study could statistically have occurred by chance alone (p>0.05).

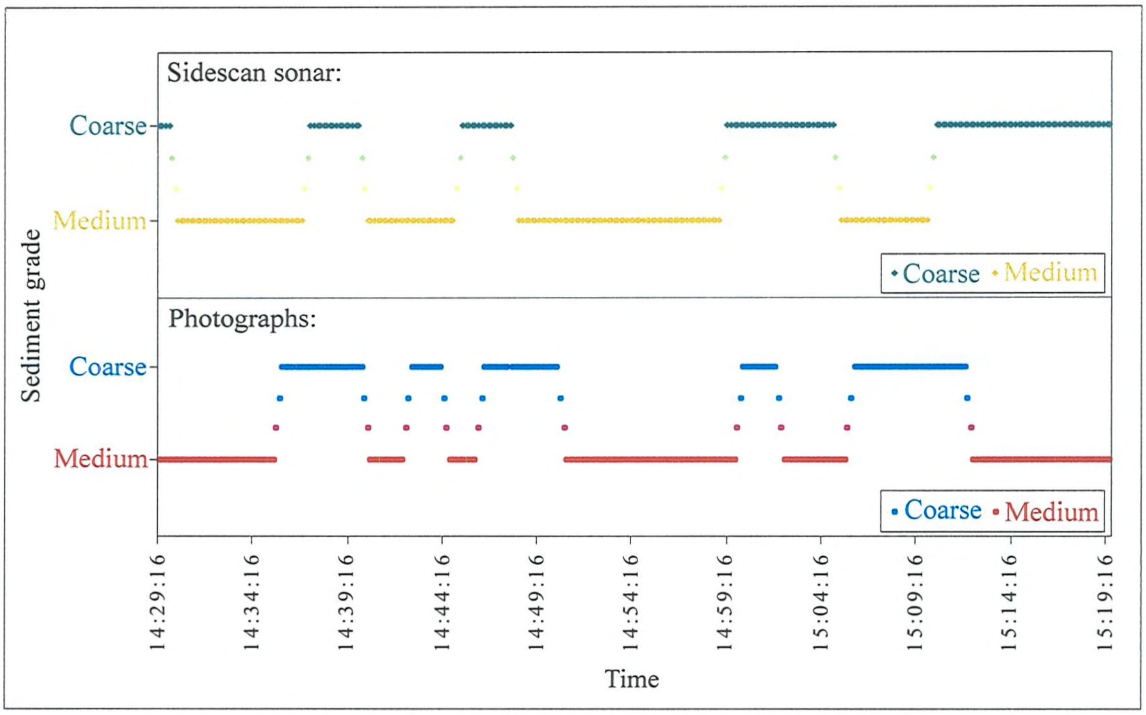


Figure 8.8. The variation in sediment type along the transects: comparison of sidescan sonar and photographic results at station 53810#1.

The results therefore indicate that there is a close match between the results of the sediment and faunal analyses of the photographic run (table 8.5). There is furthermore a close match between sidescan sonar and photography in parts of the transect where the repeated pattern of changing sediment type is present in both sets of data, however, in other parts of the transect this match is less convincing and overall the match is not significant (p>0.05).

TOBI sidescan sonar images	Low backscatter	High backscatter
Sediment	Finer sediment dominated by sand and gravel.	Coarse sediment dominated by gravel, cobbles and boulders.
Fauna	Low densities of fauna characterised by Spatangidae (purple heart urchins) and *Stichopus* sp.	High densities of fauna characterised and dominated by sponges, Cidaridae (pencil-spined sea urchins), and squat lobsters (Galatheidae).
Faunal density (ind./100 m^2)		
Spatangidae	0.64	0.05
Cidaridae	1.10	4.34
Galatheidae	0.03	1.57

Table 8.5. Summary of the iceberg plough mark data with the sediment and faunal data obtained from the photographic analysis.

8.4 DISCUSSION

The comparison and joint analysis of sidescan sonar and photographic material in the study of iceberg plough marks has not been attempted in any other studies. Although there are several deep-sea studies where photographs are used to identify and quantify the fauna (e.g. Rice *et al.*, 1982; Cailliet *et al.*, 1999), sediment types and structures (e.g. Huggett, 1987) and other features (e.g. Young *et al.*, 1985; Mauviel *et al.*, 1987; Bett *et al.*, 1995), and there are many deep-sea studies using acoustic techniques (e.g. Masson *et al.*, 1996), there are few deep-sea (if any) studies where there has been an integrated approach using photographs and sidescan sonar (or other acoustic methods). This integration is, however, a valuable method as has been shown in some recent shallow-water studies (e.g. Todd *et al.*, 2000), not only in ecological studies but also as a tool to 'ground-truth' to identify features seen on sidescan sonar images using photographs. Photographs may in addition be used as one of the tools in the assessment by the JNCC to potentially include an area of the iceberg plough mark zone west of Shetland in the Habitats Directive (92/43/EC) for protection as a 'Special Area of Conservation' (JNCC, 2002). In this study the photographs were used to identify the characteristics of the sediment present in the two 'types' of seafloor present as determined from the sidescan sonar imagery. The two 'types' of seafloor within the iceberg plough mark region were, as in a similar study by Belderson *et al.* (1973), a 'medium' sediment 'type', which was identified to mainly consist of sand

and mud, and a 'coarse' sediment 'type', which was visually dominated by gravel, cobbles and boulders. In contrast to Belderson *et al.*, (1973), however, this study used the photographs for further biological analysis to assess ecological significance of these two 'types' of seafloor. The photographic analyses furthermore reveal a very good match between the repeating patterns in the distribution of fauna and sediment types along the run.

The photographic data (faunal densities and diversity measures) revealed a relatively sparse megafaunal association with the 'medium' sediment type compared to the 'coarse' sediment, which has a richer megafaunal association, potentially linked to the increased number of habitats available there. Sediment type is known to exert a strong influence on the distribution of organisms (Tait, 1981; Parsons *et al.*, 1984). Individuals of *Munida* sp. were largely observed in burrows associated with rocks (often observed under rocks) and it therefore appears most likely that this species would be observed on coarse sediments, a suggestion supported fully (Allen, 1967; Dyer *et al.*, 1982; Hayward and Ryland, 1995) and partly (Gibson *et al.*, 2001) by other habitat descriptions for this taxon. Cranmer *et al.* (1984) reported two habitats for *Munida rugosa*: one on coarse sediment (under rocks) and one on muddy sediments. Muddy sediment is rare on the upper continental slope west of Shetland (see chapter 2; Masson, 2001), *Munida* sp. will therefore be most frequently observed on coarse, stony, sediment.

The Spatangidae were largely observed at the sediment surface of the 'medium' sediment, burying and creating furrows as they moved along, a habit also observed in other studies (Dyer *et al.*, 1982; Hayward and Ryland, 1995; Gibson *et al.* 2001). Comparisons can be made between these furrows (photographs a and b in figure 8.3) and those on a much larger scale, the iceberg plough marks (figure 8.1), where both produce higher concentrations of coarser material at the edges of the furrows as a result of the ploughing action.

While *Munida* sp. and the Spatangidae are more frequently observed on one 'type' of sediment, large numbers of Cidaridae were found on both sediment types, although the faunal density was higher on the 'coarse' sediment. In addition to being the most frequently observed group of megafauna along the run, it is possible that the Cidaridae are less restricted in their distribution by the type of sediment present and perhaps there are other environmental factors controlling their distribution. Dyer *et al.* (1982) observed *Cidaris cidaris* on the continental shelf west of Shetland on mixed sediment consisting of mostly gravel with small rocks and the occasional stretch of sand and suggested that the area west of Shetland and Orkney was the boundary of its range but they did not speculate on the environmental parameters controlling the distribution.

In contrast to the very close match between the photographic sediment and faunal datasets, the integration of the sidescan sonar and photographic material data gave a poorer match, that statistically could have occurred by chance alone ($p>0.05$). Although there is a good match over parts of the transect, there are areas that are considerably different. There are a number of factors that may explain these discrepancies:

1) Positioning inaccuracies:

The positioning system used for the ship was a differential GPS (global positioning system). The TOBI and WASP vehicles were in turn monitored and their positioning determined using an ultra-short baseline (USBL) acoustic system with reference to the ship's position (Masson *et al.*, 1996; 1997; Masson and Jacobs, 1998). Although the positions of the two instruments are known there may be a discrepancy between the recorded positions of WASP and the positions of features seen on the TOBI imagery. The TOBI data undergo a number of processing stages. Adjustments have to be made to the data to allow for slant-range, change in direction (e.g. when the ship turns) and other factors. It is possible that during this processing work the positions of some features recorded with the sidescan sonar alter. The positions of superimposed WASP runs onto sidescan images may therefore not be perfectly matched. In particular, if a photographic run is close to a boundary between two 'types' of seafloor or within an area of sidescan sonar 'line' overlap (i.e. the furthermost point away from the instrument), there is an increased chance of a 'mismatch' between data from the two techniques.

2) Transitional sediment zones

The analysis of photographs, including sediment grading, is a subjective and difficult process and when grading the sediment, the transitional zones must also be considered as a factor explaining the discrepancies between the two techniques. Although the analysis is believed to be correct as far as the recorded sediment and fauna present is concerned, the presence of a mixed sediment of the two types in some sections of the photographic run may have had some influence on the joint analysis of the two techniques, i.e. potential variability in locating boundaries. This could therefore explain some differences between the sidescan sonar and the photographic material, but it unlikely to explain the large differences noted towards the end of the transect.

3) Depth of acoustic signal penetration:

The sidescan sonar instrument TOBI operates at a frequency of 30 kHz. The resolution of the TOBI sidescan sonar imagery is approximately 5 to 10 m but the depth to which the transmitted signals penetrate the seafloor has not yet been fully established. The acoustic signals have been thought to penetrate only a few centimetres (approximately 1-3 cm) but it is possible that they penetrate further. In fact, it has recently been suggested that the penetration could be tens of centimetres (Masson *et al.*, 2003). If the signals do penetrate further it is possible that the sidescan data reveal features deeper in the sediment while the photographs illustrate the uppermost features of the substratum. For example, in an area with a thin veneer of sand overlying coarser material, the photographs will illustrate a sandy seabed while the sidescan imagery may record a coarse substratum. Further support for this possibility is detailed in the following chapter (chapter 9).

Despite these factors and the statistical result, the fact that there is an obvious observed presence of the two 'types' of seafloor present in the two sets of photographic and sidescan sonar data, together with the match in parts of the transect, do suggest that there ought to be a close, yet statistically undetected, relationship (table 8.5) between the two sampling techniques. A recent study of iceberg plough marks on the Wyville Thomson Ridge (Foden, 2002) also illustrated a close match between sidescan sonar and photographic data and reported highly structured epibenthic megafaunal communities according to sediment type. Further studies of iceberg plough mark zones using TOBI sidescan sonar and WASP photographs are, however, required to assess this relationship fully and to investigate whether the potential close match can be proven statistically.

8.5 CONCLUSIONS

The use of sidescan sonar and photographs in an integrated study of iceberg plough marks has revealed the presence of two 'types' of seafloor, with an associated megafauna (table 8.5). Although there is a match between the two techniques, further study is required to assess whether the match between photographic and sidescan sonar observations determined here is more generally applicable in areas of iceberg plough marks. Potential methods to improve the results from this example of photographic and sidescan integration include:

1) improving the resolution of the TOBI seabed classification, for example by analysis of greyscale levels, beyond 'high' and 'low' backscatter areas; 2) similarly improving the resolution of photographic seabed classification, for example by quantification of gravel/cobble/boulder cover, beyond 'coarse' and 'medium'; and 3) analysis of additional sites within the iceberg plough mark zone to assess whether the patterns seen here are present throughout the zone.

9 INTEGRATION AND INTERPRETATION OF ACOUSTIC AND PHOTOGRAPHIC DATA: A CASE STUDY OF THE 'DARWIN MOUNDS'

9.1 INTRODUCTION

The 'Darwin Mounds', named after the RRS *Charles Darwin*, are a group of numerous small seabed mounds inhabited by the deep-water coral *Lophelia pertusa* (Bett, 2001b). The mounds are located just south of the Wyville Thomson Ridge, in the northeast corner of the Rockall Trough at a depth of approximately 1000 m (figure 9.1), a depth at which dredgings in the 1860s had revealed the presence of *Lophelia pertusa* (Thomson, 1873). More recently, *Lophelia pertusa* has been shown to be widely distributed through the Atlantic (Wilson, 1979b, Mortensen *et al.*, 1995; Mortensen *et al.*, 2001) and other oceans (Rogers, 1999; AFEN, 2001). It has a number of growth forms from small isolated colonies, through smaller 'coppices' of about 10 m across, to larger reefs tens of metres high and hundreds of metres long (Wilson, 1979a; AFEN, 2001). Reefs such as the 'Darwin Mounds' can be thousands of years old (see Mortensen *et al.*, 1995) and are of considerable ecological and conservation importance (AFEN, 2001). The 'Darwin Mounds' have received considerable public and press interest in recent years including a newspaper report (Sunday Times, London, 22 June 1997) announcing the presence of a 'giant coral reef' off northwest Scotland, covering the greater part of the Faroe-Shetland Channel, a statement, however, considered to be unfounded (AFEN, 2001). The Darwin Mounds are, however, considered to be important by the Joint Nature Conservation Committee (JNCC) and the area has recently become protected through an emergency European Commission regulation from damaging fishing activities (JNCC, 2003). The area has also been proposed as a Special Area of Conservation (SAC) under the EU Habitats Directive (JNCC, 2002).

The discovery of the 'Darwin Mounds' was made in the summer of 1998 during the cruise of RV *Colonel Templer* (Masson and Jacobs, 1998), representing the first stage of AMES 1998 with photographic confirmation of the presence of corals made from RRS *Charles Darwin* cruise 112, the second stage of AMES 1998 (Bett, 1999). The initial discovery of the 'Darwin Mounds' was made using the TOBI sidescan sonar vehicle. Additional observations have subsequently been made during RRS *Discovery* cruise 248 in 2000 (Bett *et al.*, 2001a). These observations reveal the presence of some hundred mounds in two main fields, known as the eastern and western Mounds (figure 9.2), covering a total area of approximately 100 km^2 (Bett, 2000b). The aim of this study is to illustrate the use of an integrated approach to examine a particular feature on the seabed, in this case the 'Darwin Mounds', and highlight the differences between different types of observation systems used during the surveys.

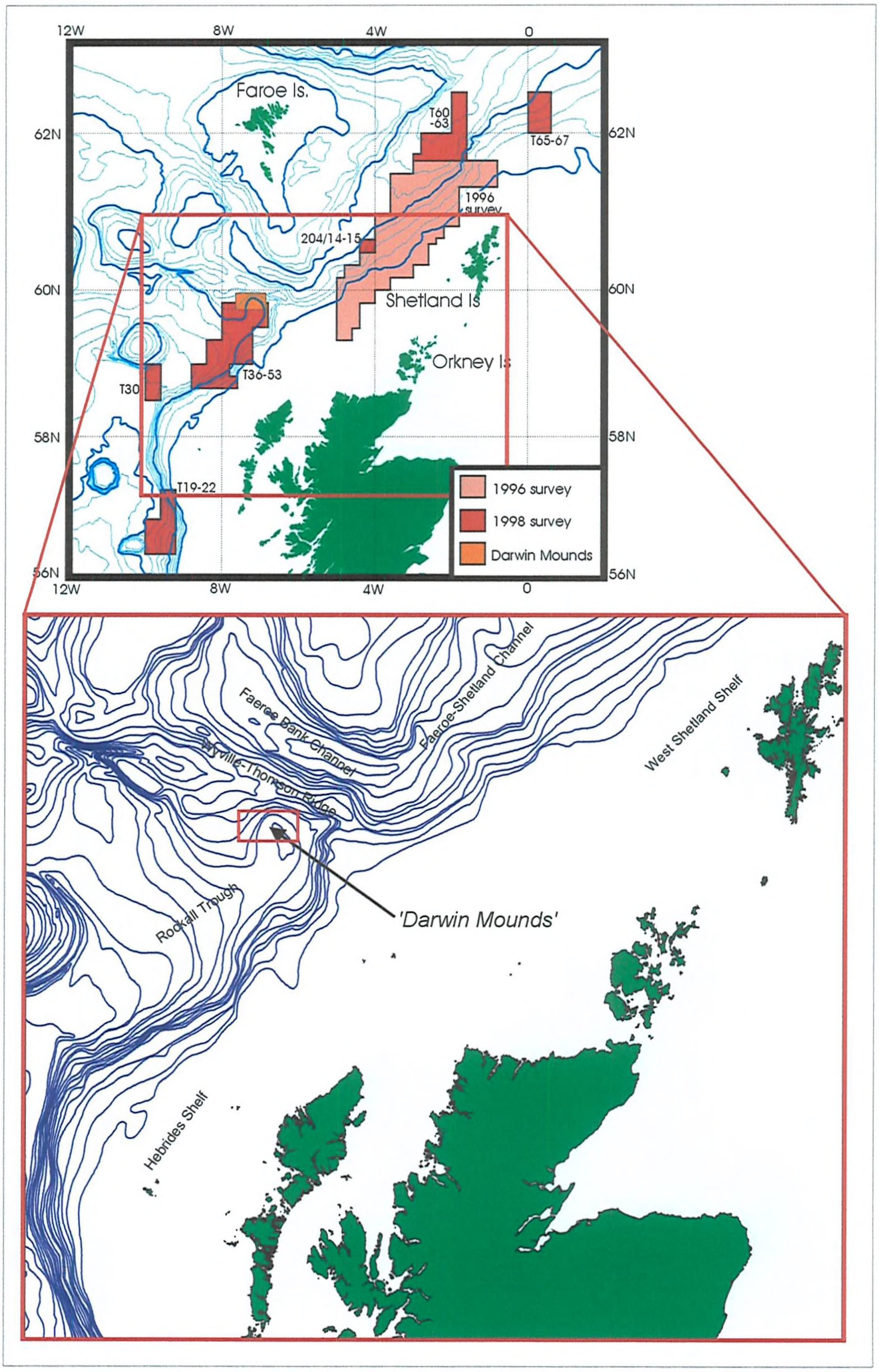


Figure 9.1. Location of the 'Darwin Mounds' in relation to Scotland as well as AMES 1996 and 1998.

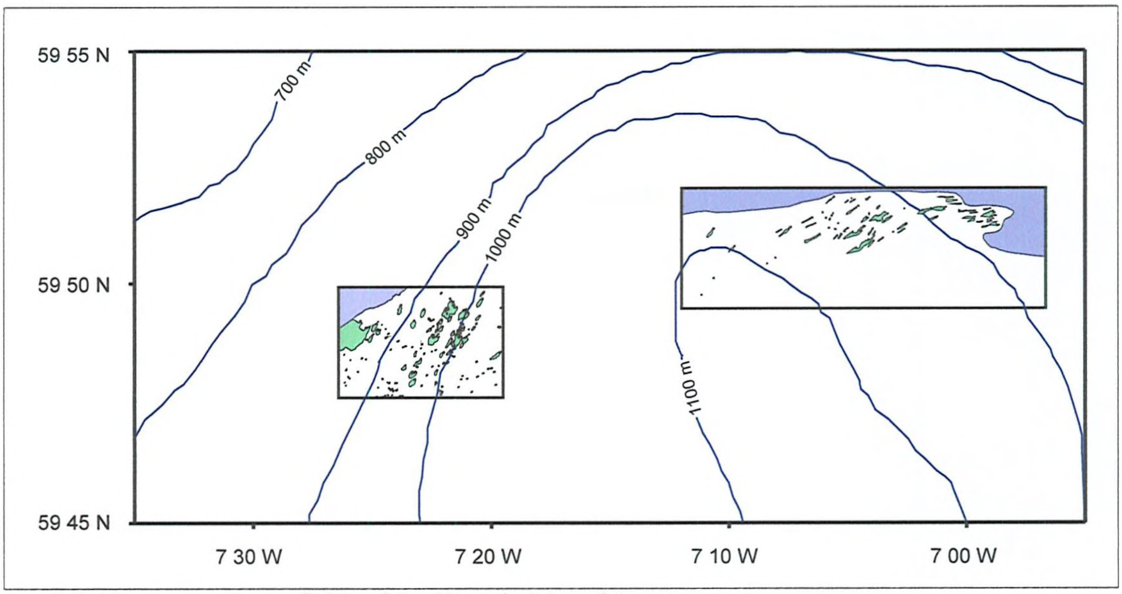


Figure 9.2. The east and west fields of the 'Darwin Mounds'.

9.2 METHODS

The survey of the 'Darwin Mounds' in 1998 from RV *Colonel Templer* (Masson and Jacobs, 1998) was carried out using TOBI sidescan sonar (30kHz), seabed profiling (3.5 kHz) and echo sounding (10 kHz). WASP video footage material was also acquired during RRS *Charles Darwin* cruise 112 (Bett, 1999). Additional information and observations were subsequently obtained (including personal observations) during RRS *Discovery* cruise 248 in July 2000 (Bett *et al.*, 2001a) using high frequency sidescan sonar (GeoAcoustics dual frequency system: 100 kHz and 410 kHz), coring (gravity corer and a box core) and additional video footage from the SOC SHRIMP (Seabed High Resolution Imaging Platform) vehicle (Bett *et al.*, 2001a). The high frequency sidescan sonar (see chapter 3 for information about TOBI) has a swath of 600 m at 100 kHz and 200 m at 410 kHz (Bett *et al.*, 2001a). At 410 kHz the 'fish' is towed at approximately 10 m above the seafloor, a difficult task considering the seabed depth of 1000 m (personal observation). The data obtained from all these instruments were studied using an integrated approach to investigate the capabilities of the equipment and attempt to explain the features seen in the study area. The mounds and the other features are first studied using the TOBI sidescan images and these results are compared to those of the echo sounder and the high frequency sidescan sonar images. All results are subsequently discussed together with results from other studies of the area.

9.3 RESULTS - OBSERVATIONS

On the TOBI sidescan imagery the mounds appear as bright (high backscatter), sub-circular targets approximately 100 m in diameter (figure 9.3 and 9.4). An additional feature, not seen on other deep-water mounds, is the presence of what are known as 'tails' associated with the mounds (Masson and Jacobs, 1998; Bett, 2000b; Bett, 2001a). These tails have a moderately high acoustic backscatter signal on TOBI sidescan sonar imagery. Their size and shape vary but they usually appear to be larger than the mounds in size and they are generally teardrop-shaped with a common orientation leading from the mounds towards the southwest. The background, or surrounding seafloor, has a low backscatter signal.

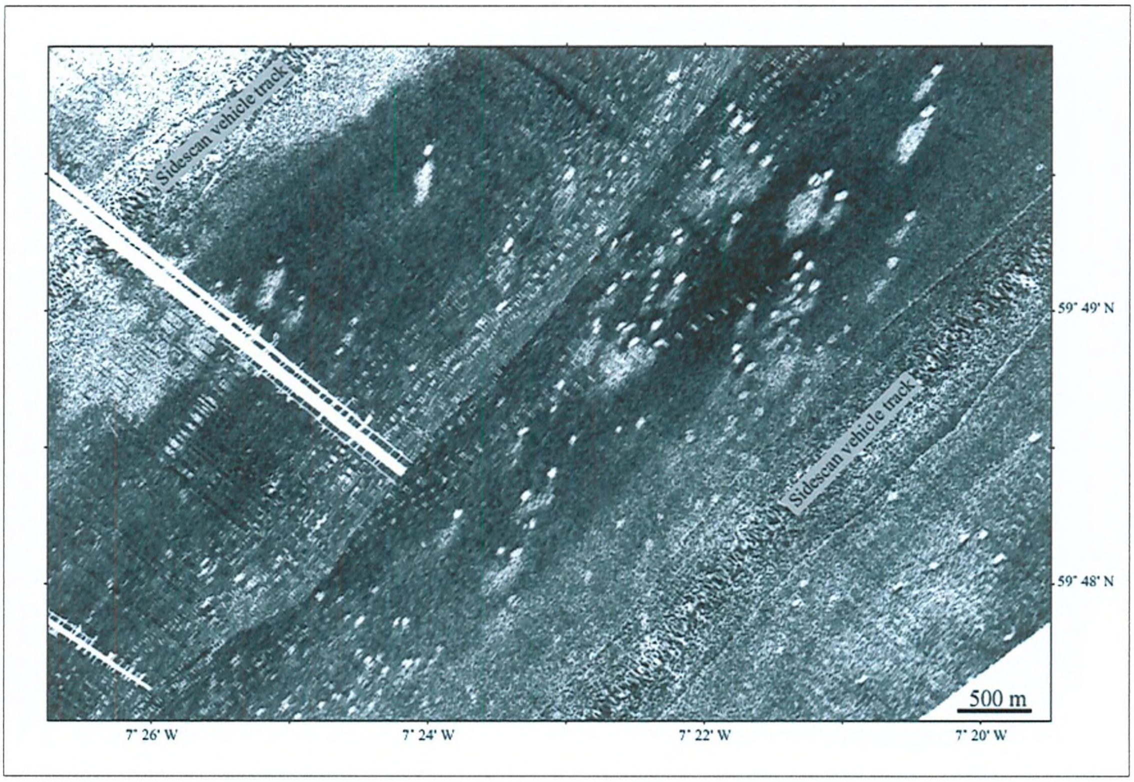


Figure 9.3. Sidescan (TOBI) sonar image of the Darwin Mounds west field (dark colour represent low backscatter and light colour represent high backscatter).

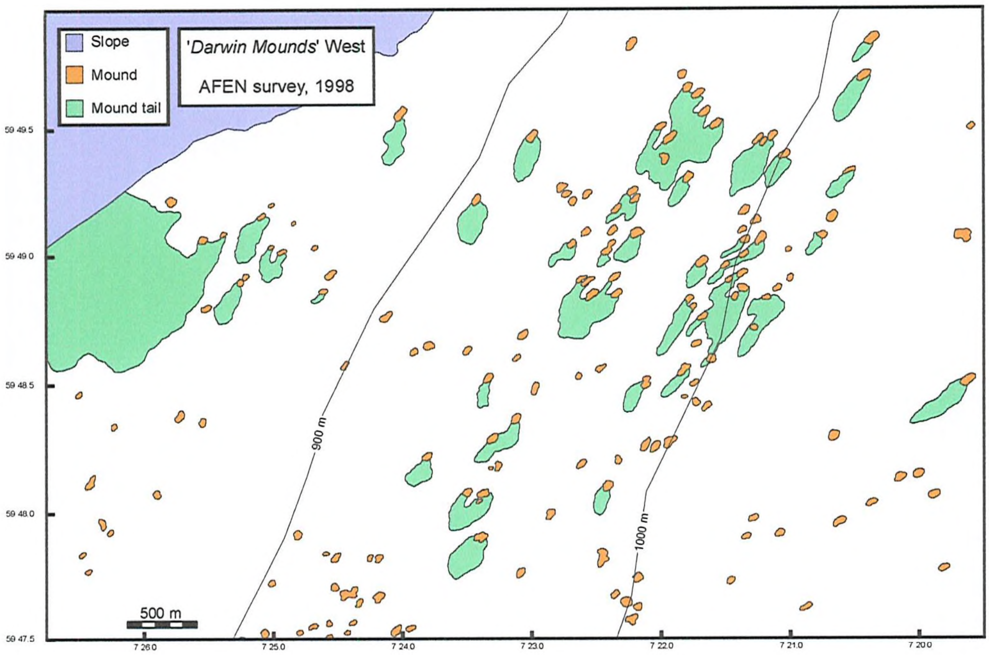


Figure 9.4. Sidescan sonar interpretation of the Darwin Mounds west field.

Seabed profiling (3.5 kHz) carried out across the targets verified the presence of some seafloor elevation and the echo sounding (10 kHz) confirmed elevations of approximately 5 m for the mounds and the absence of elevation of the tails (figure 9.5). The echo sounder returns were furthermore reduced in strength on the mounds, a characteristic observed in other studies (Mortensen *et al.*, 2001) and a feature used to identify their location prior to additional (video and coring) sampling.

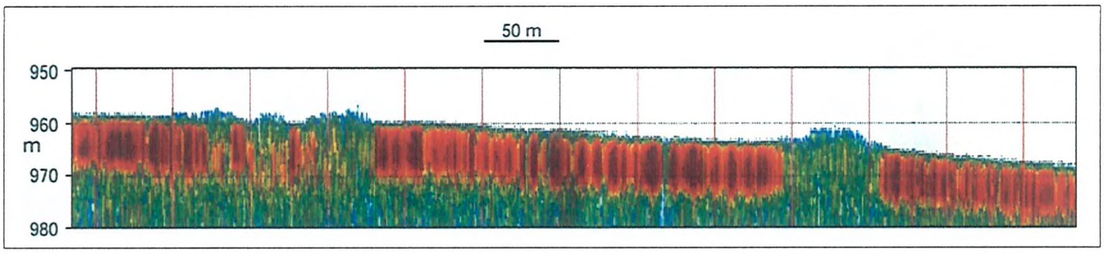


Figure 9.5. Echo sounder (10 kHz) record from the Darwin Mounds.

The GeoAcoustics 100/410 kHz sidescan sonar was used to obtain high resolution images of the 'Darwin Mounds'. Figures 9.6, 9.7 and 9.8 are from the Darwin Mounds and surrounding areas. The 100 kHz sidescan sonar image in figure 9.6 is from an area to the south of the Darwin Mounds west field, an area already surveyed using TOBI sidescan sonar. The figure illustrates the presence of two larger mounds (approximately 20 m and 10 m across respectively) and a number of smaller boulders surrounded by a fairly featureless seafloor but any other features are difficult to discern. The TOBI imagery from this area revealed the presence of mounds but in contrast to the 'Darwin Mounds', these mounds lacked 'tails'. The 100 kHz image (figure 9.6) illustrates the presence of mounds and as with the TOBI imagery the mounds here have no apparent 'tails'.

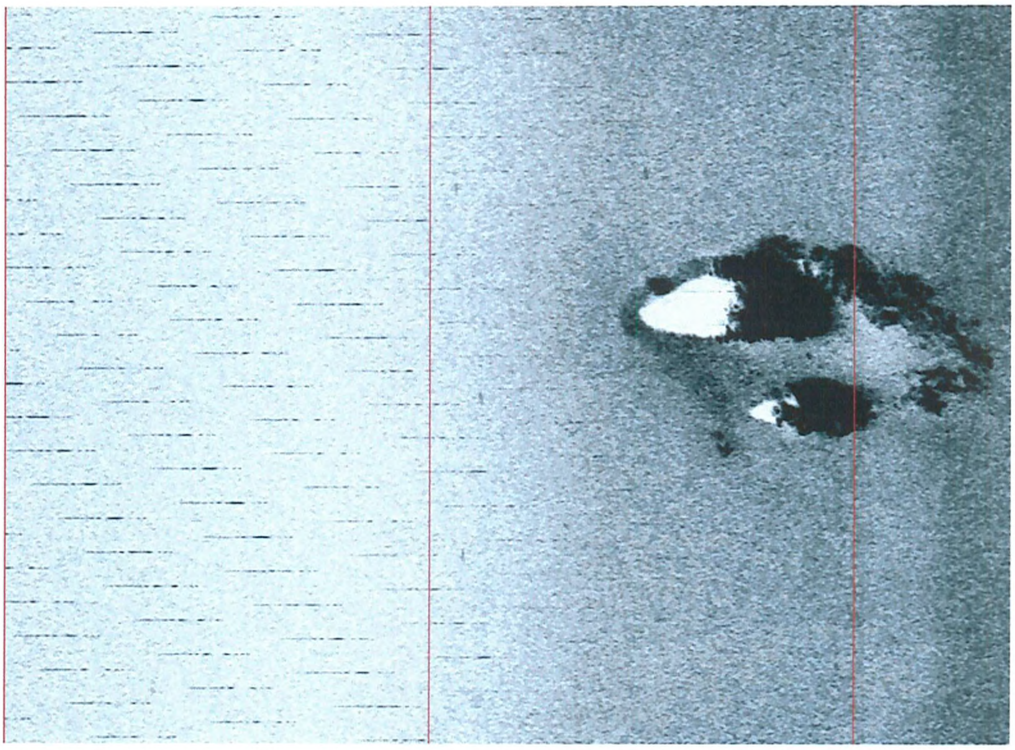


Figure 9.6. 100kHz sidescan sonar image of a tail-less mound from an area south of the 'Darwin Mounds' west fields (dark colour represents high backscatter). The distance between the red lines is approximately 50 m (image (L8/1957) courtesy of Dr Andrew Wheeler, University College Cork).

The 410 kHz sidescan sonar image (figure 9.7) illustrates two mounds, both being approximately 50 m across, with a 'speckled' appearance consisting of a large number of 'black spots'. The 'black spots' are high backscatter returns, typically <1 m across, together with what appears to be a number of boulders constituting the majority of the mound. The surrounding seafloor is relatively featureless apart from an area (low left) of the lower mound where an area of low backscatter return can be seen, a return lower than that of the other surrounding seafloor. The second 410 kHz sidescan sonar image (figure 9.8) also illustrates the presence of two mounds and a number of 'black spots' but these are much fewer in number than the ones identified in figure 9.7. There are in addition a number of parallel streaks across at least one of the two mounds and the surrounding seafloor on the upper part of the image.

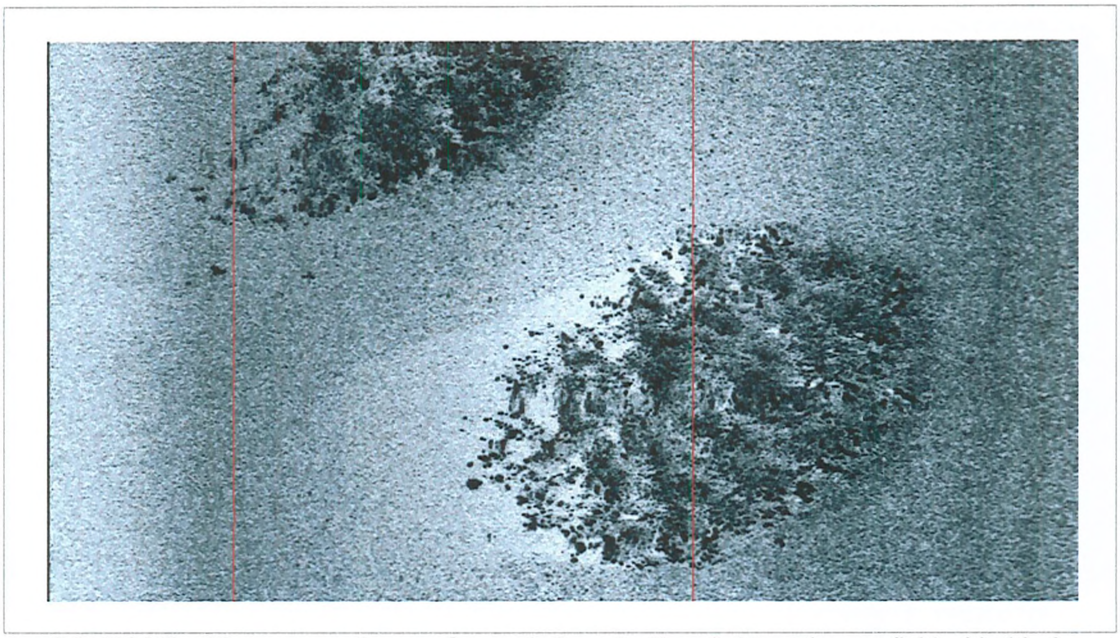


Figure 9.7. 410 kHz sidescan sonar image of mounds from the Darwin Mounds west field with 'black spots' of high backscatter. The distance between the red lines is approximately 50 m (image (L712055) courtesy of Dr Andrew Wheeler, University College Cork).

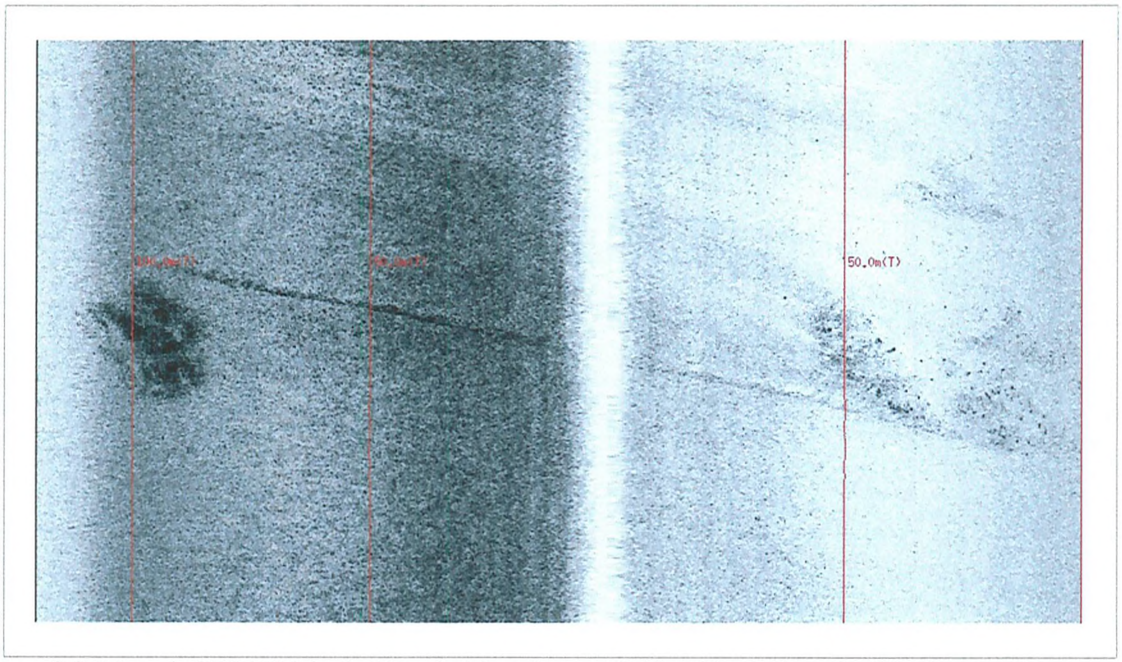


Figure 9.8. Mounds (410 kHz) in the Darwin Mounds west fields with trawl marks. The distance between the red lines is approximately 50 m (image (L9_2145) courtesy of Dr Andrew Wheeler, University College Cork).

Figure 9.7 and 9.8 are from within the Darwin Mounds west field, an area identified, using TOBI imagery, to have mounds with 'tails' (figure 9.3). The 410 kHz sidescan sonar imagery (figures 9.7 and 9.8) from the same region reveals the presence of the mounds but in contrast to the TOBI imagery the 410 kHz imagery does not reveal features readily identifiable as mound 'tails', the latter typically being much larger (c.f. figure 9.3) than the feature seen here (figure 9.7). The pattern seen around the lower of the two mounds in figure 9.7 (a feature not visible on the upper mound) is believed to be a scouring, or deposition, effect rather than a 'tail', an interpretation based on the lack of backscatter signals in the lee of, and close to, the mound. Support for these interpretations has recently been given in a more detailed study of the Darwin Mounds (Masson *et al.*, 2003).

One of the aims of using the high resolution sidescan sonar was to assess the capability of the instrument to identify features not revealed by the TOBI 30 kHz imagery. Both the 100 and 410 kHz sidescan sonar images clearly reveal the presence and outline of the mounds, but while the use of high resolution 410 kHz sidescan sonar reveals individual 'black spots' (referring to high backscatter, figure 9.7), it is difficult to identify any such 'black spots' in the 100 kHz imagery (figure 9.6). The size of the 'black spots' (typically <1 m across) together with SHRIMP footage (personal observation) suggest that these features are colonies of deep-water coral including *Lophelia pertusa*, a suggestion also made in a recent publication (Masson *et al.*, 2003). These observations suggest by implication that the high frequency sidescan sonar (410 kHz) has a resolution of approximately 1 m.

In addition to the discovery of 'black spots' in the 410 kHz imagery, figure 9.8 appears to show features illustrating the impact of deep-water trawling on the mound. The streaks are believed to be marks created by trawl nets towed across the mound as similar marks have been observed in other areas of AMES 1996 (see chapter 5 and 7). One of the mounds (to the right in figure 9.8) appears to have been damaged and there is furthermore a lack of 'blacks spots' (i.e. coral) compared to figure 9.7, features potentially linked to trawling.

Table 9.1 summarises the acoustic observations made in the Darwin Mounds area. Note that there is a difference between the backscatter returns of TOBI and the high-resolution sidescan sonar instruments, illustrated by the recorded returns from the tail regions.

Acoustic parameters	**Mound**	**Tail**	**Background**
Relative backscatter (30kHz)	High	Moderate	Low
Relative backscatter (100/410 kHz)	High	Low	Low
Bathymetric profile	Elevated	Level	Level
Echo sounder (10 kHz) return	Reduced	Normal	Normal

Table 9.1. Summary of acoustic parameters from the Darwin Mounds.

9.4 DISCUSSION

On discovering the Darwin Mounds, using the 30 kHz TOBI sidescan sonar, the mounds appeared to be rather unique in possessing 'tails', a feature not seen on other deep-water mounds (e.g. Kenyon *et al.*, 1998). These apparently downstream features are clearly visible on the 30 kHz imagery but have no obvious physical expression at the seabed. The integration of 30 and 100/410 kHz sidescan sonar has, however, revealed, what appears to be, a difference in the recorded backscatter returns of the two sidescan sonar systems. TOBI records reveal the presence of tails while the high-resolution sidescan sonar imagery record similar backscatter levels in the tail and background regions. The mounds could easily be identified on both the 100 and 410 kHz images but the 'tails' were not detected at either frequency (figure 9.6 and figure 9.7), an interpretation that has now also been made in a detailed study of the Darwin Mounds (Masson *et al.*, 2003). The difference between the backscatter returns from the TOBI and the high resolution sidescan sonar instruments may potentially be explained by the difference in the depth of acoustic signal penetration (as briefly discussed in chapter 8). Low frequencies (20 Hz – 10 kHz) are typically used for sediment, sub-bottom and seismic profiling (e.g. Wright, 1997; Kenyon, *et al.*, 1998), allowing deeper penetration into the seabed while higher frequencies (10 kHz – 500 kHz) are used for seabed surface surveys (Blondel and Murton, 1997), generally allowing for less penetration into the seabed (see figure 9.5). It is possible that the 30 kHz TOBI signals penetrated deeper into the sediment (a few centimetres), or perhaps even several tens of centimetres depending on the surface geology (Masson *et al.*, 2003), giving a 'volume backscatter' while the high resolution sidescan signals are scattered at the sediment surface. The TOBI imagery may therefore reveal sediment characteristics or other features buried below the sediment surface, features therefore not detected by the high resolution sidescan sonar instrument. This issue needs further investigation.

The 'tails' do, however, appear to be a 'real' feature characterised by the presence of dense populations of the giant protozoan (xenophyophore) *Syringammina fragilissima*. The video records from the AMES 1998 study of the Darwin Mound area have been analysed (table 9.2), demonstrating the nature of the mounds, the tails and the associated fauna (Bett, 2000b, Bett, 2001a). The video footage from the tails reveals a seafloor very similar to the background sediment with no apparent change in the physical nature of the seafloor or its sediments. However, there is a dramatic change in the associated fauna found in the tails where a high-density population of the xenophyophore *Syringammina* *fragilissima* is seen (table 9.2). Mound tails have recently been shown to be characterised by a surficial sand layer thinner than that of the background surrounding seafloor beyond the mounds and their tails (Masson *et al.*, 2003), which consists of rippled foraminiferous sand with a fauna typical of similar depths (approximately 1000 m) throughout the Rockall Trough (Bett, 2000b).

Faunal density (/ 100m^2)	**Mound**	**Tail**	**Background**
Xenophyophores	29.5	32.8	2.1
Metazoan invertebrates	4.3	2.3	1.6
Fish	5.4	5.2	4.5
Coral	Several colonies ranging from 1 to c. 70	Single isolated colony attached to boulder	None

Table 9.2. Summary of visual observations made in the Darwin Mounds area from RRS *Charles Darwin* cruise 112 (from Bett, 2000b, Bett, 2001a).

While the Darwin Mounds are believed to have been created through a process involving fluid escape from the seabed (Masson *et al.*, 2003), a suggestion also made by other authors (Hovland and Thomsen, 1997; Bett, 2000b; Mortensen *et al.*, 2001), the reason for the mounds in this region having tails is believed to be linked to downstream effects as a result of the presence of the mounds in an area of current flow towards the southwest (Bett, 2000b; Masson *et al.*, 2003). The tails were initially believed to have been created by scouring or increased particle deposition (Bett, 2000b), but the recent discovery showing that the tails consist of the thinner surficial sand layer than the surrounding background seafloor suggest a lower rate of sediment deposition in the lee of the mounds, although a scouring effect is also a possible explanation (Masson *et al.*, 2003).

The proposed inclusion of the Darwin Mounds in the European Commission Habitats Directive (JNCC, 2002) indicates the level of ecological and conservation importance of this area. In addition to the distinctive fauna found in the tail regions, the video records (table 9.2) also showed the mounds to be inhabited by numerous living coral colonies dominated by *Lophelia pertusa*, although in some instances no, or only a few, live corals are seen. One other deep-water colony-forming coral, *Madrepora oculata,* is also present (Masson *et al.*, 2003), a species also observed together with *Lophelia pertusa* on large carbonate mounds in the Porcupine Seabight (Kenyon *et al.*, 1998). The coral mounds furthermore provide habitats for many different sessile and hemi-sessile species including sponges, seastars (e.g. Brisingidae) and large populations of xenophyophores (Bett, 2000b, Masson *et al.*, 2003), all features likely to contribute to the motivation for the protection of this area. The occurrence of *Lophelia pertusa* on the Darwin Mounds (Masson *et al.*, 2003) and some other areas (Mortensen *et al.*, 1995; Mortensen *et al.*, 2001) have been attributed to elevation, location and the enhanced currents (and therefore the coral's chances of encounter more food particles), characteristics creating the preferred habitat for the coral and other suspension feeding organisms.

The use of the 410 kHz, high resolution sidescan sonar, led to the discovery of the 'black spots' (figure 9.7) on the Darwin Mounds. These 'black spots' referring to high backscatter, are not visible on the 100 kHz imagery but may be explained by referring to the video records from the region. The video records allow for the identification of coral 'blocks' or patches on these mounds, often around a 1 m across but both larger and smaller patches were also seen (personal observation). The *Lophelia* corals consist of a hard skeletal tree-like structure (Wilson, 1979a) and considering the sizes of coral seen on the videos from the mounds, these features represent the most likely explanation for the high backscatter returns (or 'black spots') seen on the high frequency sidescan sonar imagery, an interpretation supported by the detailed study of Masson *et al.* (2003). Other features such as cobbles and boulders also seen on and around the mounds give lower high backscatter returns and are not believed to be the black spot high backscatter returns seen on the sidescan imagery.

In addition to the discovery of 'black spots' in the 410 kHz imagery, figure 9.8 appears to show features illustrating the impact of deep-water trawling on the mound. The streaks are believed to be marks created by trawl nets towed across the mound resulting in an apparent reduced visible outline and most likely a reduced elevation of the mound as well. There is in addition an apparent lack of blacks spots (i.e. coral blocks) compared to figure 9.7, a feature also potentially linked to trawling. Commercial trawling on the Atlantic Margin has been reported to extend to depths in excess of 1,000 m (Aikman, 1997; Roberts *et al.*, 2000) and potential trawl marks have been observed in the west of Shetland region, although the majority were found on the upper slope (see chapter 5 and 7; Bett, 1999; Bett, 2000c). While the environmental effects of the oil and gas industry in the UK Atlantic Margin have attracted considerable concern, the fishing industry generally receives little comment other than in respect of fish stocks (Bett, 2000c). Trawling is likely to have a direct and largely lethal effect on encrusting fauna (Jones, 1992; Roberts *et al.*, 2000; Bett, 2000c) Associated mega- and macrofauna may suffer similar direct effects and/or indirectly through habitat removal (Thrush *et al.*, 1995; Bett, 2000c). A biological group potentially particularly vulnerable to this form of disturbance is the deep-sea coral *Lophelia* (Fredriksen *et al.*, 1992; Bett, 2000c; Mortensen *et al.*, 2001) and its associated fauna as some forms (e.g. sessile megafauna) have been shown to take a long time to recover (Bluhm *et al.*, 1995; Roberts *et al.*, 2000). Other studies indicate the potential for long-term ecosystem-wide changes (Holme, 1983; Thrush *et al.*, 1995) and there may be a need to consider impacts of trawling on a variety of spatial and temporal scales (Thrush *et al.*, 1995). All of these aspects are likely to have lead to the recent emergency European Commission regulation put in place to protect the Darwin Mounds (JNCC, 2003), particularly considering the apparent large effects trawling can have on an area such as a mound and the surrounding seabed.

9.5 CONCLUSIONS

The Darwin Mounds investigation is an excellent example of how the integration of techniques can be used to study new and unfamiliar features found in the deep sea. The collected data consist of information from different scales, from the large (sidescan sonar images) to the small (seabed photographs), all of which will aid in the analysis and understanding of the environment of this particular area. The different techniques complement each other and an improved and more complete description of a site is possible. Although this integrated study of the Darwin Mounds has been shown to be a successful approach to further our understanding of this region, additional work will be required to fully explain all of the features. The region has been shown to consist of a large number of mounds, inhabited by the deep-water coral *Lophelia*, and the rather unique features, the tails, not seen elsewhere on deep-sea mounds. The TOBI sidescan sonar imagery revealed the presence of the 'tails' on the Darwin Mounds, features that do not appear to have a physical expression at the seabed nor to be detectable on high resolution sidescan sonar imagery. The tails are, nevertheless, ecologically relevant in that they are characteristically inhabited by dense populations of xenophyophores. The "discrepancies" between the TOBI and high resolution sidescan sonar imagery may be explained by the difference in signal penetration into the seabed but as in the study of the 'iceberg plough marks' (chapter 8), further investigations are required to fully understand these results.

The use of high resolution sidescan sonar has been shown to be beneficial in adding further information about the features observed on the Darwin Mounds. While the 100kHz images clearly revealed the mounds and other large features (e.g. trawl marks), the 410 kHz system gave much higher resolution, more clearly illustrating the effects of trawl marks (figure 9.8), but also potentially allowing the identification of individual coral patches in some cases (Figure 9.7). The latter may be a potential tool for rapid surveys of other deep-sea mounds to further assess the distribution and extent of deep-water corals.

10 SUMMARY AND CONCLUSIONS

10.1 INTRODUCTION

The Atlantic Margin Environmental Surveys (AMES) were carried out in 1996 and 1998 (Bett, 1997; 1999) and as part of these surveys, photographic sampling using the Wide-Angle Seabed Photography (WASP) vehicle was also carried out. In this study, a total of 19 photographic stations (see chapter 4) have been used with 18 stations from the AFEN sampling programme carried out in 1996 (Bett, 1997) and one station (M200) from a Department of Trade and Industry (DTI) survey in 2000 (Bett, 2001b). The processing and analysis of these photographs resulted in a total of 4537 photographs covering approximately 87,760 m^2 of the seabed.

The main aim of this study was to analyse the extensive collection of photographic and video material in order to characterise and understand the seabed environment of the Atlantic Margin, particularly the area west of Shetland. The key objectives were to integrate biological and geological data to improve the understanding of the seabed sedimentary environment and the processes that created it as well as describing the biological communities present west of Shetland. The video material was largely from AFEN 1998 and this material was also used to produce a video summarising the different seabed environments within the survey area (Bett and Axelsson, 1999). The main findings of this study are summarised below.

10.2 SUMMARY AND CONCLUSIONS

10.2.1 Chapter 4: the effects of frame selection on photographic analysis and results

Photographic analysis often appears to be carried out by simply excluding low-quality frames and there is no set standard for using frames of a particular altitude for final analysis and exclude the rest. Frame selection is the process where photographs, taken using vertically mounted cameras, are included or excluded depending on the altitude at exposure. The photographic sampling using WASP resulted in 4537 photographs but as the camera is vertically mounted, the altitude varies between frames and this affects the results considerably. The aim of this chapter was to assess the effects various altitudes had on the results and assess whether there was a case for standardising the selection of frames before final analysis of the data. The results of the study revealed the following main facts:

- The proportion of frames available for analysis decreased with a decrease in altitude.

- Megafaunal and *lebensspuren* densities overall and for individual taxa increased with a decrease in altitude. The rate of increase in density was particularly high at 6 m altitude.
- The proportion of frames containing recorded megafaunal data increased with a decrease in altitude.

These results lead to a discovery of a cut-off point identified at 6 m, where megafaunal and *lebensspuren* densities increased rapidly with a small decrease in altitude, while still leaving sufficient number of frames available for analysis. In addition, from processing and analysing the photographs, megafaunal and *lebensspuren* identification was regarded to be difficult at altitudes in excess of 6 m, further supporting the suggestion of using 6 m as the cut-off point for frame selection. Considering the large variations seen in megafaunal and *lebensspuren* densities when using different altitudes, photographic analysis may benefit from some level of standardisation using frame selection rather than simply subjectively excluding poor quality frames. Frame selection may therefore be a more widely applicable method for analysis of photographs taken using vertically mounted cameras and allow better comparisons to be made between different studies.

10.2.2 Chapter 5: the seafloor environment along a bathymetric transect west of Shetland

The main aim with this chapter was to investigate the seabed environment west of Shetland and analyse the seabed photographs to study the megafaunal and sedimentary distributions as well as any other features such as evidence of current flow. Analysis of the photographs from 13 sites along a bathymetric transect west of Shetland, from 200 m to 1400 m, revealed the following main results:

- There is an overall decrease in sediment grain size with depth but considerable variation in sediment type at the local scale. The sedimentary environment can be categorised into a number of different zones: the iceberg plough mark zone, the along-slope current zone and the channel floor.
- There is a division of the megafaunal communities present into two main layers, one deep-, cold-water layer and one shallow, warm-water layer with the boundary occurring at approximately 600 m.
- The current regime largely follows that of the general hydrography identified in the Faroe-Shetland Channel (e.g. Turrell *et al.*, 1999; Masson, 2001) with strong

currents (peaking at 0.8 m/s) towards the northeast on the upper continental slope (<500 m) and somewhat weaker currents towards the south-southwest at depth (>900 m). On the lower continental slope, the direction of flow is less clear but the photographic analysis appears to indicate a flow towards the northeast at depths of $\leq$ 900 m.

- There is an overall increase in megafaunal density with depth and significant correlations have been found between megafaunal density and sediment grain size.
- Megafaunal diversity (Shannon-Wiener and Margalef's species richness) decreases with depth and significant correlations have been found between megafaunal diversity and depth, temperature and sediment grain size.
- Three local-scale features have been identified: the iceberg plough mark zone (200-500 m) with the associated fauna closely related to the type of sediment present; the 'sponge-belt' (500-600 m) dominated by sponges of a variety of species; and a sand contourite (800-900 m) with a characteristic fauna dominated by acorn-worms.
- A depth trend has been found within the stations from 200 m down to 600 m and significant correlations were found with both depth and temperature.
- Trawling activity has been observed down to 600 m, an activity believed to be linked to the availability of commercially valuable species within the shallow-, warm-water layer (Gordon, 2001).

The results in this bathymetric study are similar to other studies in the area. The sedimentary distributions are similar to those identified by Masson (2001) and the current regime largely follows those identified by a number of authors (e.g. Turrell *et al.*, 1999; Masson, 2001). The megafaunal distributions with regards to density, diversity and the 2-layer system are also seen in the macrofaunal distributions west of Shetland (Bett, 2000a, 2001a; Narayanaswamy, 2001). The large-scale division of the megafauna largely reflect the distribution of water masses in the channel (see chapter 2; Turrell *et al.*, 1999) and the lower level of species diversity seen at depth within the Faroe-Shetland Channel has been linked to geographic isolation and the recovery from the effects of glaciation (Gage and Tyler, 1991; Rex *et al.*, 1993). Although species diversity has been suggested to be uniformly high in the deep sea, the results seen here support the suggestion that this generalisation may be too simplistic (Poore and Wilson, 1993; AFEN, 2000; Gage *et al.*, 2000).

10.2.3 Chapter 6: lebensspuren distribution along a bathymetric transect west of Shetland

Lebensspuren is a German term adopted to describe the physical manifestation, such as tracks, trails and burrows, of benthic animals in sediments. These different burrowing and feeding activities continually disturb and rework the sediments, a process known as bioturbation, activities that can profoundly affect the sediment properties. The main aim of this study was to identify and describe the main *lebensspuren* present along the bathymetric transect west of Shetland and to investigate whether there are any variations in type and number of traces with depth. The analysis revealed the following main features:

- A large-scale bathymetric trend dividing the traces into a shallow- and a deep-water layer.
- Crawling traces are dominant on the upper continental slope (200-500 m), while dwellings (including burrows) are dominant at mid- and lower slope areas (600-1100 m). The channel floor (1200-1400 m) is dominated by a mixture of crawling, grazing (spoke-burrows) and dwelling traces.
- A depth trend is found within the shallow-water stations (200-600 m), a trend believed to be associated with the sediment distribution.
- There is a highly significant correlation between WASP sediment grading interpretation and relative frequency of traces, indicating that the sediment distribution is the most important factor influencing trace distribution, but a combination of factors including the temperature, the current regime and the food resources present are also believed to be important factors, particularly in the division of the *lebensspuren* distribution into two layers.

Few studies of *lebensspuren* have been carried out at the Atlantic Margin and comparisons are therefore difficult. In addition, studies of *lebensspuren* have often adopted rather complex classification schemes (see e.g. Mauviel and Sibuet, 1985; Young *et al.*, 1985), making comparisons between studies difficult. The attempt to classify traces into a simpler system, e.g. Seilacher (1953), and standardise the classification schemes may make comparative studies easier.

10.2.4 Chapter 7: the along-slope study

Analysis of photographs from three geographic regions (north, mid and south) and three depths (300 m, 500 m and 800 m) along the continental slope west of Shetland was carried out revealing sedimentary and megafaunal variations along the slope at all depths:

- The photographic analysis revealed no apparent along-slope variation in sediment characteristics at 300 m but at 500 m the sediment is coarser in the northern- and mid-regions to that of the southern region, while at 800 m the sediment is fine in the northern- and mid-regions but coarse in the south.
- Species diversity (Shannon-Wiener, Margalef's, Pielou's indices as well as rarefaction) increase with latitude at 300 m but at 500 m, the mid-region has the highest species diversity and the lowest evenness. No clear trend in species diversity is found at 800 m.
- At 500 m, the 'sponge-belt' is an obvious feature in the northern- and mid-regions but less apparent in the south.
- At 800 m. acorn-worms are characteristic megafauna of the northern- and mid-regions but absent from the south.
- The megafaunal distribution is divided into two main layers, separating the 800 m stations from the sites at 300 m and 500 m.

Along-slope variations were reported within both the macrofauna and the sedimentary distribution west of Shetland (Bett, 2001a, Masson, 2001). The coarser sediment observed at depth in the southern region was believed to be associated with stronger currents than those seen in the mid- and northern regions, a suggestion linked to a constriction of the channel, while finer material was allowed to settle out in the northern region as a result of a widening of the channel and lower current flow.

10.2.5 Chapter 8: an integrated study of the iceberg plough marks on the upper continental slope west of Shetland.

The use of sidescan sonar and photographs in an integrated study of iceberg plough marks has revealed the presence of two 'types' of seafloor, 'coarse' and 'medium' sediments. The megafauna are closely associated with the sediment present where squat lobsters and pencil-spined heart urchins (cidarids) are associated with the 'coarse' sediment ($p=<0.01$) while irregular urchins (spatangoids) are associated with the 'medium' sediment type ($p<0.01$). A similar relationship was identified in a recent study of iceberg plough marks on the Wyville Thomson Ridge (Foden, 2000) and as iceberg plough marks have been identified on many high latitude continental shelves and slopes, it is possible that similar relationships are present between the type of sediment and fauna in other regions. The iceberg plough mark habitat of the UK Atlantic Margin is now being assessed for its conservation value and a portion of the plough mark zone may be selected for protection under the EC Habitats Directive (92/43/EC) as a 'Special Area of Conservation' to represent 'reefs', one of the main habitat variants identified to occur in UK offshore waters (JNCC, 2002).

10.2.6 Chapter 9: integration of sidescan sonar and photographic sampling data: a case study of the 'Darwin Mounds'.

The Darwin Mounds consist of a number of mounds inhabited by the deep-water coral *Lophelia pertusa* and the aim of this study was to illustrate the use of an integrated approach to study a deep-sea environment and to assess the relative strengths of the different sampling methods (low and high frequency sidescan sonar, echo sounders and photography). The low frequency sidescan sonar (TOBI) was used to map a large area. The high frequency sidescan sonar was subsequently used to focus in on particular targets as identified from the TOBI imagery, in this case the Darwin Mounds. Photography was then used to 'ground-truth' the sidescan sonar images and identify coral colonies. The main findings were:

- A large number of mounds were identified with both sidescan sonar systems but while the TOBI images revealed the presence of 'tails' (consisting of a thin sand layer and characterised by dense populations of xenophyophores) on the Darwin Mounds, these features were not seen on the high frequency images.
- As a result of the difference between the two sidescan sonar systems with regards to the 'tails', a suggestion has been made that there is a difference in the depth of penetration into the sediment of signals transmitted from TOBI and those of high frequency sidescan sonar systems, where high frequency sonar signals appear to produce backscatter from the uppermost surface of the seabed while the TOBI signals appear to give a 'volume backscatter' including features buried slightly deeper in the sediment.
- The use of high frequency (410 kHz) sidescan sonar gave high resolution images clearly illustrating the outline of the mounds but also the effects of trawl marks and potentially allowing the identification of individual coral patches in some cases.

The study of the 'Darwin Mounds' illustrated the advantage of using an integrated approach to study a complex feature by using information from different scales, from the large (sidescan sonar images) to the small (seabed photographs), all of which will assist in the analysis and understanding of the environment of this particular area. Both *Lophelia pertusa* and the Darwin Mounds have in recent years received a lot of attention and the Darwin Mounds have recently been protected under an emergency European Commission regulation under the Common Fisheries Policy (JNCC, 2003), indicating the level of ecological and conservation importance of this area. The use of high frequency sidescan sonar has not only here been shown to be a useful tool for detecting the presence of coral patches but also to study the effects of, for example, trawling and this method could prove to be a good option for similar studies where rapid surveys of other mounds could be carried out to assess whether deep-sea corals are present and also to assess the extent of trawling activity.

10.2.7 Main conclusions

Overall, the sedimentary environment conforms with the interpretations made by Masson (2001) while the current regime identified from photographic analysis conforms largely to the hydrographic observations made by Turrell *et al.* (1999) in particular but also by others (e.g. Kenyon, 1986; Saunders, 1990; Stoker *et al.*, 1993; Bett, 2001a; Masson, 2001). The results from chapter 5, 6 and 7 show that there is a division of the megafaunal and *lebensspuren* distributions into two main layers, one deep-, cold-water layer and one shallow-, warm-water layer, results also seen in the macrofaunal distributions (Bett, 2000a, 2001a: Narayanaswamy, 2001) and largely reflecting the water mass distribution within the Faroe-Shetland Channel (see chapter 2; Turrell *et al.*, 1999). To illustrate the megafaunal distribution results further, additional cluster and ordination analyses have been carried out using all of the available megafauna data (figures 10.1 and 10.2), with the results clustering and ordering all the shallow-water sites (200-600 m) together and all the deep-water sites ($\geq$ 700 m) together.

In the correlation analysis studies in the various chapters, depth, sediment grain size and temperature have been identified as the most important environmental parameters influencing the megafaunal distribution. These results are further supported by the Spearman's rank correlation analyses (table 10.1 and 10.2), where highly significant results are found between MDS x and depth ($p<0.01$), temperature ($p<0.01$) and sediment grain size (Phi mean and median; $p<0.01$).

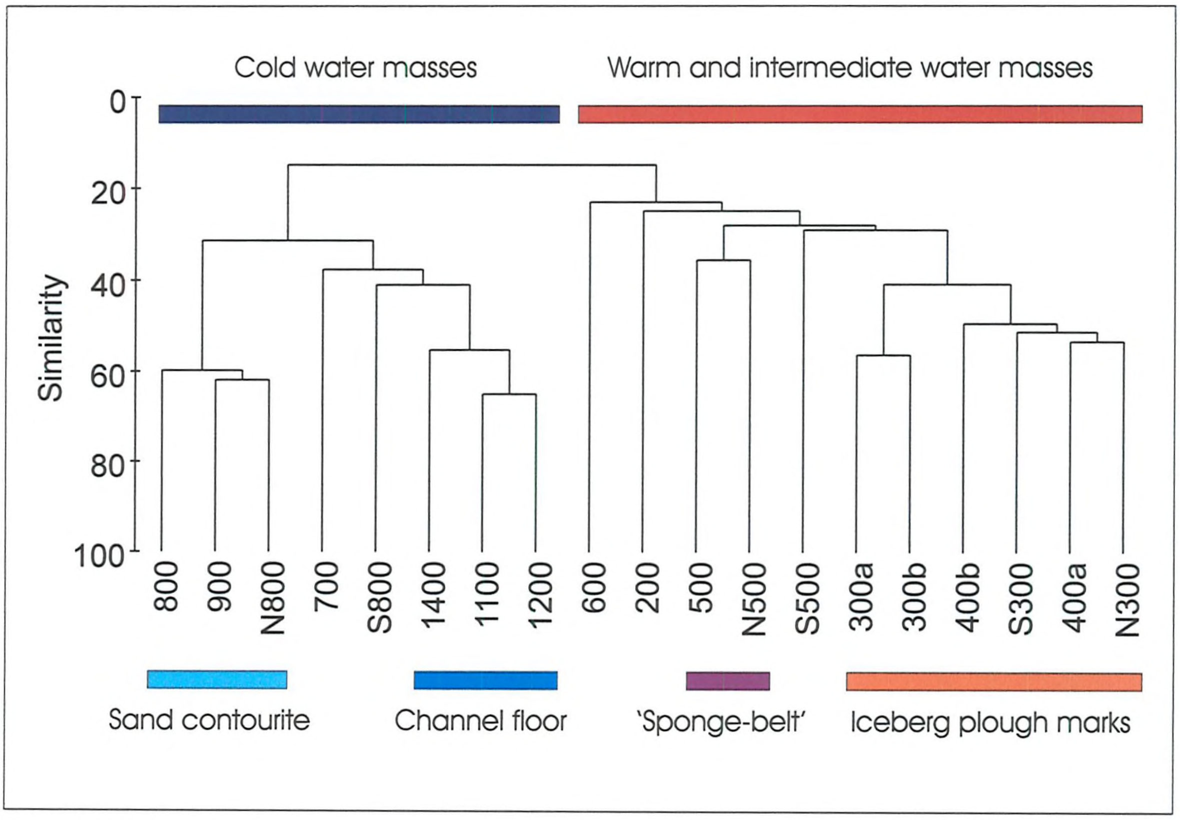


Figure 10.1. Cluster analysis of all the stations included in this study.

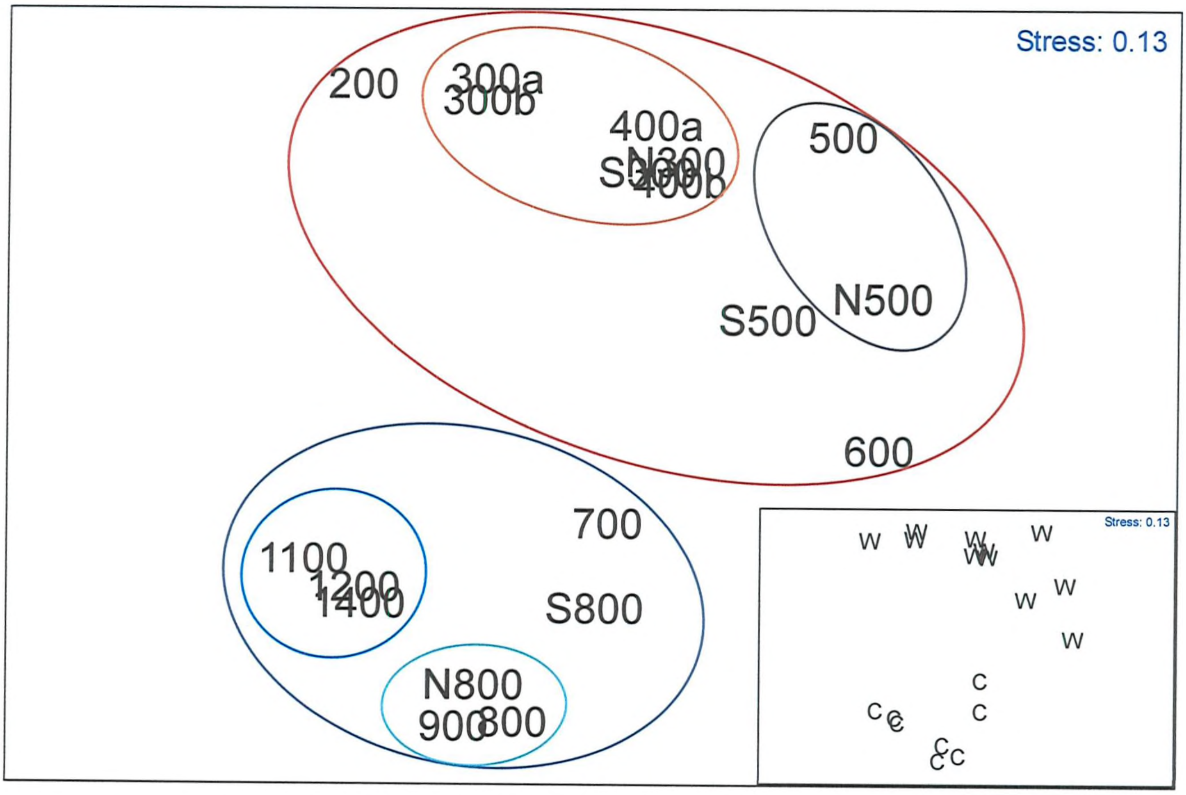


Figure 10.2. Ordination (multi-dimensional scaling) of all the stations in this study (the insert illustrating the division of the sites into warm (W) and cold (C) water sites).

In order to assess this further the MDS x and y ordinates (figure 10.3) and temperature (figure 10.4) have been plotted against depth and the plots illustrate similar trends with regards to the temperature variation with depth and near mirror images of the depth trends when comparing the MDS x and y ordinates with temperature range. The plot of the MDS x ordinate show relatively coherent groups of warm and cold sites at each end of the axis, while the MDS y ordinate show continuous variation with depth within the warm and cold sites. These results are very similar to those reported for the macrofauna (see figure 16b, Bett, 2001a), where both the cold and intermediate sites show very similar depth trends and groupings. Bett (2001a) identified temperature as the most influential environmental parameter on the distribution of the MDS ordinates, a result also seen in this study, although other parameters have also been shown to have significant correlations with the MDS ordinates in this study. Note that Bett (2001a) identified three groups (warm, intermediate and cold), a result not seen here but as only one site from 200 m was available in this study (while Bett (2001a) had several), it is possible that another layer is present within the megafaunal distribution as suggested in chapter 5. Bett (2000a, 2001a) furthermore suggested that the intermediate layer identified in those studies represented an 'ecotone' (an overlapped boundary between two 'communities') and it is possible that the warm layer identified in this study (see chapter 5) could also be explained by this concept, particularly considering the similarities in the results from the studies.

<table>
<tr><th>Environmental variables</th><th colspan="2">MDS x</th><th>MDS y</th></tr>
<tr><td>Depth (m)</td><td colspan="2">-0.778*</td><td>-0.224</td></tr>
<tr><td>Maximum temperature (°C)</td><td colspan="2">0.818*</td><td>0.337</td></tr>
<tr><td>Temperature range (°C)</td><td colspan="2">0.875*</td><td>0.139</td></tr>
<tr><td rowspan="3">Significant levels (two-tailed test; from Fowler and Cohen, 1992)</td><td><i>Tabulated value</i></td><td><i>Significance level</i></td><td><i>Description</i></td></tr>
<tr><td><i>0.608</i></td><td><i>0.01</i></td><td><i>Highly significant*</i></td></tr>
<tr><td><i>0.462</i></td><td><i>0.05</i></td><td><i>Significant</i></td></tr>
</table>

Table 10.1. Spearman's rank correlation analysis results between MDS x and y ordinates temperature and depth (n=19).

<table>
<tr><th>Environmental variables</th><th colspan="2">MDS x</th><th>MDS y</th></tr>
<tr><td>Phi (mean)</td><td colspan="2">-0.752*</td><td>0.090</td></tr>
<tr><td>Phi (median)</td><td colspan="2">-0.811*</td><td>0.022</td></tr>
<tr><td>WASP sediment interpretation</td><td colspan="2">-0.820*</td><td>0.123</td></tr>
<tr><td rowspan="3">Significant levels (two-tailed test; from Fowler and Cohen, 1992)</td><td><i>Tabulated value</i></td><td><i>Significance level</i></td><td><i>Description</i></td></tr>
<tr><td><i>0.645</i></td><td><i>0.01</i></td><td><i>Highly significant*</i></td></tr>
<tr><td><i>0.490</i></td><td><i>0.05</i></td><td><i>Significant</i></td></tr>
</table>

Table 10.2. Spearman's rank correlation analysis results between MDS x and y ordinates and sediment grain size (n=17).

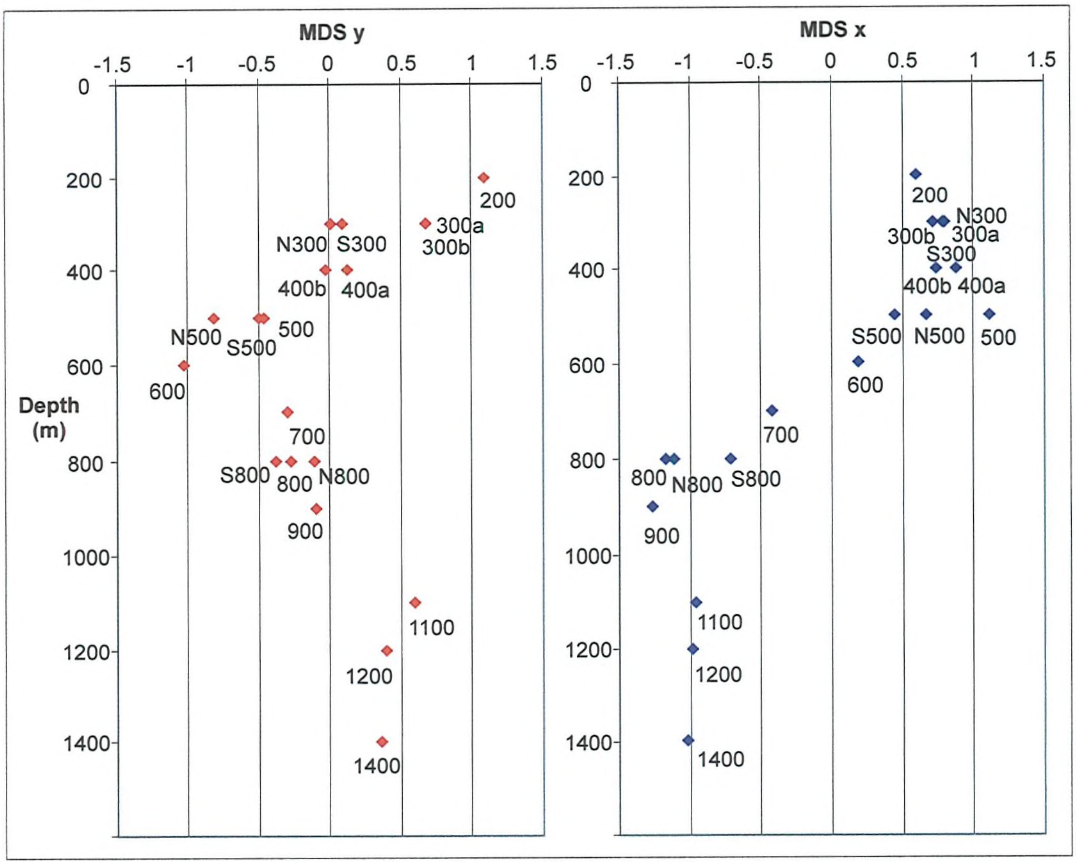


Figure 10.3. The variation in MDS x and y ordinates with depth stations.

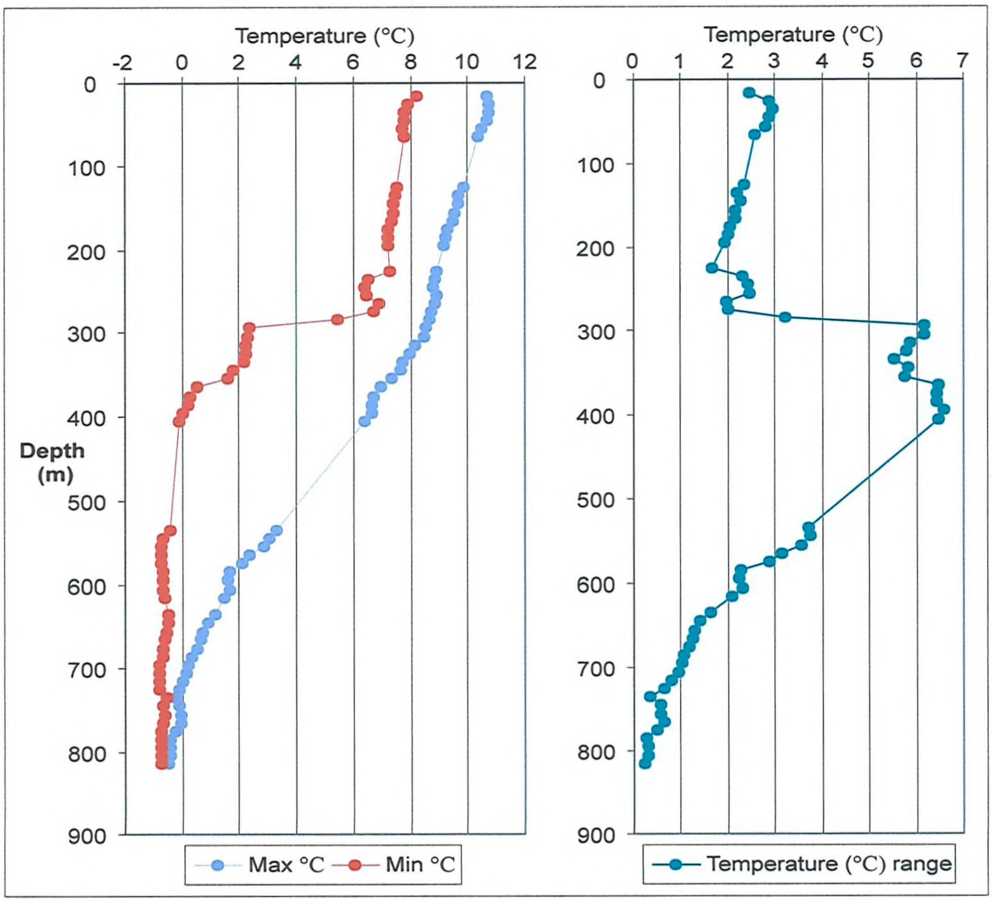


Figure 10.4. The variation in temperature with depth along the continental slope west of Shetland.

In addition to these large-scale results, megafaunal density increases overall with depth while species diversity decreases with depth. Within these large overall distributions with depth, there are also a number of zones largely identified from the sediment distributions, zones also reflected in the small-scale distribution of the megafauna including the iceberg plough mark zone best developed at 300-400 m, 'sponge-belt' at 500-600 m (although less developed at S300) and the characteristic megafauna (particularly the acorn-worms but also the anemones and sea spiders) observed on the sand contourite between 800-900 m in the north- and mid-regions (not present at S800).

The results in this chapter together with those seen in the other chapters in this thesis suggest significant correlations between megafaunal composition and depth, sediment grain size and temperature and, in summary (figure 10.5), the large-scale distribution of the megafauna appears to reflect the distribution of the water masses in the Faroe-Shetland Channel (i.e. an upper (warm/intermediate) layer and a lower (cold) layer although within these two main layers there are also a number of local-scale zones as well as overall bathymetric trends (e.g. density and diversity) in the distribution of the fauna.

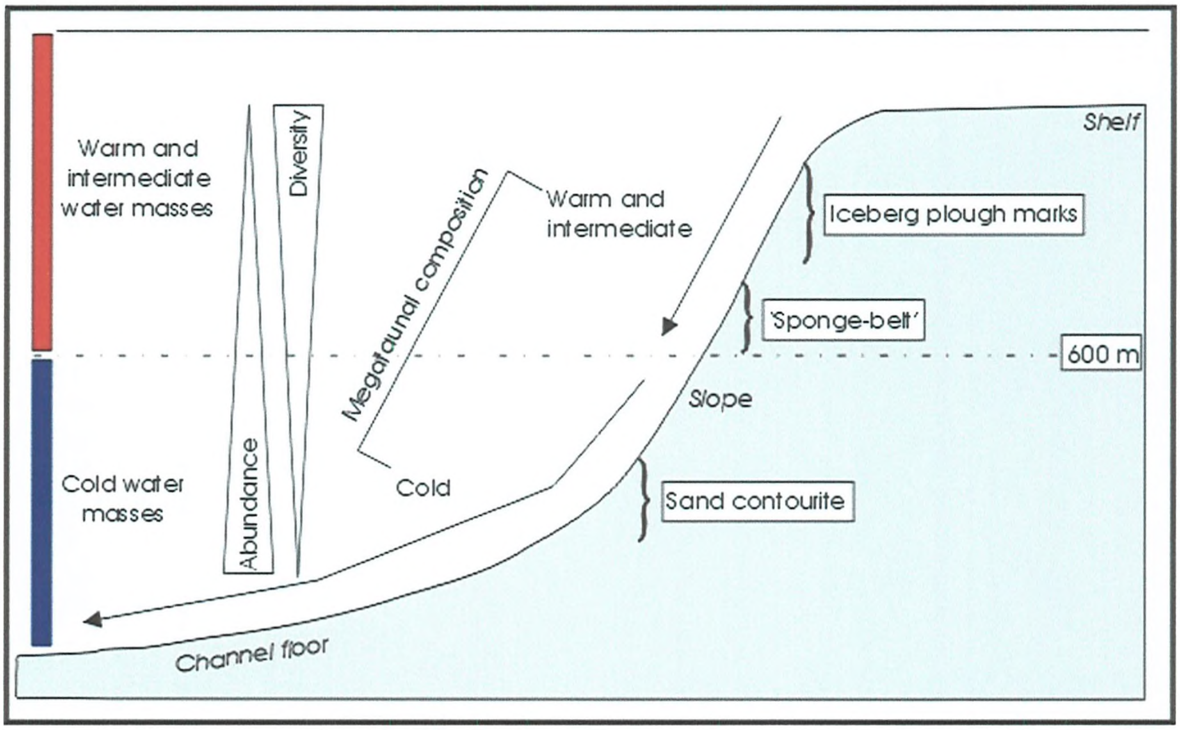


Figure 10.5. Summary of the megafaunal distributions along the continental slope west of Shetland.

10.3 IMPROVEMENTS TO THE STUDY

There are a number of issues that could have improved the results in this study. To enable statistical analysis to be carried out, there is a need for replication of samples with a minimum of two, and preferably more, samples from any one site (McIntyre *et al.*, 1984; Skoog *et al.*, 1994). In this report there is only one photographic run from each site, apart from the sites at 300 m and 400 m along the bathymetric transect, where two runs are available. Although this may be a desired requirement, the costs and timescales normally available in deep-sea sampling make these desires difficult to fulfil. One other possible solution might have been to split the photographic runs into two or three separate 'samples' but this was not carried out as a result of the lack of frames in some (e.g. 53913#1 and 53926#1) of the photographic runs, particularly after frame selection.

Megafaunal identification is notoriously difficult but improvements to this aspect of the study would make the results better, not only to obtain more information about the fauna generally, but also because it would most likely allow for more small-scale analysis where local-scale trends (e.g. variations within the iceberg plough marks) within the megafaunal distribution could be assessed further. It should, however, be noted that identification is extremely hard unless the fauna is physically available. This could be achieved by carrying out simultaneous seabed sampling, although it does not always lead to samples containing the fauna in question as many sampling devices may sample the macro- and meiofauna well but perhaps not the megafauna. In addition, the specimens caught are sometimes damaged during sampling, making identification difficult and sometimes impossible. More photographs at lower altitudes could help in the identification of fauna but also in the detection of other features. If altitude is low throughout the photographic runs it could potentially lead to the lack of other information as a smaller area of the seabed would be photographed but as long as the photographs are taken at altitudes of ≤ 6 m with an even spread of photographs over all the altitude-intervals, most features should be detectable. In addition, deep-sea sampling is dependent on the sea state and photographic sampling using instruments such as WASP is made more difficult when the sea conditions are severe. If more photographs with altitudes of < 6 m were obtained, the analysis may have been improved as detection and identification of fauna and other features is easier when the altitude is lower.

The results of the along-slope study showed some variations both in sediment and megafaunal distributions but further sites are needed to assess this fully. This would not only allow for along-slope variation analysis but also further analysis of the bathymetric changes in density, species diversity and faunal composition at different locations within the Faroe-Shetland Channel.

The sponge cover at 500 m was not fully enumerated. To develop an additional method for studying the sponges at both 500 m and 600 m, where the number of individuals was extremely high, would be of considerable interest. It may be possible to develop a digitising method where the photographs are scanned and sponges identified and quantified using these images. Additional quantification and identification of these sponges may improve the understanding of the variations in megafaunal density and species diversity with depth.

The apparent close relationship between sidescan sonar and photographic analysis results in the iceberg plough mark zone was not proven statistically. Additional sites within the iceberg plough mark zone are therefore required to further assess any megafaunal differences but also to allow additional study of the relationship between photographic and sidescan sonar results and assess the differences in acoustic signal penetration using different sidescan sonar frequencies (see below).

10.4 FUTURE WORK

The AFEN surveys of 1996 and 1998 collected a vast amount of data leading to an increased knowledge and understanding of the seafloor environment along the eastern section of the Faroe-Shetland Channel (Masson, *et al.*, 1996, 1997; Masson and Jacob, 1998; Russell *et al.*, 1999; AFEN, 2000; Bett, 1997, 1999, 2000a, 2001a, 2001b; Masson, 2001; Masson *et al.*, 2001b; Narayanaswamy, 2001). Apart from the aspects noted in this study, there are other aspects, particularly recently discovered features that may need further study. This includes the sand contourite at the bottom of the continental slope west of Shetland and the fauna associated with this sediment feature in particular. The acorn-worms (enteropneusts) were a novel discovery as discussed in this thesis but little is known about them and additional research about this taxonomic group would be of considerable interest.

The discovery of at least a two-layer system within the megafaunal distribution was significant, particularly since a similar system was discovered for both size fractions of the macrofauna (Bett, 2000a, 2001a; Narayanaswamy, 2001) and the hydrography (Turrell *et al.*, 1999). There was, however, a suggestion that a further layer was present within the macrofauna (Bett, 2000a) with the boundary at approximately 300 m and because of the megafauna present at the 200 m site (55456#1), exemplified by the scaphopod *Antalis entalis*, it is possible that there is an additional layer within the megafauna as well. The scaphopods were also observed on the continental shelf by Künster *et al.* (1992) but they have not been observed anywhere else along the bathymetric transect (see chapter 5) or in the along-slope study along the continental slope (see chapter 7) west of Shetland. Further sampling and analysis of photographs from sites at depths of approximately 200 m would therefore be of interest to verify whether a third layer is present within the megafauna west of Shetland.

As noted in the previous section, the results from the along-slope study showed some variations in both sediment characteristics and megafaunal distributions but additional sites will be required to establish these patterns fully and allow statistical analysis on the data as well.

In the study of the iceberg plough marks (chapter 8), a close relationship was found between the sedimentary and megafaunal features when studying the photographs but the integration of sidescan sonar images and photographs did not reveal a significant relationship, despite the fact that both sets of data revealed the two types of sediment. Further analysis of both photographs and sidescan sonar images from within the iceberg plough marks is therefore desirable to further assess associations between the sediment types and the megafauna. Furthermore, during both the iceberg plough mark and the 'Darwin Mounds' studies it was suggested that there was a difference in TOBI sidescan sonar signal penetration into the sediment depending on the type of sediment present. Additional work using high frequency sidescan sonar instruments in areas where either TOBI sidescan sonar has been or will be used could hopefully clarify whether there is a difference in the penetration of the low and high frequency sidescan sonar instruments. This could further assist in the decision of the type of sidescan sonar equipment to use in future studies of iceberg plough marks when combining it with photography.

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www.kystnett.no	Norwegian marine fauna
www.sams.ac.uk	The Scottish Association for Marine Science
www.ku.dk	University of Copenhagen
www.mbl.suite.dk	University of Copenhagen (Marine Laboratory)
www.zi.ku.dk	University of Copenhagen (zoological institute)
www.gla.ac.uk	Glasgow University

Appendix A

Members of the Atlantic Frontier Environmental Network (AFEN)

In 1998 the membership of AFEN comprised:

Agip (UK) Ltd, Amerada Hess Ltd, Amoco (UK) Exploration Company Limited, ARCO British Ltd, BG E&P Ltd, BP Exploration Operating Company Ltd, Chevron U.K. Ltd, Conoco (U.K.) Ltd, Deminex UK Oil and Gas Limited, Elf Exploration UK plc, Enterprise Oil plc, Esso Exploration and Production UK Ltd, Fina Exploration Ltd, Marathon Oil UK Ltd, Mobil North Sea Ltd, Phillips Petroleum Company U.K. Ltd, Saga Petroleum Ltd, Shell U.K. Exploration and Production, Statoil Ltd, Texaco Britain Ltd, Total Oil Marine plc, Veba Oil & Gas, Joint Nature Conservation Committee, Fisheries Research Services, and the Department of Trade and Industry.