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# 1. EXECUTIVE SUMMARY

**Background**

Commercial extraction of the UK marine aggregate resource peaked in 1989, and has remained relatively steady in recent years at around 23 million tonnes per annum from around the England and Wales coastline. The general public has shown increasing concern that marine sand and gravel extraction may have adverse effects on the environment and fisheries. These fears have grown, in particular, at localities off the eastern and southern English coastlines, which are characterised by the occurrence of a number of dredging licences in close proximity. These concerns are encapsulated by the recent interest of the UK marine aggregates industry in the coarse aggregates deposit of the eastern English Channel.

Studies of benthic recolonization following the cessation of marine aggregate extraction in U.K. waters and elsewhere are limited, and are largely confined to experimental studies. Investigations of the physical and biological status of licensed areas in the U.K. at various times following cessation of commercial dredging are very limited and so judgments as to the likely progress towards environmental restoration are often based on predictions rather than real data.

This research was undertaken to address this deficiency by assessing the status of seabed substrata and associated benthic fauna within and outside areas where dredging had ceased and to conduct follow up sampling to monitor progress towards full recolonization. The current report details work conducted by The Centre for Environment, Fisheries and Aquaculture Science (CEFAS) over the course of a four year research programme. It was funded by the Office of the Deputy Prime Minister (ODPM), the Department for Environment, Food and Rural Affairs (Defra) and The Crown Estate as part of a joint policy initiative to address this important gap in current knowledge. The project was also overseen by a Steering Group, membership of which is given in an Annex to the main report.

**Objectives and Methodology**

The report provides a detailed account of a research project into the recolonization of a number of marine aggregate extraction sites following the cessation of dredging. The main objectives of this study are:

- to understand the rate at which the seabed recovers following marine aggregate extraction;
- to identify measures to enhance the potential for the rehabilitation of dredged areas and;
- to investigate whether different historical levels of dredging intensity affect the subsequent rate and nature of benthic recolonization at marine aggregate extraction sites after the cessation of dredging.

The objectives were achieved through a review of existing data, a series of field surveys and numerical modelling conducted over a four year period. Pilot surveys were conducted at seven sites around the U.K coast in the first year of study, which facilitated the decision-making process regarding site selection and the identification, on a site-specific basis, the most cost-effective survey and sampling strategies for time-series investigations and 'one off' spatial evaluations.

The approach to field surveys was therefore to concentrate sampling activity at a number of representative extraction sites including both time-series investigations and surveys extending over a wider area. Four sites within disused licensed areas around the coast were identified each representative of different time periods since effective cessation of dredging and subjected to different intensities of dredging.

Comprehensive time-series investigations of the sediments and benthic macrofauna were conducted between 2001 and 2003 at stations corresponding with different degrees of dredging intensity for the four locations, namely: Area 408 (Humber), Area 222 (Thames) and Hastings Areas X and Y. Two of these sites are located in the North Sea, one offshore from Felixstowe in the outer Thames region (Area 222) and the other offshore from the Humber estuary (Area 408). Both these extraction areas are isolated from the possible impacts of dredging from other licensed areas.

In addition, two extraction areas within the eastern English Channel were targeted for study, both located on the Hastings Shingle Bank (Hastings Area X and Y). These latter sites were selected because they both contained similar deposits and biological habitats, but were exposed to different dredging regimes in terms of the frequency and intensity of extraction operations and time elapsed since dredging ceased (with the potential to force differing degrees of impact between areas).

Information from The Crown Estate's Electronic Monitoring System (EMS) used by marine minerals dredging operators was used to target precisely locations of varying dredging intensity during the design of seabed surveys. Areas of the seabed subjected to higher and lower levels of dredging intensity were sampled alongside reference locations. These latter sites were located well outside the likely influences of dredging operations and chosen to be representative of undredged conditions in the wider environment.

The main sampling tools were a 0.1 $m^2$ Hamon grab fitted with a video camera and light and a heavy duty 2 m beam trawl which were used to determine the benthic assemblages and sediment characteristics. Remote survey methods such as sidescan sonar, bathymetric systems, Acoustic Ground Discrimination

Systems (AGDS) and photography were also employed to provide an indication of the spatial distribution of sediments in the wider area encompassing the dredged site, to estimate the likely spatial extent of dredging disturbance and to provide a regional context for time-series investigations of representative sites. Relationships between the level of dredging intensity, physical habitat characteristics and assemblages were investigated using a range of univariate and multivariate statistical techniques.

Two spatially extensive surveys of the macrofauna and sediments were also conducted as part of this programme at Area 222 and at the Hastings Shingle Bank. The purpose of these investigations was to check the 'representativeness' of selected treatment and reference sites sampled as part of time-series investigations.

**Findings from field studies**

Sidescan sonar surveys indicate that the physical effects (i.e. presence of weathered dredge tracks or pits) can be detected at least three years after the cessation of extraction at Hastings Area Y, four years after at Area 408, seven years after at Hastings X and 10 years after at Area 222.

In general, sediments collected from areas previously exposed to higher levels of dredging intensity contained proportionally more sand and less gravel than other sampled sediments. There was also evidence for greater patchiness in the substrata within the surveyed extraction sites. This variability among replicate samples was also evident in some of the biological samples from dredged locations and may be an identifiable symptom of perturbed conditions. However, this propensity for extraction sites to exhibit variability in terms of sediment characteristics and species composition needs to be referenced against a high degree of natural variability and small-scale sediment patchiness that can be encountered in benthic ecosystems even at locations which appear, superficially, to be relatively homogeneous.

The absence of comprehensive baseline data for each of the extraction areas precludes definitive attribution of cause and effect relationships. Despite this, evidence from this study suggests that the fauna remains in a perturbed state in areas previously subjected to 'high' levels of dredging intensity at least three years at Hastings Area Y, four years at Area 408 and seven years at Area 222. These findings, particularly those obtained at Areas 222 and 408, appear to conflict with a small body of case studies which together suggest that substantial progress towards restoration of the fauna could be expected within two-three years following cessation of marine sand and gravel extraction.

The discrepancy between the data obtained in this investigation and other studies was considered to reflect differences in the magnitude of dredging disturbance. For example, many previous investigations were concerned with the effects of relatively short lived dredging campaigns, whereas this study examined the status of former extraction sites which had been subjected to the effects of repeated dredging over many years. Furthermore, the use of EMS data in this study provided the opportunity to target accurately the intensity and location of dredging, thus increasing the ability to discriminate the effects of aggregate extraction.

Deposits exposed to lower levels of dredging intensity at Area 222 and Hastings Area X were found to be almost indistinguishable from the surrounding sediments in terms of species variety and population densities of macrobenthic invertebrates within a period of 6-7 years after relinquishment. This suggests that similar deposits exposed to comparable environmental conditions and levels of dredging disturbance would be expected to recover within a period of 6-7 years following the cessation of dredging, provided a substrate layer broadly similar to the pre-dredging sea floor deposits remains.

Results also indicate that the geographical location of the extraction sites and the percentage of sand explained regional differences in the fauna i.e. the results tend to be site-specific. This site-specificity which will also include variability in the dredging history and any particular extraction practices employed can complicate the prediction of likely effects at both extant and prospective extraction areas.

A spatially extensive survey at the Hastings Shingle Bank revealed that the distribution of sediments and associated benthic assemblages across the region was characterised by broad areas of sandy gravels, gravelly sands and sands. Furthermore, reference locations were found to be physically indistinguishable from both dredged and undredged gravelly deposits within the region. This finding supports the selection of these sites as appropriate reference points against which the effects of aggregate extraction may be judged over time. The area within which samples were collected for the assessment of the effects of low levels of dredging intensity at Hastings Area Y may be less useful as a long-term monitoring site, since it was found to be located across the boundaries of two sediment types. Therefore, samples collected from this area were considered to be subject to the confounding effects of variability arising from natural and anthropogenic factors.

At Area 222, a comparison of sidescan sonar and multibeam bathymetric surveys provided further insights in terms of the distribution of sediments and seabed features within and in the vicinity of the extraction site. The separation of the two main macrofaunal assemblages identified in this area accords with the location of a gently rising bank which lies almost at right angles to the local tidal axis. Coincident with increasing water depth is an apparent fining of the sediment to the west of the historic extraction site and these factors appear to influence the distribution of the benthic assemblages in the area. There was also evidence of a distinctive biological assemblage located within areas known to have been previously dredged.

These spatial surveys in conjunction with acoustic (sidescan sonar, AGDS and bathymetry surveys) and visual (underwater photography) techniques have provided a robust approach to assessing the site-specific effects of marine aggregate extraction in relation to the wider distribution of faunal assemblages and sediments. In addition, such an approach has proved essential for the understanding of cause/effect relationships and as a useful adjunct for the interpretation of time-series investigations.

When the outcome of the above studies are considered in combination, they indicate that the effects of extraction on the benthic fauna and sediments may persist over time within dredging areas and that the period for benthic 'recovery' appears to depend on the local environment and the magnitude of disturbance.

**Lessons for future monitoring studies.**

A number of findings have implications for the improved evaluation of potential dredging areas and subsequent monitoring of environmental impacts at marine aggregate extraction sites. In particular, EMS information proved to be very useful for precisely targeting locations of varying dredging intensity during the design of seabed surveys and for the interpretation of findings. This approach assisted the evaluation of the recovery of dredged areas after cessation. One important recommendation arising from this study is, therefore, that greater account is taken of EMS information during the design and interpretation of ongoing monitoring surveys at current aggregate extraction areas.

Complementary surveys of the epifauna populations using trawls also provided additional information, beyond that obtained from conventional grab sampling, about the status of the disused extraction areas in terms of the range and relative abundance of species present and the distribution of biomass across different size classes. Results indicated that there was no evidence for a shift to smaller sized epifaunal specimens at the dredged sites in any of the extraction areas, rather there was an absence or reduction in the abundance of epifaunal species belonging to the smaller size classes, equating to a decline in productivity. Results from these analyses also provided evidence of a relationship between tidal current strength, the associated mobility of sand and the composition of epifaunal assemblages.

The employment of a number of the techniques and approaches adopted as part of time-series investigations in this study are advocated for use in ongoing monitoring programmes, where the emphasis is on assessing temporal trends before, during and after dredging activity. Furthermore, the outcome of this research, emphasizes the importance of including a spatial component in such monitoring programmes, in order to check the 'representativeness' of annually sampled sites.

**Framework for future studies**

The impacts of marine aggregate extraction on the benthic environment were reviewed through an assessment of the literature and the findings from field studies undertaken as part of this research programme. Many of the field studies reported in the literature are the results of investigations on the impacts of short-term dredging events and these have proved useful in determining the rates and processes leading to benthic re-establishment following aggregate extraction.

By drawing together the findings from a wide variety of sources, it has been possible to propose a general pattern of benthic response to marine aggregate extraction which is presented. From the results of this programme and from the limited information from existing studies, it is clear that re-establishment of a biological assemblage similar to that which existed prior to dredging can only be attained if the topography and original sediment composition are restored and the natural hydrodynamic regime has not been changed. This needs to be tested to establish its general validity in all environments, particularly in areas which have been exposed to dredging operations over many years.

**Measures to enhance the potential for the rehabilitation of dredged areas**

The research programme also set out to identify management strategies for minimising the environmental consequences of ongoing dredging activity and maximising the prospects for rehabilitation of sediments following the cessation of dredging. The report suggests several management strategies, following consideration of the outcome of field surveys. These include controlling the level of dredging intensity on a site-specific basis and rotating dredging operations to different zones whilst leaving 'fallow' areas to rehabilitate over a period of several years. It is recommended that the wider environmental and operational cost-benefits of adopting such measures, including the impacts on other ecosystem components and/or other users of the marine environment, are closely examined prior to their application.

**Development of a 'mobility index'**

As a further complement to field surveys, an initial assessment was made of the potential for the prevailing hydrodynamic conditions in the vicinity of centres of dredging activity to mobilise the bed sediments. This work was undertaken by HR Wallingford in collaboration with CEFAS and is presented as an Annex to the main report. The study considered the hydrodynamic conditions at ten locations around the south and east coasts of England as derived from a combination of computational flow and wave models held by HR Wallingford. The outcome of analysis of flow and wave data was used to classify extraction sites based on the potential for mobility of sand-sized material under the action of waves and tides.

These analyses resulted in the production of a 'mobility index' which was examined alongside the results of benthic sampling in order to produce an index of natural environmental variability. It is hoped that future developments in this area will allow confident predictions to be made of the recovery capacity of sites in advance of the granting of aggregate dredging licences.

**Desk study on methodology for evaluating the vertical distribution and stability of gravel reserves.**

Finally, as part of this research programme, a desk study has been conducted by the British Geological Survey in collaboration with CEFAS into the 'state of the art' of methodology for evaluating the vertical distribution and stability of commercial gravel reserves. This review examines the relative merits of different physical and geophysical methods used in the measurement of these aspects of seabed structure. A detailed account of this work is presented in a separate report (James and Limpenny, 2000).

**Recommendations**

A series of recommendations including areas for further research have been identified as a result of this study and are presented.

For further information on this report, please contact Dr S E Boyd (mailto:s.e.boyd@cefas.co.uk).

# 2. INTRODUCTION

Each year in the UK, around 23 Mt of sand and gravel is extracted from the seabed from licensed areas, as a source of aggregate for the construction industry, to supplement land-based sources, or as a source of material for beach nourishment (Singleton, 2001). Typically, marine aggregate in U.K. waters is dredged by trailer suction hopper dredgers. Dredging using such dredgers is carried out whilst the ship is underway leading to the production of shallow linear furrows approximately 1 to 3 m in width and generally 0.2 to 0.3 m in depth per pass (Kenny and Rees, 1994). Whilst the main method of dredging in the U.K. is through trailer dredging, a number of vessels in the U.K. fleet are also able to dredge by anchoring or remaining stationary over the deposit. This is usually referred to as static suction hopper dredging and is employed in areas where the deposit is spatially restricted or locally thick (e.g. East of the Isle of Wight, in the Bristol Channel and off the North Wales coast). In this case, dredging usually results in saucer-shaped depressions, typically up to 8 to 10 m deep with slopes of ~5 degrees and 200 m in diameter (Dickson and Lee, 1972; BMAPA *pers. comm.*).

The length of time that trailer-dredged furrows or depressions created by static dredging will remain as distinctive features on the seabed depends on the ability of tidal currents or wave action to erode crests or transport sediments into them (Millner *et al.* 1977; van der Veer *et al.*, 1985). Erosion of dredge tracks in areas of moderate wave exposure and tidal currents have been observed to take between 3 to >7 years (Millner *et al.*, 1977; Kenny and Rees, 1996; Limpenny *et al.*, 2002; Boyd *et al.*, 2003). At an experimental dredged site off Norfolk, U.K. in 25 m of water, dredge tracks appeared to be have been completely eroded within 3 years of the cessation of dredging (Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998). In this case, infill resulted mainly from sand in transport. However, in an area exposed to long period waves, dredge tracks (of 0.3-0.5 m deep) were found to completely disappear in a gravelly substrate at a depth of 38 m within 8 months (van Moorsel and Waardenburg, 1991; van Moorsel 1993, 1994). In contrast, dredged depressions created by static dredging have been reported to remain as recognisable seabed features for several years at a location off Hastings in the Eastern English Channel (Shelton and Rolfe, 1972). Dickson and Lee (1973) concluded that at this location many years, perhaps amounting to decades, would be required for the dredged seabed to revert to its pre-dredging condition.

Changes in sediment composition as a result of dredging are well documented in the literature (Dickson and Lee, 1972; Shelton and Rolfe, 1972; Kaplan *et al.*, 1975; van der Veer *et al.*, 1985; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000). Such changes range from minor alterations to surficial granulometry (McCauley *et al.*, 1977; Poiner and Kennedy, 1984) to an increase in the proportion of fine sands (Desprez, 2000; van Dalfsen *et al.*, 2000) or an increase in gravel through the exposure of coarser sediments (Kenny *et al.*, 1998). As infill of dredged depressions or tracks is typically dependent in U.K. waters on the mobilization of sands by tidal currents, this can result in a change of sediment composition from sandy gravels to gravelly sands (Dickson and Lee, 1972, 1973; Shelton and Rolfe, 1972; van der Veer *et al.*, 1985). Particular dredging practices can also contribute to the fining or coarsening of sediments over time. For example, the aggregate extraction industry carries out screening activities in order to meet specific sand/gravel requirements of the construction industry. Typically, the construction industry requires marine aggregate to be supplied with a gravel content of greater than 50%. Where the *in-situ* gravel content of the resource being dredged is lower than this, dredgers employ on-board screening to increase the gravel content of cargoes. Vessels use either static screen boxes or screening towers to alter the composition of the dredged aggregate by passing the water/aggregate mix over a mesh screen. Assuming the intention is to increase the gravel content, a proportion of the finer material and water will pass through the screen and be returned to the sea by means of a reject chute (BMAPA *pers. comm.*). Hitchcock and Drucker (1996) and Newell *et al.* (1999) estimated that up to 1.6-1.7 times the total cargo is discharged into the surrounding water column due to the screening process during the typical loading of a dredged cargo at some extraction areas in the UK. Clearly, estimates such as these are site specific and will vary in relation to the grain size of seabed sediments, the grading required for the cargo and the efficiency of the dredger. Over time, the progressive removal of the original sandy gravel and its replacement by sandier sediments through screening activities has the potential to result in a gradual fining of the sediment within the extraction areas, although in some instances this increase in sand may be temporary due to the reworking capabilities of tides and waves (Stride, 1982; Nunny and Chillingworth, 1986).

Dredging can also lead to the production of plumes of suspended material. Material can arise from the mechanical disturbance of the seabed sediment by the draghead. However, the outwash of material from spillways from the vessel hopper can generate a far greater quantity of suspended material. A further source of suspended material results from the rejection of unwanted sediment fractions by screening activities. Suspended sediments arising from the latter two processes have been termed surface plumes (Hitchcock and Drucker, 1996). Their areal extent and excursion are dependent on the sediment particle size, total quantity of material suspended, velocity of discharge and the local hydrodynamics (Hitchcock and Drucker, 1996; Alluvial Mining Limited, 1999). Studies have shown that the sedimentation of sand-sized particles is principally confined to a zone of a few hundred metres from the point of discharge *via* the spillways (Hitchcock and Drucker, 1996; Newell *et al.,* 1998, 1999). However, recent work has suggested that dredging and overboard screening results in the deposition of well-sorted fine sands which are subsequently transported much greater distances (up to at least 2000 m) away from the site of discharge (Evans, 2000; Coastline Surveys Europe Limited, 2002).

As the extraction of marine sand and gravel has its primary impact at the seabed, assessment of the effects of this activity has conventionally targeted bottom substrata and their associated benthic fauna (Millner *et al.*, 1977; Desprez, 2000; van Dalfsen *et al.*, 2000). Historically, the scientific study of coarser sediments has presented a significant challenge, largely on account of the difficulties of obtaining reliable quantitative samples (Eleftheriou and Holme, 1984). As a consequence, information on the nature and distribution of benthic assemblages and their wider role in the marine ecosystem, is considerably more limited than in areas of soft sediments.

Differences in the type of dredger employed, as well as the nature of the receiving environment, have the potential to influence the spatial scale of impact on the benthic fauna, both in terms of the direct effect of removal of sediments and the indirect effects of extraction associated with the deposition of suspended sediments. The significance of sedimentation from plume fall-out or from screening operations on the benthic fauna and its effect on the rate of recolonization is an issue which has been receiving increasing attention (Poiner and Kennedy, 1984; Desprez, 2000; Newell *et al.*, 2002; Boyd and Rees, 2003; Newell *et al.*, 2004). One study of a fine sediment site in Moreton Bay, Australia, showed enhanced abundances of benthic invertebrates adjacent to dredged subtidal sandbanks which may have been linked to sedimentation of plume material (Poiner and Kennedy, 1984). Increased sedimentation and resuspension as a consequence of dredging in deposits of clean mobile sands are generally thought to be of less concern, as the fauna inhabiting such areas tend to be adapted to naturally high levels of suspended sediments caused by wave and tidal current action (Millner *et al.* 1977). Effects of sediment deposition and resuspension may be more significant in gravelly habitats dominated by encrusting epifaunal taxa due to the abrasive impacts of suspended sediments (Desprez, 2000; Boyd and Rees, 2003). This effect was highlighted in a study of a gravel extraction site in the eastern English Channel, where the indirect impacts of sand deposition discharged with the dredger were shown to be of greater consequence than the direct effects of extraction for the recolonization of macrobenthic species (Desprez, 2000). At this location, effects beyond the extraction site were manifested by a reduced complement of species, lower densities, and a significantly reduced biomass, compared with nearby locations. More recently, Newell *et al.* (2002) also found some evidence for the impacts of dredging to extend beyond the margins of a licensed extraction site in the North Sea, in terms of the suppression of benthic biomass. They suggested that this may have been the result of impacts associated with the re-mobilisation of sediments introduced by screening activities.

Of those studies which have considered the effects of marine aggregate extraction on the benthic fauna, most have concentrated on establishing the rates and processes of macrobenthic recolonization upon cessation of dredging (Cressard and Dubyser, 1975; Kenny *et al.*, 1998; Desprez, 2000; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; van Dalfsen and Essink, 2001). The estimated time required for 'recovery' of the benthic fauna following marine aggregate extraction may vary depending on the nature of the habitat, the scale and duration of disturbance, hydrodynamics and associated bed load transport processes, the topography of the area and the degree of similarity of the habitat to that which existed prior to dredging (for review see Newell *et al.*, 1998).

Available evidence indicates that dredging causes an initial reduction in the abundance, species diversity and biomass of the benthic community and that substantial progress towards full restoration of the fauna and sediments can be expected within a period of approximately 2-3 years following cessation (Kenny *et al.*, 1998; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; van Dalfsen and Essink, 2001; Newell *et al.*, 2002). For example, van Dalfsen *et al.* (2000) suggested that recolonization of a dredged area by polychaete worms occurred within 5-10 months after the cessation of dredging in a site located within the North Sea, with restoration of biomass to pre-dredge levels anticipated to occur within 2-3 years. Such studies have been mainly concerned with the effects of dredging operations conducted over a relatively short time-scale e.g. up to periods of 1 year (Kenny *et al.*, 1998; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; van Dalfsen and Essink, 2001). Under such circumstances, any more subtle effects e.g. on seasonal recruitment success to the locality, arising from prolonged dredging over several years would clearly be expected to be minimal. Assessments of 'recovery' usually involve an examination of a number of community parameters such as abundance, numbers of species, diversity and biomass prior to disturbance and then at various intervals subsequently (Bonsdorff, 1983, Kenny *et al.*, 1998, Desprez, 2000). Typically, re-establishment of biomass dominants and age structures tends to take longer than other community attributes to return to pre-dredging levels following marine aggregate extraction (Rees, 1987; Kenny *et al.* 1998; van Dalfsen *et al.* 2001; Newell *et al.*, 2002; Vanaverbeke *et al.*, 2003).

Few studies have addressed the consequences of long-term dredging operations on the recolonization of biota or the composition of sediments following cessation (Desprez, 2000; Newell *et al.*, 2002; Newell *et al.*, 2004). Thus, there is limited information which is directly applicable to the impacts of commercial dredging operations in U.K. waters, where the life-time of a typical production licence is at least 15 years. Since investigations of the physical and biological status of licensed extraction sites in the UK at various times following cessation of commercial dredging are limited, judgements as to the likely progress towards environmental restoration and the time-scales involved are often based on predictions rather than real data. This is exemplified in the recent Regional Environmental Assessment undertaken for the Eastern English Channel Area, where predictions on the recolonization potential of macrofaunal species were erected without recourse to information and/or data on the effects of extraction in an environmentally similar habitat (Posford Haskoning, 2003). Of the available studies which have examined the longer term impacts of marine aggregate extraction there is also some disparity in the findings ranging from minimal effects of disturbance following cessation of dredging (Newell *et al.*, 2002) to significant changes in community structure which persist over many years (Desprez, 2000). These inconsistencies further complicate the prediction of the likely effects of dredging in other areas. Information was therefore required from field-studies to address some of the gaps in knowledge on the mode and rate of recolonization of benthic fauna following the cessation of dredging in habitats exposed to commercial dredging practices.

## 2.1. Objectives

The focus of this research programme was to assess the status of the seabed sediments and associated benthic communities within and outside areas where dredging has ceased and to conduct follow-up sampling to monitor progress towards full recolonization. The outcome of survey work also has the notable benefit of allowing questions about the present status of locations hitherto subject to commercial exploitation to be answered directly, rather than by inference. Specific objectives were:

- To understand the rate at which the seabed recovers following marine aggregate extraction;
- To identify measures to enhance the potential for the rehabilitation of dredged areas;
- To investigate whether different historical levels of dredging intensity affect the subsequent rate and nature of benthic recolonization at marine aggregate extraction sites after the cessation of dredging.

## 2.2. Selection of survey sites

A review was initially conducted in order to aid site selection. Information from the aggregate extraction industry and The Crown Estate concerning dredging activities was gathered, with a view to:

i. identifying locations at which dredging had ceased, or was likely to do so within the study period;
ii. establishing from recent Electronic Monitoring System data and any earlier information the historical patterns of dredging intensity within licensed blocks;
iii. determining the annual quantities removed;
iv. documenting the method of dredging and any screening activities.

Sites were sought which were geographically varied and, as far as possible, representative of current extraction practices and biological habitats around the U.K. coast. Pilot surveys were conducted at 7 sites around the U.K. coast in the first year of study, which facilitated the decision-making process regarding site selection, and the identification on a site-specific basis of the most cost-effective survey and sampling strategies for time-series investigations and 'once off' spatial evaluations. By this means, four sites within disused licensed areas around the coast were identified, each representative of differing times since effective cessation of dredging and subject, historically, to different intensities of dredging (see Table 2.1).

Two of these sites are located in the North Sea, one offshore off Felixstowe in the outer Thames region (Area 222) and the other offshore from the Humber estuary (Area 408). Both these extraction areas are isolated from the possible impacts of dredging from other licensed areas. In addition, two extraction areas within the eastern English Channel were targeted for study, both located on the Hastings Shingle Bank (Hastings Areas X and Y). These latter sites were selected on the grounds that both contained similar deposits and biological habitats, but were exposed to different dredging regimes in terms of the frequency and intensity of extraction operations (with the potential to force differing degrees of impact between areas). The four areas shown in Figure 2.1 represent the sites over which the techniques described in Section 3.0 were applied. Table 2.1 presents the main characteristics of the extraction sites investigated in this study.

### *2.2.1 Area 222*

Area 222 is located approximately 20 miles east of Felixstowe off the southeast coast of England in water depths of between 27 m and 35 m Lowest Astronomical Tide (LAT). This site, with an overall area of approximately 0.3 km$^2$, was first licensed for sand and gravel extraction in 1971 with a peak in extraction activity recorded as 872,000t in 1974. Extraction continued at levels >100,000 t per annum until 1995, before the site was relinquished by the industry in 1997. Limited historical information exists on the dredging practices employed at this site, although it is believed that sand:gravel ratios of dredged cargoes were adjusted by screening, with excess sand being discharged

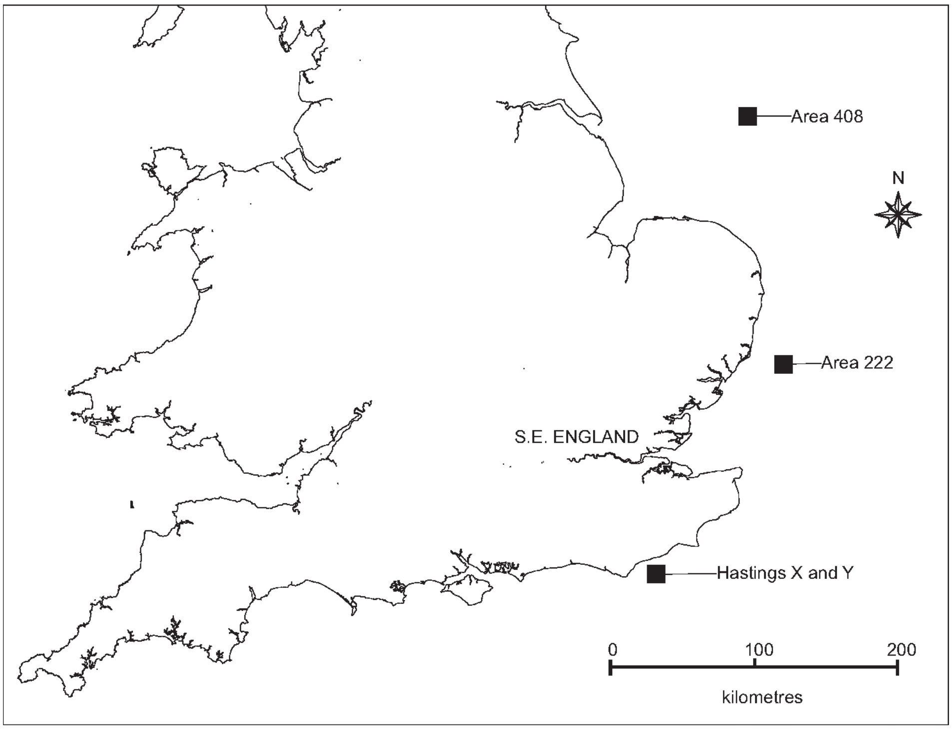



***Figure 2.1. Map showing location of aggregate extraction areas surveyed between 2001-2003***

overboard at the site of dredging (M. Russell *pers. comm.*). It is thought that both trailer suction hopper dredgers and static suction hopper dredgers may have operated at and within the vicinity of the licensed site (M. Russell *pers. comm.*). Gravel deposits in this region tend to have a relatively impoverished epifauna dominated by 'resilient' motile species such as hermit crabs and the starfish *Asterias rubens* and with a much reduced sessile faunal component. This is a consequence of the resuspension and scouring action of sands, which are naturally disturbed by peak spring tidal currents in this region. Such communities are characteristically able to tolerate disturbance.

The geology of the area is characterised by an eroded basal unit of London Clay which is overlain by Pleistocene sediment deposited during the drainage of the land surface that existed at the end of the Pleistocene. These sediments were re-worked during the Holocene to form thin (generally <1 m) veneers of gravelly sediments. Thicker deposits of these sediments are present within palaeovalleys (Harrison, 1998). Dredging activity at Area 222 appears to have been concentrated within a thickened section of these sediments that encroaches into the northern part of the site and is also present to the north east of the site (ARC Marine Ltd, 1997).

### 2.2.2 Area 408

To augment the range of possible dredging scenarios, Zone 2 in Area 408 was selected for the study, since it is representative of a 'fallow' area within a currently zoned licence. Dredging at Zone 2 in Area 408 commenced relatively recently, in 1996, reaching a peak in 1998 with the extraction of 948,459 tonnes of sand and gravel (Newell *et al.*, 2002), but extraction operations were temporarily suspended in this zone from 2000. Zone 2 is located approximately 60 miles east of the Humber estuary and was exploited for marine aggregate using trailer suction hopper dredgers. This zone has an overall area of approximately 2.6 $km^2$. Water depths range from approximately 20 m to 25 m LAT.

The geological resource targeted within Zone 2 of Area 408 is comprised of a 1-2 m thick discrete lens of gravelly sand, formed as a result of the re-working and winnowing of Pleistocene sediments (Coastline Surveys Europe Limited, 2001). The geological setting of Area 408 is comprehensively described in Coastline Surveys Europe Limited (2002).

In comparison with Area 222, there is a greater volume of historical information on the pattern, duration and intensity of dredging activities at Area 408. Screening of dredged cargoes was routinely carried out at Area 408, with sands being returned to the seabed. Recent work by Coastline Surveys Europe Limited (2002) and by Evans (2000) suggest that marine aggregate extraction and screening activities at this site may contribute to the deposition of well-sorted fine sands which may subsequently be transported distances up to at least 2000 metres to the south east. Deposits located at Area 408 are characterised by opportunistic polychaete worms and crustacea (Newell *et al.*, 2002). Such species would be expected to rapidly recolonize sediments following the cessation of dredging.

***Table 2.1. Main characteristics of the extraction sites studied as part of this research programme.***

| Parameter | Area 222 | Hastings Area X | Hastings Area Y | Area 408 (Zone 2) |
|---|---|---|---|---|
| Geographic location of study site | 20 miles east of Felixstowe, southern North Sea | Hastings Shingle Bank, 6 miles south of Hastings, eastern English Channel | Hastings Shingle Bank, 6 miles south of Hastings, eastern English Channel | 60 miles east of Humber Estuary, North Sea |
| Size of licensed area | 0.3 km$^2$ | 1.35 km$^2$ (prior to 2001) | 3.1 km$^2$ (prior to 2001) | 2.6 km$^2$ |
| Total quantities extracted over lifetime of dredging activity | 10.2 Mt. Unknown proportion of this extracted from outside licensed area | The only dredging campaign prior to 2002 was in 1996, when 1.3 Mt was extracted | Total of 16 Mt extracted during annual campaigns between 1988 and 2000 | 1.5 Mt in annual campaigns between 1996 and 1999 |
| Lifetime of dredging activity | 1971 - 1996 | Dredged during 1996, extraction resumed during 2002 | 1988-2000 | 1996-1999 |
| Maximum hours of dredging per year in hours, in the high dredging intensity box recorded in 100 m by 100 m area (since 1993) | 39.5 | 28.5 | 10.25 | 14.25 |
| Type of dredger employed | Static suction hopper dredger and trailer suction hopper dredgers | Trailer suction hopper dredgers | Trailer suction hopper dredgers | Trailer suction hopper dredgers |
| Screening | There is limited information from historical records, although it is probable that screening occurred at this site | All-in cargoes | All-in cargoes | Sand returned to seabed as screened material |
| Water Depth | 27-35 m | 15-21 m | 16-25 m | 20-25 m |
| Geological provenance of the resource | Localised thickened layer of reworked lag deposits ~3 m thick | Infilled palaeovalley >10 m thick | Infilled palaeovalley >10 m thick | Reworked lag sediments in localised lens ~1-2 m thick |
| Maximum tidal velocity | 2.3 kn (1.17 m s$^{-1}$) | 2.6 kn (1.32 m s$^{-1}$) | 2.6 kn (1.32 m s$^{-1}$) | 1.4 kn (0.71 m s$^{-1}$) |

Areas 408 and 222 are located on the East Coast where aggregate deposits are present as relatively thin layers (Nunny and Chillingworth, 1986). Such deposits are typically dredged using trailer suction hopper dredgers, with the cargoes being screened and sands being the main sediment fraction which are returned to the seabed. The thickness of the worked layer in these areas is normally of the order of a few metres, although localised deposits of considerable thickness do exist in these regions. In contrast, extraction licences on the south coast of England tend to exploit discrete deeper deposits of coarser aggregate. The cargoes dredged from such sites are typically 'all-in'. Therefore, to account for some of the dredging practices employed on the south coast, two sites (Hastings Area X and Y) on the Hastings Shingle Bank were targeted for study.

### 2.2.3 Hastings Area X and Y

The Hastings Shingle Bank forms a distinctive topographic feature aligned in an ENE/WSW direction at water depths of between 16 m and 25 m LAT (EMU, 1999). The outline of Area X, prior to the introduction of the new licence boundary in 2001, formed an irregular polygon with a total area of 1.35 km$^2$. Area Y also had an irregular outline and a total licensed area of 3.1 km$^2$. The aggregate resources that are present in sub-areas X and Y are associated with infilled palaeovalleys which meander over the Hastings Shingle Bank and are truncated at their southern extent. These palaeovalleys are characteristically infilled with deposits of sandy gravel up to 15 m thick and 500 m wide (Evans, 1998; EMU, 1999) and it is these localised resources that are targeted by the industry. Extraction of marine aggregate has been licensed on the Hastings Shingle Bank since 1988. Since then, there have been numerous alterations to the boundaries of the extraction licences on the Bank. Dredging licences at sub-areas X and Y were both relinquished in 2001 and replaced by a new licence in the same year. Although this new licence encompassed parts of the old sub-areas X and Y, areas of the seabed from both these relinquished areas lie outside of the new licence boundaries. This presented the opportunity to investigate benthic recolonization in two disused areas of the bank. Despite the location of two sub-areas X and Y within close geographical proximity, they have very different extraction histories. Sub-area Y was actively dredged between 1988 and 2001, with extraction activity at its peak between 1996-1998. Over 7 million tonnes of material was removed during this period. However, at sub-area X, dredging was only carried out in 1996 and again in 2002. Cargoes were 'all in' at both these sites i.e. no screening activity was undertaken.

Historical studies of the benthic fauna in the Hastings region have been conducted to address monitoring conditions associated with dredging licences (Kenny, 1998; EMU, 1999), and as part of R&D programmes (Kenny *et al.*, 1991; Brown *et al.*, 2001; Hewer *et al.*, 2002; Brown *et al.*, 2004; Foster-Smith *et al.*, 2004). R&D investigations were also conducted prior to the commencement of dredging operations and therefore provide a useful baseline (Shelton and Rolfe, 1972; Rees, 1987) against which later studies can be judged. A range of sampling techniques have been employed in such studies including conventional approaches such as grabs, dredges and divers or remote methods such as video, sidescan sonar and Acoustic Ground Discrimination Systems. A significant feature of all these studies is the reported range and diversity of macrobenthic species encountered within undredged gravel deposits on the Hastings Shingle Bank. For example, gravel substrates within the undredged parts of the Hastings Shingle Bank are characterised by a range of epifaunal species including the soft coral, dead man's fingers (*Alcyonium digitatum*), the sea urchin *Psammechinus miliaris*, the sea anemone *Metridium senile*, the hydroid *Sertularia*, the serpulid polychete *Pomatoceros triquete*r and the encrusting bryozoan *Schizomavella* (Brown *et al.*, 2001; Hewer *et al.*, 2002; Brown *et al.*, 2004). In contrast, dredged deposits in this region are reported to be sandier and support a more limited range of sessile epifaunal species compared to elsewhere on the Hastings Shingle Bank (Brown *et al.*, 2001; Hewer *et al.*, 2002; Brown *et al.*, 2004).

Whilst the differing dredging histories (in terms of the rate of extraction, particular dredging practices and intensity of extraction etc) complicate a direct geographic comparison of effects, the four selected sites account for some of the current and historic dredging practices employed in English waters and are representative of several habitats where dredging is occurring. However, it was not within the scope of the project to account for all combinations of dredging scenarios practiced in the U.K. across the full range of habitats currently exploited for marine aggregate. Nevertheless, in parallel with the development of hydrodynamic indices (see Annex I), it is hoped that data arising from this study will provide the means to make inferences to other sites and improve the predictive capability with regard to the environmental effects of dredging activity, whether recently ceased, ongoing or planned.

# 3. METHODS

## 3.1. Sampling design

Since 1993, every vessel dredging on a Crown Estate licence in the UK has been fitted with an Electronic Monitoring System (EMS). It consists of a PC electronically linked to the navigation system and one or more dredging status indicators. This automatically records the date, time and position of all dredging activity, every 30 seconds, to disk. Many of the dredgers operating in U.K. waters are fitted with Differential Global Positioning Systems which allow the EMS to operate with a typical accuracy of ±10 m. EMS information was interrogated in order to locate areas of the seabed within the extraction licences which had been subjected to different levels of dredging intensity. Limited records exist on the level of the dredging intensity that these locations were subjected to prior to the introduction of the EMS in 1993. Stations were randomly distributed within each area ('stratified random sampling') and allocated in proportion to the size of the sampling box. Replicate samples were also collected from nearby reference locations which were considered to be representative of the wider environment surrounding the extraction licences and outside of the influence of any potential effects on the benthos from aggregate extraction.

Selection of appropriate reference sites was aided by the use of sidescan sonar and video images of the seabed (see below for methodology) and following criteria given in Anon (1997) and Boyd (2002). Data arising from this design provide a comparative evaluation of 'treatment' and 'reference' groups. In this way, the outcome of survey work can be used to test whether there are differences in the structure of macrobenthic communities from reference areas compared with areas that have previously been exposed to different levels of dredging intensity. Note that the 'reference' areas are not considered representative of baseline conditions, as there was insufficient information on which to determine what actually constitutes the likely pre-dredging status of an area.

## 3.2. Sample collection

Sample collection followed the methodology given in Boyd (2002). Samples for analysis of the macrobenthic fauna and sediment particle size were collected with a $0.1m^2$ Hamon grab from *RV CIROLANA* in 2000-2002 and from *RV CEFAS ENDEAVOUR* in 2003. This device was employed, as it has been shown to be particularly effective on coarse substrates (Kenny and Rees, 1994, 1996; Seiderer and Newell, 1999). The original design was for a grab, which samples an area of about $0.25\ m^2$ (Oele, 1978). More recently, CEFAS has introduced a smaller device, sampling an area of $0.1m^2$ (see Boyd, 2002). As $0.1\ m^2$ is the conventional surface sample unit employed in most benthic surveys of continental shelf sediments conformity with this size allows direct comparison of results with those from a wide variety of sources using a range of other sampling devices. The Hamon grab consists of a rectangular frame forming a stable support for a sample bucket attached to a pivoted arm (Figure 3.1). On reaching the seabed, tension in the wire is released which activates the grab. Tension in the wire during inhauling then moves the pivoted arm through a rotation of 90°, driving the sample bucket through the sediment. At the end of its movement, the bucket locates onto an inclined rubber-covered steel plate sealing it completely. This results in the sediment rolling towards the bottom of the sample bucket, thereby reducing the risk of gravel becoming trapped between the leading edge of the bucket and the sample retaining plate, and thus preventing part of the sample being washed out.

All locations were sampled at the same time of year between May and July. Replicate samples were collected from areas of the seabed that had been identified from EMS as being of high and lower dredging intensity. Replicate samples were also collected from nearby reference sites.

Following estimation of sample volume, a 500 ml sub-sample was removed for laboratory particle size analysis. The whole sample was then washed over 5 mm and 1 mm square mesh sieves to remove the fine sediment. The two resultant fractions (1-5 mm and >5 mm) were back-washed into separate containers and fixed in 4-6% buffered Formaldehyde solution (diluted in seawater) with the addition of 'Rose Bengal' a vital stain.

## 3.3. Acoustic and video surveys

Sidescan sonar surveys were undertaken using the Datasonics™ SIS 1500 digital chirp system using the Triton Isis™ data acquisition software. The Delphwin™ software package was used to post-process the data, and provided georeferenced mosaiced images of the sonar data. Such surveys were undertaken in order to provide an indication of the spatial distribution of sediments in the wider area encompassing the dredged sites and to estimate the spatial extent of both direct and indirect effects of dredging. Furthermore, the sidescan sonar surveys provide information on the distribution and stability of bedforms.

Where conditions allowed, photographic surveys using underwater video and stills techniques were conducted using a Simrad™ video camera and a Benthos DSC™ 4000 digital stills camera mounted within a robust metal frame. These surveys were used to obtain additional groundtruth information on the physical and biological status of the seabed. The camera frame was lowered close to the seabed as the vessel drifted with the tide. Video images were recorded automatically onto both high-resolution SVHS and digital tapes.

***Figure 3.1. A 0.1m² Hamon grab with attached video camera supported on an open frame to facilitate retrieval of the sample into a moveable container following controlled release from the grab bucket***

Multibeam surveys were carried out using a dual head, hull mounted, Kongsberg Simrad EM 3000D high-resolution multibeam sonar. The data were corrected in real time for vessel movements using a Simrad motion reference unit (MRU5). Soundings were acquired using TEI Inc, Triton Isis™ software and data were tidally corrected and gridded using the TEI Inc, Bathypro™ processing package. The data was presented using TEI Inc, Delphmap™ software. Given the depths of water encountered, multibeam swath widths were typically half of the sidescan swath widths.

## 3.4. Macrofaunal sample processing

Macrofauna samples were processed according to the guidelines given in Boyd (2002). The >5 mm sample fraction was first washed with fresh water over a 1 mm mesh sieve in a fume cupboard, to remove excess Formaldehyde solution, then back-washed onto a plastic sorting tray. Specimens were removed and placed into labelled glass jars containing a preservative of 70% Industrial Methylated Spirits. Specimens were identified, where possible, to species level. The 1-5 mm fraction was first washed over a 1 mm sieve then back-washed into a 10 litre bucket. The bucket was filled with fresh water and the sample was then gently stirred in order to separate the animals from the sediment. Once the animals were in suspension, the sample was decanted over a 1mm mesh sieve. This process was repeated until no more material was recovered. Specimens from this fraction were placed into labelled petri-dishes for identification and enumeration. The sediment was then placed on plastic trays and examined under an illuminated magnifier for any remaining animals such as bivalves not recovered in the decanting process, which were then added to the petri-dishes. The blotted wet weight (in milligrams) for each species recorded from replicate samples was also recorded.

## 3.5. Sediment particle size analysis

The sediment sub-samples from each grab were analysed for their particle size distributions. Samples were first wet-sieved on a 500 µm stainless steel test sieve using a sieve shaker. The <500 µm sediment fraction passing through the sieve, was allowed to settle from suspension in a container for 48 h. The supernatant was then removed using a vacuum pump and the remaining <500 µm sediment fraction was washed into a petri-dish, frozen for 12 h and freeze-dried. The total weight of the freeze-dried fraction was recorded. A sub-sample of the <500 µm fraction was then analysed using a laser sizer. The >500 µm fraction was washed from the test sieve into a foil tray and oven dried at ~ 90°C for 24 h. It was then dry sieved on a range of stainless steel test sieves, placed at 0.5 phi intervals, down to 1 phi (500 µm). The sediment on each sieve was weighed to 0.01 g and the values recorded. The results from these analyses were combined to give a full particle size distribution for each sample.

## 3.6. Data processing

### *3.6.1. Sediment variables*

Particle size distribution data have been presented using cumulative frequency distribution curves. Changes in the shape of the curve for any given sample when compared to another, reflect the variations in the particle size distribution of those samples.

A correlation-based principal components analysis (PCA) was applied to ordinate results from the sediment analyses. The data array is thought of as defining the positions of samples in relation to axes representing the full set of environmental variables measured, one axis for each variable. The first principal component (PC1) is then defined as the direction in which the variance of sample points projected perpendicularly onto the axis is maximised. The second principal component (PC2) is defined as the axis perpendicular to PC1 (Clarke and Warwick, 1994).

Analysis of similarities (ANOSIM, Clarke, 1993) was performed on sediment particle size data to test the significance of differences in particle size composition between treatments.

### 3.6.2. Macrofaunal assemblage structure

***Univariate analyses***

Ash free dry weights (AFDW) were calculated using standard conversion factors (Ricciardi and Bourget, 1998). The univariate measures, total abundance (N), numbers of macrofaunal species (S) and biomass (AFDW) were calculated. This allows a visual interpretation of any trends (e.g. increasing or decreasing abundance at different sampling locations and over time) and their statistical significance, whereas this judgement is more difficult for results obtained by multivariate data analyses. The significance of differences between treatments was tested using one-way ANOVA.

***Multivariate analyses***

Non-parametric multi-dimensional scaling (MDS) ordination using the Bray-Curtis similarity measure (Bray and Curtis, 1957) was applied to species abundance data. Initially, the overall similarity between every pair of samples is calculated taking all the species into consideration. The samples are then plotted in such a way that distances between pairs of samples reflect their relative dissimilarity in species composition. The MDS ordination can therefore be used to identify groups of samples having similar faunal assemblages. A stress value gives an indication of how well the two-dimensional plot represents the multi-dimensional sample relationship. Values between 0.05 and 0.2 generally correspond to a good representation of sample similarities (Clarke and Warwick, 1994).

Warwick and Clarke (1993) noted that in a variety of environmental impact studies, the variability among samples collected from impacted areas was much greater than from reference sites. The suggestion was that this variability, in itself, may be on identifiable symptom of perturbed situations. To test whether this pattern was evident with the data from dredged sites examined in this study, the comparative Index of Multivariate Dispersion (IMD) was calculated. IMD has a maximum value of +1 when all similarities among impacted samples are lower than any similarities among reference samples. The converse case gives a minimum for IMD of –1, and values near zero imply no difference between groups.

The comparative Index of Multivariate Dispersion is restricted to the comparison of only 2 groups e.g. reference versus high dredging intensity samples and therefore is usually complemented by calculation of the relative Index of Multivariate Dispersion (r.IMD; Somerfield *et al.*, 1993). This index has a value of 1, if the relative dispersion of samples corresponds to the 'average dispersion'. Values greater than 1 are obtained if replicate samples are more variable than average. In contrast, a value lower than 1 is achieved if replicate samples are less variable than average.

Analysis of similarities (ANOSIM, Clarke, 1993) was performed to test the significance of differences in macrofauna assemblage composition between samples. The nature of the community groupings identified in the MDS ordinations was explored further by applying the similarity percentages program (SIMPER) to determine the contribution of individual species to the average dissimilarity between samples.

The techniques above have been used to identify patterns in the biological data. In an attempt to establish the causes of faunal distributions further statistical analyses were conducted. Multivariate approaches were used to link biological patterns to environmental variables (see Clarke and Warwick, 1994). A visual expression of the relationships between the macrofaunal and other environmental datasets was obtained by superimposing the environmental data as symbols, in linear dimensions proportional to the selected environmental variables, upon the output of the MDS ordination. The relationships between multivariate community structure and environmental variables were further assessed using the BIOENV programme. In this procedure, rank correlations ($\rho$w) between a similarity matrix derived from the biotic data and matrices derived from various subsets of environmental data are calculated, thereby defining suites of environmental variables which best explain the biotic structure. All multivariate analyses were performed using the software package PRIMER v. 5, developed at the Plymouth Marine Laboratory (Clarke and Gorley, 2001).

# 4. TEMPORAL INVESTIGATIONS OF THE PHYSICAL AND BIOLOGICAL STATUS OF AREA 222

## 4.1 Methods

### *4.1.1 Study site*

The study site (designated 'Area 222') is located approximately 20 miles east of Felixstowe off the southeast coast of England (Figure 4.1) in water depths of between 27 m and 35 m Lowest Astronomical Tide (LAT). The tidal ellipse in the region is rectilinear and is aligned in a NNE - SSW direction. The predicted net bed sediment transport direction in the area is to the north east (HR Wallingford, 2002). The dredging history and geological setting of the site are described in Section 2.0.

### *4.1.2. Sampling design*

Area 222 was not dredged in the 4 years prior to sampling (Figure 4.2). Sampling was conducted in July 2000-2003, i.e. 4, 5, 6 and 7 years after the cessation of dredging. Historical information (from 1993 onwards) on the location and intensity of dredging was used to direct sampling. Replicate samples of the macrofauna and sediments were collected from areas representing 2 different levels of dredging intensity 1) >10 hours of dredging within a 100 m by 100 m block during 1995 and 2) <1 hour of dredging within a 100 m by 100 m block during 1995 (Figure 4.3). In addition, a reference site (Reference site 1) was sampled in 2000-2003 and this was augmented by sampling at a second reference site (Reference site 2) in 2001-2003.

With this design, the area of high dredging intensity represents conditions following the repeated removal of commercial aggregate from most of the total surface area of a 100 m by 100 m block, many times over the course of 1 year. This assumes that a dredger, typically a trailer suction hopper dredger, moves slowly over the seabed at a speed of 2 kt and creates a dredge track approximately 2.5 m wide (Millner *et al.*, 1977; van Moorsel and Waardenberg, 1990; Kenny and Rees, 1994). It also assumes that the dredger works systematically across an area. In practice, particular deposits will be more frequently targeted by the dredging industry and therefore, under the treatment designated as the high dredging intensity, some areas of the seabed may have been dredged in the past on a regular basis, whereas other areas of the seabed may only have been dredged once or twice in a year. In contrast, the area of low dredging intensity represents conditions after the removal of up to about 90% of the total surface area in a similar 100 m by 100 m block in a single year. However, some locations within this treatment may have only experienced limited exposure to the direct effects of extraction, allowing survival of some species and recolonization

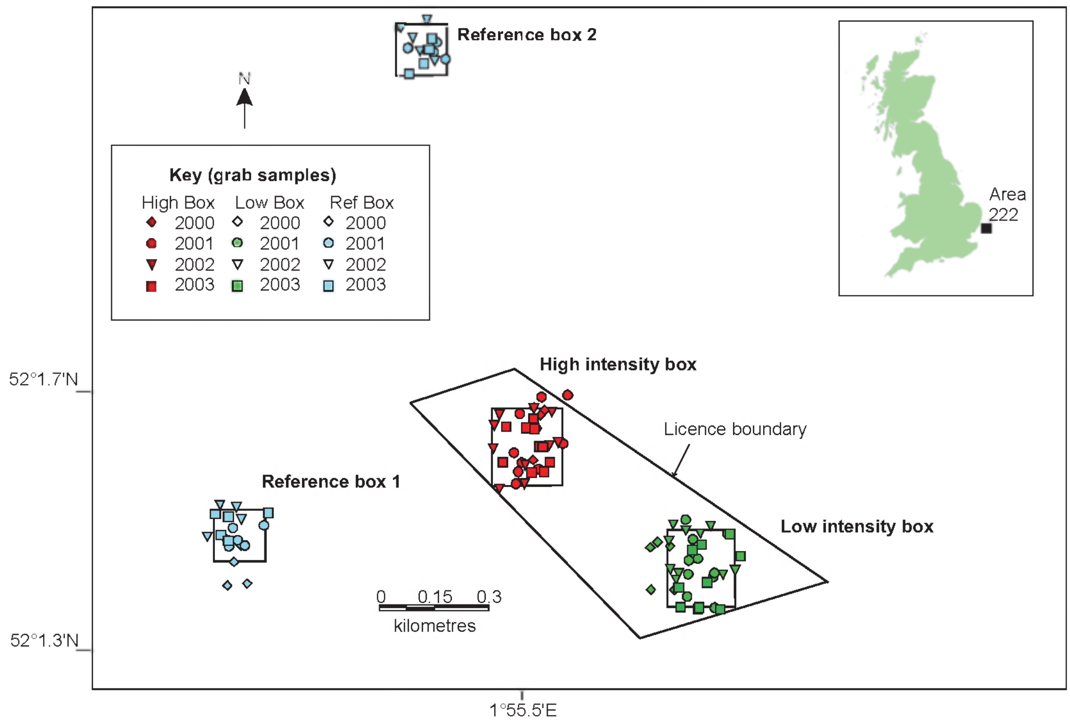



***Figure 4.1. Map showing the location of Area 222 aggregate extraction licence and sampled stations from the surveys carried out in 2000-2003***

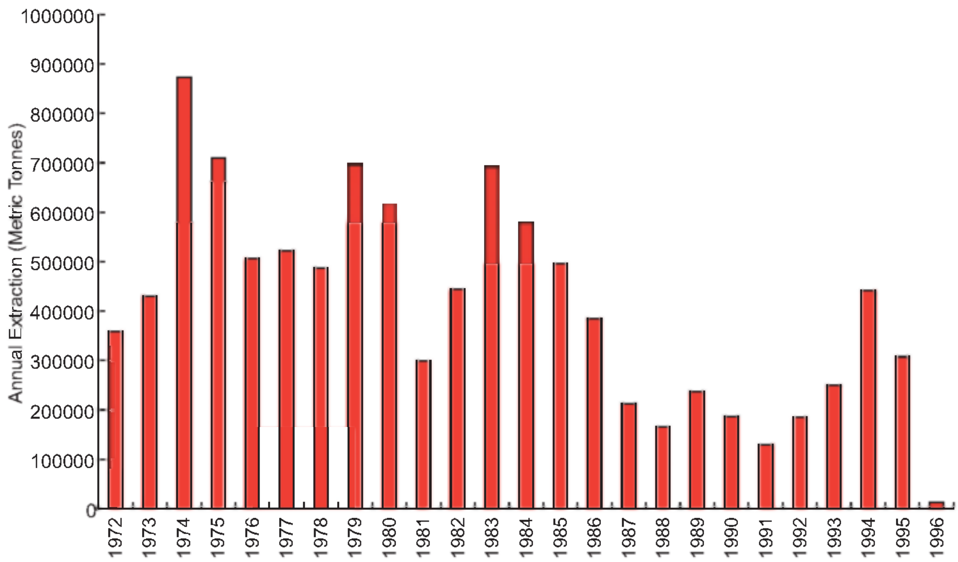



***Figure 4.2. Annual quantity of aggregate extracted from Area 222 over the period 1972-1996***

by others whilst extraction was ongoing. In addition, the low dredging intensity samples were collected approximately 400 m to the south of the area of high dredging intensity (see Figure 4.3). Direct studies on sediment settlement suggest that sand is deposited at distances up to 300-600 m down current from a dredger, with the possibility of plume effects and the remobilization of sediments extending significantly beyond this (Hitchcock and Drucker, 1996; Newell *et al*., 2001; Newell *et al*., 2002). Therefore, the area of low intensity was potentially subjected to any indirect effects (e.g. transport of unconsolidated sediments) associated with the nearby more intensive dredging activity. Sampling details for locations sampled as part of the Area 222 time-series investigations are presented in Table 4.1.

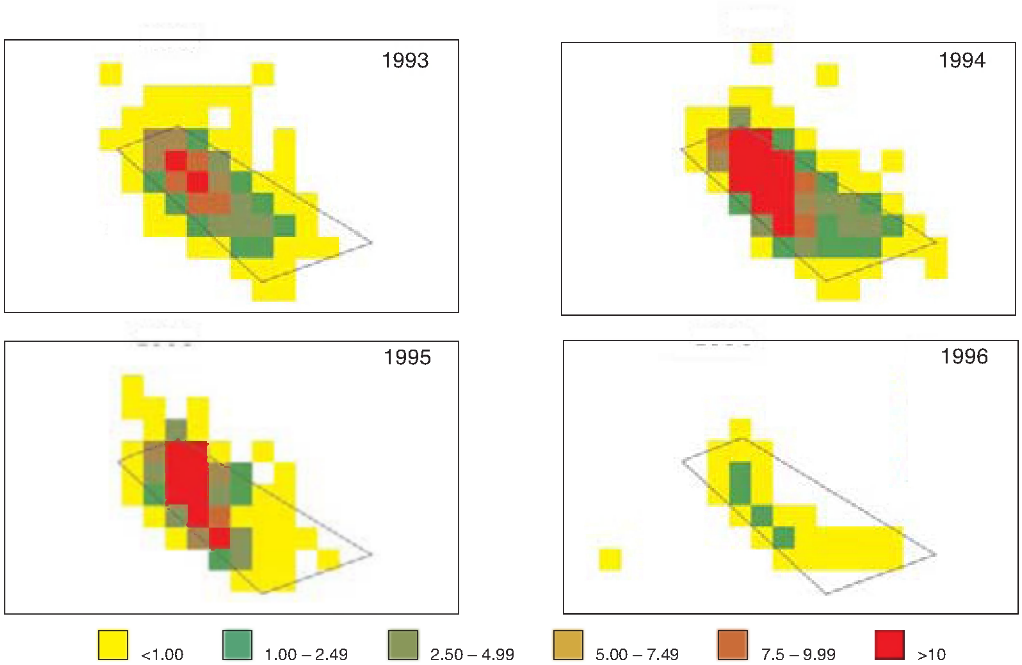



***Figure 4.3. Location and intensity of dredging (in hours) over each 100 m x 100 m block at Area 222 between 1993 and 1996***

**Table 4.1. Sampling details for locations sampled as part of the time-series investigations at Area 222. Box co-ordinates given as positions in WGS 84 from top right and bottom left hand corners of the sampling box**

| Treatment | Code | Box co-ordinates | | Area ($m^2$) | Number of samples collected | | | |
|---|---|---|---|---|---|---|---|---|
| | | Latitude | Longitude | | 2000 | 2001 | 2002 | 2003 |
| High intensity box | HIGH '00 to '03 | 52° 01.686' N<br>52° 01.572' N | 01° 55.554' E<br>01° 55.536' E | ~40,000 | 5 | 10 | 10 | 10 |
| Low intensity box | LOW '00 to '03 | 52° 01.506' N<br>52° 01.392' N | 01° 55.968' E<br>01° 55.806' E | ~40,000 | 5 | 10 | 10 | 10 |
| Reference site 1 | REF 1 '00 to '03 | 52° 01.530' N<br>52° 01.470' N | 01° 54.828' E<br>01° 54.726' E | ~20,000 | 5 | 5 | 5 | 5 |
| Reference site 2 | REF 2 '01 to '03 | 52° 02.256' N<br>52° 02.184' N | 01° 55.278' E<br>01° 55.158' E | ~20,000 | 0 | 5 | 5 | 5 |

## 4.2. Results

### 4.2.1. Sediment characteristics

Sediment particle size characteristics are presented in Table 4.2 and the cumulative particle size distribution curves for each of the survey years are presented in Figure 4.4. Grain size descriptions relate to the Udden-Wentworth scale (Wentworth, 1922).

In all years, particle size data from the replicate sediments sampled at the site of high dredging intensity show a large degree of variability in the gravel and coarse sand fractions. Reference site 2 was sampled in 2001, 2002 and 2003 and sediments from this location show more variability between replicates than those found at either Reference site 1 or the site of low dredging intensity. An ordination by PCA of sediment particle size data from the Hamon grab samples is illustrated in Figure 4.5.

In terms of particle size distribution, sediments collected from the area of low dredging intensity and the reference locations were more similar to each other than to sediments from the area of high dredging intensity. This was due to the higher percentage of coarse sand from samples collected from the area of high dredging intensity compared with the samples from the area of low dredging intensity and reference locations. This is reflected in the PCA ordination by

**Table 4.2. Mean values (±SD) of sediment particle size characteristics from samples collected at Area 222 (codes as in Table 4.1).**

| Year | Sample Code | Mean particle size [mm] | Sorting | Skewness | Kurtosis | Gravel [%] | Coarse Sand [%] | Medium Sand [%] | Fine Sand [%] | Silt/clay [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | REF1 00 | 1.04 (±1.45) | 4.27 (±0.63) | 0.36 (±0.56) | 2.26 (±0.96) | 45.87 (±13.73) | 12.92 (±7.37) | 4.50 (±3.33) | 5.72 (±1.93) | 30.99 (±19.6) |
| | LOW 00 | 1.78 (±0.51) | 3.22 (±0.28) | 0.64 (±0.11) | 2.90 (±0.25) | 51.75 (±5.34) | 9.64 (±0.66) | 22.37 (±2.06) | 9.50 (±1.87) | 6.75 (±3.92) |
| | HIGH 00 | 1.76 (±0.91) | 1.92 (±0.89) | -0.26 (±0.86) | 4.30 (±3.03) | 34.84 (±22.70) | 40.95 (±25.60) | 20.72 (±7.42) | 2.95 (±1.99) | 0.54 (±0.63) |
| 2001 | REF1 01 | 1.04 (±0.65) | 3.81 (±0.68) | 0.76 (±0.21) | 3.08 (±1.16) | 43.72 (±13.54) | 20.86 (±8.53) | 12.11 (±7.42) | 5.40 (±2.80) | 17.92 (±9.18) |
| | REF2 01 | 2.10 (±1.38) | 3.38 (±0.77) | 1.05 (±0.34) | 4.41 (±1.73) | 49.33 (±19.02) | 25.05 (±11.58) | 9.86 (±8.55) | 5.36 (±2.18) | 10.41 (±8.95) |
| | LOW 01 | 2.05 (±0.83) | 3.27 (±0.44) | 0.88 (±0.36) | 3.70 (±0.39) | 54.30 (±10.48) | 10.08 (±6.53) | 20.75 (±7.27) | 9.12 (±2.48) | 5.76 (±3.20) |
| | HIGH 01 | 1.41 (±1.07) | 1.83 (±1.22) | 0.55 (±0.79) | 12.87 (±10.11) | 25.36 (±24.51) | 53.25 (±29.38) | 16.20(±6.25) | 3.00 (±4.52) | 2.19 (±3.72) |
| 2002 | REF1 02 | 0.54 (±0.36) | 4.71 (±0.55) | 0.28 (±0.29) | 1.77 (±0.36) | 40.78 (±7.97) | 12.16 (±2.74) | 7.85 (±5.65) | 4.92 (±1.36) | 34.30 (±10.91) |
| | REF2 02 | 2.06 (±1.56) | 3.63 (±0.97) | 0.82 (±0.77) | 3.57 (±1.36) | 51.42 (±15.59) | 19.61 (±8.73) | 6.00 (±3.43) | 4.11 (±0.70) | 18.85 (±23.64) |
| | LOW 02 | 1.23 (±0.72) | 3.44 (±0.57) | 0.58 (±0.25) | 2.97 (±0.72) | 44.35 (±9.81) | 10.34 (±4.21) | 23.48 (±6.66) | 10.57 (±3.193) | 11.27 (±7.12) |
| | HIGH 02 | 1.29 (±0.69) | 1.94 (±0.96) | 0.02 (±0.68) | 6.06 (±4.10) | 27.24 (±15.86) | 49.86 (±20.91) | 18.69 (±6.28) | 1.81 (±1.73) | 2.40 (±5.25) |
| 2003 | REF1 03 | 0.69 (±0.59) | 4.52 (±0.38) | 0.25 (±0.59) | 2.07 (±0.57) | 40.78 (±12.98) | 13.63 (±4.11) | 5.10 (±3.65) | 5.05 (±1.64) | 35.43 (±18.25) |
| | REF2 03 | 2.53 (±2.68) | 3.55 (±0.73) | 0.95 (±0.71) | 3.77 (±2.08) | 50.21 (±21.95) | 24.22 (±8.83) | 4.58 (±2.41) | 3.74 (±1.47) | 17.24 (±16.35) |
| | LOW 03 | 1.35 (±0.28) | 3.41 (±0.36) | 0.71 (±0.20) | 3.11 (±0.28) | 48.09 (±6.01) | 11.61 (±3.79) | 22.95 (±5.15) | 7.94 (±1.98) | 9.41 (±3.29) |
| | HIGH 03 | 1.89 (±0.98) | 2.35 (±0.97) | 0.13 (±0.97) | 4.29 (±2.84) | 39.47 (±19.55) | 39.27 (±23.59) | 16.16 (±4.38) | 2.23 (±2.15) | 2.85 (±3.38) |

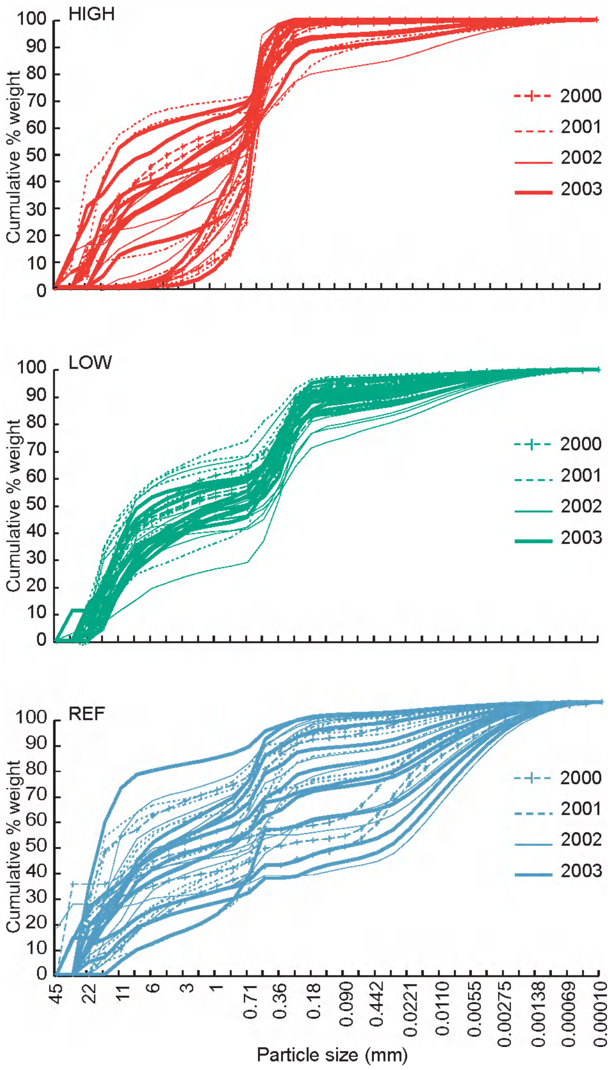



*Figure 4.4.* ***Sediment particle size distributions determined from replicate samples taken from sites of high and lower levels of dredging intensity at Area 222 and the two reference sites***

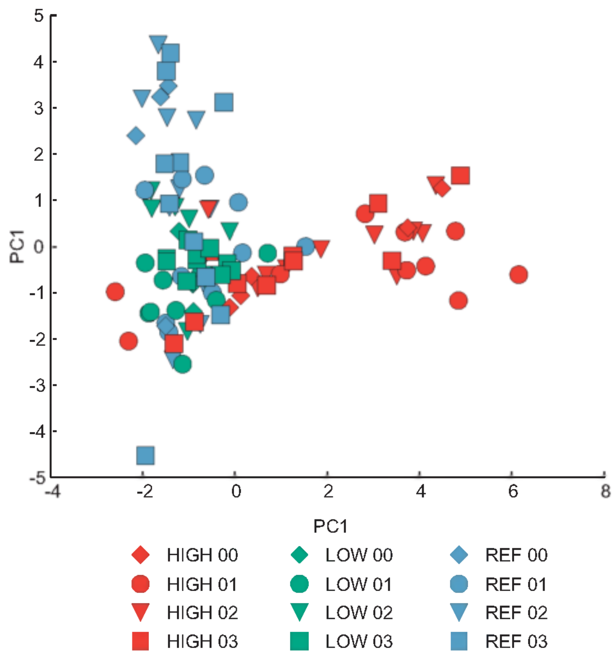



*Figure 4.5.* ***Two dimensional correlation-based PCA ordination of sediment particle size data from Area 222. Total variance explained by the first two principal components = 69%. For variables involved in the correlation see Table 4.2***

the separation of the high dredging intensity samples from the low dredging intensity and reference samples (Figure 4.6). The particle size distributions of samples from within the area of low dredging intensity were also more consistent over time, as depicted by the tighter clustering of samples in the PCA ordination. In contrast, there was a much higher degree of particle size variability between replicate samples collected from the area of high dredging intensity and the reference locations, as represented by the much wider spread of samples from these locations in the PCA ordination. The separation of sediments collected from the area of low dredging intensity and the reference locations (Figure 4.6) is largely on account of the higher silt/clay content of some of the reference samples.

Seventy percent of the total variation is explained by the first two principal components, indicating that the two-dimensional ordination gives an appropriate representation of the similarity between the collected sediments. Table 4.3 shows the analysis of similarities results (ANOSIM, Clarke, 1993) for particle size data between samples collected from the different treatments over the 4-year period of study. There was no significant difference ($p<0.05$) in the particle size distribution of sediments collected at the reference sites over all years. Sediments collected from the high dredging intensity site were also similar to each other in all years. The only significant difference in the sediments collected at the site of low dredging intensity year on year, was between those collected in 2001 and 2003. Otherwise sediments collected at this site were similar between years.

The ANOSIM test indicates that there is a significant difference ($p<0.05$) between both dredged sites and the reference sites in all years. Furthermore, there is also a significant difference between the high dredging intensity site and the low dredging intensity site in all years.

**Table 4.3. *R-values derived from the ANOSIM test for sediment particle size characteristics (mean diameter in mm, sorting coefficient, kurtosis, skewness, % gravel, % coarse sand, % medium sand, % fine sand, % silt/clay) from locations of high and lower levels of dredging intensity and from 2 reference sites in the vicinity of Area 222 sampled in 2000-2003. Performed on normalised Euclidean distance data. Values range from ±1 and zero. A zero value indicates high similarity, and a value of ±1 indicates low similarity between samples. * denotes a significant difference at p<0.05. (codes as in Table 4.1).***

| | HIGH ‘00 | LOW ‘00 | REF1 ‘00 | HIGH ‘01 | LOW ‘01 | REF1&2 ‘01 | HIGH ‘02 | LOW ‘02 | REF1&2 ‘02 | HIGH ‘03 | LOW ‘03 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| HIGH ‘00 | | | | | | | | | | | |
| LOW ‘00 | 0.500* | | | | | | | | | | |
| REF1 ‘00 | 0.516* | 0.604* | | | | | | | | | |
| HIGH ‘01 | 0.001 | 0.236* | 0.373* | | | | | | | | |
| LOW ‘01 | 0.512* | -0.150 | 0.663* | 0.445* | | | | | | | |
| REF1&2 ‘01 | 0.384* | 0.214* | 0.160 | 0.389* | 0.323* | | | | | | |
| HIGH ‘02 | -0.007 | 0.458* | 0.665* | 0.070 | 0.624* | 0.449* | | | | | |
| LOW ‘02 | 0.527* | -0.116 | 0.690* | 0.521* | 0.109 | 0.368* | 0.618* | | | | |
| REF1&2 ‘02 | 0.479* | 0.365* | -0.091 | 0.469* | 0.470* | 0.032 | 0.565* | 0.486* | | | |
| HIGH ‘03 | -0.082 | 0.191* | 0.380* | 0.145 | 0.344* | 0.200* | 0.005 | 0.439* | 0.321* | | |
| LOW ‘03 | 0.729* | 0.057 | 0.808* | 0.523* | 0.152* | 0.399* | 0.604* | 0.008 | 0.525* | 0.426* | |
| REF1&2 ‘03 | 0.415* | 0.364* | -0.108 | 0.428* | 0.507* | 0.057 | 0.522* | 0.521* | -0.072 | 0.313* | 0.542* |

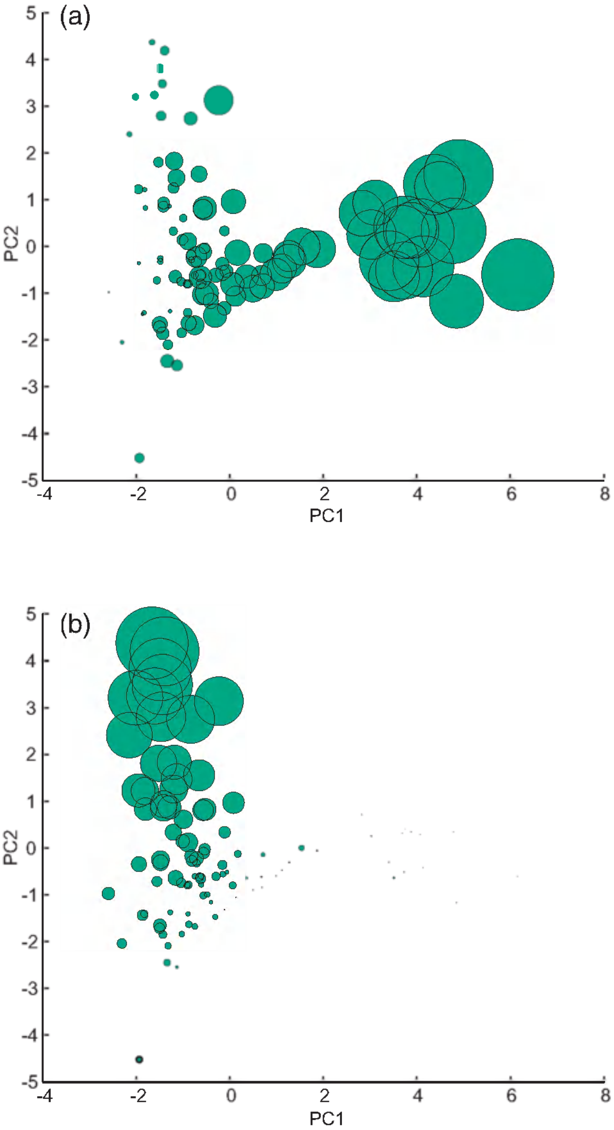



**Figure 4.6. *The same two-dimensional correlation-based PCA ordination as in Figure 4.5, but with superimposed circles proportional in diameter to values of (a) percentage coarse sand and (b) percentage silt/clay***

### *4.2.2. Acoustic surveys*

Sidescan sonar surveys were conducted at Area 222 in 2000-2003. Figure 4.7 shows the output of the sidescan sonar survey conducted in 2002. Operational factors such as weather conditions and the acoustic resolution applied, which may affect the quality of the acoustic record, have been taken into account when comparing the output from the sidescan sonar surveys over time.

The substrata and seabed features within, and in the vicinity of Area 222 identified from the later sidescan sonar surveys are consistent with those observed in 2000 (Boyd *et al.*, 2003). Disturbed sandy sediments interspersed with patches of sandy gravel and occasional small outcrops of consolidated clay predominate in the northern part of the extraction site. EMS records indicate that this area was subjected to the most intensive dredging activity in the years immediately prior to relinquishment, and some evidence of the effects of the trailer suction hopper dredging remains within this part of the site (Figure 4.8). Sidescan sonar surveys conducted between 2001-2003 extend to the north of the extraction site and encompass an area of disturbed seabed previously only surveyed in part in the 2000 survey. This area of seabed to the northeast of the extraction site is uneven, consisting of a series of interconnected pits consistent with the effects of static suction hopper dredging (Figure 4.9). Thus, as noted in previous investigations, it appears that the seabed in this area has been dredged (without a licence) some time prior to the introduction of the EMS in 1993 (Boyd *et al.*, 2003). The area of disturbed seabed extends up to 1000 m away from the northern limit of the extraction site and is characterised by stable, slightly muddy sandy gravels, interspersed by patches of clean rippled sand which form the base of the pit structures. Sediment transport features associated with the zone of out of area dredging also appear to extend up to 1500 metres to the northeast of the northern extent of this disturbed area.

A number of large sand waves (up to ~10 m high), whose crests run at right angles to the tidal axis, lie to the north of Area 222. The presence of these features may be the result of deposition and subsequent entrainment of screened sands produced during the dredging activity within and adjacent to Area 222. Furthermore, the sidescan sonar data indicates that those substrata surrounding Area 222 which have not been directly or indirectly affected by historic dredging activity are similar, being composed of a mixture of sand, gravel and to a lesser extent silt with the occasional outcrop of clay. It should be noted that whilst sidescan sonar is effective in describing the nature of the sediment surface it provides no information on buried substrata.

Changes in the physical status of the seabed have been assessed over the surveyed areas between 2000 and 2003. Particular attention has been given to two areas of seabed that show a persisting physical impact from historic dredging activity (Figures 4.8 and 4.9). Sidescan imaging shows little change in the nature and the distribution of the substrata over the wider survey area between 2000 and 2003. In each year, the seabed substrata surrounding the areas of dredging impact (including those found at the reference sites (Figures 4.10 and 4.11) are stable, mixed sediments.

Within the licensed extraction site, there appears to be some variability in the spatial distribution of sediments over time. Figure 4.8 shows a sidescan sonar image of the same area of seabed within and immediately surrounding Area 222, in each of the four survey years. These images show that whilst there has been some re-distribution of sandy material within the licensed extraction site there has been little apparent change in the overall amount of sand present. Trailer suction hopper dredge tracks are present within and immediately to the north of the extraction site in all years and there appears to be little modification of their appearance over the duration of these surveys. The location of the track features is consistent with the findings of the seabed condition survey carried out in 1996 (ARC Marine Ltd., 1997).

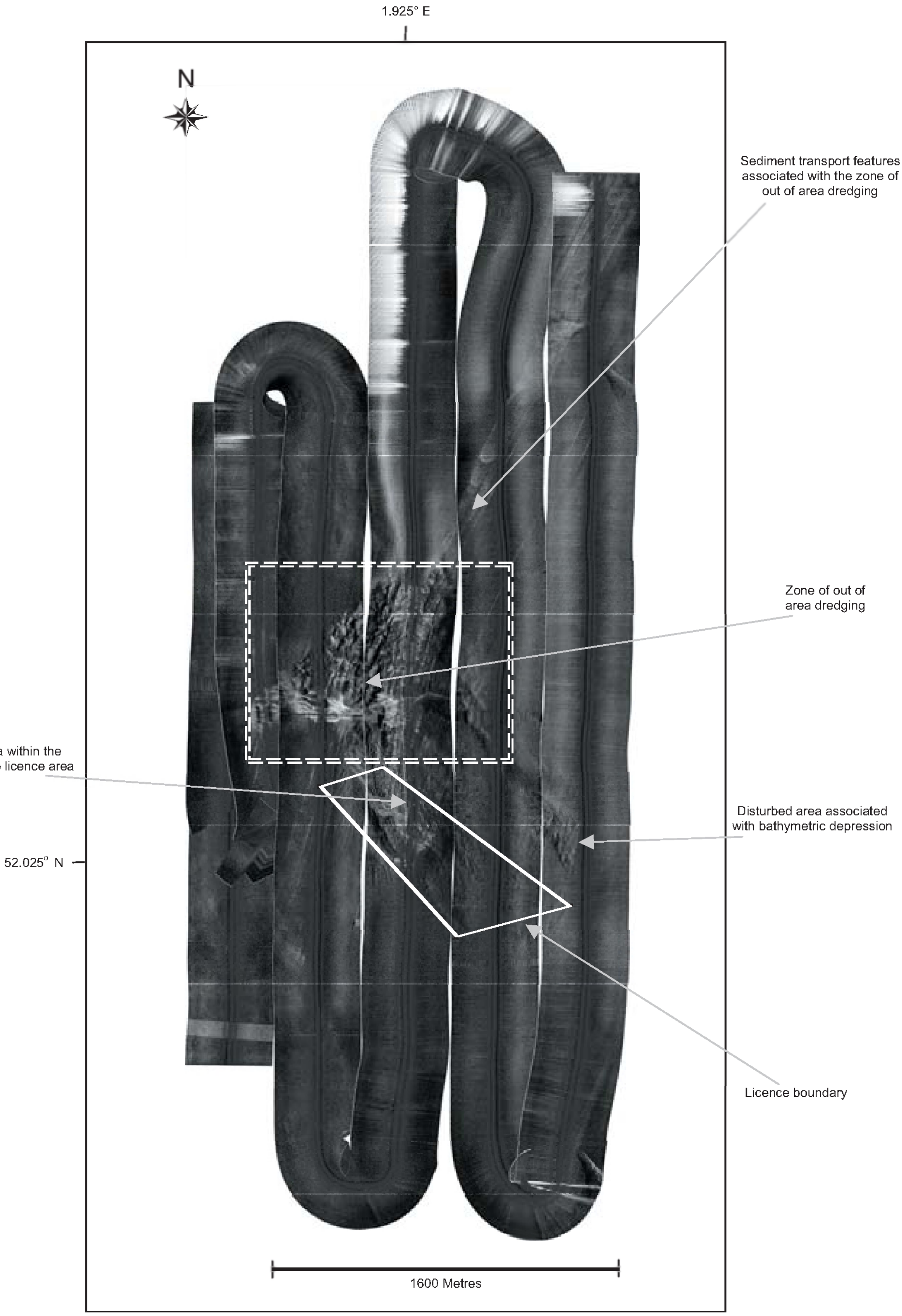



***Figure 4.7. A sidescan sonar mosaic derived from a survey undertaken in 2002 showing the distribution of substrata within and surrounding the former extraction site at Area 222, southern North Sea***

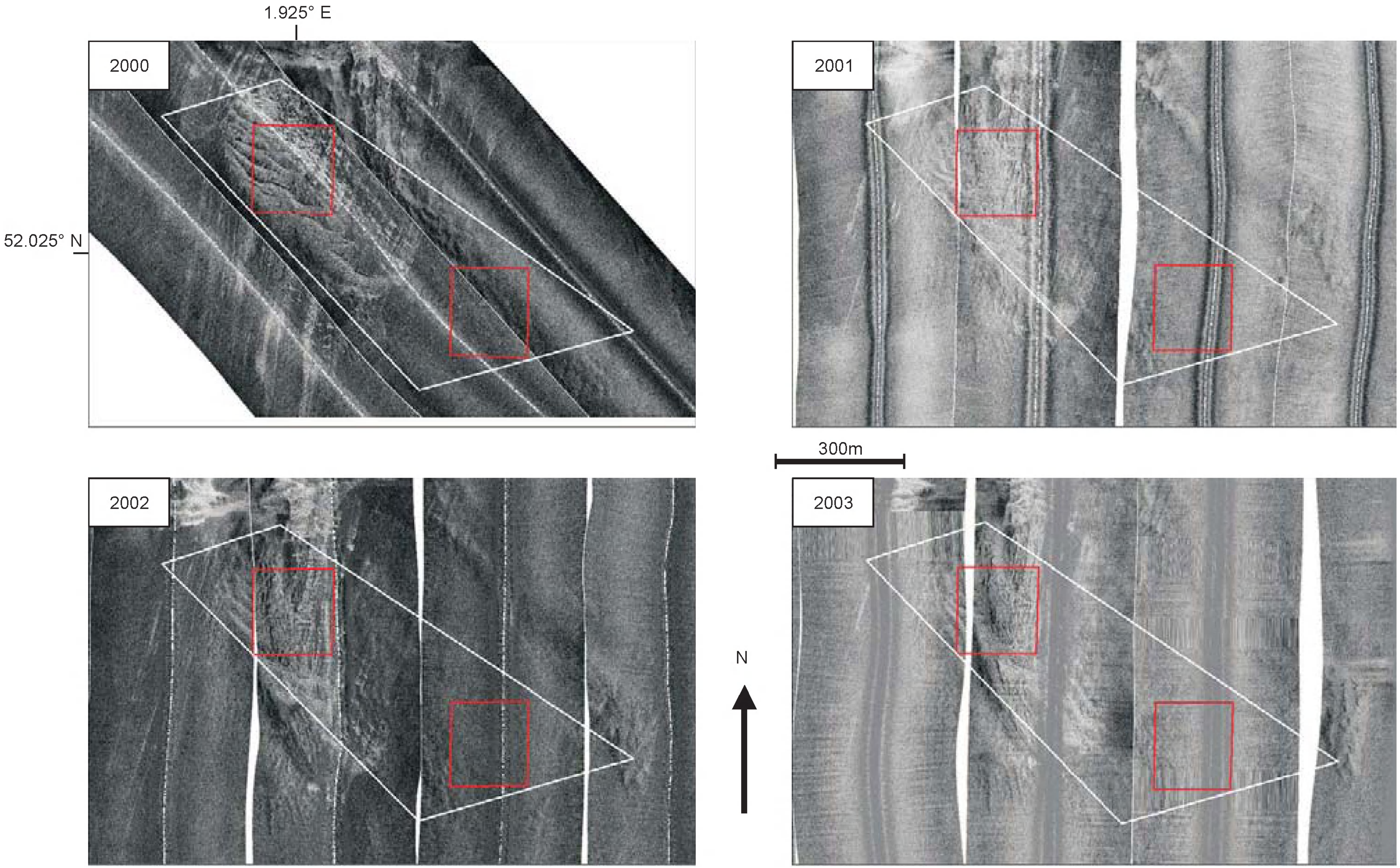



*Figure 4.8.* ***Sidescan sonar images of the relinquished Area 222 aggregate extraction licence, collected in 2000-2003. The boundary of the former extraction licence is outlined in white and the high (top left red box in each image) and low (bottom right red box in each image) intensity sampling boxes are in red***

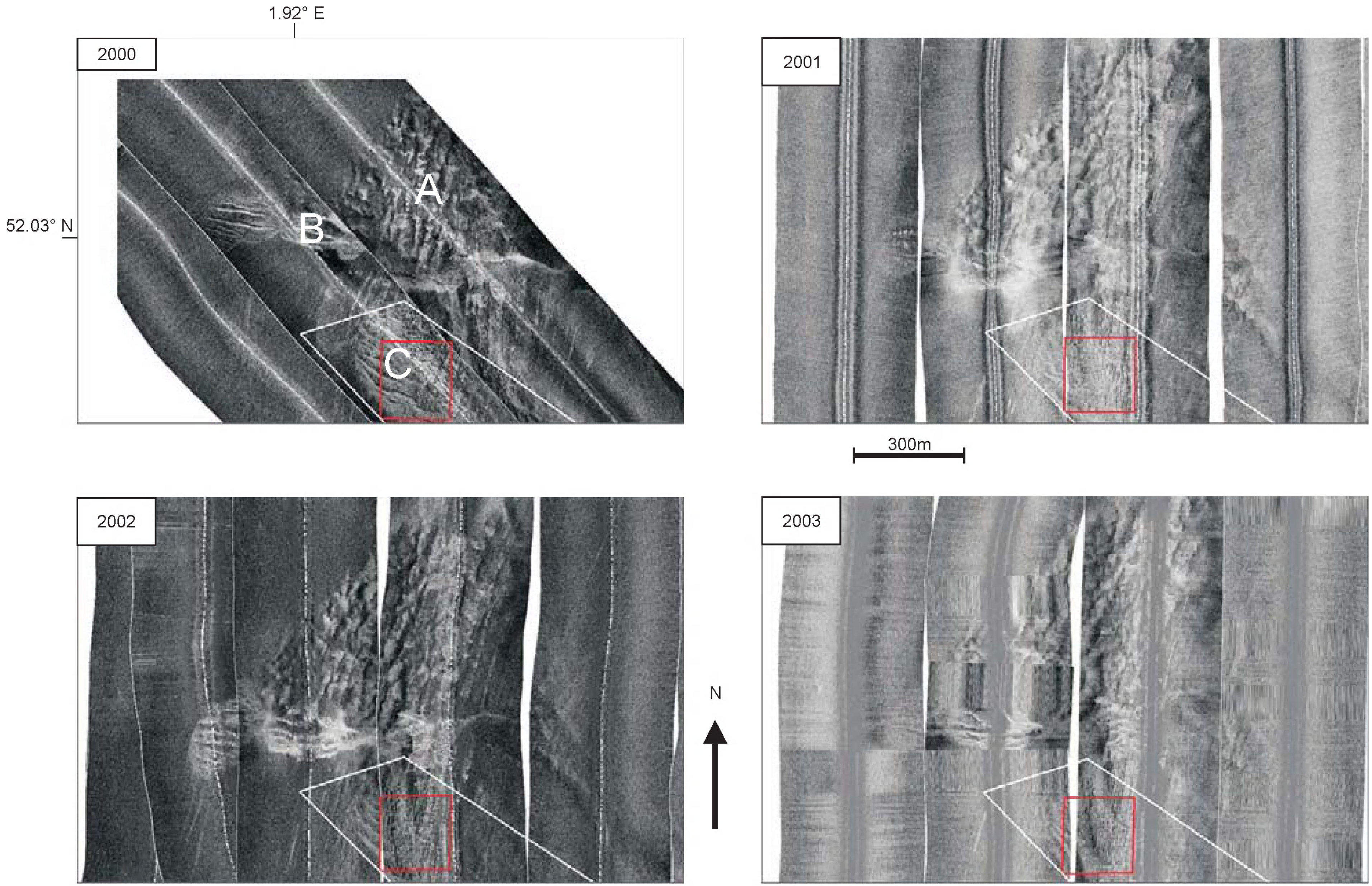



*Figure 4.9.* ***Sidescan sonar images of a disturbed area of seabed to the north of Area 222 (2000–2003). A) Area of disturbed seabed to the north of the extraction site. B) Large sand waves. C) Disturbed area within the extraction site***

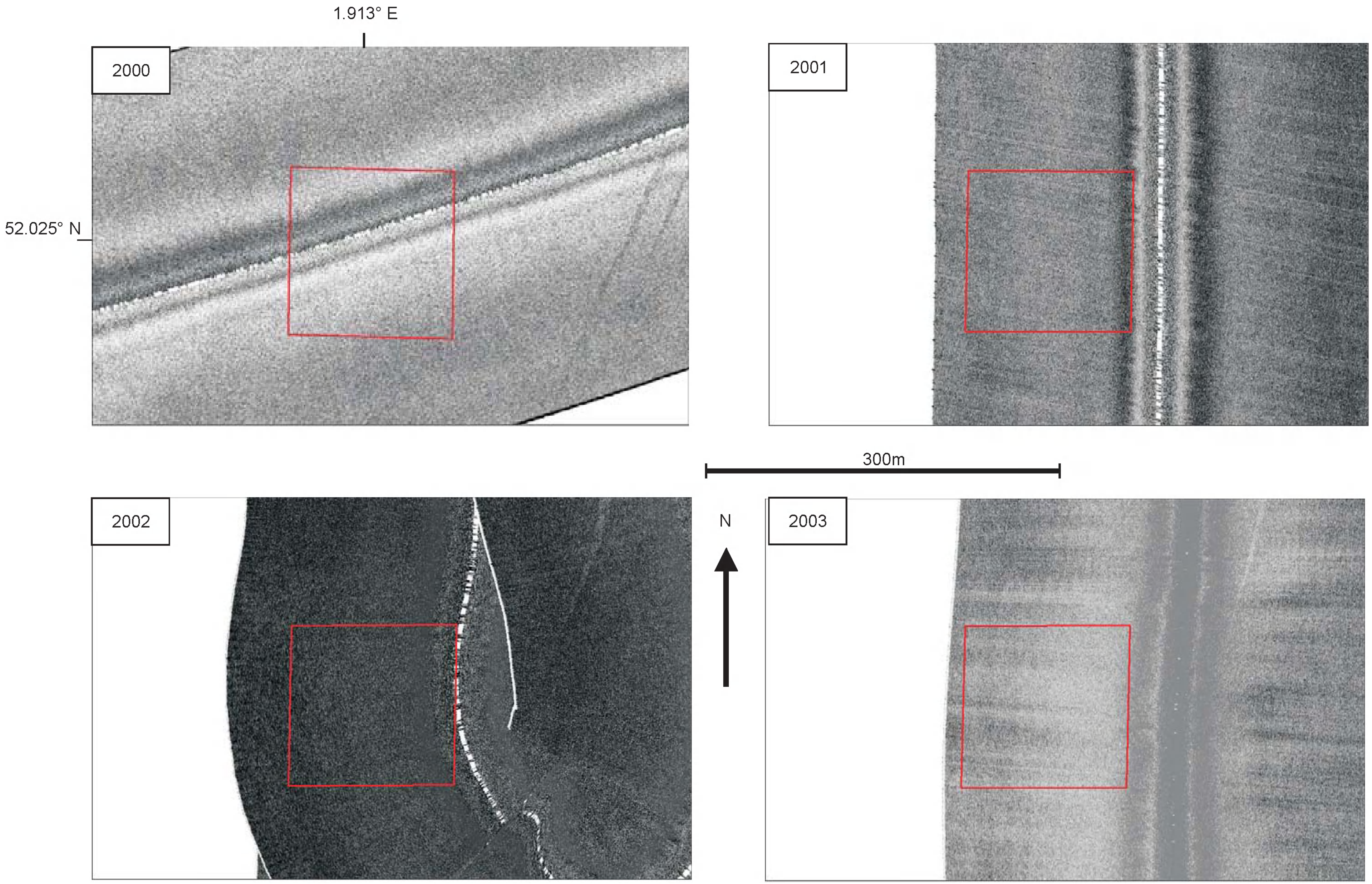



*Figure 4.10. Sidescan sonar images of Area 222 reference box 1 (2000–2003)*

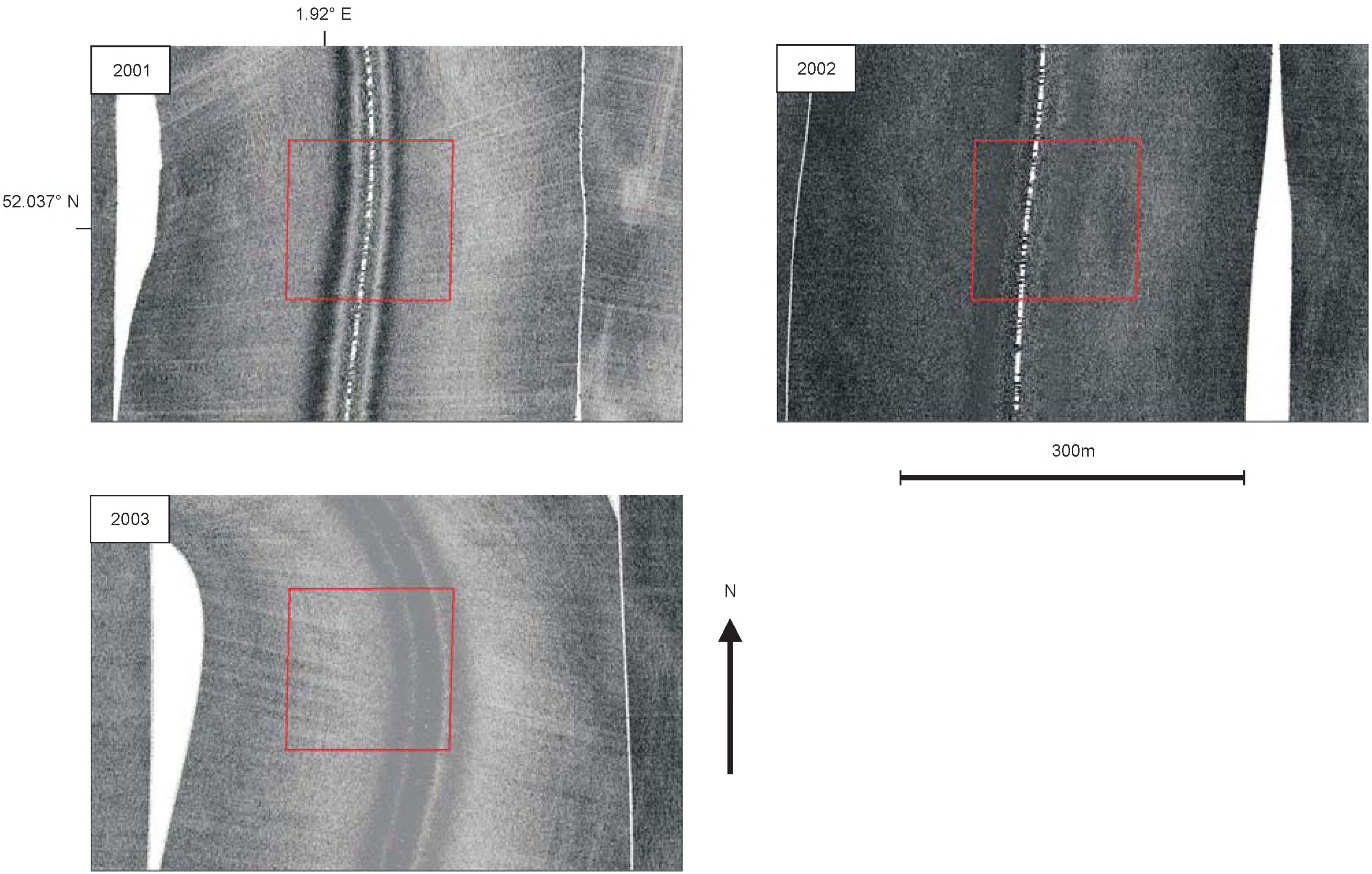



Figure 4.11. Sidescan sonar images of Area 222 reference box 2 (2001–2003)

Sandy substrates in the area of high dredging intensity


Clay outcrops in the area of high dredging intensity


Coarse substrates in the area of low dredging intensity


Coarse substrates at the reference site


***Figure 4.12 (a-d). Underwater photographic images taken from within and outside Area 222 in 2000. Each image represents an area of seabed of approximately 1.5 m by 1.0 m***

### 4.2.3. Underwater video surveys

In 2001, video camera tows were carried out at reference site 1, the high and low intensity dredging sites and at the area of static suction hopper dredging to the north of the licensed site. Elevated levels of suspended loads, which obscured the visibility, prevented a detailed assessment of the sediments over these sites, but an effective characterisation of the sediments was possible using the images collected. Sediments at the reference site and at the site of low dredging intensity appeared superficially similar and consisted of stable, sandy, muddy, medium and coarse gravels. Attached and motile epifauna were common at both sites and included serpulid, hydroid and echinoid species. There was no visible evidence of seabed disturbance at either of these sites. Images collected from the area of static suction hopper dredging showed that the majority of the sediments were composed of very clean, gravelly sands and sandy gravels. These were interspersed with patches of clean sand several metres across. Attached epifauna was less common at this site than at the reference or low dredging intensity sites. Within the high dredging intensity sampling box, inside the northern part of the licensed site, the sediments were more variable in nature. Patches of shelly sandy gravel gave way to areas of clean coarse sand that became more gravelly, before returning to finer sediments again. Epifaunal species were sparse over this area of the seabed. Still photographic images were collected in 2000 from the areas of high and low dredging intensity and reference site 1. Representative images which typify the sediments in these locations are shown in Figure 4.12.

### 4.2.4. Macrofaunal assemblage structure

A total of 308 non-colonial taxa were identified from one hundred and five 0.1 $m^2$ Hamon grabs collected from the different treatment sites at Area 222.

*Univariate analyses*

Excepting values of abundance in 2002, population densities, numbers of species and biomass of macrofaunal invertebrates were significantly lower ($p<0.05$) in the site exposed to the highest level of dredging intensity compared with the site of lower dredging intensity and reference conditions from 2000-2003. In 2002, higher densities of *Pomatoceros lamarcki* recorded in one of the samples collected from reference site 2 have increased the variability around the mean. In this year therefore there was no recorded difference between the dredged sites and reference conditions in terms of population densities, although there was still a difference between the sites of higher and lower dredging intensity.

Interestingly, densities of benthic invertebrates have increased over time in the area of low dredging intensity (Figure 4.13). By 2002 deposits from this area were indistinguishable from the surrounding sediments in terms of all the calculated univariate measures of community structure. This implies that over the course of this investigation that the species richness and population densities at the area of low dredging intensity have been restored within a period of 6 years following the cessation of dredging.

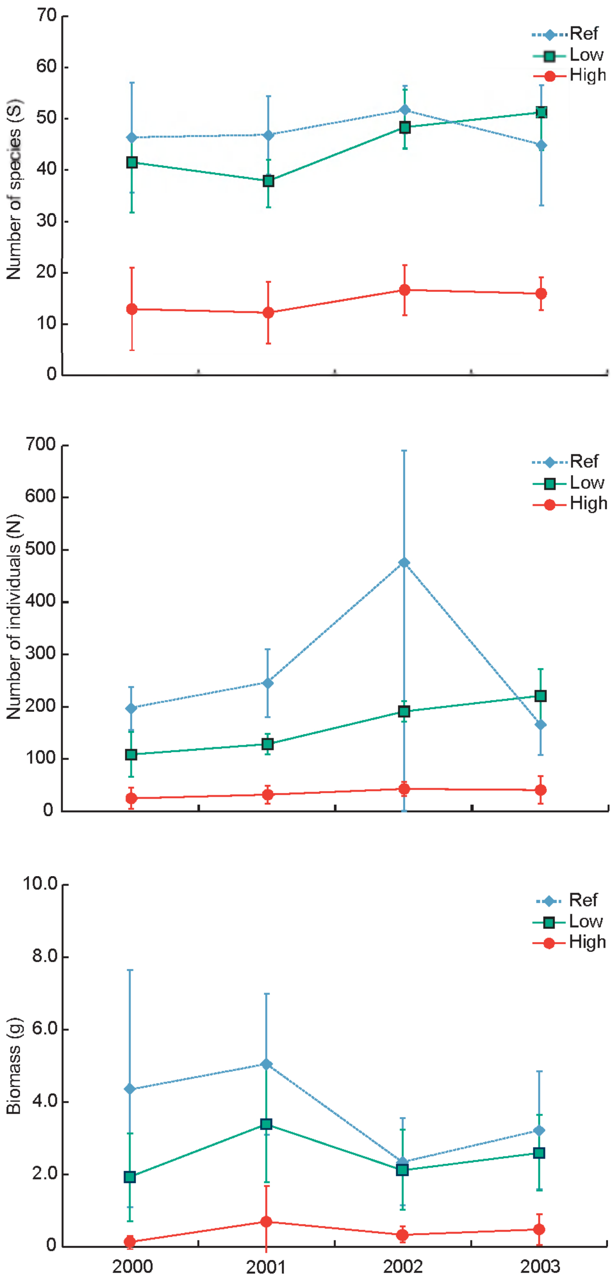



***Figure 4.13. Summary of means and 95% confidence intervals for number of species (S), number of individuals (N) and biomass (AFDW) at Area 222 from sites of high and lower levels of dredging intensity and two nearby reference sites in 2000-2003***

In general, differences between the site of high dredging intensity and other sample locations were due to the reduced abundance of a range of macrofaunal species characterising nearby sediments including *Pomatoceros lamarki*, *Pisidia longicornis*, *Lumbrinereis gracilis* and *Amphipholis squamata*. Densities of these species varied greatly between different locations and between different years (Figure 4.14). Densities of the brittle star, *Amphipholis squamata* increased between 2000 and 2002, whilst densities of *Lanice conchilega*, a sand dwelling polychaete were significantly higher at all sampled sites in 2001.

***Multivariate analyses***

The MDS ordination for macrofaunal assemblages collected at sites of high and lower dredging intensity and at the 2 reference sites is presented in Figure 4.15. While the reference samples and low dredging intensity samples show tight clustering of replicates indicating a high stability of the spatial pattern, the high intensity replicates are much more diffusely distributed. This separation of the individual sample replicates from the area of high dredging intensity indicates that they are biologically dis-similar (see also Table 4.4).

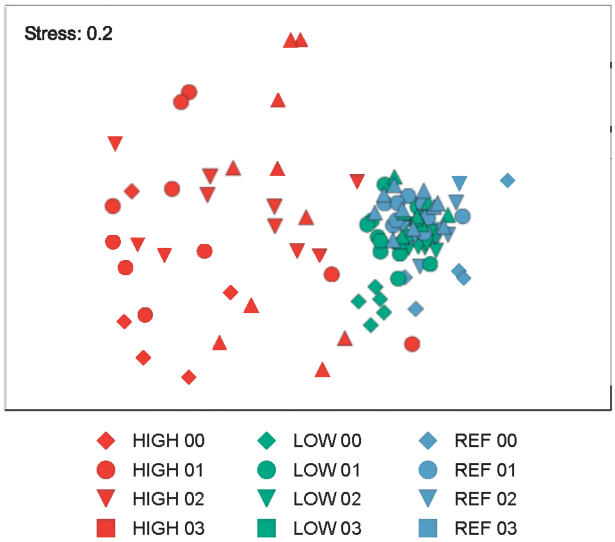



***Figure 4.15. MDS of Bray-Curtis similarities from 4th root transformed species data 4-7 years (2000-2003) after the cessation of dredging at sites of high and lower levels of dredging intensity and at the reference sites***

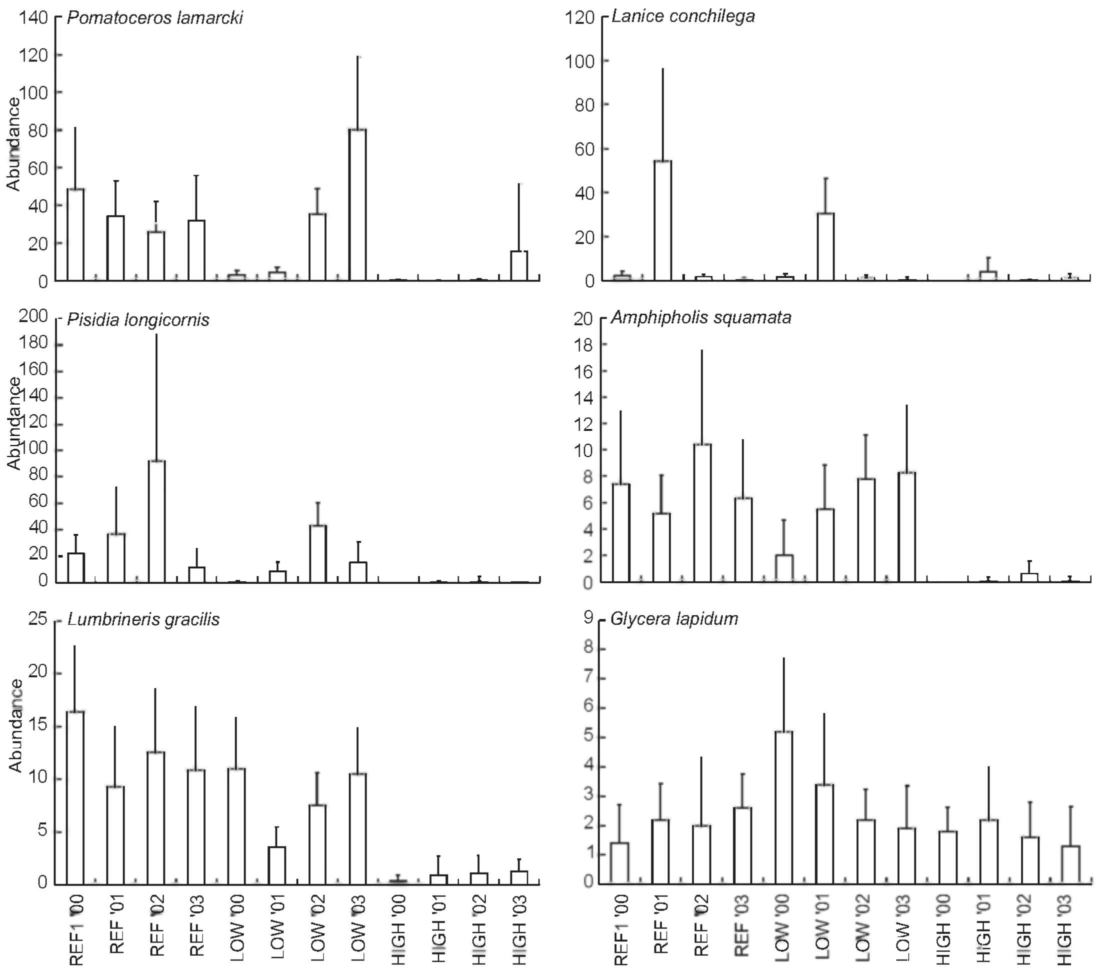



***Figure 4.14. Means (±SD) of abundances of selected macrofaunal species sampled in 2000-2003 at sites of high and lower levels of dredging intensity and two reference sites (codes as in Table 4.1)***

**Table 4.4. Index of Multivariate Dispersion (IMD) between all pairs of conditions**

| Year | Conditions compared | IMD |
|---|---|---|
| 2000 | High/Reference Site 1 | +0.920 |
| | High/Low | +1.000 |
| | Low/Reference Site 1 | -0.260 |
| 2001 | High/Reference Sites 1 & 2 | +0.902 |
| | High/Low | +0.834 |
| | Low/Reference Sites 1 & 2 | +0.283 |
| 2002 | High/Reference Sites 1 & 2 | +0.899 |
| | High/Low | +0.985 |
| | Low/Reference Sites 1 & 2 | -0.588 |
| 2003 | High/Reference Sites 1 & 2 | +0.972 |
| | High/Low | +0.986 |
| | Low/Reference Sites 1 & 2 | -0.391 |

**Table 4.5. Relative Index of Multivariate Dispersion (r.IMD) in each year**

| Year | Site | r.IMD |
|---|---|---|
| 2000 | High intensity | 1.587 |
| | Low intensity | 0.750 |
| | Reference Site 1 | 0.909 |
| 2001 | High intensity | 1.608 |
| | Low intensity | 0.883 |
| | Reference Sites 1 & 2 | 0.699 |
| 2002 | High intensity | 1.561 |
| | Low intensity | 0.368 |
| | Reference Sites 1 & 2 | 0.777 |
| 2003 | High intensity | 1.702 |
| | Low intensity | 0.534 |
| | Reference Sites 1 & 2 | 0.813 |

The comparative Index of Multivariate Dispersion (IMD) has been calculated in order to contrast the multivariate variability amongst samples taken from the dredged sites with samples from the reference locations. IMD has a maximum value of +1 when all similarities among impacted samples are lower than any similarities among reference samples. The converse case gives a minimum for IMD of –1, and values near zero imply no difference between groups. In Table 4.4, IMD values are compared between each of the sites for each year. Comparisons between the site of high dredging intensity and the reference sites and the sites of high and lower dredging intensity give the most extreme values of IMD i.e. close to +1. In comparison, there is little difference between the low dredging intensity and reference samples in terms of variability in multivariate structure. Thus, a pattern of high variability in multivariate structure with increased disturbance is clearly evident in all years at Area 222.

The comparative Index of Multivariate Dispersion is restricted to the comparison of only 2 groups and therefore is usually complemented by calculation of the relative Index of Multivariate Dispersion (r.IMD). Table 4.5 confirms the conclusions from above, i.e. that there is a larger variability in community composition at the site of high dredging intensity in comparison with the other sampled locations.

Macrofaunal assemblages generally discriminated well between different sampling locations in each year (Figure 4.15). ANOSIM results in Table 4.6 also confirm the patterns observed in the MDS ordinations. Macrofauna assemblages at all locations were significantly different ($p < 0.05$) from each other in terms of species composition, apart from samples from the area of high dredging intensity in 2000 and 2001 and 2001 versus 2002.

Figure 4.16 a-e provides a visual expression of the relationships between the macrofaunal data and the sediment particle size characteristics. Samples collected from the area of high dredging intensity are separated on the MDS from the rest of the samples on account of a greater proportion of the % coarse sand and less silt/clay. The relationships between the macrofaunal data and measured environmental variables are explored further in Section 9.

Further exploration of the community groupings subject to differing levels of dredging impact was undertaken using the similarity percentages program (SIMPER). Results revealed that the average similarity between replicate samples collected for each of the groups was low, particularly for samples collected from the area of high dredging intensity (see Table 4.7). This reflects the relatively few shared species found between replicate samples obtained from the area of high dredging intensity.

The output from SIMPER also indicates which taxa contribute the most towards similarity between replicate samples from within each of the groups. Characterising species from each of the groups were similar over time. From the area of high dredging intensity, characterising species tended to be infaunal species typically associated with sandy sediments. Juvenile animals also typified high intensity samples. This suggests an active process of recolonization by juvenile animals invading the dredged deposits. In contrast, those species characterising the areas of low dredging intensity and reference areas were typically larger and included both infaunal and epifaunal species and these species represented a range of different phyla.

Information from SIMPER and ANOSIM also reveal that the differences between the area of high dredging intensity and the reference areas are more pronounced than between the area of low dredging intensity and the reference areas. These differences in the sample groups are maintained over the four year period of study.

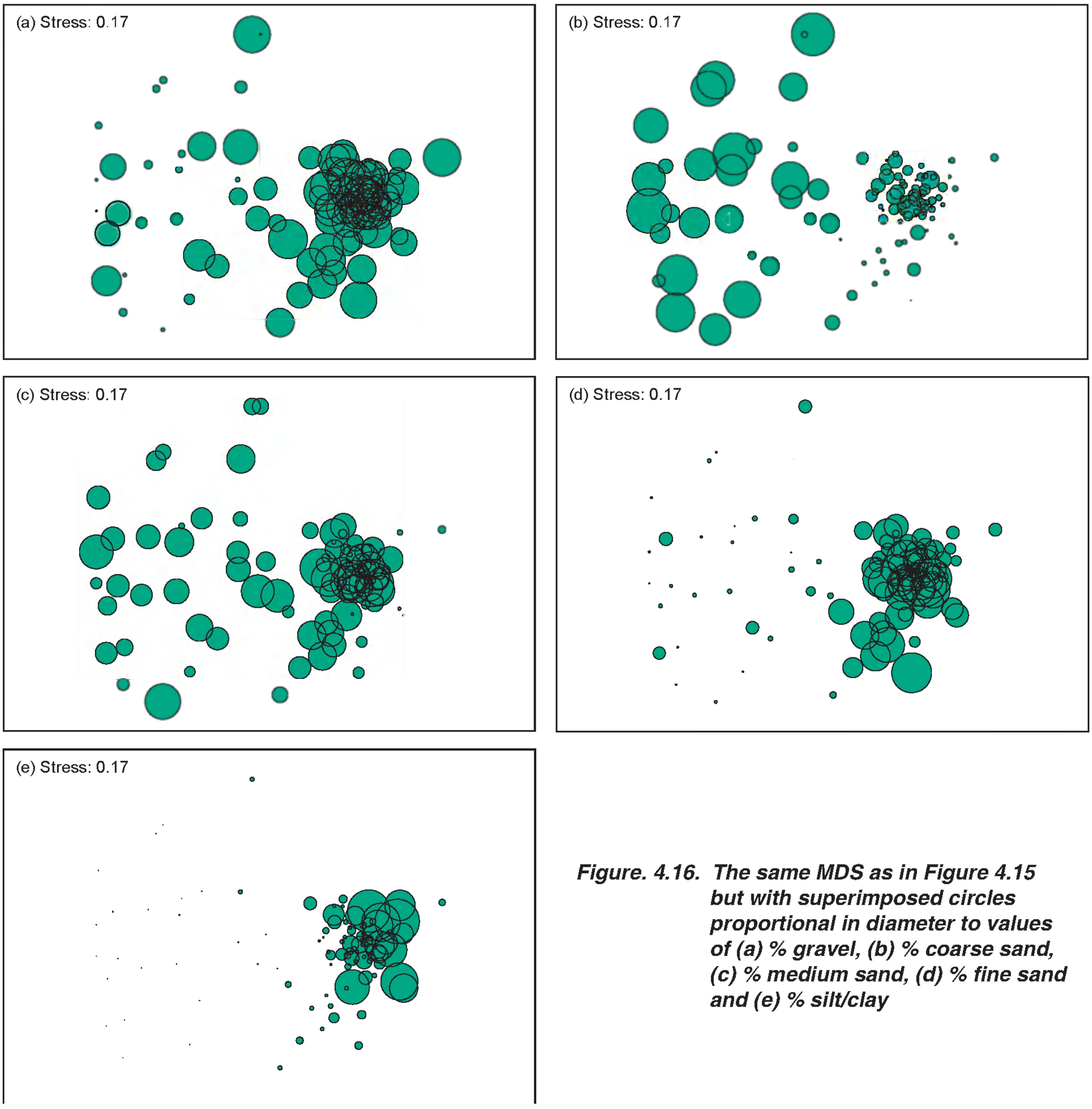



***Figure. 4.16. The same MDS as in Figure 4.15 but with superimposed circles proportional in diameter to values of (a) % gravel, (b) % coarse sand, (c) % medium sand, (d) % fine sand and (e) % silt/clay***

***Table 4.6. R-values derived from the ANOSIM test for macrofaunal assemblages (4th root transformed) from locations of higher and lower dredging intensity and from 2 reference sites in the vicinity of Area 222 sampled in 2000 - 2003. Values range between one and zero. A zero value indicates high similarity, and a value of 1 indicates low similarity between samples. * denotes significant difference at p < 0.05 (codes as in Table 4.1)***

| | HIGH '00 | LOW '00 | REF1 '00 | HIGH '01 | LOW '01 | REF1&2 '01 | HIGH '02 | LOW '02 | REF1&2 '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| HIGH '00 | | | | | | | | | | | |
| LOW '00 | 0.836* | | | | | | | | | | |
| REF1 '00 | 0.952* | 0.872* | | | | | | | | | |
| HIGH '01 | 0.236 | 0.588* | 0.729* | | | | | | | | |
| LOW '01 | 0.984* | 0.847* | 0.881* | 0.686* | | | | | | | |
| REF1&2 '01 | 0.991* | 0.997* | 0.934* | 0.734* | 0.332* | | | | | | |
| HIGH '02 | 0.518* | 0.557* | 0.791* | 0.125 | 0.659* | 0.729* | | | | | |
| LOW '02 | 0.993* | 0.996* | 0.950* | 0.773* | 0.617* | 0.744* | 0.714* | | | | |
| REF1&2 '02 | 0.992* | 0.978* | 0.812* | 0.824* | 0.724* | 0.509* | 0.730* | 0.396* | | | |
| HIGH '03 | 0.380* | 0.299* | 0.523* | 0.332* | 0.552* | 0.642* | 0.190* | 0.633* | 0.644* | | |
| LOW '03 | 0.992* | 0.955* | 0.937* | 0.777* | 0.602* | 0.632* | 0.727* | 0.463* | 0.463* | 0.633* | |
| REF1&2 '03 | 0.987* | 0.976* | 0.916* | 0.767* | 0.648* | 0.395* | 0.728* | 0.712* | 0.420* | 0.571* | 0.361* |

**Table 4.7. Results from SIMPER analysis of macrofauna data from Area 222 (all taxa excluding colonial species, 4th root transformed), listing the main characterising species from samples subject to differing levels of dredging impact from 2000-2003. Average abundance, average similarity and the % contribution to the similarity made by each characterising species is shown. Also listed is the cumulative percentage and the overall average similarity between replicate samples from within each group**

| Group | Taxonomic Group | Average abundance | Average Similarity | % Contribution | Cumulative % | Overall Average Similarity |
|---|---|---|---|---|---|---|
| HIGH '00 | *Glycera lapidum* (agg.) | 1.8 | 7.98 | 26.9 | 26.9 | **29.66%** |
| | *Sphaerosyllis taylori* | 2.4 | 4.29 | 14.47 | 41.37 | |
| LOW '00 | *Lumbrinereis gracilis* | 11.0 | 3.40 | 6.55 | 6.55 | **51.89%** |
| | *Exogone verugera* | 5.4 | 2.76 | 5.31 | 11.86 | |
| | *Glycera lapidum* (agg.) | 5.2 | 2.75 | 5.29 | 17.15 | |
| | *Notomastus* sp. | 4.8 | 2.61 | 5.03 | 22.19 | |
| | *Polycirrus* spp. | 4.6 | 2.47 | 4.77 | 26.95 | |
| | *Spiophanes bombyx* | 2.8 | 2.25 | 4.33 | 31.28 | |
| | *Ascidiidae* (juv.) | 2.6 | 2.23 | 4.30 | 35.58 | |
| | NEMERTEA | 2.0 | 2.19 | 4.23 | 39.81 | |
| | *Echinocyamus pusillus* | 1.8 | 2.12 | 4.10 | 43.91 | |
| REF1 '00 | *Pomatoceros lamarcki* | 48.6 | 3.77 | 7.78 | 7.78 | **48.47%** |
| | *Pisidia longicornis* | 22.2 | 3.26 | 6.73 | 14.51 | |
| | *Lumbrinereis gracilis* | 16.4 | 3.23 | 6.67 | 21.18 | |
| | *Polydora caulleryi* | 6.6 | 2.37 | 4.88 | 26.06 | |
| | *Amphipholis squamata* | 7.4 | 2.32 | 4.79 | 30.85 | |
| | *Sabellaria spinulosa* | 5.2 | 2.21 | 4.56 | 35.41 | |
| | *Harmothoe* spp. | 6.8 | 2.01 | 4.15 | 39.56 | |
| | *Polydora flava* | 2.8 | 2.00 | 4.12 | 43.67 | |
| HIGH '01 | *Glycera lapidum* (agg.) | 2.2 | 7.81 | 29.23 | 29.23 | **26.72%** |
| | *Spisula* sp. (juv.) | 3.9 | 7.79 | 29.17 | 58.40 | |
| LOW '01 | *Lanice conchilega* | 30.4 | 4.41 | 9.03 | 9.03 | **48.81%** |
| | *Pisidia longicornis* | 8.9 | 3.09 | 6.33 | 15.36 | |
| | *Amphipholis squamata* | 5.5 | 2.99 | 6.13 | 21.49 | |
| | *Harmothoe* spp. | 4.4 | 2.76 | 5.65 | 27.14 | |
| | *Echinocymanus pusillus* | 4.9 | 2.73 | 5.59 | 32.73 | |
| | *Lumbrineris gracilis* | 3.6 | 2.69 | 5.51 | 38.24 | |
| | OPHIUROIDEA (juv.) | 3.6 | 2.14 | 4.39 | 42.63 | |
| REF1&2 '01 | *Lanice conchilega* | 30.40 | 4.41 | 9.03 | 9.03 | **52.10%** |
| | *Pisidia longicornis* | 8.90 | 3.09 | 6..33 | 15.36 | |
| | *Amphipholis squamata* | 5.5 | 2.99 | 6.13 | 21.49 | |
| | *Harmothoe* spp. | 4.4 | 2.76 | 5.65 | 27.14 | |
| | *Echinocymanus pusillus* | 4.9 | 2.73 | 5.59 | 32.73 | |
| | *Lumbrineris gracilis* | 3.6 | 2.69 | 5.51 | 38.24 | |
| | OPHIUROIDEA (juv.) | 3.6 | 2.14 | 4.39 | 42.63 | |
| HIGH '02 | *Spisula* sp. (juv.) | 6.6 | 7.09 | 23.48 | 23.48 | **26.72%** |
| | NEMERTEA | 2.8 | 4.69 | 15.53 | 39.01 | |
| | *Glycera lapidum* (agg.) | 1.6 | 3.16 | 10.47 | 49.48 | |
| LOW '02 | *Pisidia longicornis* | 43.0 | 3.99 | 6.98 | 6.98 | **57.11%** |
| | *Pomatoceros lamarcki* | 35.5 | 2.78 | 4.86 | 11.84 | |
| | *Sepulidae* | 8.7 | 2.63 | 4.60 | 16.45 | |
| | *Amphipholis squamata* | 7.8 | 2.61 | 4.57 | 21.02 | |
| | *Lumbrineris gracilis* | 7.5 | 2.53 | 4.42 | 25.44 | |
| | *Scalibregma inflatum* | 7.3 | 2.39 | 4.19 | 29.63 | |
| | *Caulleriella alata* | 7.6 | 2.38 | 4.17 | 33.80 | |
| | *Notomastus* | 6.3 | 2.14 | 3.75 | 37.55 | |
| | *Echinocyamus pusillus* | 4.5 | 2.10 | 3.67 | 41.23 | |
| REF1&2 '02 | *Pisidia longicornis* | 91.9 | 3.41 | 6.76 | 6.76 | **50.40%** |
| | *Pomatoceros lamarcki* | 239.2 | 2.77 | 5.49 | 12.25 | |
| | *Lumbrineris gracilis* | 12.6 | 2.66 | 5.28 | 17.53 | |
| | *Serpulidae* | 7.8 | 2.39 | 4.74 | 22.28 | |
| | *Amphipholis squamata* | 10.4 | 2.27 | 4.50 | 26.77 | |
| | *Laonice bahusiensis* | 3.9 | 1.99 | 3.96 | 30.73 | |
| | *Caulleriella alata* | 4.8 | 1.82 | 3.61 | 34.34 | |
| | *Cheirocratus* sp. | 5.5 | 1.69 | 3.36 | 37.70 | |
| | *Ampelisca spinipes* | 5.2 | 1.53 | 3.03 | 40.73 | |

***Table 4.7. continued:***

| Group | Taxonomic Group | Average abundance | Average Similarity | % Contribution | Cumulative % | Overall Average Similarity |
|---|---|---|---|---|---|---|
| HIGH '03 | *Glycera lapidum* (agg.) | 1.3 | 2.71 | 11.33 | 11.33 | **23.94%** |
| | *Lumbrineris gracilis* | 1.3 | 2.69 | 11.22 | 22.55 | |
| | *Aonides paucibranchiata* | 2.4 | 2.07 | 8.65 | 31.20 | |
| | *Pomatoceros lamarcki* | 15.5 | 1.58 | 6.58 | 37.78 | |
| | *Notomastus* | 1.0 | 1.36 | 5.67 | 43.45 | |
| LOW '03 | *Pomatoceros lamarcki* | 70.6 | 4.69 | 8.60 | 8.60 | **54.56%** |
| | *Serpulidae* | 18.2 | 3.29 | 6.03 | 14.63 | |
| | *Lumbrineris gracilis* | 10.5 | 2.98 | 5.47 | 20.1 | |
| | OPHIUROIDEA (juv.) | 12.9 | 2.96 | 5.43 | 25.53 | |
| | *Scalibregma inflatum* | 10.1 | 2.66 | 4.88 | 30.40 | |
| | *Amphipholis squamata* | 8.3 | 2.61 | 4.78 | 35.18 | |
| | *Echinocyamus pusillus* | 4.2 | 2.30 | 4.22 | 39.40 | |
| | *Pisidia longicornis* | 15.2 | 2.24 | 4.11 | 43.51 | |
| REF1&2 '03 | *Pomatoceros lamarcki* | 30.7 | 3.39 | 6.74 | 6.74 | **50.29%** |
| | *Lumbrineris gracilis* | 10.9 | 3.11 | 6.19 | 12.93 | |
| | *Serpulidae* | 14.1 | 3.06 | 6.08 | 19.01 | |
| | *Scalibregma inflatum* | 9.8 | 2.77 | 5.51 | 24.52 | |
| | *Amphipholis squamata* | 6.3 | 2.52 | 5.01 | 29.53 | |
| | *Harmothoe* spp. | 5.6 | 2.40 | 4.77 | 34.30 | |
| | *Echinocyamus pusillus* | 4.3 | 2.36 | 4.69 | 38.99 | |
| | *Glycera lapidum* (agg.) | 2.6 | 2.21 | 4.40 | 43.40 | |

# 5. TEMPORAL INVESTIGATIONS OF THE PHYSICAL AND BIOLOGICAL STATUS OF HASTINGS AREAS X AND Y

## 5.1. Methods

### *5.1.1. Study site*

The study site is located approximately 6 nautical miles south of Hastings off the south coast of England (Figure 5.1) in water depths of between 14 m and 40 m below chart datum. The tidal ellipse is aligned in a northeast/ southwest direction with a maximum spring tidal current velocity of 2.6 knots (Admiralty Chart 536). On the flood tide the flow is in a northeast direction, whilst water flows southwest on the ebb. Current meter studies in the area (HR Wallingford, 1993; HR Wallingford, 1999; Rees, 2000) and observations of seabed transport features (EMU, 1999) indicate that the net sediment transport is in a north-easterly direction.

A number of authors have investigated the capacity for the physical and biological recovery of the seabed at Hastings Shingle Bank following the cessation of dredging (Dickson and Lee, 1972; Shelton and Rolfe, 1972; Rees, 1987; Pendle and Rees, 1995; Kenny, 1998). For example, Dickson and Lee (1972) reported on a variety of experiments which showed that dredge pits and furrows may persist for many years in this area. At the same time Shelton and Rolfe (1972) investigated the associated impacts of dredging on the benthos and reported that the finer sediments found in dredge pits supported an altered fauna to the surrounding coarser deposits. In 1986, a survey of fauna in the proposed extraction area was carried out by Rees (1987) in order to establish a baseline against which the future effects of dredging could be assessed. A comparison of this work with that of Shelton and Rolfe (1972) provided close agreement, suggesting relatively stable conditions on the Bank. In both studies, an abundant epifaunal component was identified from samples taken on the Shingle Bank. Both Shelton and Rolfe (1972) and Rees (1987) suggest that biological recovery will be dependent on the attainment of similar physical conditions to those which existed prior to dredging.

In 1991, a study was carried out at Area Y (Lees, 1993) to investigate the impacts on sediments and benthos resulting from four years of dredging activity. Results from this and a further study (Pendle and Rees, 1998) showed that samples subjected to the impacts of dredging supported fewer species than samples taken in undisturbed areas of the Bank. In 1997, in support of an application to extend the existing licence further south on the Hastings Shingle Bank, a survey of the benthos and sediments was carried out (Kenny, 1998). Results from this study indicated that the potential for recovery of the benthos following cessation of dredging in this area may be high, owing to

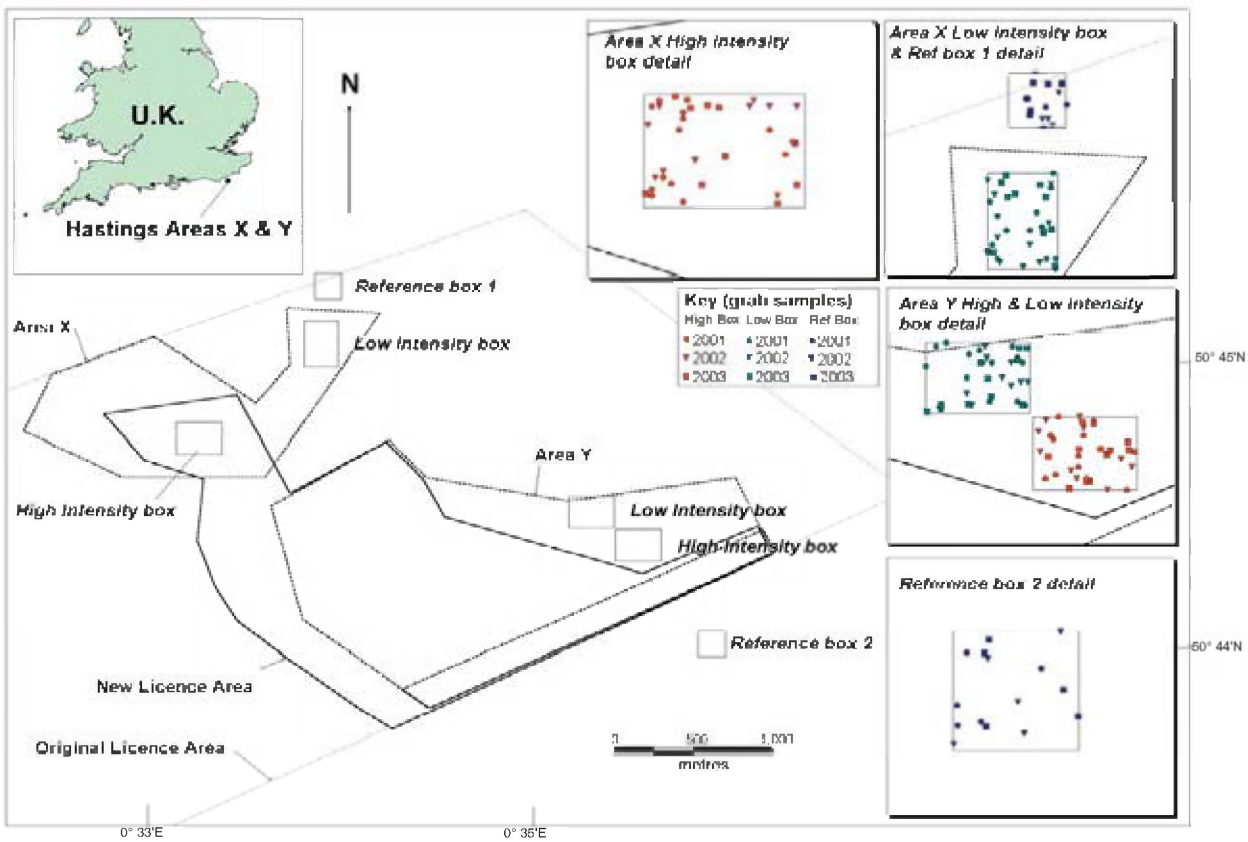



*Figure 5.1. Location of grab sampling in relation to positions of historic (original, Area X and Area Y) and current (New licence area) aggregate extraction licences on the Hastings Shingle Bank*

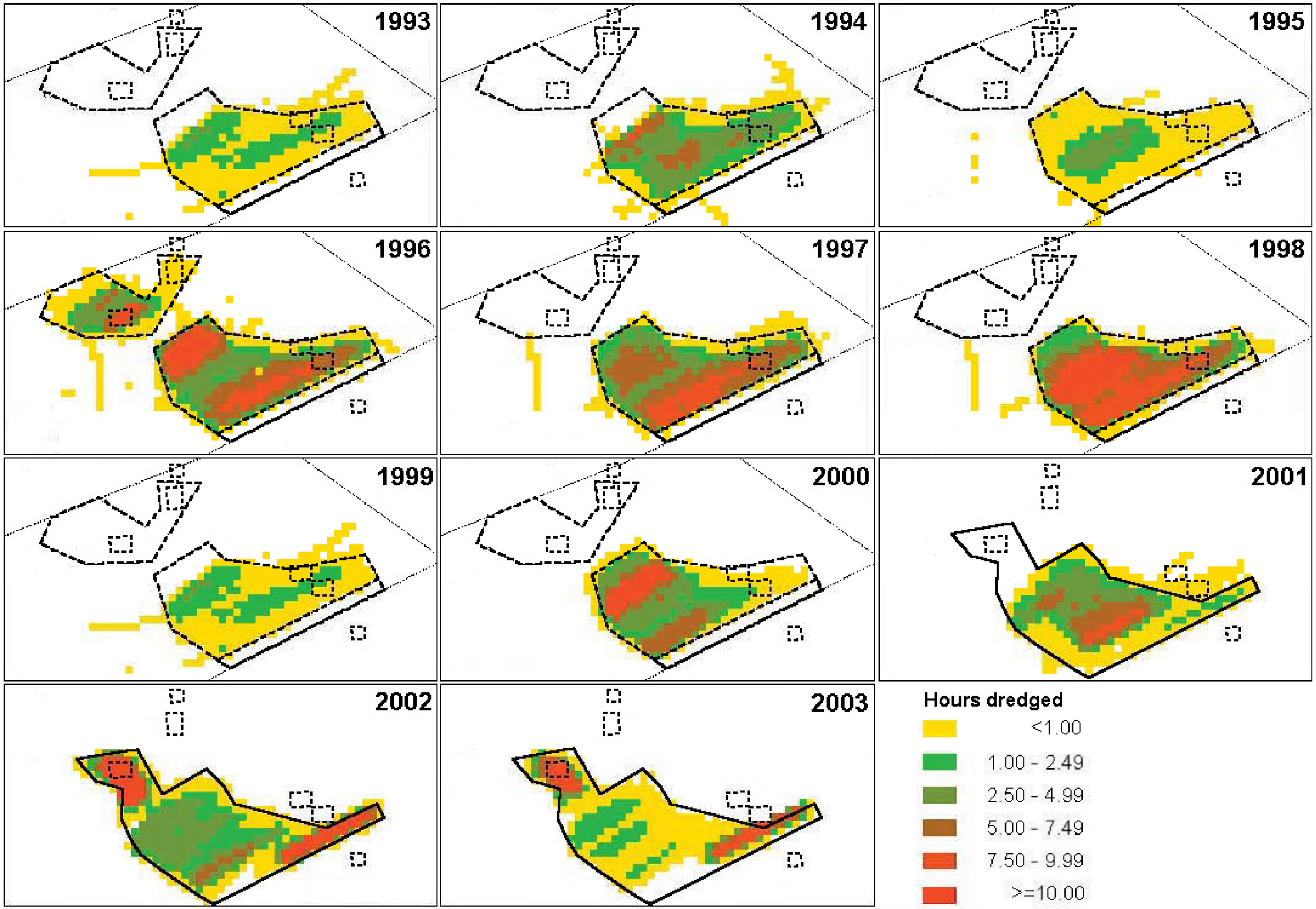



*Figure 5.2. Location and intensity of dredging (hours) over each 100 m x 100 m block at Hastings Area X & Y in relation to the positions of the high and low sampling sites in years 1993 to 2003 (source EMS data provided by the Crown Estate)*

the absense of any long-lived and slow growing taxa prior to dredging. The current study allows the opportunity to further examine the processes involved in recolonization of deposits following the cessation of dredging and also to assess the progress against predictions erected in these earlier studies

Hastings Shingle Bank has been licensed for aggregate dredging since September 1988. Over this period there have been a number of changes to the boundaries of the extraction licences at this site. Sub areas X and Y, shown in Figure 5.1, were both relinquished in 2001 and replaced by a new licence in the same year. This new licence encompasses parts of the old sub-areas X and Y (see Figure 5.1). However, parts of both of these relinquished areas which were dredged at various intervals in the past, fall outside of the new licence making them suitable for an investigation of benthic recolonization following the cessation of dredging activity.

### 5.1.2. Sampling design

**Hastings Area X**

Based on EMS data from 1996, the year that dredging had last taken place within Area X at the inception of this study, areas of high and lower levels of dredging intensity were identified (see Figure 5.2). The area of high dredging intensity represents >4.99 hours of dredging within each 100 m by 100 m block whereas the area of low dredging intensity is equivalent to < 1 hour of dredging within each 100 m by 100 m block. Treatment boxes, measuring 300 m by 200 m, were assigned to these two areas of seabed. Within each treatment box, 10 randomly positioned 0.1 $m^2$ Hamon grab samples were collected in 2001, 2002 and 2003, that is 5, 6 and 7 years after the cessation of dredging. However, dredging resumed in the north of the new extraction area during May 2002, an area which co-incided with the Hastings Area X high dredging intensity sampling box. Dredging intensity ranged between 2.5 –14.99 hours within each 100 m by 100 m block. Therefore, results from the Area X high box in 2002 and 2003 represent conditions within a current extraction area. In addition, two reference boxes (Reference box 1 & 2) were also sampled over the same period. The area of each reference box was half that of the high and low dredging intensity boxes and replicates were taken at each site. As described in earlier sections, this approach was adopted in order to achieve the same sampling density per unit area at both dredged and reference locations. Details of the locations sampled as part of the Area X time-series investigations are presented in Table 5.1.

**Hastings Area Y**

EMS data suggest that dredging took place within the relinquished zone of Area Y in 2001 (Figure 5.2). However, following consultation with Posford Haskoning Limited, we established that the only dredging event that took place in the relinquished zone after 2000 was an isolated ‘out of area’ dredging incident on the 16th of May 2001 within the southern half of the Hastings Area Y high dredging intensity sampling box (details are shown in Figure 5.3). The other apparent episodes of dredging relate to the vagaries of the EMS system and not to contact of a dredger draghead with the seabed. The 2001 field-sampling programme did not commence until after this

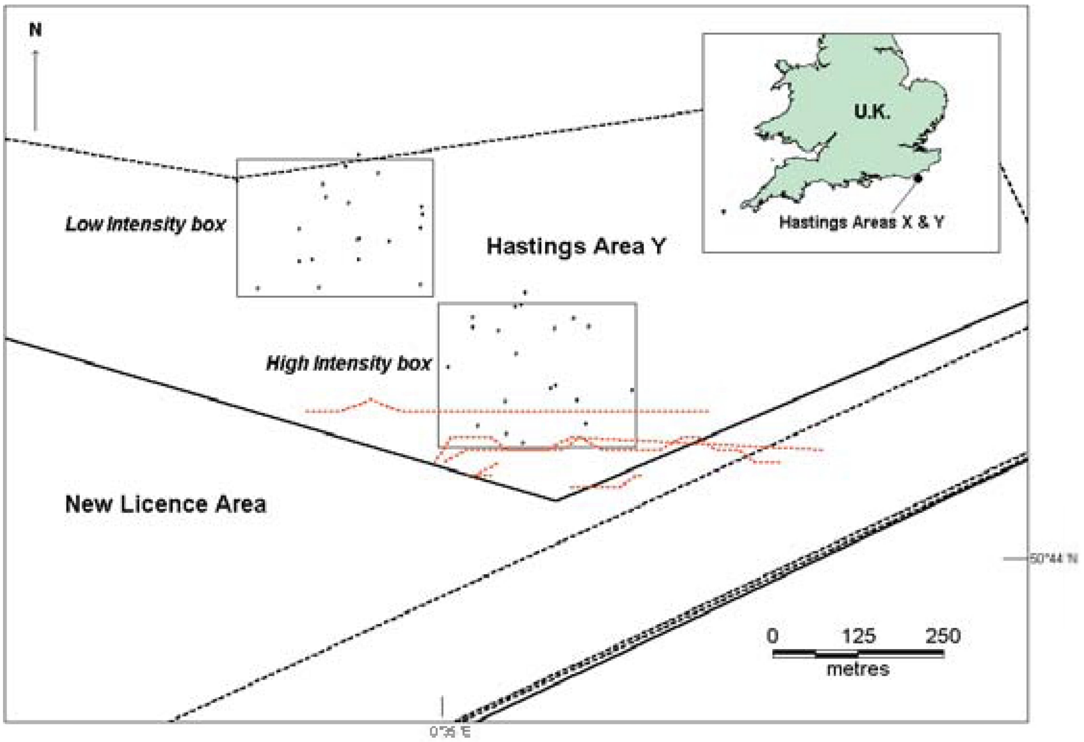



*Figure 5.3. Location of ‘out of area’ dredging tracks from May 2001 (red hashed lines)*

***Table 5.1. Co-ordinates of treatment boxes in Areas X and Y***

| | Treatment | Code | Box co-ordinates | | Area ($m^2$) | Number of samples collected | | |
|---|---|---|---|---|---|---|---|---|
| | | | Latitude | Longitude | | 2001 | 2002 | 2003 |
| Area X | High intensity box | HIGH '01 to '03 | 50°44.784'N | 00°33.090'E | ~60 000 | 10 | 10 | 10 |
| | | | 50°44.670'N | 00°33.336'E | | | | |
| | Low intensity box | LOW '01 to '03 | 50°45.144'N | 00°33.780'E | ~60 000 | 10 | 10 | 10 |
| | | | 50°44.982'N | 00°33.960'E | | | | |
| | Reference box 1 | REF '01 to '03 | 50°45.314'N | 00°33.833'E | ~30 000 | 5 | 5 | 5 |
| | | | 50°45.221'N | 00°33.980'E | | | | |
| Area Y | High intensity box | HIGH '01 to '03 | 50°44.406'N | 00°35.454'E | ~60 000 | 10 | 10 | 10 |
| | | | 50°44.292'N | 00°35.700'E | | | | |
| | Low intensity box | LOW '01 to '03 | 50°44.520'N | 00°35.202'E | ~60 000 | 10 | 10 | 10 |
| | | | 50°44.412'N | 00°35.448'E | | | | |
| | Reference box 2 | REF '01 to '03 | 50°44.046'N | 00°35.898'E | ~30 000 | 5 | 5 | 5 |
| | | | 50°43.954'N | 00°36.047'E | | | | |

date and consequently the results from some stations within the high intensity box may reflect conditions 2 months, and others 1 year 2 months after cessation of dredging. Historical information on the location and intensity of dredging within the relinquished zone of Area Y between 1993-2000 was used to identify areas of high and lower levels of activity. During 1997 and 1998, values of dredging intensity ranged between 5 and 14.99 hours per annum within each 100m by 100m block in the area of high dredging intensity. Dredging activity declined thereafter from 2.5 to 4.99 hours in 1999 to <1 to 2.49 hours in 2000. Within the area of low dredging intensity the intensity of dredging has consistently remained below 2.49 hours and between 1998 and 2000 was not greater than 1 hour per annum for any 100 m by 100 m block. Within each treatment box, 10 randomly positioned 0.1 $m^2$ Hamon grab samples were collected in 2001, 2002 and 2003, that is 1, 2 and 3 years after the cessation of dredging. Again, the samples collected from reference boxes 1 & 2 were used to compare results from the high and low treatment boxes with the wider environment. Details of the positions of sampling boxes are given in Table 5.1.

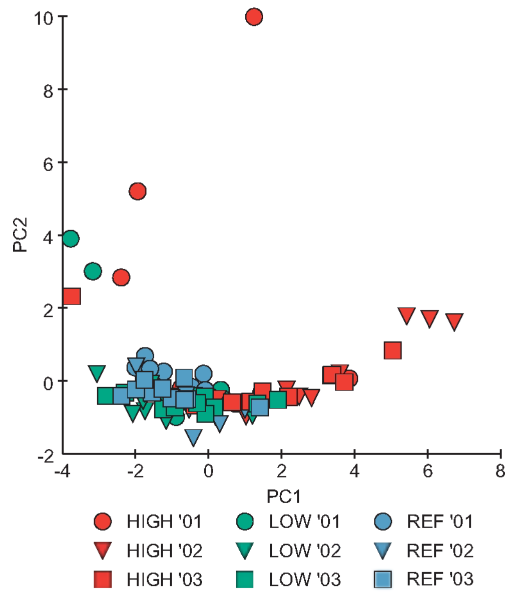



***Figure 5.4 . Two-dimensional correlation-based PCA ordination of untransformed sediment particle size data (2002 to 2003) from Area X. For variables involved in the ordination see Table 5.3***

## 5.2. Results (Hastings Area X)

### *5.2.1. Sediment characteristics*

An ordination by PCA of the sediment particle size data from the Hamon grab samples is illustrated in Figure 5.4. The tight clustering of samples reflects a high degree of similarity between sampling sites, particularly between the low dredging intensity and reference sites. This observation is confirmed by the result of an ANOSIM test (Table 5.2). A number of predominately sandy samples, not encountered at the reference sites, were found at the dredged sites (see Figure 5.5 and 5.6). Figure 5.5 reveals underlying reasons for the separation of samples in the PCA ordination of particle size data. Sediments from the high dredging intensity site were generally coarser and better sorted than either those of the low dredging intensity or reference sites, due to the presence of higher proportions of gravel and consequently lower amounts of other sediment fractions (see Table 5.3). The results of an ANOSIM test reveal little change in the sediments from both the low dredging intensity and reference boxes over the 3 years of study. Of particular interest, is that samples from the high intensity site became more dissimilar (on account of a higher proportion of gravel) to those taken at the low intensity and reference sites, following the resumption of dredging activity within the high intensity box in 2002. This may suggest that coarser sediments have been exposed at Hastings Area X as a consequence of extraction operations, or that sands mobilised during dredging operations have moved away from this area.

***Table 5.2. R-values derived from the ANOSIM test for sediment particle size characteristics (mean diameter in mm, sorting coefficient, kurtosis, skewness, % Gravel, % Coarse Sand, % Medium Sand, % Fine Sand, % Silt/Clay) from locations of higher and lower dredging intensity and from 2 reference sites in the vicinity of Area X sampled between 2001 and 2003. Performed on normalised Euclidean distance data. Values range between ±1 and zero. A zero value indicates high similarity, and a value of ±1 indicates low similarity between samples. * denotes significant difference at p<0.1; ** denotes significant difference at p<0.05. Untransformed data***

| | HIGH '01 | LOW '01 | REF '01 | HIGH '02 | LOW '02 | REF '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|
| LOW '01 | 0.003 | | | | | | | |
| REF '01 | 0.178** | 0.095* | | | | | | |
| HIGH '02 | 0.115** | 0.278** | 0.590** | | | | | |
| LOW '02 | 0.154** | 0.107** | 0.064 | 0.486** | | | | |
| REF '02 | 0.226** | 0.174** | 0.095* | 0.562** | -0.019 | | | |
| HIGH '03 | 0.082* | 0.184** | 0.544** | 0.022 | 0.467** | 0.558** | | |
| LOW '03 | 0.065* | 0.017 | 0.100* | 0.315** | -0.002 | 0.045 | 0.296** | |
| REF '03 | 0.215** | 0.175** | -0.035 | 0.59** | -0.011 | -0.018 | 0.550** | 0.089* |

## 5.2.2. Acoustic and underwater camera surveys

Figures 5.7 to 5.10 show sidescan sonar images collected from the Area X high and low dredging intensity boxes and reference boxes 1 & 2, between 2001 and 2003. In 2001, weathered dredge tracks, orientated in a NE/SW direction, were clearly visible within the area of high intensity dredging. These observations are consistent with other studies in the area (Brown *et al.,* 2001, *Brown et al.*, 2004). The tracks were infilled with sand and it appeared that a number of these individual tracks had agglomerated into larger, elongated sandy features.
In 2002, recent dredging activity (characterised by a generally N/S track orientation) had begun to mask these historic dredging related features (EMU, 1999) and in 2003 they had all but disappeared. Underwater video evidence from 2003 (Figures 5.11-5.13) shows that the seabed within the high intensity box was extremely uneven. Dense dredge tracks covering the seabed were characterised by steep ridges of clean gravel on either side of the track, the bases of which were infilled with sand. This is in contrast to video images collected in 2001, prior to the recommencement of dredging, when the seabed within the high dredging intensity box was relatively flat and consisted of gravelly sand, sandy gravel and patches of rippled sand. This is consistent with the sidescan sonar imagery collected in that year.

Weathered dredge tracks are apparent from the sidescan sonar image within the low intensity box in all three years, but to a far lesser degree than in the high intensity box. Video images collected in the low intensity dredging box in 2003 (Figure 5.12) are similar to those collected in 2001, with a smooth flat sediment profile comprising of flat sandy gravel occasionally masked by sand veneers. Sidescan sonar images of the reference box show that the surrounding sediments are generally similar year on year and consist of flat generally featureless sandy gravels, with occasional sand veneers. However, in 2002, the sidescan sonar image provides some evidence that demersal fishing activity has occurred in this area (Figure 5.9). Sediments at reference box 2 do not appear to have changed between 2001 and 2003. However, two sets of paired tracks, probably caused by demersal trawlers, crossed the box in 2002 (Figure 5.10).

The multibeam bathymetry survey carried out in 2003 shows that the seabed within the high dredging intensity box at Area X is very uneven and has been lowered by approximately 3 metres when compared with the surrounding seabed (Figure 5.14). This is consistent with the information provided by a parallel survey also carried out in 2003 (Coastline Surveys Europe Ltd, 2003).

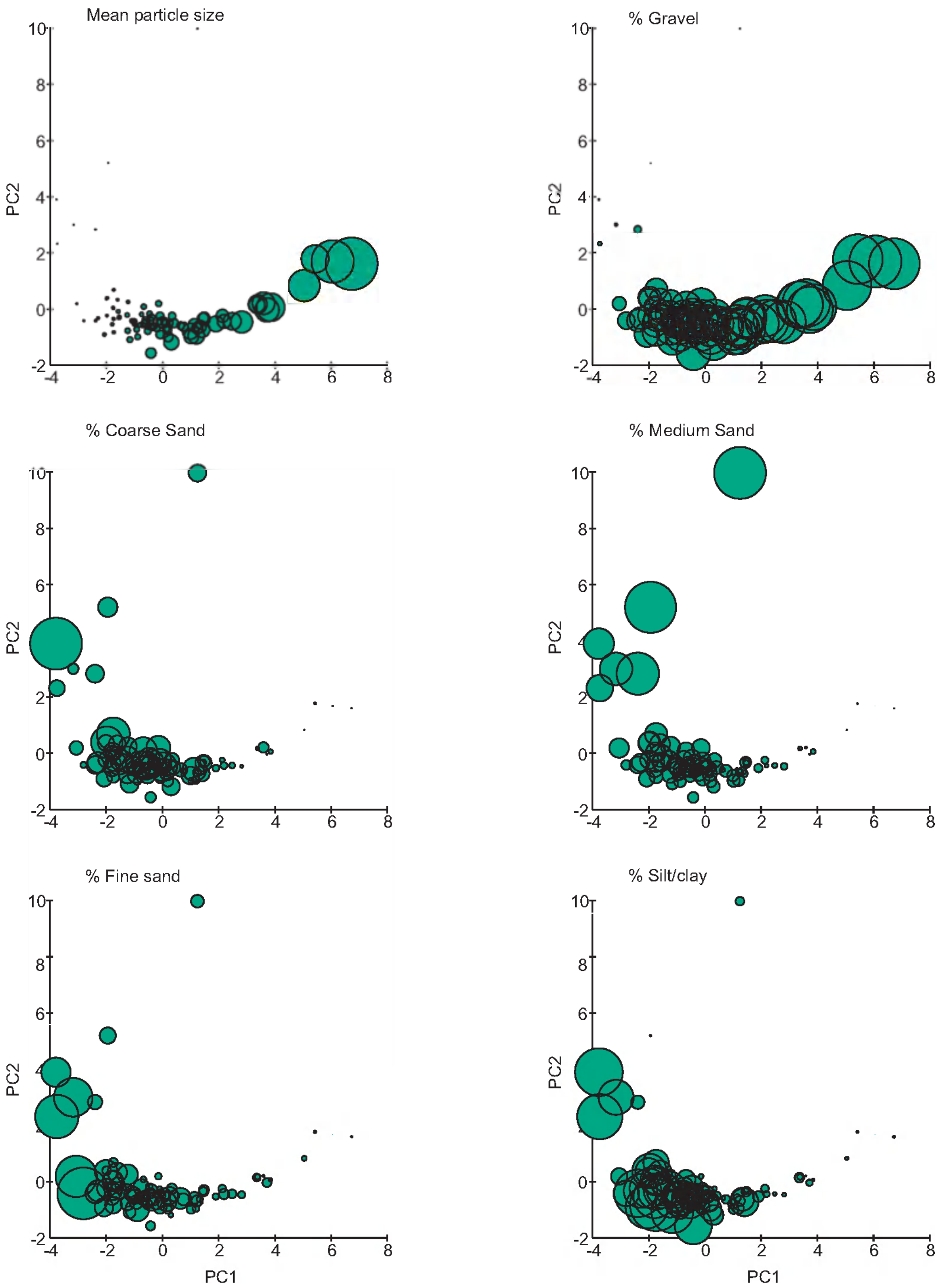



***Figure 5.5.** The same two-dimensional correlation based PCA ordination as in Figure 5.4, but with superimposed circles proportional in diameter to values of percentage gravel, coarse sand, medium sand, fine sand and silt/clay*

***Table 5.3. Mean values (±SD) of sediment particle size characteristics for each site (codes as in Table 5.1)***

| Year | Treatment code | Mean particle size [mm] | Sorting | Skewness | Kurtosis | Gravel [%] | Coarse Sand [%] | Medium Sand [%] | Fine Sand [%] | Silt/clay [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2001 | HIGH '01 | 3.25 (±3.43) | 2.40 (±0.95) | 1.25 (±1.31) | 8.66 (±11.95) | 48.36 (±31.44) | 3.58 (±2.39) | 35.29 (±28.53) | 10.97 (±4.38) | 1.81 (±1.12) |
| | LOW '01 | 2.55 (±1.53) | 2.85 (±0.49) | 0.96 (±0.53) | 4.62 (±2.74) | 50.67 (±25.36) | 5.25 (±3.63) | 25.61 (±13.22) | 15.09 (±8.92) | 3.36 (±2.42) |
| | REF 1 '01 | 1.31 (±0.58) | 2.97 (±0.19) | 0.54 (±0.23) | 3.31 (±0.21) | 45.62 (±8.22) | 4.71 (±0.49) | 28.76 (±5.17) | 16.85 (±2.67) | 4.05 (±1.36) |
| | REF 2 '01 | 2.17 (±0.82) | 3.00 (±0.35) | 0.89 (±0.17) | 3.73 (±0.58) | 55.50 (±7.25) | 6.39 (±2.36) | 28.07 (±3.88) | 6.51 (±1.75) | 3.54 (±2.04) |
| 2002 | HIGH '02 | 9.58 (±6.03) | 2.18 (±0.76) | 1.73 (±0.80) | 8.13 (±6.24) | 83.77 (±11.8) | 1.61 (±1.36) | 7.89 (±6.29) | 5.92 (±4.66) | 0.82 (±0.64) |
| | LOW '02 | 2.39 (±1.84) | 3.28 (±0.21) | 0.58 (±0.51) | 2.90 (±0.30) | 52.97 (±12.72) | 4.24 (±1.07) | 23.89 (±5.61) | 13.72 (±8.63) | 5.19 (±2.55) |
| | REF 1 '02 | 2.42 (±1.18) | 3.32 (±0.30) | 0.77 (±0.16) | 3.00 (±0.16) | 57.52 (±7.06) | 4.09 (±0.62) | 21.46 (±3.82) | 11.18 (±2.98) | 5.75 (±0.79) |
| | REF 2 '02 | 3.72 (±2.62) | 3.16 (±0.26) | 0.78 (±0.11) | 3.17 (±0.18) | 59.11 (±11.71) | 6.81 (±1.75) | 24.69 (±6.51) | 5.08 (±1.76) | 4.31 (±1.98) |
| 2003 | HIGH ,03 | 5.93 (±3.80) | 2.40 (±0.33) | 1.55 (±0.86) | 6.21 (±3.19) | 73.23 (±25.30) | 2.58 (±2.15) | 9.61 (±12.19) | 12.68 (±10.27) | 1.90 (±2.25) |
| | LOW '03 | 3.06 (±1.78) | 3.15 (±0.19) | 0.78 (±0.56) | 3.14 (±0.98) | 58.85 (±13.69) | 3.65 (±1.43) | 19.84 (±5.08) | 13.69 (±1.99) | 3.97 (±1.30) |
| | REF 1 '03 | 1.23 (±0.31) | 3.12 (±0.13) | 0.44 (±0.10) | 2.76 (±0.12) | 45.96 (±4.51) | 4.30 (±0.65) | 27.75 (±2.12) | 15.97 (±1.92) | 6.02 (±1.72) |
| | REF 2 '03 | 3.30 (±1.97) | 3.05 (±0.17) | 0.92 (±0.48) | 3.55 (±1.22) | 61.52 (±9.72) | 6.63 (±1.31) | 22.94 (±7.24) | 4.70 (±1.66) | 4.21 (±1.19) |

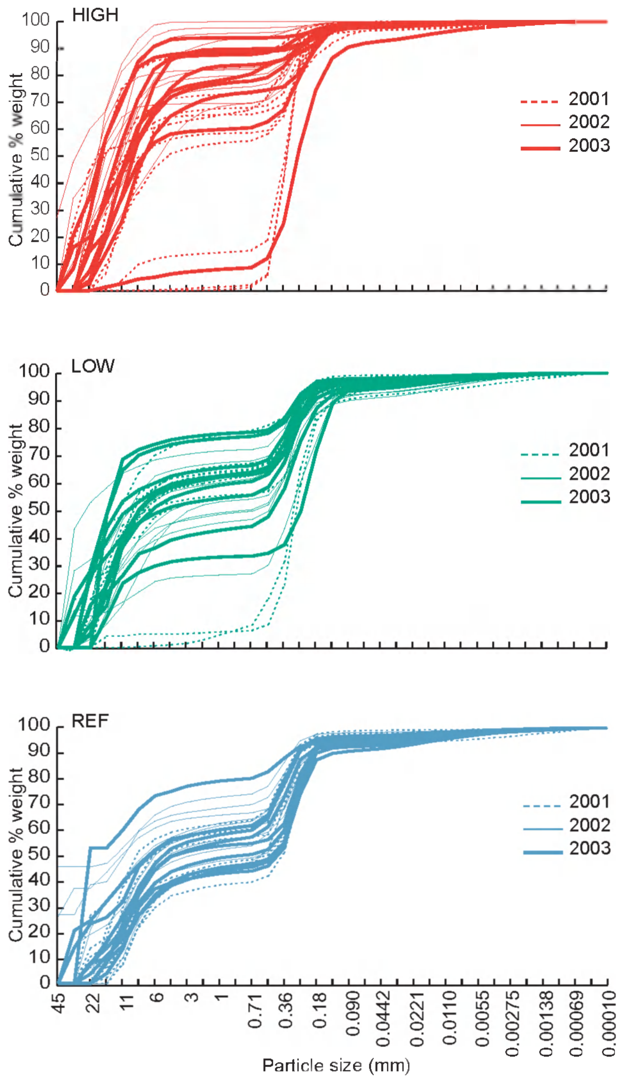



***Figure 5.6. Sediment particle size distributions determined from replicate samples taken from sites of high and lower levels of dredging intensity at Area X and the two reference sites between 2001 and 2003***

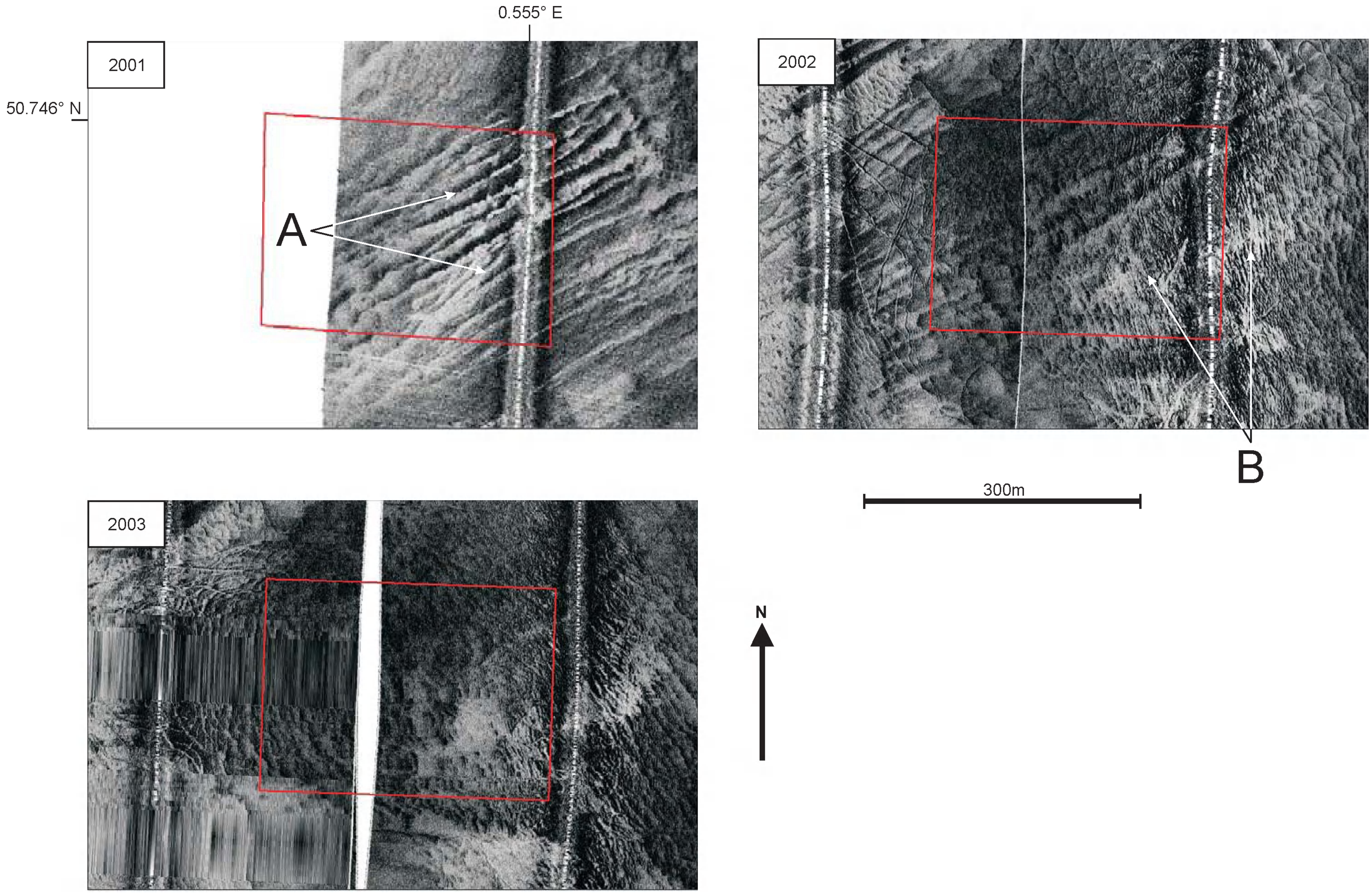



*Figure 5.7. Sidescan sonar images of the high dredging intensity box at Area X (2001-2003). A) Weathered dredge tracks in 2001 in NE/SW orientation. B) Tracks generated by recent dredging activity*

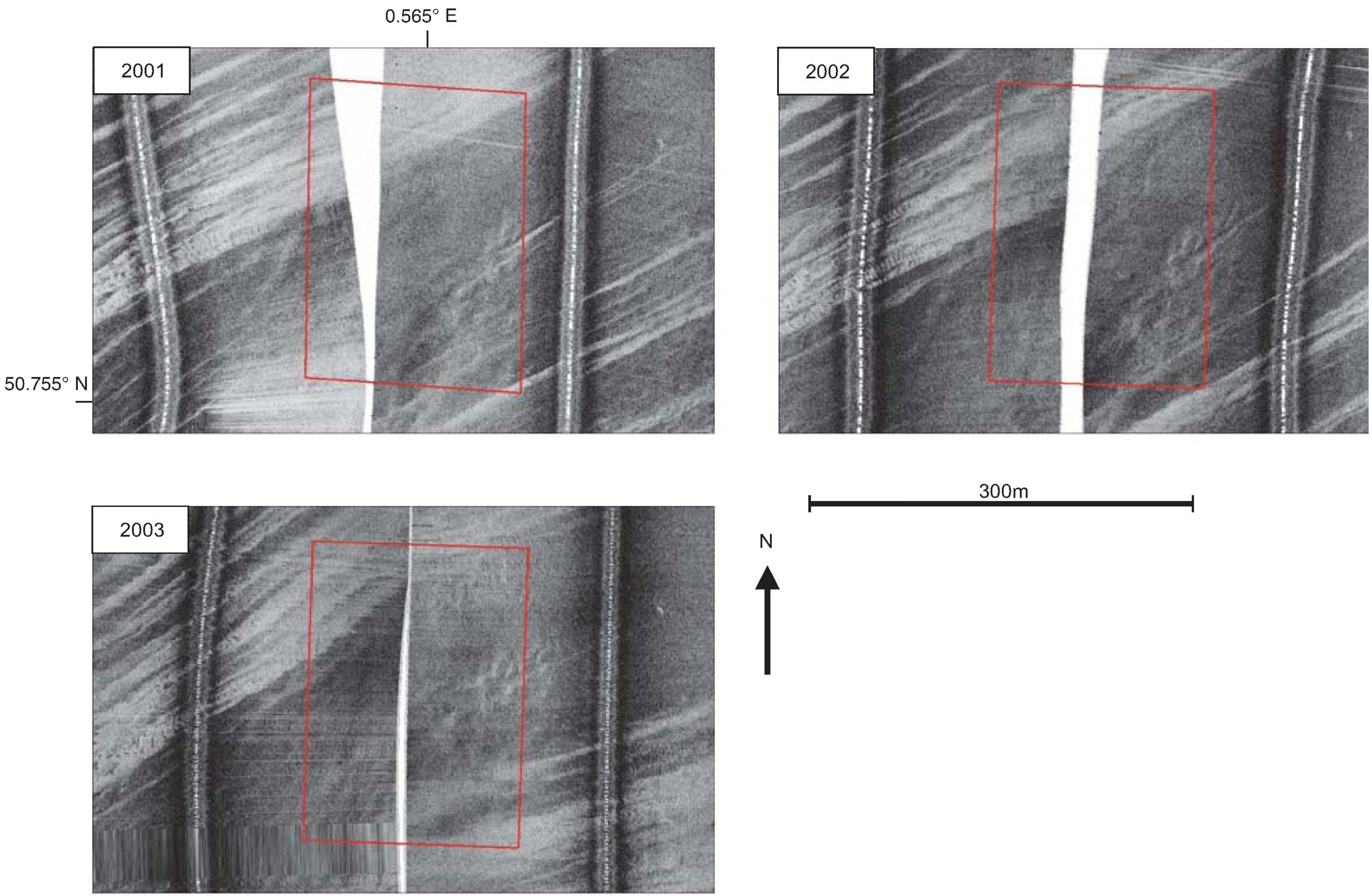



*Figure 5.8. Sidescan sonar images of the low dredging intensity box at Area X (2001-2003)*

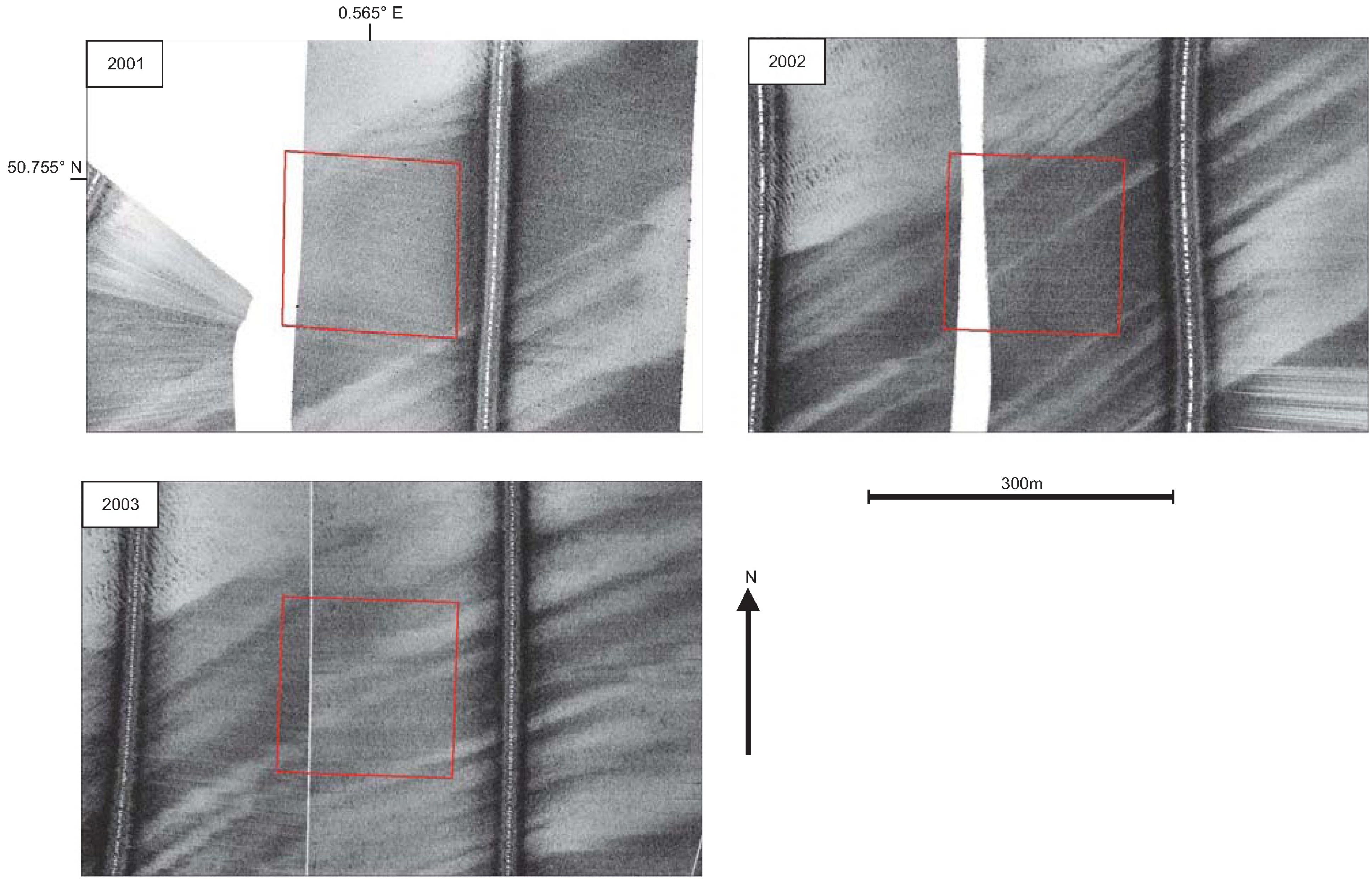



Figure 5.9. Sidescan sonar images of Reference box 1 (Area X) (2001-2003)

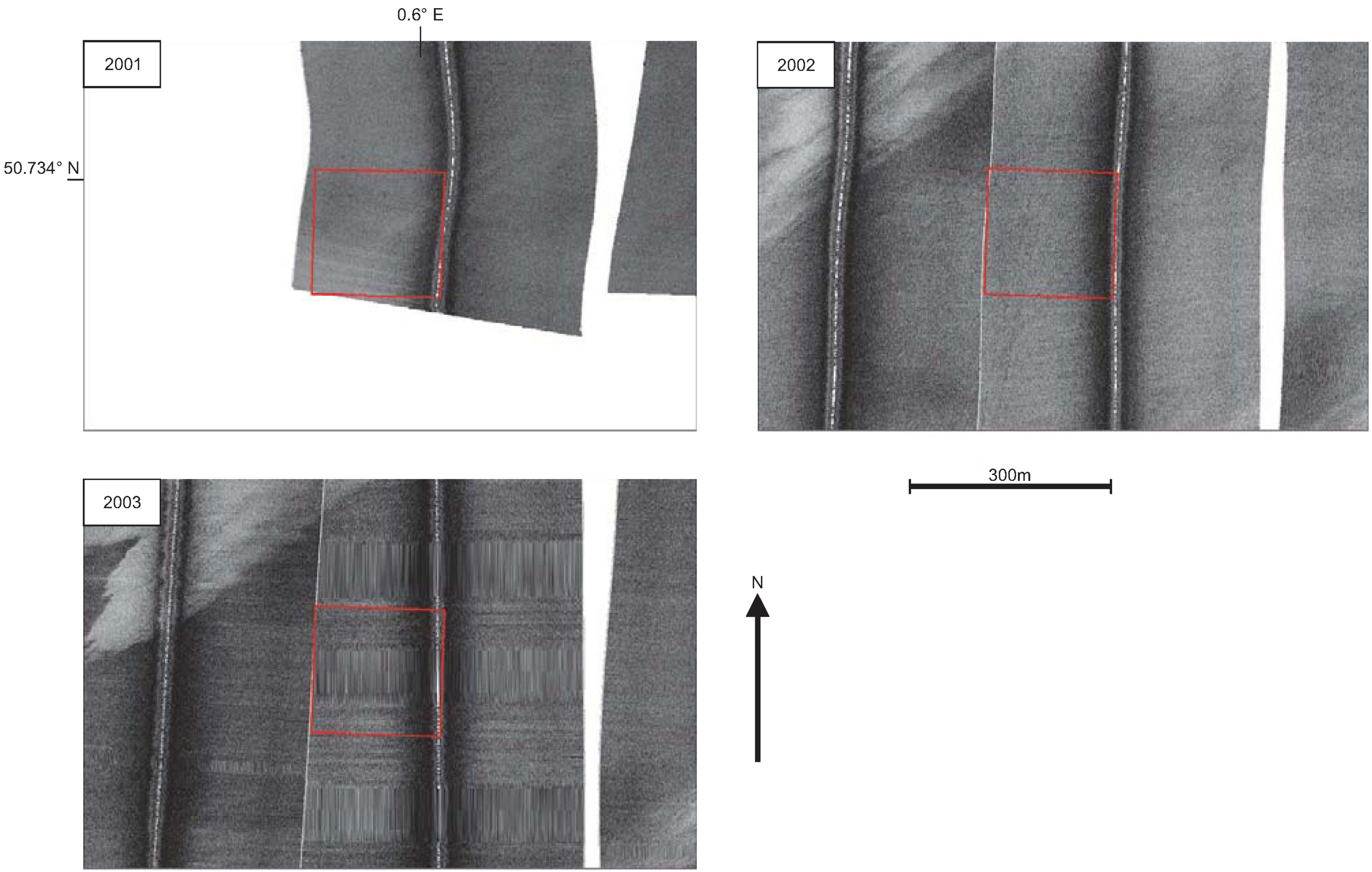



*Figure 5.10. Sidescan sonar images of Reference box 2 (Area Y) (2001-2003)*

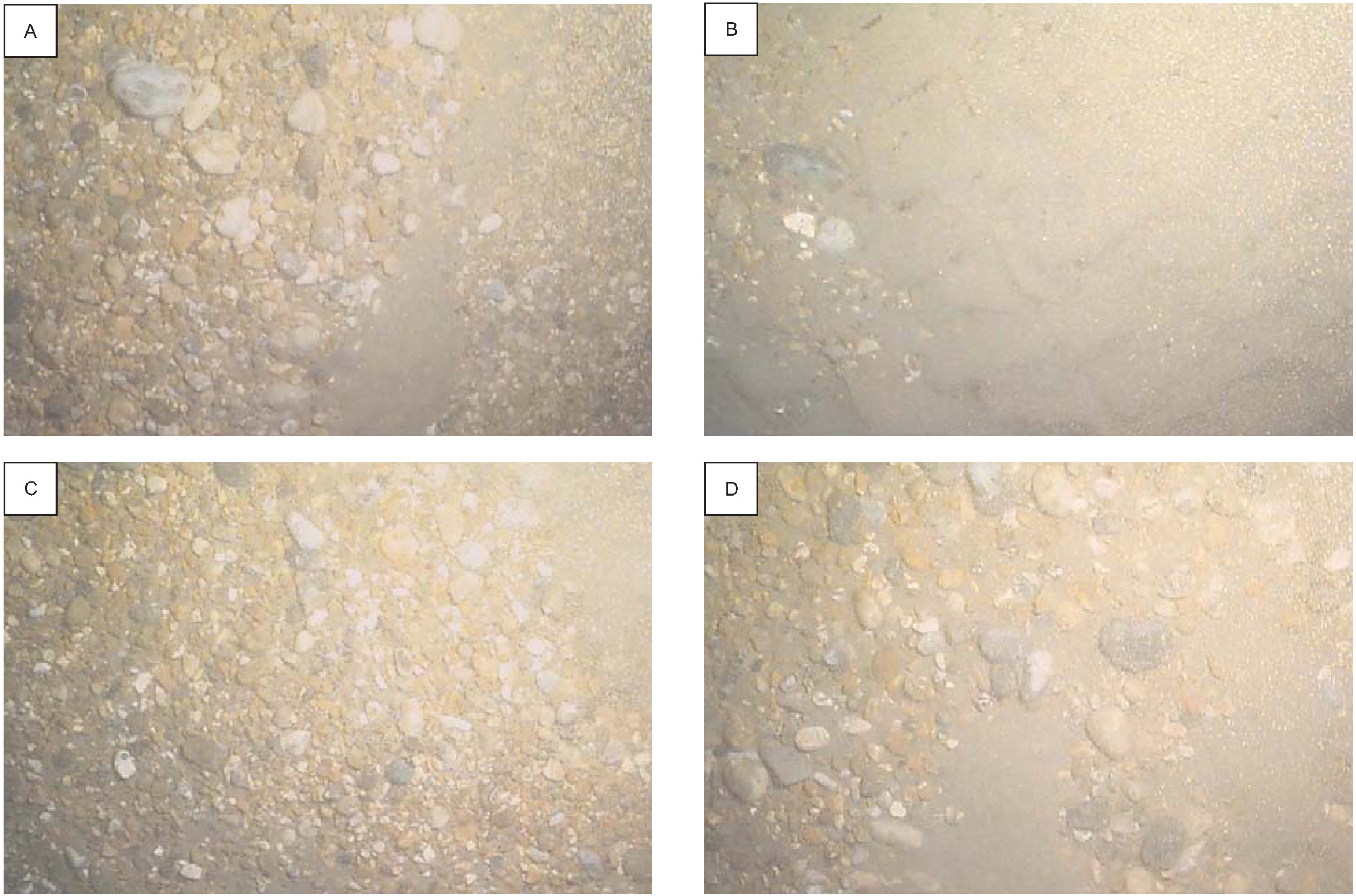



*Figure 5.11. Underwater still images taken within the high dredging intensity box at Area X in 2003*

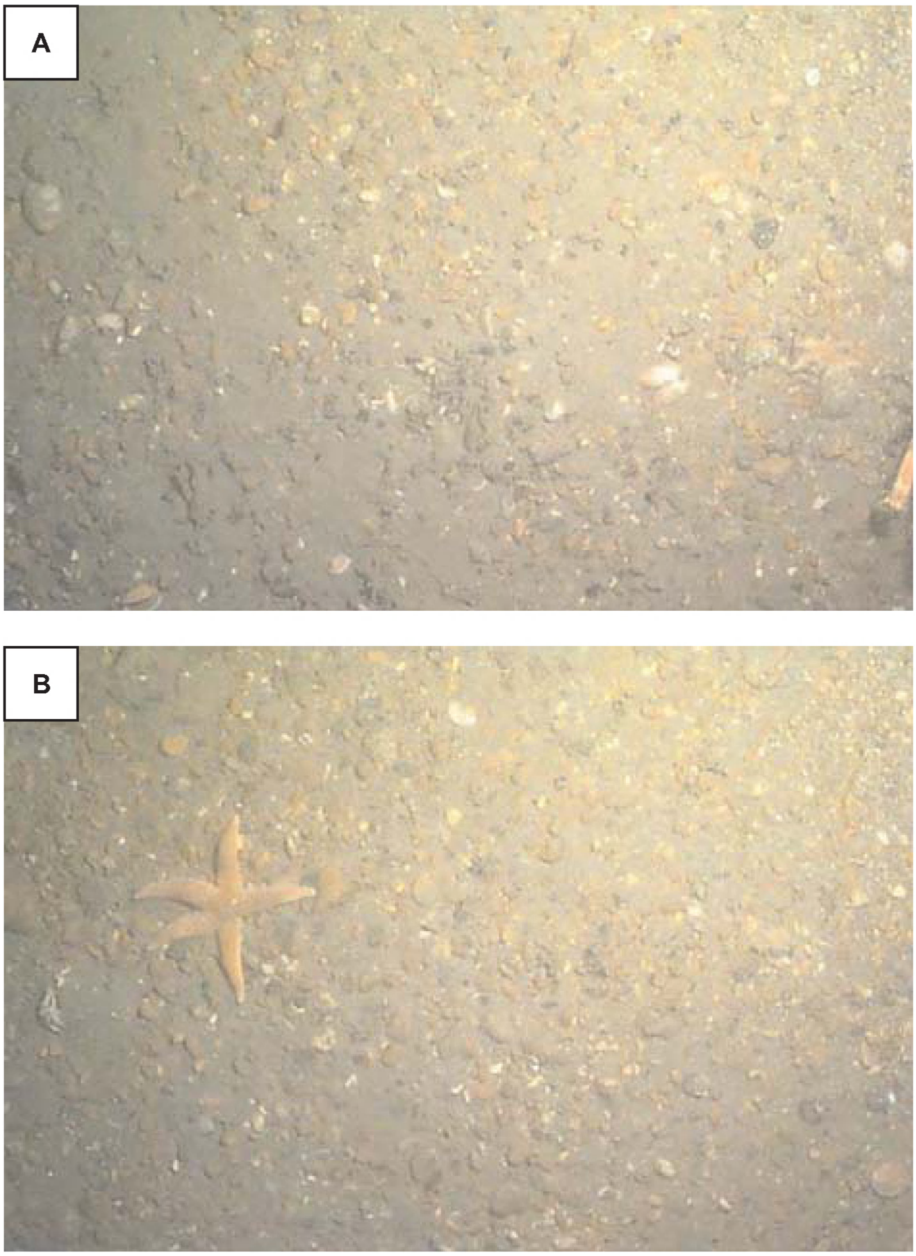



***Figure 5.12. Underwater still images taken within the low dredging intensity box at Area X in 2003***

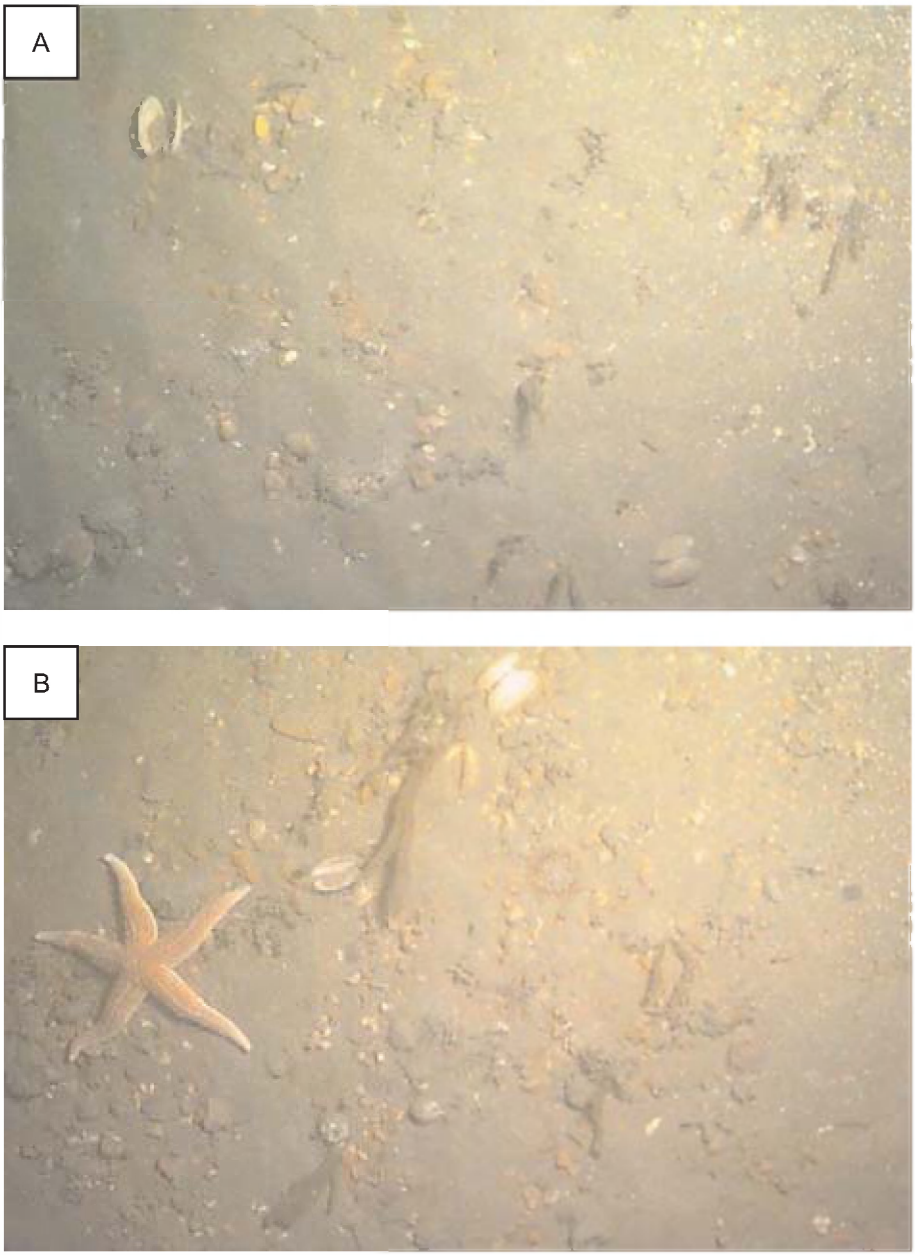



***Figure 5.13. Underwater still images taken within Reference box 1 (Area X) in 2003***

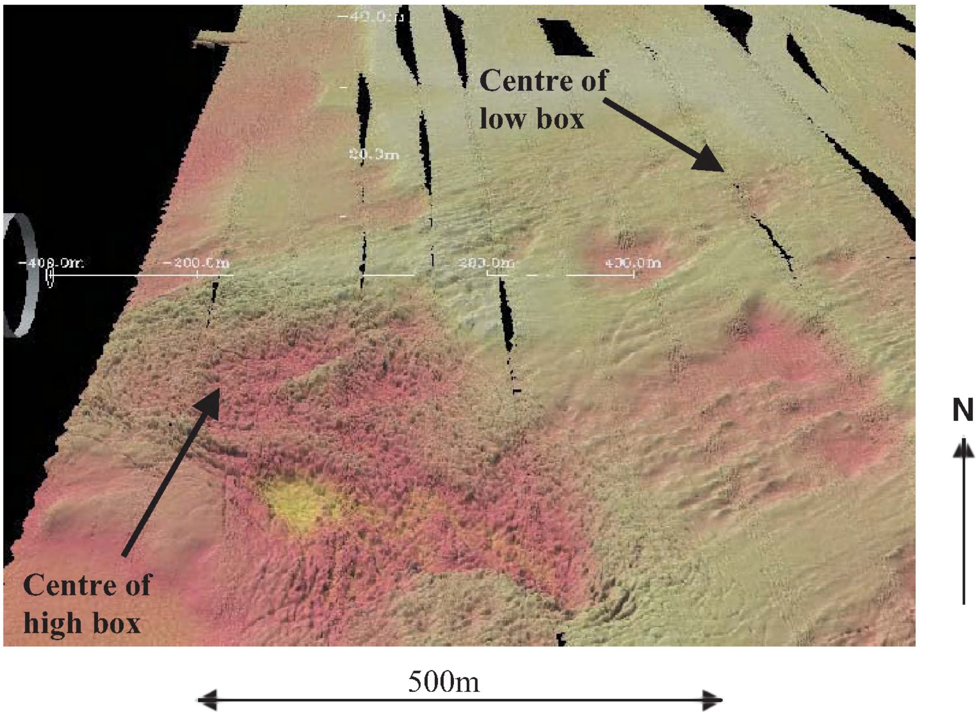



*Figure 5.14* ***Multibeam bathymetry of the area surrounding Hastings Area X. The central points of the high and low dredging intensity boxes are shown***

### *5.2.3. Macrofaunal assemblage structure*

Overall, a total of 368 species were found at Area X from the 90 samples collected between 2001 and 2003 (228 species in 2001, 294 species in 2002 and 236 species in 2003).

**Univariate Analyses**
Figure 5.15 shows a comparison of various univariate measures at each sampling site in 2001, 2002 and 2003. In 2001, 5 years post cessation, a one-way ANOVA detected no significant differences ($p>0.05$) in either the number of individuals or biomass between the three sites. However, numbers of species at both the site of high and low dredging intensity were significantly ($p<0.05$) lower in comparison with the reference sites. The lack of difference in the total counts of macrofauna in 2001 can be attributed to elevations of the barnacle *Balanus crenatus* from within the area of high dredging intensity which had the effect of masking reductions in the abundance of many other species at this site. This species appears to fulfil a role as an opportunistic coloniser of gravel substrata exposed during the dredging process. Similarly, high densities of this species were found within a few of the more gravelly samples obtained from the area of low dredging intensity. Despite this local enhancement of *Balanus*, the total density of macrofauna was lower from within the area of low dredging intensity compared to elsewhere.

In 2002, following the resumption of dredging within the high dredging intensity box, the numbers of species, individuals and biomass were significantly lower ($p<0.05$) than both the low dredging intensity and reference boxes. In terms of the number of species and individuals there were no significant differences between the low dredging intensity and reference boxes. Following dredging within the high intensity box in 2003 the numbers of species, individuals and biomass remained significantly lower within the high dredging intensity box whilst no difference was detected between the low and reference boxes. The impact of aggregate dredging on the benthos at this location is explored in more detail in the following section.

The responses of selected macrofauna species were also examined at the three sites (Figure 5.16). In 2002, following the resumption of dredging within the Area X high dredging intensity box, the abundance of many species fell sharply (e.g. *Balanus crenatus*, *Mysella bidentata* and *Echinocyamus pusillus*). Differences between the low dredging intensity and reference boxes were less distinct (e.g. *Sabellaria spinulosa* and *Pomatoceros lamarki*).

**Multivariate analyses**
Figure 5.17 shows the output from the non-metric multi-dimensional scaling ordinations of data from the Hamon grab surveys at Area X. Evident from this figure, like that of the particle size PCA ordination, is

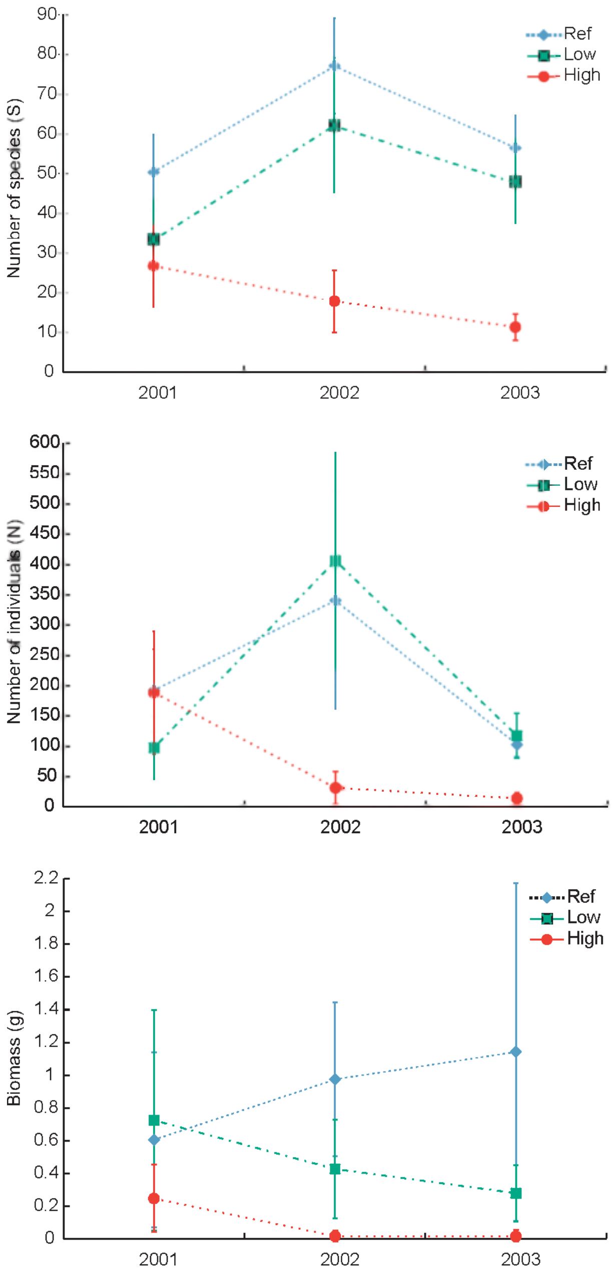



***Figure 5.15.*** ***Summary of means and 95% confidence intervals for numbers of species (S) and numbers of individuals (N) and biomass AFDW from sites of high and lower levels of dredging intensity at Area X and at two nearby reference sites from 2001 to 2003***

the large degree of overlap of samples from the areas of low dredging intensity and the reference sites. Only 2 samples from the low dredging intensity box were found outside the main cluster in 2001 and only 1 in 2002 and 2003. Similarly, over half of the samples from the high dredging intensity box were present in the main cluster in 2001. However, high dredging intensity samples were more diffusely separated on the MDS in 2002 and 2003. Indeed, all high dredging intensity samples from 2003 were found outside the central cluster of low dredging intensity and reference samples. This suggests that they are biologically dissimilar to samples collected elsewhere and reflects the substantially reduced densities of organisms associated with these sediments.

The comparative Index of Multivariate Dispersion (IMD) has been calculated in order to contrast the multivariate variability amongst samples taken from the dredged sites with samples from the reference locations. In Table 5.4 values are compared between each of the sites in each year. In 2001 the high and low dredging intensity sites showed similar values of variability when compared to the reference site. In 2002 the low dredging intensity site became less variable in relation to the reference site and by 2003 there was little difference between these 2 sites. However, variability at the high dredging intensity site increased markedly in comparison with the reference and the low dredging intensity sites in 2002 following resumption of dredging and remained high in 2003, presumably reflecting an impact of ongoing dredging activity.

Table 5.5 shows the results of r.IMD calculated for samples collected within and in the vicinity of Hastings Area X. This shows that, in common with the results obtained at Area 222, variability in species composition was greatest at the site of high dredging intensity and lowest at the reference sites, in all years.

***Table 5.4*** ***Index of Multivariate Dispersion (IMD) between all pairs of conditions***

| Year | Site | IMD |
|---|---|---|
| 2001 | High/ Reference | +0.484 |
| | High /Low | +0.146 |
| | Low/Reference | +0.513 |
| 2002 | High/ Reference | +0.983 |
| | High /Low | +0.697 |
| | Low/Reference | +0.416 |
| 2003 | High/ Reference | +0.842 |
| | High /Low | +0.729 |
| | Low/Reference | +0.180 |

***Table 5.5.*** ***Relative Index of Multivariate Dispersion (r.IMD) in each year***

| Year | Site | r.IMD |
|---|---|---|
| 2001 | High intensity | 1.218 |
| | Low intensity | 1.146 |
| | Reference | 0.73 |
| 2002 | High intensity | 1.564 |
| | Low intensity | 0.783 |
| | Reference | 0.353 |
| 2003 | High intensity | 1.547 |
| | Low intensity | 0.892 |
| | Reference | 0.766 |

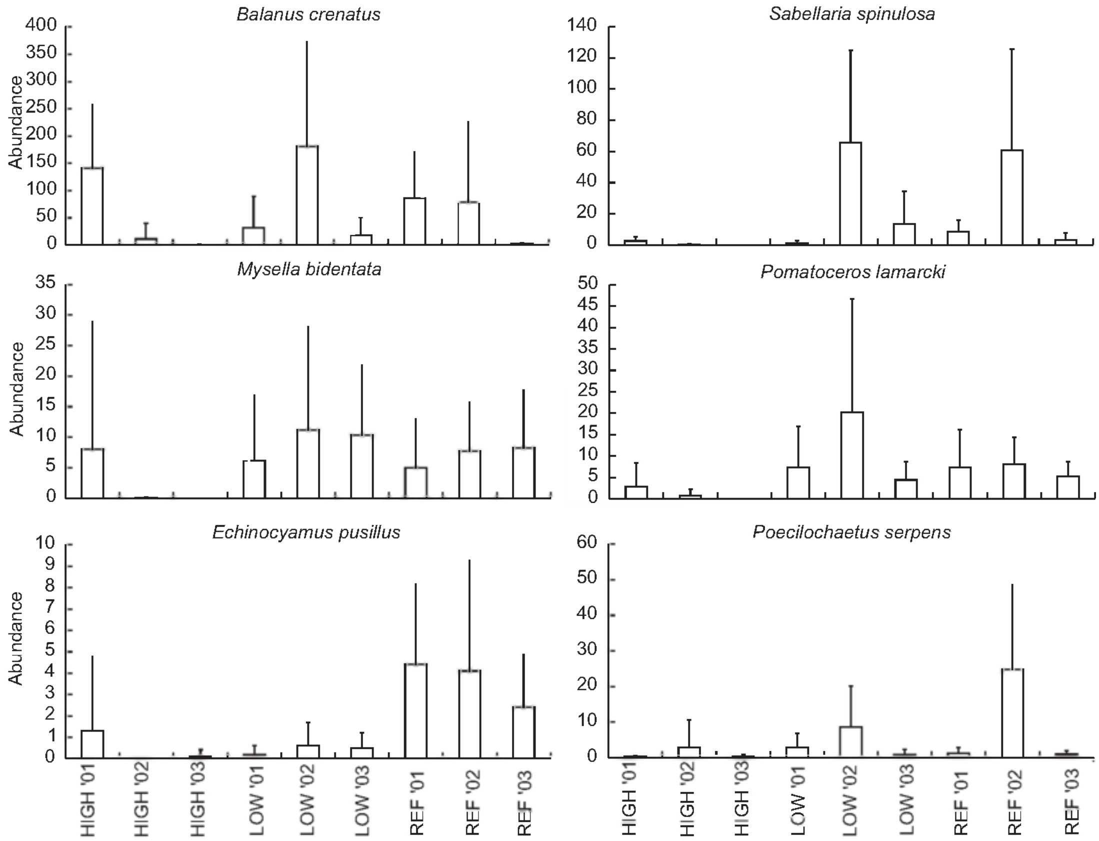



***Figure 5.16. Means (± SD) of abundances of selected macrofauna species sampled in 2001-2003 at sites of high and lower levels of dredging intensity and at two reference sites (codes as in Table 5.1)***

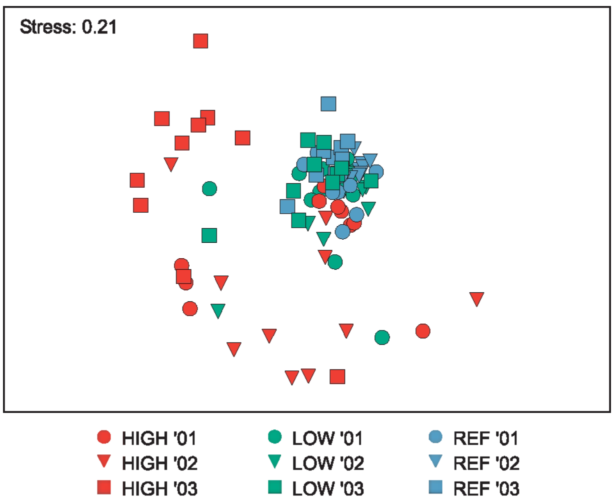



***Figure 5.17. MDS of Bray-Curtis similarities from 4th root-transformed species abundance data 5, 6 and 7 years after the cessation of dredging at the low dredging intensity site and after 5 years at the high dredging intensity site. Samples from the high dredging intensity site in 2002 and 2003 represent conditions at a currently extracted site (codes as in Table 5.9)***

***Table 5.6. R-values derived from the ANOSIM test for macrofaunal assemblages from locations of higher and lower dredging intensity and from the reference site sampled in 2001, 2002 and 2003. Values range between one and zero. A zero value indicates high similarity between samples, and a value of 1 indicates low similarity. * denotes significant difference at $p < 0.05$***

| | HIGH '01 | LOW '01 | REF '01 | HIGH '02 | LOW '02 | REF '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|
| LOW '01 | 0.091** | | | | | | | |
| REF '01 | 0.150** | 0.097** | | | | | | |
| HIGH '02 | 0.303** | 0.283** | 0.542** | | | | | |
| LOW '02 | 0.241** | 0.194** | 0.266** | 0.440** | | | | |
| REF '02 | 0.507** | 0.339** | 0.398** | 0.622** | 0.157** | | | |
| HIGH '03 | 0.361** | 0.505** | 0.616** | 0.340** | 0.560** | 0.649** | | |
| LOW '03 | 0.268** | 0.094* | 0.252** | 0.519** | 0.216** | 0.385** | 0.553** | |
| REF '03 | 0.373** | 0.152** | 0.240** | 0.648** | 0.294** | 0.287** | 0.595** | 0.045 |

Comparison of ANOSIM R values in 2001 show that although significant differences exist between samples from the high and low dredging intensity sites and the reference sites, these differences are relatively minor (Table 5.6). In 2002, the differences between the low dredging intensity site and the reference sites continue to be small and by 2003 no significant difference ($p>0.05$) could be detected between these two areas. This indicates that the biological communities at the low dredging intensity and reference sites are indistinguishable from one another by multivariate techniques in 2003. Furthermore, this suggests that restoration of the fauna was achieved in those parts of Hastings Area X exposed to lower levels of dredging intensity after a period of approximately 7 years since the cessation of dredging. However, in 2002 following resumption of dredging, and also in 2003, the high dredging intensity site was significantly different to the reference sites.

Community groupings were explored further using the similarity percentages programme SIMPER (Table 5.7). Generally, the fauna at all sites is characteristic of sandy gravel sediments. In 2001, the barnacle *Balanus crenatus* characterised all sample groups, although its relative importance in terms of its percentage contribution to the overall similarity of sample groups differed between sites. For example, sediments from the area of high dredging intensity appeared to be heavily dominated by *Balanus*, whilst sediments from the area of low dredging intensity and the reference sites showed a more equitable distribution of species. This suggests that dredging may have resulted in the removal of a range of sensitive species, thus restricting the fauna at the site of high dredging intensity to fast growing colonizers capable of establishing themselves in the unstable conditions present following a brief interlude in extraction operations. In 2002 and 2003, the dominance of *Balanus* had been replaced by the mobile crustacean species *Pandalina brevirostris*, *Pisidia longicornis* and the polychaete worms *Lagis koreni* and *Scalibregma inflatum.*

***Table 5.7. Results from SIMPER analysis of macrofauna data from Area X (all taxa excluding colonial species, 4th root transformed), listing the main characterising species from samples subject to differing levels of dredging impact from 2001. Average abundance and the % contribution to the similarity made by each characterising species is shown. Also listed is the cumulative percentage and the overall average similarity between replicate samples from within each group***

| Group | Taxon | Average Abundance | Average Similarity | % Contribution | Cumulative % | Overall Average Similarity |
|---|---|---|---|---|---|---|
| HIGH '01 | *Balanus crenatus* | 140.90 | 5.37 | 20.24 | 20.24 | **26.53%** |
| | *Galathea intermedia* | 2.20 | 2.41 | 9.08 | 29.32 | |
| | *Spiophanes bombyx* | 1.20 | 1.76 | 6.63 | 35.95 | |
| | *Lagis koreni* | 1.00 | 1.71 | 6.46 | 42.41 | |
| LOW '01 | *Lumbrineris gracilis* | 2.60 | 2.26 | 7.64 | 7.64 | **29.61%** |
| | *Balanus crenatus* | 31.50 | 2.13 | 7.18 | 14.82 | |
| | *NEMERTEA* | 1.70 | 2.11 | 7.12 | 21.94 | |
| | *Pomatoceros lamarcki* | 7.40 | 1.94 | 6.54 | 28.48 | |
| | *Notomastus* sp. | 1.30 | 1.57 | 5.31 | 33.79 | |
| | *Poecilochaetus serpens* | 2.90 | 1.38 | 4.66 | 38.45 | |
| | *Lagis koreni* | 1.80 | 1.38 | 4.66 | 43.11 | |
| REF '01 | *Balanus crenatus* | 85.30 | 3.02 | 7.53 | 7.53 | **40.16%** |
| | *Lumbrineris gracilis* | 5.70 | 2.79 | 6.95 | 14.48 | |
| | NEMERTEA | 2.70 | 2.39 | 5.94 | 20.42 | |
| | *Aonides oxycephala* | 3.20 | 2.34 | 5.84 | 26.26 | |
| | *Sabellaria spinulosa* | 8.60 | 2.24 | 5.59 | 31.85 | |
| | *Scalibregma inflatum* | 6.00 | 2.11 | 5.26 | 37.10 | |
| | *Notomastus* sp. | 2.40 | 1.84 | 4.58 | 41.69 | |
| HIGH '02 | *Pandalina brevirostris* | 1.20 | 3.75 | 20.85 | 20.85 | **18.00%** |
| | *Pisidia longicornis* | 1.00 | 2.62 | 14.55 | 35.41 | |
| | *Balanus crenatus* | 11.30 | 2.44 | 13.58 | 48.98 | |
| LOW '02 | *Balanus crenatus* | 181.10 | 3.90 | 10.00 | 10.00 | **39.10%** |
| | *Sabellaria spinulosa* | 65.60 | 2.55 | 6.54 | 16.54 | |
| | *Spiophanes bombyx* | 2.60 | 1.82 | 4.66 | 21.20 | |
| | *Pomatoceros lamarcki* | 20.20 | 1.49 | 3.82 | 25.03 | |
| | NEMERTEA | 2.50 | 1.24 | 3.19 | 28.21 | |
| | *Lumbrineris gracilis* | 5.20 | 1.13 | 2.89 | 31.10 | |
| | *Nephtys* (juv.) | 1.30 | 1.11 | 2.84 | 33.94 | |
| | *Lagis koreni* | 5.30 | 1.06 | 2.71 | 36.65 | |
| | *Galathea intermedia* | 2.10 | 0.93 | 2.39 | 39.04 | |
| | *Pomatoceros triqueter* | 3.30 | 0.91 | 2.33 | 41.37 | |
| REF '02 | *Poecilochaetus serpens* | 24.80 | 2.20 | 4.44 | 4.44 | **49.41%** |
| | *Sabellaria spinulosa* | 60.90 | 2.01 | 4.06 | 8.51 | |
| | *Lagis koreni* | 6.30 | 1.78 | 3.60 | 12.10 | |
| | *Pomatoceros lamarcki* | 8.10 | 1.72 | 3.49 | 15.59 | |
| | *Mysella bidentata* | 7.70 | 1.68 | 3.40 | 18.99 | |
| | *Lumbrineris gracilis* | 6.40 | 1.64 | 3.31 | 22.30 | |
| | *Upogebia* (juv.) | 3.90 | 1.62 | 3.27 | 25.57 | |
| | *Balanus crenatus* | 78.80 | 1.60 | 3.25 | 28.82 | |
| | NEMERTEA | 6.70 | 1.58 | 3.20 | 32.02 | |
| | *Galathea intermedia* | 2.70 | 1.44 | 2.92 | 34.93 | |
| | *Notomastus* sp. | 2.70 | 1.38 | 2.79 | 37.73 | |
| | *Harmothoe impar* | 2.70 | 1.37 | 2.77 | 40.50 | |
| HIGH '03 | *Lagis koreni* | 1.20 | 4.60 | 26.07 | 26.07 | **17.65%** |
| | *Scalibregma inflatum* | 0.70 | 2.72 | 15.41 | 41.48 | |
| LOW '03 | *Lumbrineris gracilis* | 5.50 | 3.13 | 8.57 | 8.57 | **36.47%** |
| | NEMERTEA | 3.00 | 2.69 | 7.37 | 15.94 | |
| | *Polycirrus* sp. | 2.50 | 2.56 | 7.02 | 22.96 | |
| | *Mysella bidentata* | 10.30 | 2.48 | 6.80 | 29.77 | |
| | *Scalibregma inflatum* | 4.90 | 2.33 | 6.39 | 36.16 | |
| | *Lagis koreni* | 2.90 | 2.19 | 6.01 | 42.17 | |
| REF '03 | *Mysella bidentata* | 8.20 | 2.23 | 5.66 | 5.66 | **39.34%** |
| | *Pomatoceros lamarcki* | 5.20 | 2.08 | 5.28 | 10.93 | |
| | *Spiophanes bombyx* | 1.90 | 2.06 | 5.24 | 16.17 | |
| | *Lumbrineris gracilis* | 5.60 | 2.04 | 5.20 | 21.37 | |
| | NEMERTEA | 3.20 | 2.02 | 5.13 | 26.51 | |
| | *Lagis koreni* | 3.70 | 1.97 | 5.01 | 31.51 | |
| | *Scalibregma inflatum* | 6.00 | 1.76 | 4.49 | 36.00 | |
| | *Polycirrus* sp. | 2.20 | 1.38 | 3.51 | 39.50 | |
| | *Notomastus* sp. | 2.00 | 1.34 | 3.41 | 42.92 | |

## 5.3. Results (Hastings Area Y)

### *5.3.1. Sediment characteristics*

A PCA ordination of particle size data obtained at Hastings Area Y clearly shows some overlap of samples from all sites (Figure 5.18). The high dredging intensity and reference sites are more tightly clustered than samples from the low dredging intensity site. These results are confirmed by the result of an ANOSIM test (Table 5.8). Of interest, is the greater variability of samples in terms of sediment particle size characteristics from the dredged sites in comparison with the reference locations. Samples from the high dredging intensity and reference boxes are both characterised by higher proportions of gravel and to a lesser extent medium sand (Figures 5.18 and 5.19). A greater proportion of silt/clay at the reference sites contributes to the difference with the high intensity samples. In contrast, low intensity samples are dominated by medium sand with a lower proportion of gravel. These observations are clearly illustrated in Figure 5.19 showing values of each particle size fraction in the PCA ordination. A number of samples from dredged sites were dominated by sand and these predominately sandy samples were not encountered at the reference sites (see Figure 5.20). Presumably, this reflects the heterogeneous nature of substrata within the area, caused by the patchy impact of dredging within this former extraction area (see also Newell *et al.*, 2002). Interestingly, this possibility is supported by evidence from sidescan sonar and underwater images of the region which shows sandier sediments present within dredged furrows separated by coarser undisturbed deposits. In 2002, however, sediments from the area of high dredging intensity appear to be coarser and more uniform in their distribution. This may have resulted from the slumping of the coarser deposits into the dredged furrows and/or the transport of sand away from the area. A summary of sediment particle size characteristics of samples taken from each of the treatment boxes is shown in Table 5.9.

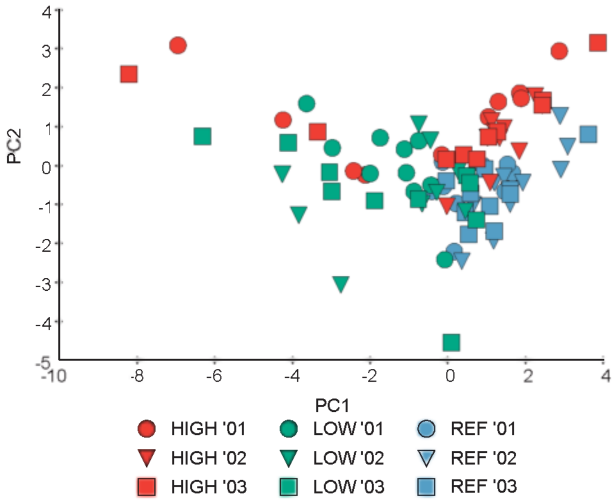



***Figure 5.18 Two-dimensional correlation-based PCA ordination of untransformed sediment particle size data (2001 to 2003) from Area Y. For variables involved in the ordination see Table 5.9***

***Table 5.8. R-values derived from the ANOSIM test for sediment particle size characteristics (mean diameter in mm, sorting coefficient, kurtosis, skewness, % Gravel, % Coarse Sand, % Medium Sand, % Fine Sand, % Silt/Clay) from locations of higher and lower dredging intensity and from 2 reference sites in the vicinity of Area Y sampled between 2001 and 2003. Performed on normalised Euclidean distance data. Values range between ±1 and zero. A zero value indicates high similarity, and a value of ±1 indicates low similarity between samples. * denotes significant difference at p<0.1; ** denotes significant difference at p<0.05. Untransformed data***

| | HIGH '01 | LOW '01 | REF '01 | HIGH '02 | LOW '02 | REF '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|
| LOW '01 | 0.279** | | | | | | | |
| REF '01 | 0.265** | 0.391** | | | | | | |
| HIGH '02 | 0.120** | 0.670** | 0.227** | | | | | |
| LOW '02 | 0.118* | 0.063 | 0.080* | 0.303** | | | | |
| REF '02 | 0.319** | 0.640** | 0.070 | 0.253** | 0.288** | | | |
| HIGH '03 | -0.021 | 0.306** | 0.141** | 0.015 | 0.106** | 0.181** | | |
| LOW '03 | 0.166** | 0.079** | 0.182** | 0.411** | -0.016 | 0.333** | 0.183** | |
| REF '03 | 0.296** | 0.460** | -0.037 | 0.291** | 0.165** | -0.020 | 0.179** | 0.230** |

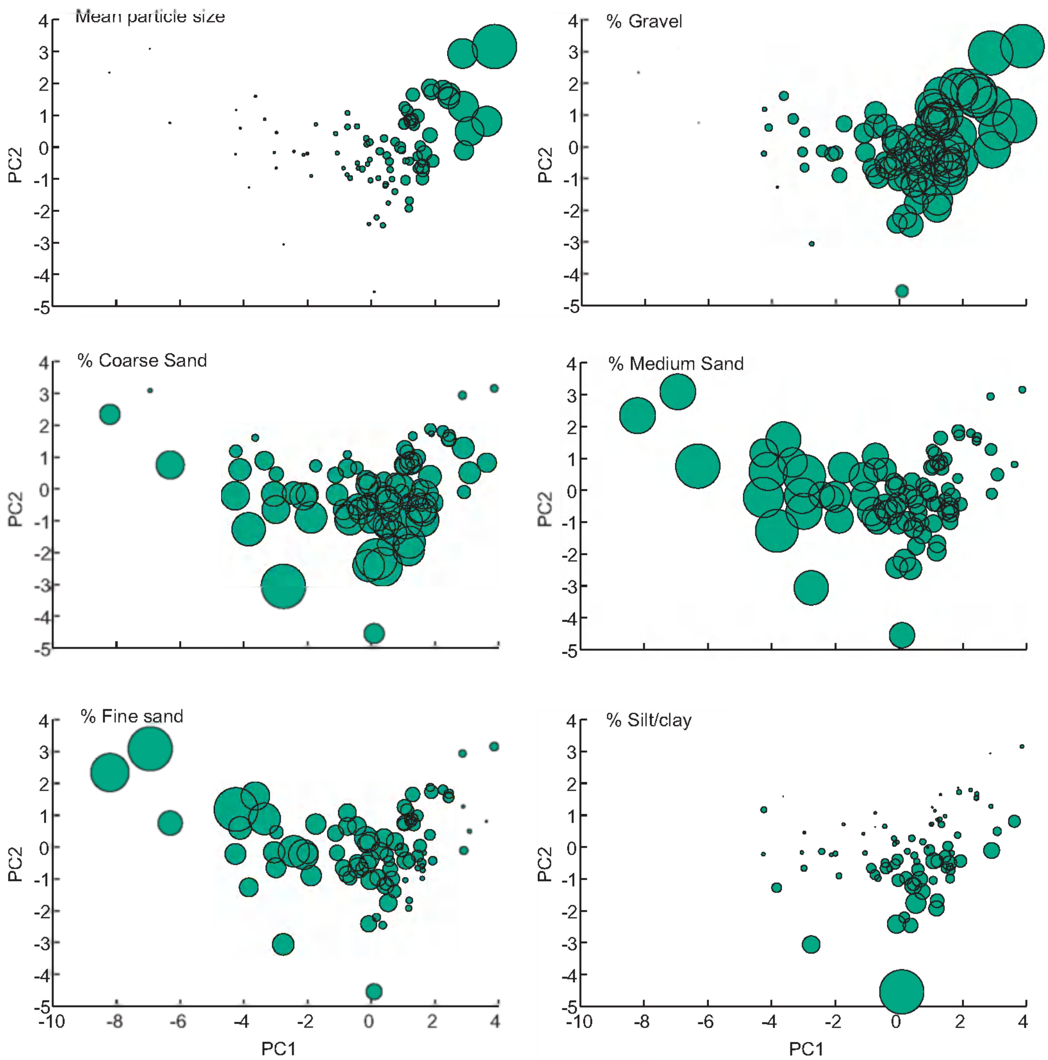



***Figure 5.19. The same two-dimensional correlation based PCA ordination as the previous Figure, but with superimposed circles proportional in diameter to values of percentage gravel, coarse sand, medium sand, fine sand and silt/clay***

### *5.3.2. Sidescan sonar surveys*

Figure 5.21 shows the sidescan sonar images of the sediments within and surrounding the high and low dredging intensity boxes at Hastings Area Y between 2001 and 2003. These images show the presence of weathered dredge tracks which are aligned in a NE/SW direction within both of the boxes. The tracks are clearly present within the high dredging intensity box in all years and, to a lesser degree, within the low dredging intensity box in 2001 and 2002. Unfortunately, in 2003, poor imagery makes it difficult to confirm their presence within the low dredging intensity box in that year. Generally, where present, the tracks have weathered and infilled with sand to such an extent that they have agglomerated to form elongated sandy features and are difficult to distinguish as individual tracks.

In all years, the sediments in the low dredging intensity box appear to comprise of a distinct sandy facies (possibly agglomerated dredge tracks) and another coarser facies. The sediments within the high dredging intensity box appear to be coarser in nature but are also characterised by dredged tracks which are infilled with sand to some degree. The disposition of the sediments within the two boxes may therefore explain the coarser nature of the sediment samples collected within the high intensity dredging box in comparison to those collected within the low intensity dredging box.

Dredging commenced to the south of the boxes in 2002 and evidence of this activity can be seen as intensive dredge tracks in the south eastern corner of the images that were collected in 2002 and 2003. Given that the net sediment transport pathway in the area is to the north east (HR Wallingford, 1993; HR Wallingford,

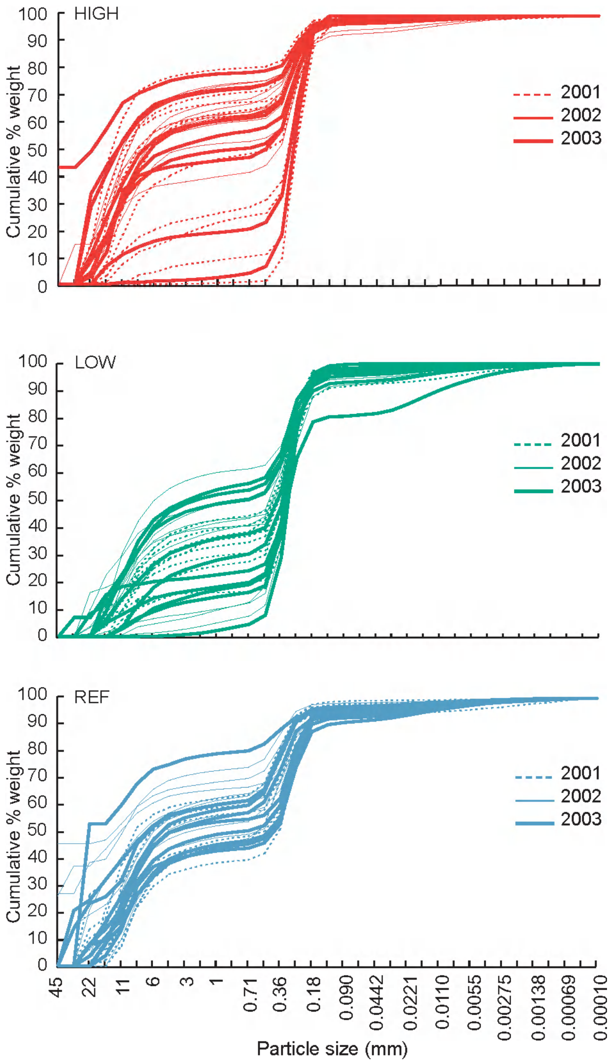



***Figure 5.20. Sediment particle size distributions determined from replicate samples taken from sites of high and lower dredging intensity at Area Y and the two reference sites between 2001 and 2003***

1999; EMU, 1999 and Rees, 2000) it might be expected that any fine sediment that had been mobilised as a result of this activity might contribute to a fining of the sediment within the high and, to a lesser extent low, dredging intensity boxes. However, the comparison of sidescan sonar imagery to determine evidence of subtle changes in substrate type can be difficult. This is due to a number of operational factors that affect the image quality and which can vary between surveys (e.g. weather conditions, system configuration, navigational inaccuracies). Nevertheless, a comparison between the 2001, 2002 and 2003 surveys suggests that there may have been some deposition of fine material immediately to the north of the northern margin of the recent dredging activity, and also to the east of the high intensity dredging box. This may explain the disappearance of a characteristic pair of dredge tracks that were present to the east of the high box in 2001 and 2002 but were not evident in 2003 (Figure 5.22). The PSA data do not provide any evidence of fining of sediment within either box over time.

The multibeam bathymetry data collected in 2003 shows the location of the high and low dredging intensity boxes in relation to the topographic features present at the seabed (Figure 5.23). The weathered dredged furrows caused by suction trailer dredging activity can be clearly seen within the high and, to a much lesser extent, low dredging intensity boxes. The physical effects of the recent dredging activity to the south west of the boxes is also apparent (Figure 5.23) and provides a comparison between the topographical manifestation of weathered and fresh dredging impacts.

***Table 5.9. Mean values (±SD) of sediment particle size characteristics and other environmental variables for each sampling box at Area Y in 2001 and 2002***

| Year | Treatment code | Mean particle size [mm] | Sorting | Skewness | Kurtosis | Gravel [%] | Coarse Sand [%] | Medium Sand [%] | Fine Sand [%] | Silt/clay [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2003 | HIGH '03 | 3.07 (±2.83) | 2.68 (±0.71) | 0.01 (±1.51) | 4.62 (±6.07) | 50.91 (±24.06) | 3.81 (±1.06) | 25.81 (±14.38) | 17.91 (±9.77) | 1.55 (±0.96) |
| | LOW '03 | 0.74 (±0.53) | 2.40 (±0.84) | -0.43 (±0.95) | 4.47 (±2.83) | 28.13 (±17.43) | 5.87 (±0.80) | 44.29 (±14.33) | 17.59 (±4.57) | 4.12 (±5.47) |
| | REF 1 '03 | 1.23 (±0.31) | 3.12 (±0.13) | 0.44 (±0.10) | 2.76 (±0.12) | 45.96 (±4.51) | 4.30 (±0.65) | 27.75 (±2.12) | 15.97 (±1.92) | 6.02 (±1.72) |
| | REF 2 '03 | 3.30 (±1.97) | 3.05 (±0.17) | 0.92 (±0.48) | 3.55 (±1.22) | 61.52 (±9.72) | 6.63 (±1.31) | 22.94 (±7.24) | 4.70 (±1.66) | 4.21 (±1.19) |
| 2002 | HIGH '02 | 2.87 (±1.11) | 2.93 (±0.24) | 0.72 (±0.31) | 2.74 (±0.54) | 61.04 (±9.95) | 3.90 (±1.03) | 19.99 (±5.65) | 12.54 (±3.15) | 2.52 (±1.94) |
| | LOW '02 | 1.09 (±0.63) | 2.49 (±0.58) | 0.19 (±0.64) | 4.56 (±3.76) | 33.27 (±19.11) | 5.76 (±2.45) | 41.62 (±14.16) | 16.30 (±3.58) | 3.05 (±1.97) |
| | REF 1 '02 | 2.42 (±1.18) | 3.32 (±0.30) | 0.77 (±0.16) | 3.00 (±0.16) | 57.52 (±7.06) | 4.09 (±0.62) | 21.46 (±3.82) | 11.18 (±2.98) | 5.75 (±0.79) |
| | REF 2 '02 | 3.72 (±2.62) | 3.16 (±0.26) | 0.78 (±0.11) | 3.17 (±0.18) | 59.11 (±11.71) | 6.81 (±1.75) | 24.69 (±6.51) | 5.08 (±1.76) | 4.31 (±1.98) |
| 2001 | HIGH '01 | 2.22 (±2.04) | 2.37 (±0.77) | 0.32 (±0.92) | 5.36 (±4.10) | 43.97 (±28.18) | 3.15 (±1.76) | 28.00 (±14.18) | 22.78 (±13.63) | 1.36 (±0.95) |
| | LOW '01 | 0.79 (±0.22) | 2.53 (±0.34) | -0.22 (±0.64) | 3.73 (±1.14) | 30.40 (±8.60) | 4.29 (±1.57) | 45.15 (±9.22) | 17.82 (±4.23) | 2.33 (±2.27) |
| | REF 1 '01 | 1.31 (±0.58) | 2.97 (±0.19) | 0.54 (±0.23) | 3.31 (±0.21) | 45.62 (±8.22) | 4.71 (±0.49) | 28.76 (±5.17) | 16.85 (±2.67) | 4.05 (±1.36) |
| | REF 2 '01 | 2.17 (±0.82) | 3.00 (±0.35) | 0.89 (±0.17) | 3.73 (±0.58) | 55.50 (±7.25) | 6.39 (±2.36) | 28.07 (±3.88) | 6.51 (±1.75) | 3.54 (±2.04) |

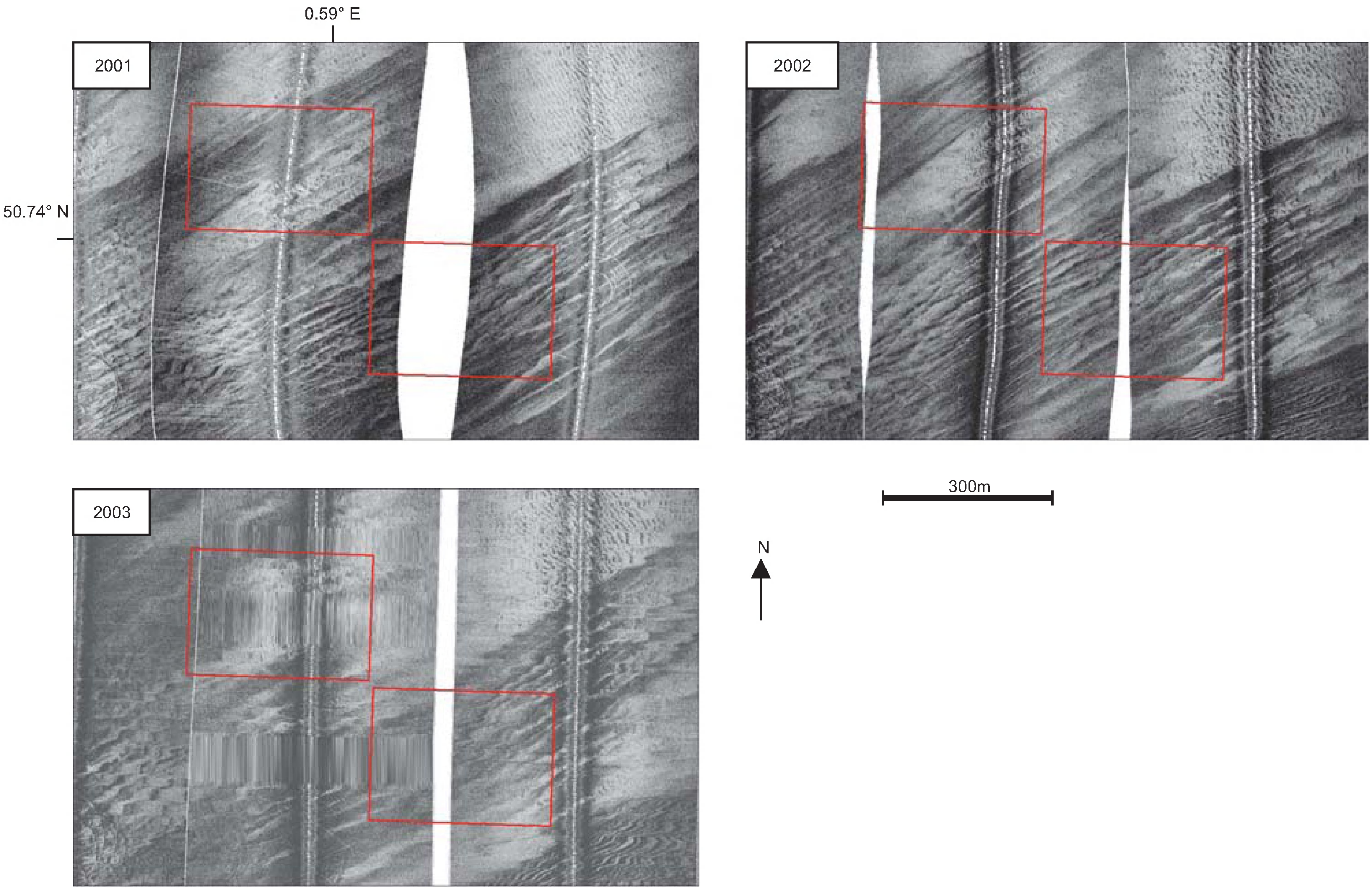



Figure 5.21. Sidescan sonar images of the high and low dredging intensity boxes at Area Y (2001-2003)

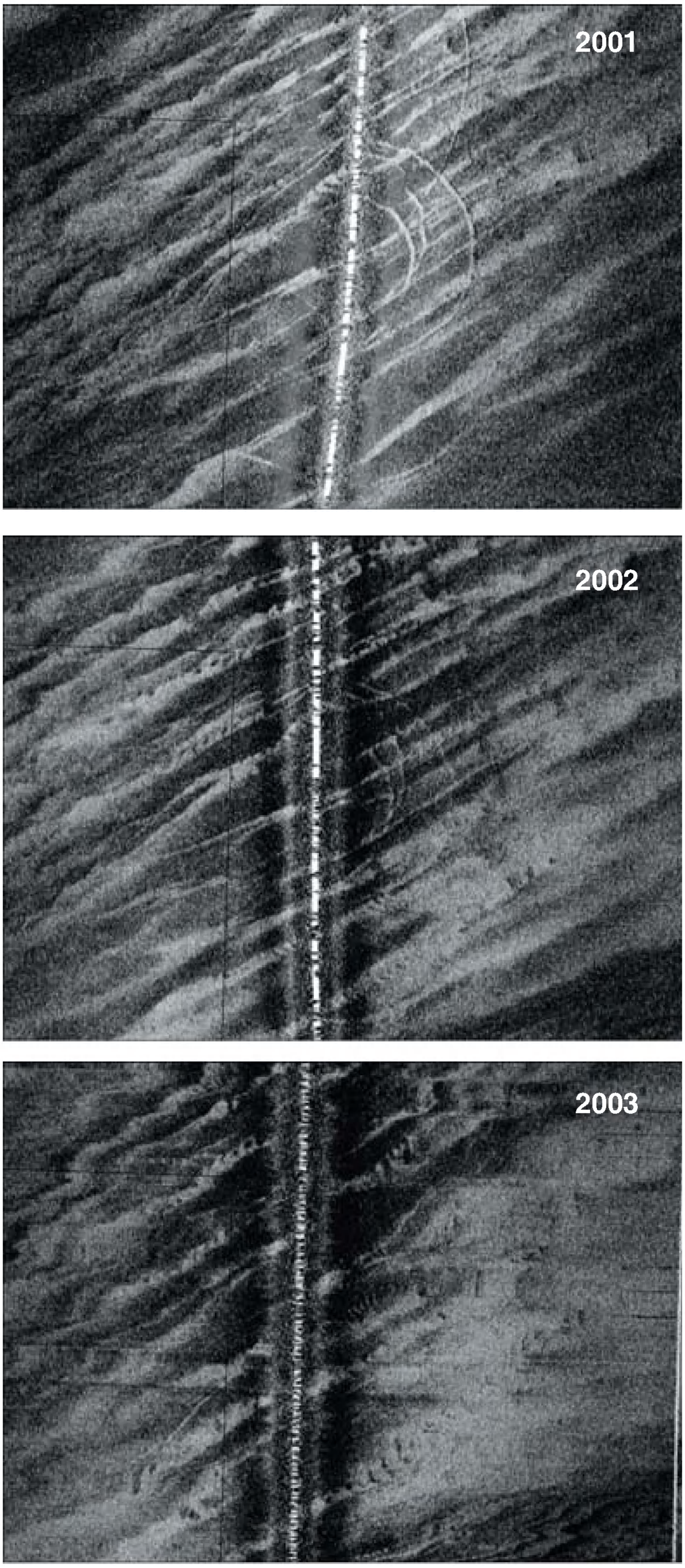



***Figure 5.22.*** ***Examples of a characteristic series of dredge tracks within the relinquished zone of Hastings Area Y which are still visible on sidescan sonar images at least two years after the cessation of dredging***

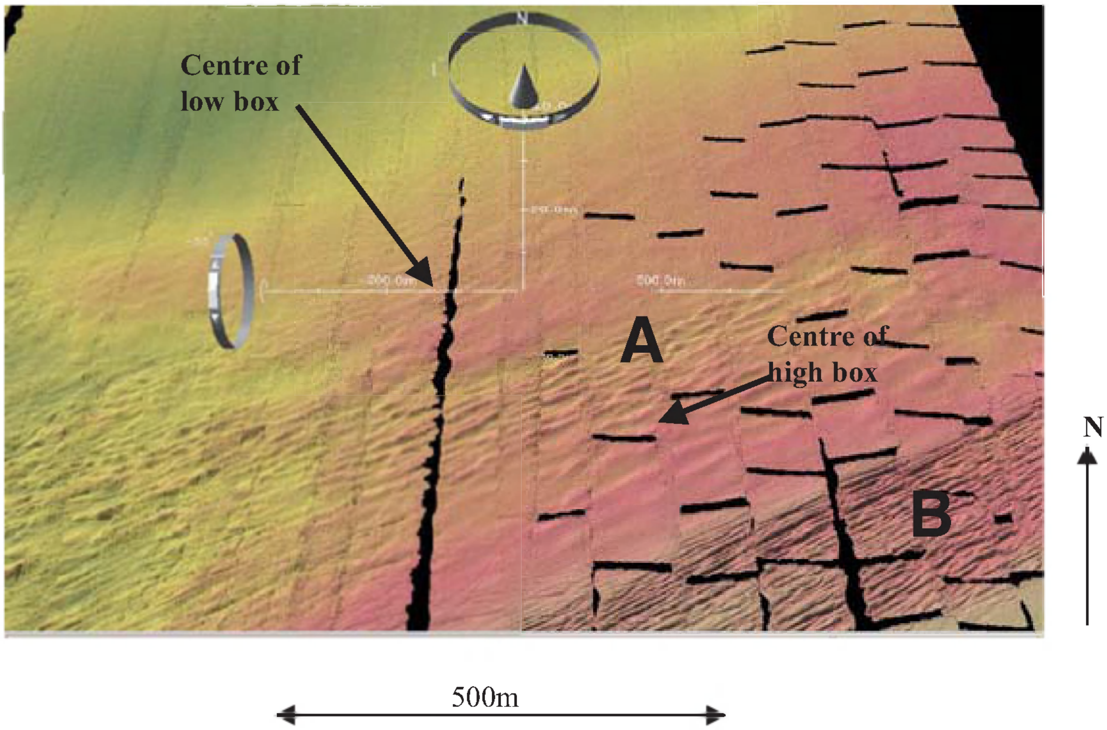



*Figure 5.23. Multibeam bathymetry of the area surrounding Hastings Area Y. The central points of the high and low dredging intensity boxes are shown. The orange shading depicts shallower water depths (~8 m - 20 m) and the yellow shading depicts deeper water (~20 m - 22 m). A) Topography of seabed area last dredged in 2000. B) Topography of seabed currently being dredged*

## 5.3.3. *Macrofaunal assemblage structure*

Overall, a total of 361 species were found at Area Y from the 90 samples collected between 2001 and 2003 (236 species in 2001, 277 species in 2002 and 236 species in 2003).

**Univariate Analysis**
With the exception of biomass in 2003, ANOVA detected significantly lower values ($p<0.05$) for numbers of species, individuals and biomass at the low dredging intensity site in comparison with the reference sites in 2001, 2002 and 2003 (Figure 5.24). This pattern was also observed at the high dredging intensity site in terms of the number of species and biomass and this reflects the absence of a range of macrofaunal species from this site compared with the reference sites. However, numbers of individuals were not significantly different, except in 2003. In terms of the differences between the high and low dredging intensity sites, significantly higher numbers of species and biomass ($p<0.05$) were detected at the high site in 2002, although these differences were not apparent in 2001 and 2003. Numbers of individuals were significantly lower at the low dredging intensity site, except in 2003. Overall, none of the sites showed any significant differences ($p>0.05$) between 2001 and 2003 in terms of numbers of species, individuals or biomass.

Figure 5.25 shows the change in abundance of selected individual species within each site from 2001 to 2003. For many species fewer individuals were found at the low intensity site. Examples include the crustaceans *Balanus crenatus* and *Galathea intermedia* and the polychaete *Pomatoceros lamarki*. A number of species, including the polychaete *Sabellaria spinulosa* and the bivalve *Mysella bidentata*, also had reduced abundances at both high and low dredging intensity sites. However, one or two species such as the burrowing amphipod *Bathyporeia elegans*, were found in higher numbers at the dredged sites, possibly as a result of the higher quantities of sand.

**Multivariate Analyses**
Figure 5.26 shows the output from the non-metric multi-dimensional scaling ordinations of macrofaunal abundance data from the Hamon grab surveys carried out at Area Y. There was a much higher degree of variability between replicate samples derived from the dredged locations compared with the reference samples, as depicted by the much wider spread of samples from the dredged sites in the MDS ordination. This higher variability at the dredged site is confirmed by results of the r.IMD with the highest values obtained at the low

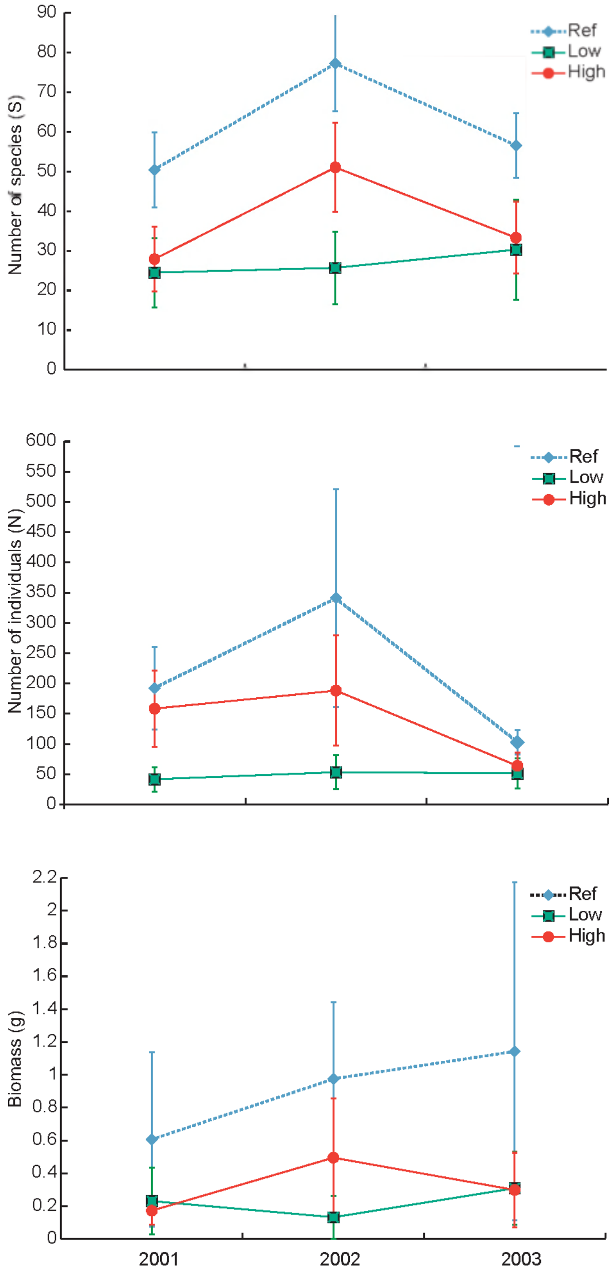



***Figure 5.24. Summary of means and 95% confidence intervals for numbers of species (S) and number of individuals (N) within each treatment area at Hastings Area Y in 2001 and 2002***

dredging intensity site (Table 5.10). The variability in species composition between replicates within this area reflects the physical heterogeneity of the site. Neither the results of IMD (Table 5.11) or an ANOSIM test (Table 5.12) provide any indication that dredged samples are, as yet, becoming more biologically similar to the reference sites over the period of investigation.

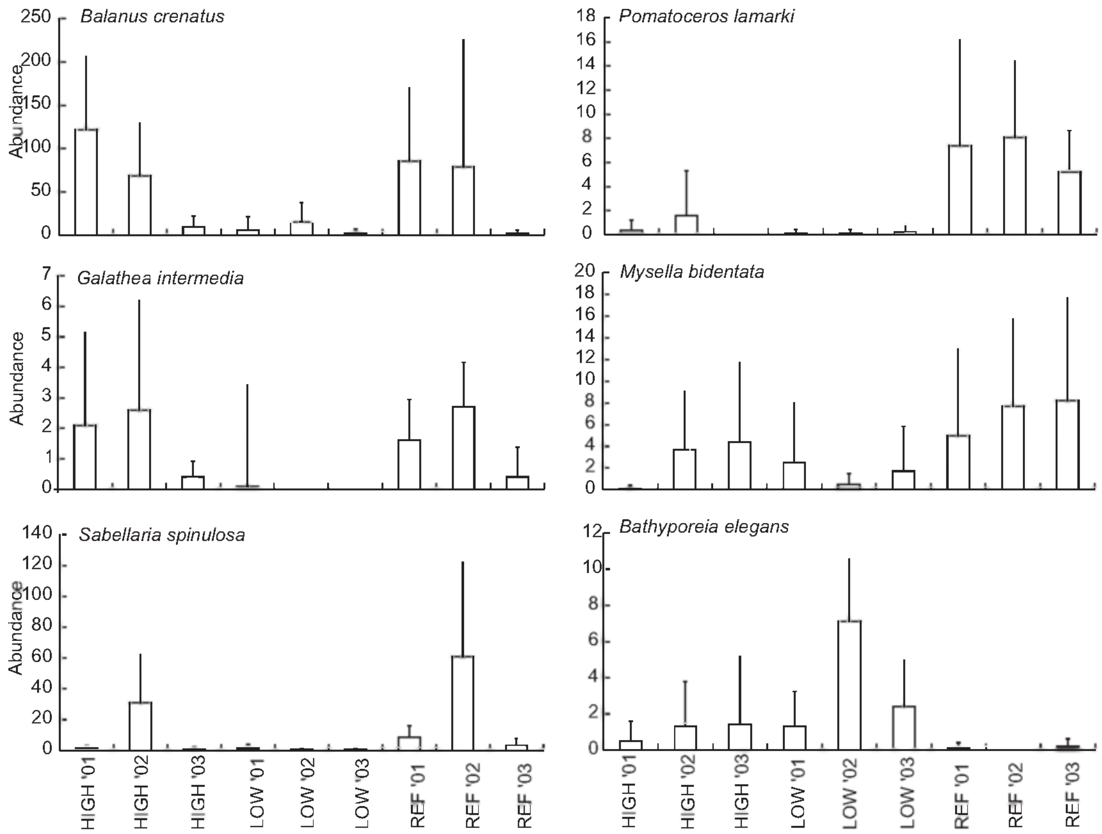



***Figure 5.25.** **Means (± SD) of abundances of selected macrofauna species sampled in 2001 to 2003 at sites of high and lower levels of dredging intensity and at two reference sites (codes as in Table 5.1)***

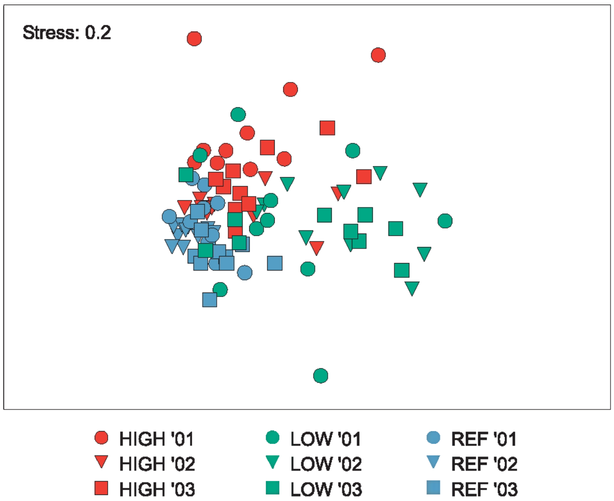



***Figure 5.26.** **MDS of Bray-Curtis similarities from 4th root transformed species abundance data 1 and 2 years (2001-2002) after the cessation of dredging at high and low levels of dredging intensity and at the reference site***

***Table 5.10.** **Relative Index of Multivariate Dispersion (r.IMD) in each year***

| Year | Site | r.IMD |
|---|---|---|
| 2001 | High intensity | 1.193 |
| | Low intensity | 1.46 |
| | Reference | 0.767 |
| 2002 | High intensity | 0.811 |
| | Low intensity | 1.261 |
| | Reference | 0.366 |
| 2003 | High intensity | 1.073 |
| | Low intensity | 1.262 |
| | Reference | 0.809 |

***Table 5.11.** **Index of Multivariate Dispersion (IMD) between all pairs of conditions***

| Year | Site | IMD |
|---|---|---|
| 2001 | High/ Reference | +0.437 |
| | High /Low | -0.250 |
| | Low/Reference | +0.724 |
| 2002 | High/ Reference | +0.434 |
| | High /Low | -0.437 |
| | Low/Reference | +0.885 |
| 2003 | High/ Reference | +0.300 |
| | High /Low | -0.229 |
| | Low/Reference | +0.465 |

***Table 5.12. R-values derived from the ANOSIM test for macrofaunal assemblages from locations of high and low dredging intensity and from the Reference site in 2001 and 2002 at Area Y. ** denotes significant difference at p < 0.01***

| | HIGH '01 | LOW '01 | REF '01 | HIGH '02 | LOW '02 | REF '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|
| LOW '01 | 0.280** | | | | | | | |
| REF '01 | 0.410** | 0.343** | | | | | | |
| HIGH '02 | 0.272** | 0.312** | 0.271** | | | | | |
| LOW '02 | 0.486** | 0.288** | 0.692** | 0.426** | | | | |
| REF '02 | 0.649** | 0.540** | 0.398** | 0.276** | 0.758** | | | |
| HIGH '03 | 0.311** | 0.161** | 0.422** | 0.193** | 0.412** | 0.634** | | |
| LOW '03 | 0.441** | 0.098* | 0.497** | 0.352** | 0.189** | 0.556** | 0.250** | |
| REF '03 | 0.647** | 0.384** | 0.240** | 0.361** | 0.678** | 0.287** | 0.415** | 0.329** |

The community groupings were explored further using the similarity percentages programme SIMPER and the results revealed characterising species from each of the treatment groups (Table 5.13). Deposits from within the area of high dredging intensity supported a mix of epifaunal and infaunal species, particularly in 2001, whereas many more epifaunal species associated with coarser sediments typified the reference samples. In contrast, characterising species from the area of low dredging intensity were mainly infaunal, more typical of sandy substrata (e.g. burrowing amphipods such as *Bathyporeia elegans* and *Gastrosaccus spinifer* were present at this site, as were the polychaetes *Spiophanes bombyx* and *Ophelia borealis*).

As with the Hastings Area X data, the barnacle *Balanus crenatus* dominated samples from both the area of high dredging intensity and reference sites in 2001. Again, the relative importance of this species in terms of its percentage contribution to the overall similarity was less in reference samples compared with those obtained from the area of high dredging intensity. Furthermore, the dominance of this species diminished at both of these sites in 2002 and again in 2003 resulting in a more equitable distribution of densities among the species.

***Table 5.13. Results from SIMPER analysis of macrofauna data from Hastings Area Y (all taxa excluding colonial species, 4th root transformed), listing the main characterising species from samples subject to differing levels of dredging impact from 2001-2003. Average abundance, and the % contribution to the similarity made by each characterising species is shown. Also listed is the cumulative percentage and the overall average similarity between replicate samples from within each group***

| Group | Taxon | Average Abundance | Average Similarity | % Contribution | Cumulative % | Overall Average Similarity |
|---|---|---|---|---|---|---|
| HIGH '01 | *Balanus crenatus* | 121.70 | 9.90 | 32.73 | 32.73 | **30.25%** |
| | *Spiophanes bombyx* | 4.20 | 2.32 | 7.66 | 40.39 | |
| | *Sabellaria spinulosa* | 1.60 | 2.11 | 6.98 | 47.37 | |
| LOW '01 | *Echinocyamus pusillus* | 2.10 | 2.85 | 12.11 | 12.11 | |
| | *Scalibregma inflatum* | 1.10 | 1.76 | 7.49 | 19.61 | |
| | *Mysella bidentata* | 2.50 | 1.39 | 5.91 | 25.52 | |
| | *Notomastus* sp. | 2.80 | 1.36 | 5.77 | 31.29 | |
| | *Spiophanes bombyx* | 2.00 | 1.27 | 5.42 | 36.71 | |
| | *Bathyporeia elegans* | 1.30 | 1.19 | 5.06 | 41.77 | |
| REF '01 | *Balanus crenatus* | 85.30 | 3.02 | 7.53 | 7.53 | **40.16%** |
| | *Lumbrineris gracilis* | 5.70 | 2.79 | 6.95 | 14.48 | |
| | NEMERTEA | 2.70 | 2.39 | 5.94 | 20.42 | |
| | *Aonides oxycephala* | 3.20 | 2.34 | 5.84 | 26.26 | |
| | *Sabellaria spinulosa* | 8.60 | 2.24 | 5.59 | 31.85 | |
| | *Scalibregma inflatum* | 6.00 | 2.11 | 5.26 | 37.10 | |
| | *Notomastus* sp. | 2.40 | 1.84 | 4.58 | 41.69 | |
| HIGH '02 | *Balanus crenatus* | 68.50 | 3.60 | 9.02 | 9.02 | **39.86%** |
| | *Sabellaria spinulosa* | 30.80 | 2.59 | 6.50 | 15.53 | |
| | *Glycera tridactyla* | 2.10 | 2.45 | 6.13 | 21.66 | |
| | *Lagis koreni* | 6.60 | 2.04 | 5.13 | 26.79 | |
| | *Spiophanes bombyx* | 4.40 | 1.75 | 4.38 | 31.17 | |
| | *Pisidia longicornis* | 1.50 | 1.74 | 4.35 | 35.52 | |
| | *Lumbrineris gracilis* | 5.00 | 1.71 | 4.29 | 39.81 | |
| | *Poecilochaetus serpens* | 7.40 | 1.47 | 3.69 | 43.50 | |
| LOW '02 | *Bathyporeia elegans* | 7.10 | 7.10 | 23.68 | 23.68 | **29.99%** |
| | *Gastrosaccus spinifer* | 1.40 | 3.28 | 10.92 | 34.60 | |
| | *Spiophanes bombyx* | 1.80 | 2.91 | 9.70 | 44.30 | |
| REF '02 | *Poecilochaetus serpens* | 24.80 | 2.20 | 4.44 | 4.44 | **49.41%** |
| | *Sabellaria spinulosa* | 60.90 | 2.01 | 4.06 | 8.51 | |
| | *Lagis koreni* | 6.30 | 1.78 | 3.60 | 12.10 | |
| | *Pomatoceros lamarcki* | 8.10 | 1.72 | 3.49 | 15.59 | |
| | *Mysella bidentata* | 7.70 | 1.68 | 3.40 | 18.99 | |
| | *Lumbrineris gracilis* | 6.40 | 1.64 | 3.31 | 22.30 | |
| | *Upogebia* (juv.) | 3.90 | 1.62 | 3.27 | 25.57 | |
| | *Balanus crenatus* | 78.80 | 1.60 | 3.25 | 28.82 | |
| | NEMERTEA | 6.70 | 1.58 | 3.20 | 32.02 | |
| | *Galathea intermedia* | 2.70 | 1.44 | 2.92 | 34.93 | |
| | *Notomastus* sp. | 2.70 | 1.38 | 2.79 | 37.73 | |
| | *Harmothoe impar* | 2.70 | 1.37 | 2.77 | 40.50 | |
| HIGH '03 | *Spiophanes bombyx* | 9.00 | 5.33 | 15.76 | 15.76 | **33.84%** |
| | *Glycera tridactyla* | 1.80 | 3.05 | 9.00 | 24.76 | |
| | *Lumbrineris gracilis* | 2.30 | 2.14 | 6.32 | 31.08 | |
| | *Scalibregma inflatum* | 2.90 | 1.88 | 5.56 | 36.64 | |
| | *Mysella bidentata* | 4.40 | 1.83 | 5.41 | 42.05 | |
| LOW '03 | *Spiophanes bombyx* | 3.70 | 3.82 | 13.36 | 13.36 | **28.58%** |
| | *Nephtys* (juv.) | 1.90 | 3.24 | 11.35 | 24.71 | |
| | *Echinocyamus pusillus* | 2.40 | 2.92 | 10.23 | 34.94 | |
| | *Scalibregma inflatum* | 1.40 | 2.51 | 8.80 | 43.74 | |
| REF '03 | *Mysella bidentata* | 8.20 | 2.23 | 5.66 | 5.66 | **39.34%** |
| | *Pomatoceros lamarcki* | 5.20 | 2.08 | 5.28 | 10.93 | |
| | *Spiophanes bombyx* | 1.90 | 2.06 | 5.24 | 16.17 | |
| | *Lumbrineris gracilis* | 5.60 | 2.04 | 5.20 | 21.37 | |
| | NEMERTEA | 3.20 | 2.02 | 5.13 | 26.51 | |
| | *Lagis koreni* | 3.70 | 1.97 | 5.01 | 31.51 | |
| | *Scalibregma inflatum* | 6.00 | 1.76 | 4.49 | 36.00 | |
| | *Polycirrus* sp. | 2.20 | 1.38 | 3.51 | 39.50 | |
| | *Notomastus* sp. | 2.00 | 1.34 | 3.41 | 42.92 | |

# 6. TEMPORAL INVESTIGATIONS OF THE PHYSICAL AND BIOLOGICAL STATUS OF AREA 408

## 6.1 Methods

### *6.1.1. Study site*

The study site, Area 408, is located in an area known as the Coal Pit, 100 km east of the Humber estuary in the southern North Sea (Figure 6.1). Water depths at Area 408 range between 22 and 33 m Lowest Astronomical Tide (LAT) and the tidal ellipse is orientated in a NW-SE direction. Maximum spring tidal velocity reaches $1.0ms^{-1}$ and the residual tidal direction and subsequent sediment transport is predominately to the south-east. However, a series of bedforms located in the west of Area 408 suggest a reversal in transport direction (Coastline Surveys Europe Ltd, 2002). The sub-bottom sediments at Area 408 consist of Pleiostocene/Holocene palaeovalleys trending in an east-west direction, infilled with glaceolacustrine and glaceomarine sediments overlaid with sands (Coastline Surveys Europe Ltd, 2001).

The site was licensed for sand and gravel extraction in 1995 and dredging commenced in 1996. As a condition of the extraction licence, the site was subdivided into a number of discrete zones in order to limit the active operational area within the licence. This was instituted in order to limit the geographical scale of environmental impact during any one period and minimise disruption to fishing or other activities. Dredging in one of these zones (Zone 2) ceased in 2000 following the removal of 1,459,131 tonnes over a period of four years between 1996 and 1999. Zone 2 occupies an area of 2.56 $km^2$. The annual quantity of aggregate extracted from this zone, together with the amounts dredged overall from Area 408 are shown in Figure 6.2. This indicates that the quantity of aggregate extracted from Zone 2 increased from a total of 174,094 tonnes in 1996 to a maximum of 948,459 tonnes in 1998. In 1999, the quantity extracted decreased to 25,324 tonnes and the zone has not been dredged since. Screening of dredged cargoes was carried out at this site in order to achieve the required ratio of sand and gravel. This screening resulted in the return of 38% of the material removed from the seabed in 1998 across the licensed area. The cessation of dredging operations in this zone allowed an investigation of the status of the seabed fauna and sediments in a 'fallow' area of a currently zoned marine aggregate extraction licence.

### *6.1.2. Sampling design*

EMS data was used in order to locate areas of seabed subjected to different levels of dredging intensity within Zone 2. Based on data from 1998, the last year of any significant dredging activity, areas of high and lower levels of dredging intensity were identified. The area of high dredging intensity represents >5 hours of dredging within each 100 m by 100 m block whereas

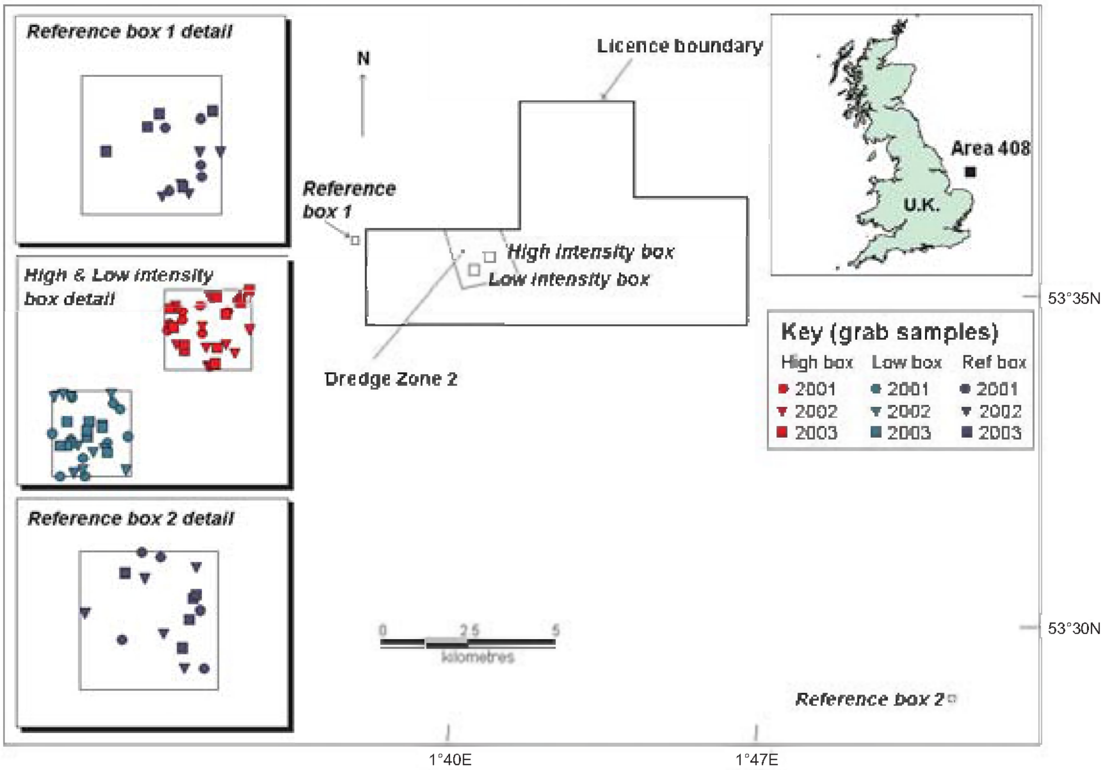



*Figure 6.1. Map showing the location of Area 408 aggregate extraction licence and sampled stations from surveys carried out in 2001, 2002 and 2003*

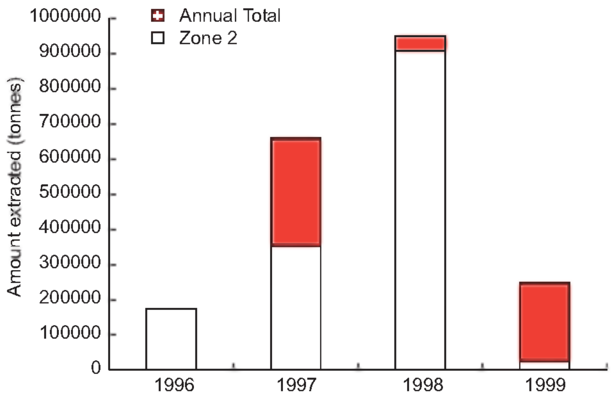



***Figure 6.2. Annual quantity of aggregate extracted from Area 408 over the period 1996 to 2000 including the tonnage taken from Zone 2***

the area of low dredging intensity is equivalent to <1 hour of dredging within each 100 m by 100 m block (see Figure 6.3). Based on this information, treatment boxes, measuring 300 m by 300 m, were assigned to these two areas of the seabed. Within each treatment box, 10 randomly positioned 0.1 $m^2$ Hamon grab samples were collected in 2001, 2002 and 2003 that is 2, 3 and 4 years after the cessation of dredging. In addition, two reference boxes (Reference Box 1 & 2) were also sampled over the same period. The dimensions of each reference box are half those of the high and low dredging intensity boxes. In order to achieve the same sampling density as the dredged treatment boxes a total of five replicate samples were collected from each of the reference boxes. When combined the data from these two reference sites provide a similar density of samples per unit area as those collected from the dredged sites. Details of the locations sampled as part of the Area 408 time-series investigations are presented in Table 6.1.

## 6.2 Results

### *6.2.1. Sediment characteristics*

An ordination by PCA of the particle size data from the Hamon grab samples is illustrated in Figure 6.4. Samples from the reference sites have a slightly higher silt/ clay content than samples collected from the dredged sites. This is reflected in the PCA ordination by the separation of the samples obtained from the reference sites from those from the dredged sites. The particle size distributions of samples from the reference sites were also more consistent, as depicted by the tighter clustering of samples in the PCA ordination. In contrast there was a much higher degree of particle size variability between samples collected from the dredged sites, as depicted by the much wider spread of samples from the dredged sites in the PCA ordination. These observations are confirmed by the results of an ANOSIM test (Table 6.2).

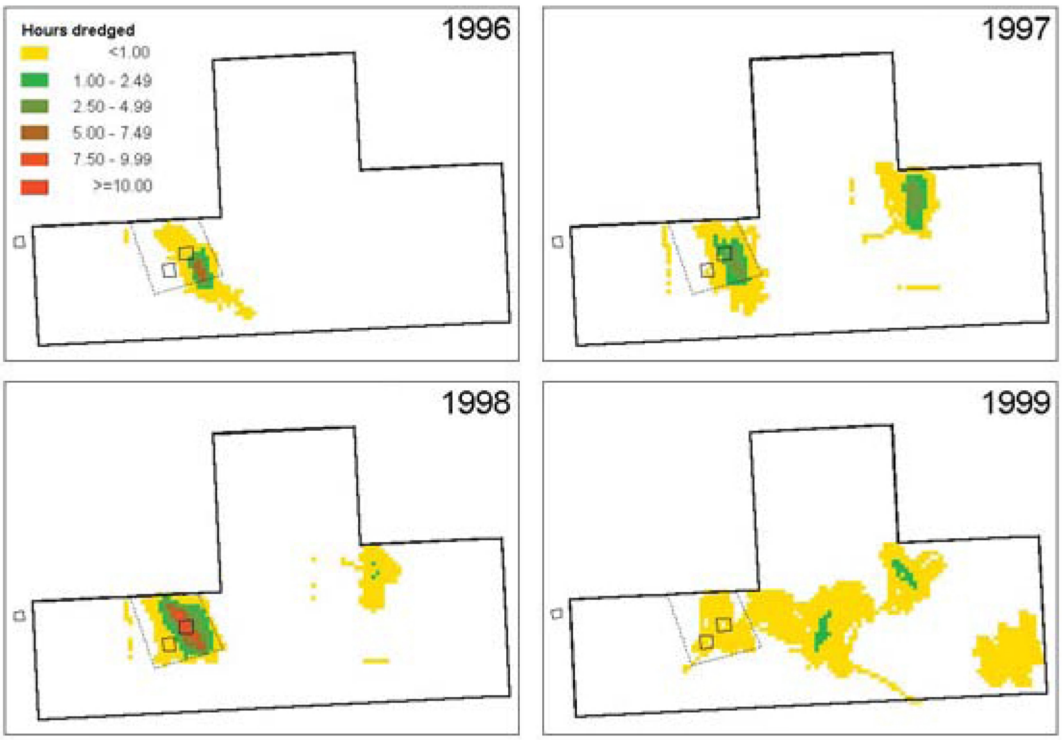



***Figure 6.3. Map showing the location and intensity of dredging (in hours) over each 100 m x 100 m block at Area 408 in relation to the position of the high and low sampling sites in Zone 2 in years 1996 to 1999 (Source EMS data provided by the Crown Estate)***

*Table 6.1. Co-ordinates of sampling boxes and numbers of samples collected from betweeen 2001 and 2003 at Area 408*

| Treatment | Code | Box co-ordinates | | Area ($m^2$) | Number of samples collected | | |
|---|---|---|---|---|---|---|---|
| | | Latitude | Longitude | | 2001 | 2002 | 2003 |
| High intensity box | HIGH '01 to '03 | 53°35.670'N | 001°40.956'E | ~90 000 | 10 | 10 | 10 |
| | | 53°35.514'N | 001°41.244'E | | | | |
| Low intensity box | LOW '01 to '03 | 53°35.472'N | 001°40.590'E | ~90 000 | 10 | 10 | 10 |
| | | 53°35.304'N | 001°40.848'E | | | | |
| Reference box 1 | REF 1 '01 to '03 | 53°35.899'N | 001°37.491'E | ~45 000 | 5 | 5 | 5 |
| | | 53°35.785'N | 001°37.683'E | | | | |
| Reference box 2 | REF 2 '01 to '03 | 53°28.737'N | 001°53.126'E | ~45 000 | 5 | 5 | 5 |
| | | 53°28.623'N | 001°53.316'E | | | | |

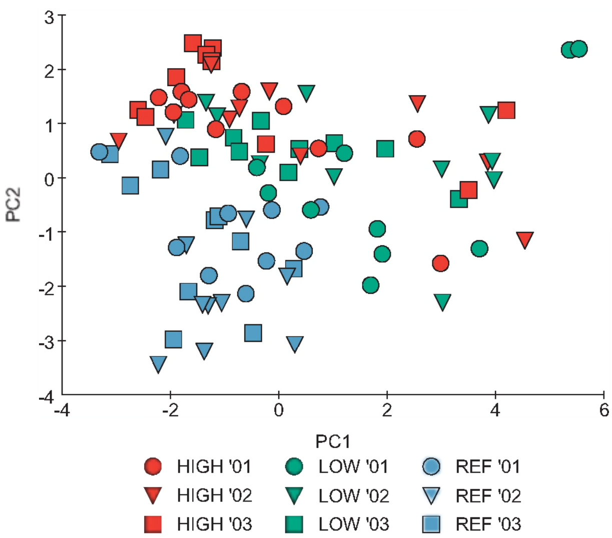



*Figure 6.4. Two-dimensional correlation-based PCA ordination of untransformed sediment particle size data (2001 to 2003) from Area 408. For variables involved in the ordination see Table 6.2*

Figure 6.5 shows overlays of various particle sizes on the PCA ordination from Figure 6.4 and reveals underlying reasons for the differences between sites. In general, differences between the dredged and the reference sites can be explained by the narrower range of particle sizes at the high and low dredging intensity boxes (i.e. dredged samples typically contain proportionately less gravel, fine sand and silt/clay and more coarse and/or medium sand). This results in dredged samples being better sorted as reflected in lower sorting coefficients. Differences between the high and low dredging intensity boxes can be largely explained by the difference in the dominant particle size fraction from each site. The area of high dredging intensity is dominated by gravel, whereas the area of lower intensity has a greater proportion of medium sand. A summary of the sediment particle size characteristics of samples taken from each of the treatment boxes is shown in Table 6.3.

*Table 6.2. R-values derived from the ANOSIM test for sediment particle size characteristics (mean diameter in mm, sorting coefficient, kurtosis, skewness, % Gravel, % Coarse Sand, % Medium Sand, % Fine Sand, % Silt/Clay) from locations of higher and lower dredging intensity and from 2 reference sites in the vicinity of Area 408 sampled in 2001-2003. Performed on normalised Euclidean distance data. Values range between ±1 and zero. A zero value indicates high similarity, and a value of ±1 indicates low similarity between samples. * denotes significant difference at p<0.1; ** denotes significant difference at p<0.05. Untransformed data*

| | HIGH '01 | LOW '01 | REF '01 | HIGH '02 | LOW '02 | REF '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|
| LOW '01 | 0.239** | | | | | | | |
| REF '01 | 0.352** | 0.33** | | | | | | |
| HIGH '02 | -0.022 | 0.212** | 0.335** | | | | | |
| LOW '02 | 0.127* | 0.051 | 0.442** | 0.049 | | | | |
| REF '02 | 0.545** | 0.484** | 0.133** | 0.506** | 0.622** | | | |
| HIGH '03 | 0.22** | 0.416** | 0.539** | 0.118** | 0.361** | 0.604** | | |
| LOW '03 | 0.239** | 0.372** | 0.54** | 0.168** | 0.214** | 0.692** | 0.246** | |
| REF '03 | 0.54** | 0.517** | 0.232** | 0.456** | 0.647** | 0.179** | 0.459** | 0.551** |

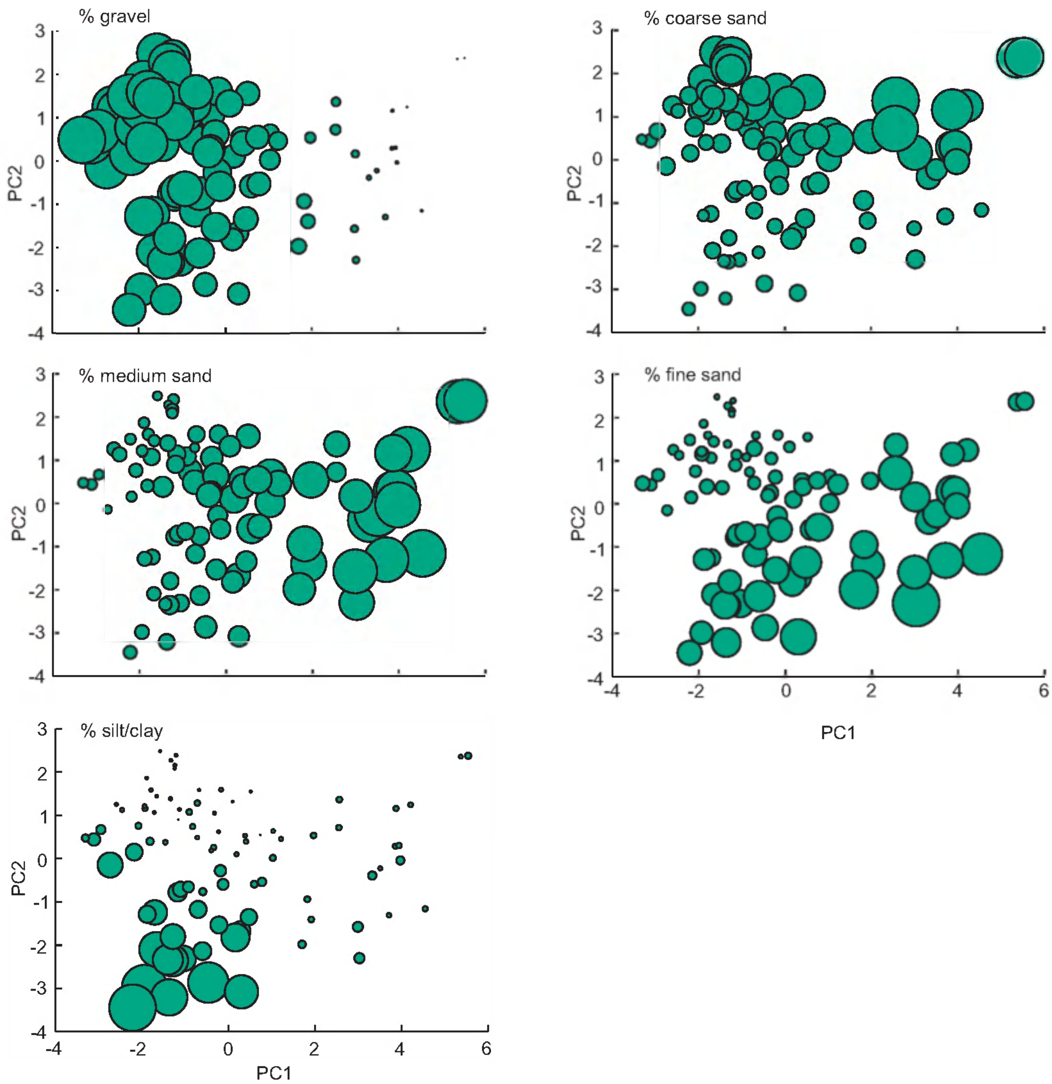



***Figure 6.5. The same two-dimensional correlation based PCA ordination as in Figure 6.4, but with superimposed circles proportional in diameter to values of percentage gravel, coarse sand, medium sand, fine sand and silt/clay***

***Table 6.3. Mean values (±SD) of sediment particle size characteristics for each site (codes as in Table 6.1)***

| Year | Treatment code | Mean particle size [mm] | Sorting | Skewness | Kurtosis | Gravel [%] | Coarse Sand [%] | Medium Sand [%] | Fine Sand [%] | Silt/clay [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2001 | HIGH ‘01 | 1.85 (±0.94) | 2.14 (±0.20) | 0.26 (±0.47) | 3.86 (±2.57) | 45.11 (±19.96) | 20.83 (±7.95) | 23.99 (±12.93) | 9.45 (±6.09) | 0.62 (±0.63) |
| | LOW ‘01 | 0.82 (±0.42) | 2.03 (±0.63) | 0.50 (±1.72) | 10.13 (±12.17) | 21.77 (±15.47) | 20.19 (±8.20) | 41.82 (±10.99) | 14.98 (±5.26) | 1.24 (±0.48) |
| | REF 1 ‘01 | 2.06 (±1.26) | 2.94 (±0.21) | 0.59 (±0.15) | 3.37 (±0.27) | 52.09 (±10.74) | 10.71 (±1.97) | 20.27 (±5.05) | 13.99 (±3.88) | 2.95 (±0.97) |
| | REF 2 ‘01 | 1.22 (±0.60) | 2.48 (±0.40) | 0.70 (±0.14) | 4.48 (±0.66) | 43.91 (±10.85) | 14.83 (±2.10) | 23.51 (±5.22) | 14.92 (±3.90) | 2.83 (±1.51) |
| 2002 | HIGH ‘02 | 1.60 (±1.05) | 2.00 (±0.58) | 0.33 (±0.21) | 5.49 (±4.72) | 37.64 (±22.94) | 23.89 (±8.15) | 26.37 (±16.50) | 11.01 (±6.87) | 1.09 (±0.37) |
| | LOW ‘02 | 1.06 (±0.76) | 1.90 (±0.51) | -0.25 (±0.69) | 6.23 (±4.53) | 24.34 (±20.33) | 23.97 (±6.05) | 37.53 (±12.55) | 13.13 (±7.41) | 1.03 (±0.62) |
| | REF 1 ‘02 | 1.31 (±0.41) | 3.04 (±0.36) | 0.35 (±0.17) | 2.87 (±0.45) | 44.08 (±7.93) | 12.23 (±1.21) | 21.6 (±2.62) | 15.79 (±4.2) | 5.32 (±2.38) |
| | REF 2 ‘02 | 1.40 (±0.71) | 3.05 (±0.48) | 0.50 (±0.19) | 3.30 (±0.64) | 46.57 (±9.66) | 13.37 (±3.25) | 20.08 (±5.22) | 14.02 (±4.07) | 5.96 (±3.05) |
| 2003 | HIGH ‘03 | 1.95 (±0.95) | 2.03 (±0.54) | 0.31 (±0.64) | 5.13 (±5.22) | 43.63(±22.34) | 23.84 (±7.32) | 24.78 (±18.25) | 7.08 (±4.73) | 0.67 (±0.17) |
| | LOW ‘03 | 1.41 (±0.67) | 2.32 (±0.35) | -0.28 (±0.42) | 3.46 (±2.69) | 34.35 (±15.13) | 21.25 (±4.23) | 34.47 (±10.24) | 9.01 (±2.93) | 0.92 (±0.33) |
| | REF 1 ‘03 | 1.13 (±0.36) | 2.75 (±1.33) | 0.42 (±0.17) | 3.32 (±0.26) | 41.52 (±7.95) | 14.58 (±0.86) | 24.93 (±4.16) | 14.34 (±2.62) | 4.63 (±2.16) |
| | REF 2 ‘03 | 1.84 (±0.85) | 2.89 (±0.28) | 0.98 (±0.25) | 4.26 (±0.91) | 57.10 (±8.87) | 13.06 (±1.56) | 14.38 (±2.98) | 9.83 (±3.99) | 5.63 (±0.28) |

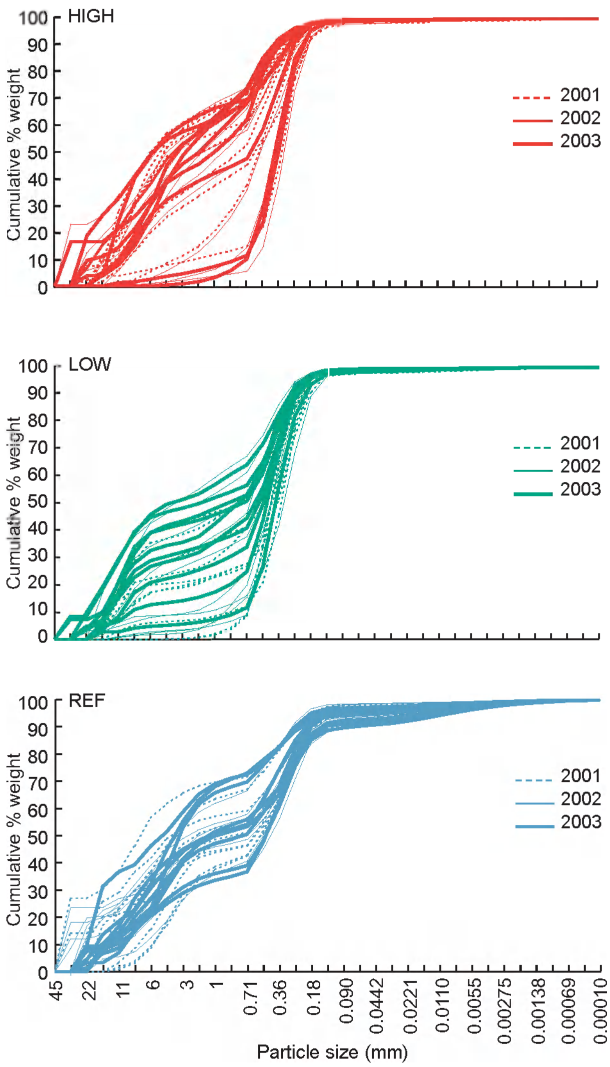



***Figure 6.6. Sediment particle size distributions determined from replicate samples taken from sites of high and low levels dredging intensity at Area 408 and the two reference sites between 2001 and 2003***

Another feature of the dredged sites is the higher variability in the composition of sediment samples. This is clearly illustrated in Figure 6.6 which shows a number of predominately sandy samples were obtained from the high and low dredging intensity boxes in all years. In contrast, all replicate samples from the reference boxes contained a substantial proportion of gravel and a higher proportion of silt/clay.

### *6.2.2. Sidescan sonar and underwater camera surveys*

Sidescan sonar data reveal differences in the distribution of sediments across the Zone 2 (Figures 6.7-6.9). Moving from east to west, the amount of exposed gravel decreases and this is increasingly overlain by a veneer of mobile sand. This sand veneer increases in thickness from east to west and appears to form sand waves in the extreme west of the zone. These changes may account for the differences in sediment composition of the high and low dredging intensity boxes. In the high box, underwater video footage shows gravel sediments are frequently exposed at the surface although there are occasional patches of what appears to be a sand veneer (Figure 6.10). Attached colonial epifaunal species such as the cnidarian *Alcyonidium diaphanum*, and the bryozoan *Flustra foliacea* and hydroids were common within the area of high dredging intensity. In contrast, sandy sediments dominated the low intensity box and the sand veneer appeared to be thicker, forming sand ripples and sand waves. Colonial epifaunal species were much less frequent in this area than in the area of high dredging intensity (Figure 6.11). Weathered dredge tracks from suction hopper dredging can still be seen in the area of high dredging intensity in 2003, four years after the cessation of dredging. The reference sites appear to be dominated by exposed gravels with conspicuous epifaunal taxa including *Alcyonium digitatum* and *Flustra foliacea* (Figure 6.12).

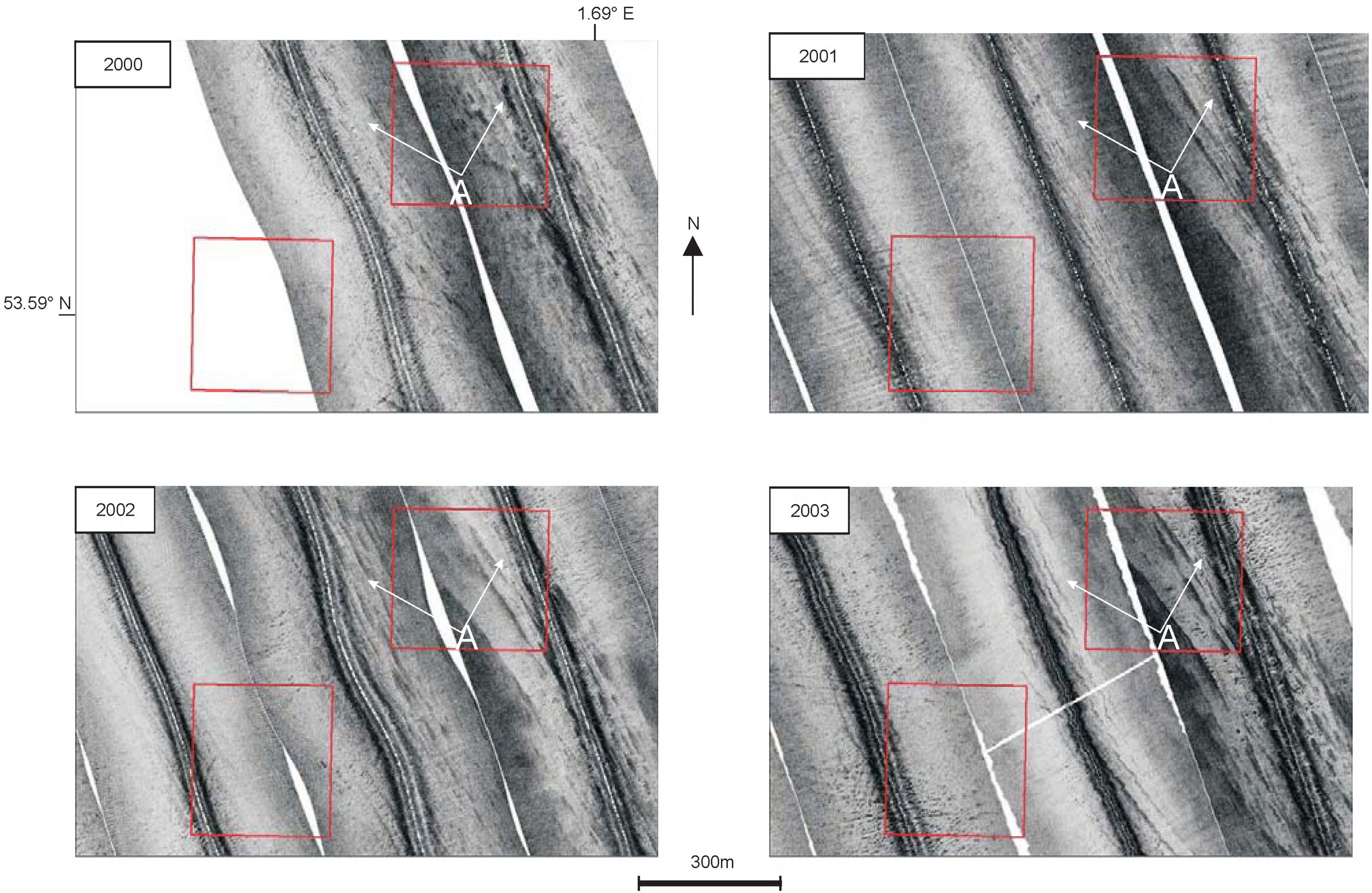



*Figure 6.7. Sidescan sonar images of HIGH (top right red box in each image) and LOW (bottom left red box in each image) treatment boxes at Area 408 (2000 – 2003). A) Area of weathered trailer suction hopper dredge tracks 2000 - 2003*

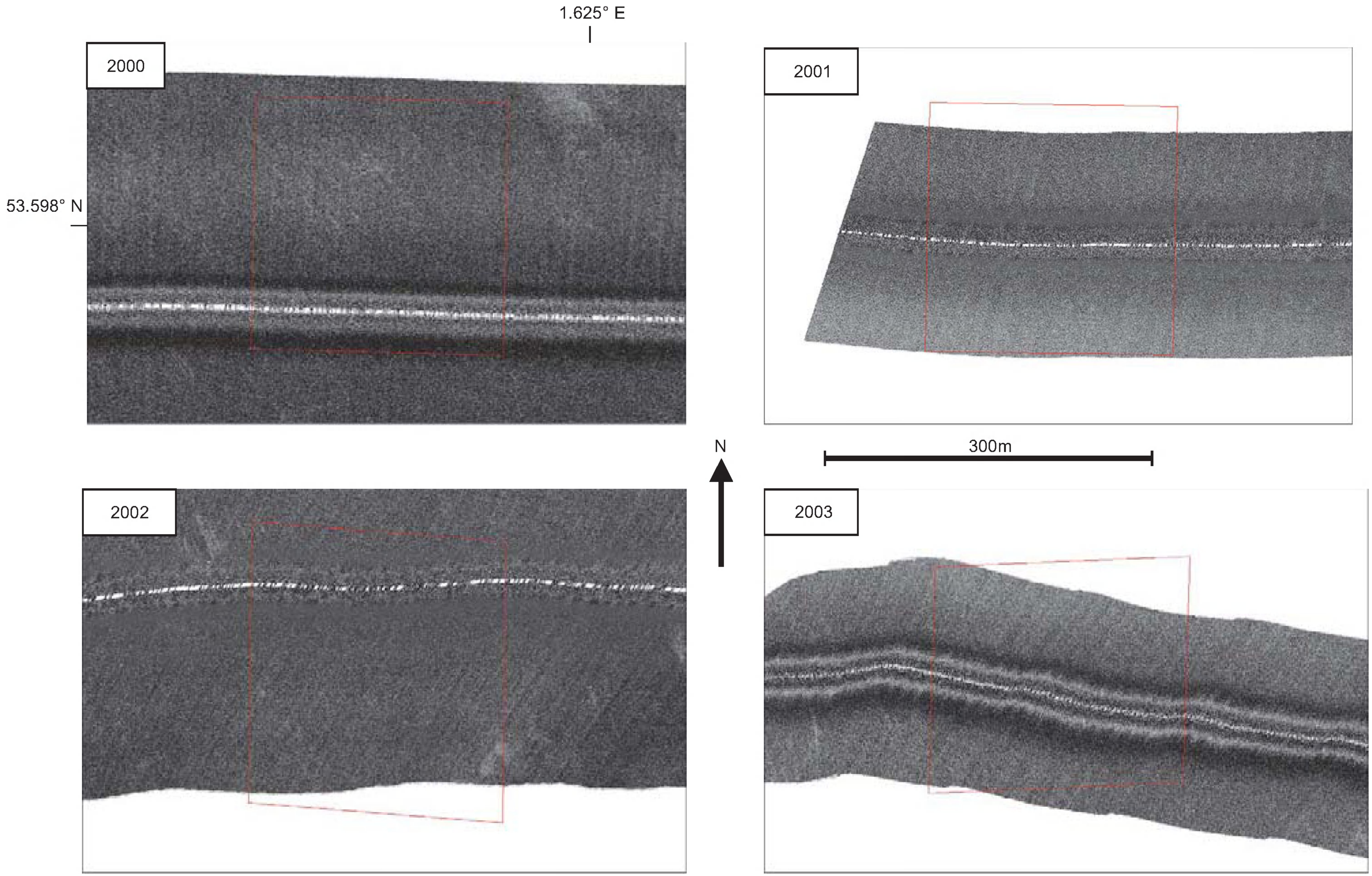



*Figure 6.8. Sidescan sonar images of REFERENCE BOX 1 at Area 408 (2002 – 2003)*

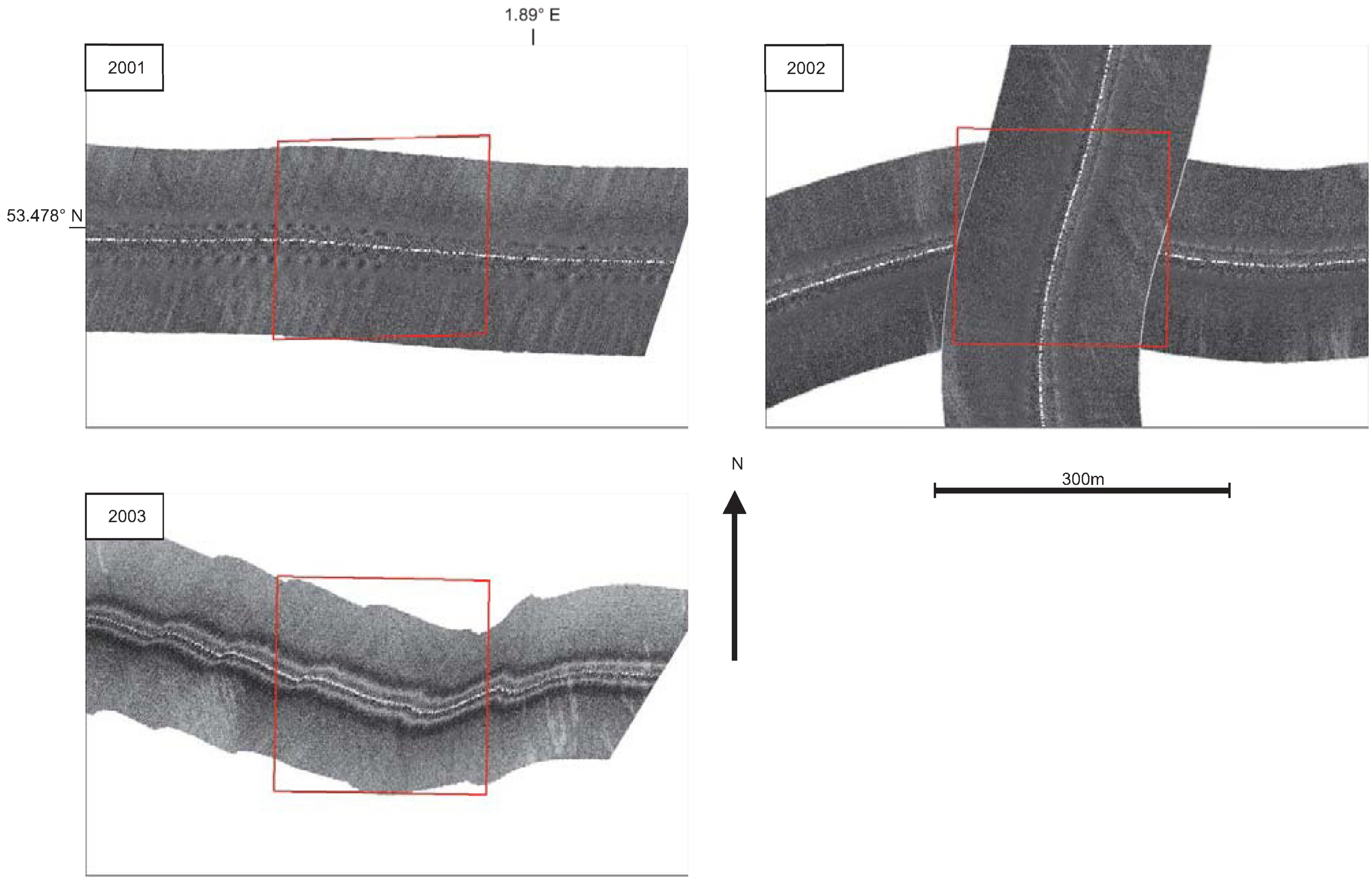



Figure 6.9. Sidescan sonar images of REFERENCE BOX 2 at Area 408 (2001 – 2003)

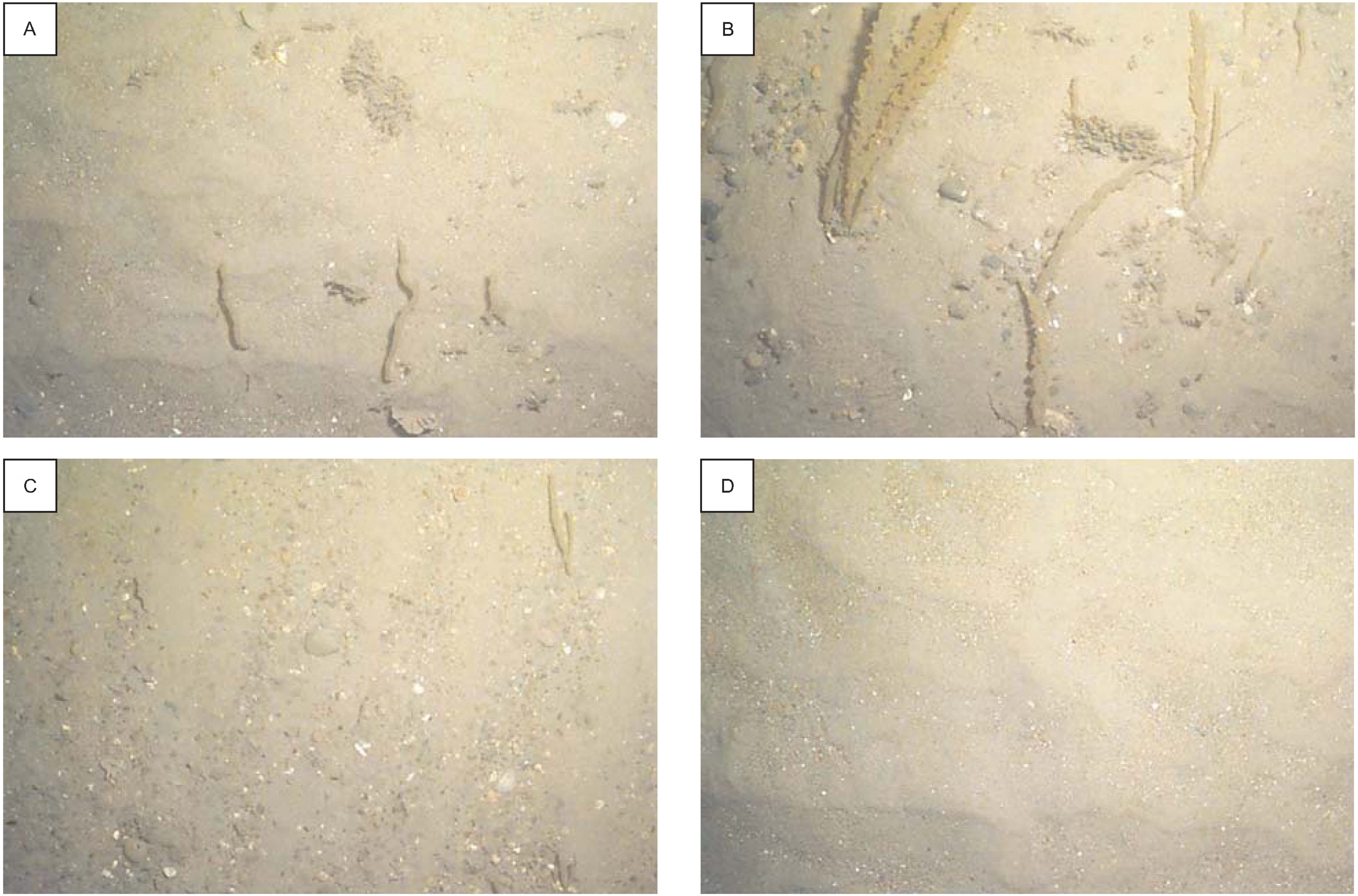


Figure 6.10. Underwater photographic images taken from within the area of high dredging intensity at Area 408 in 2003

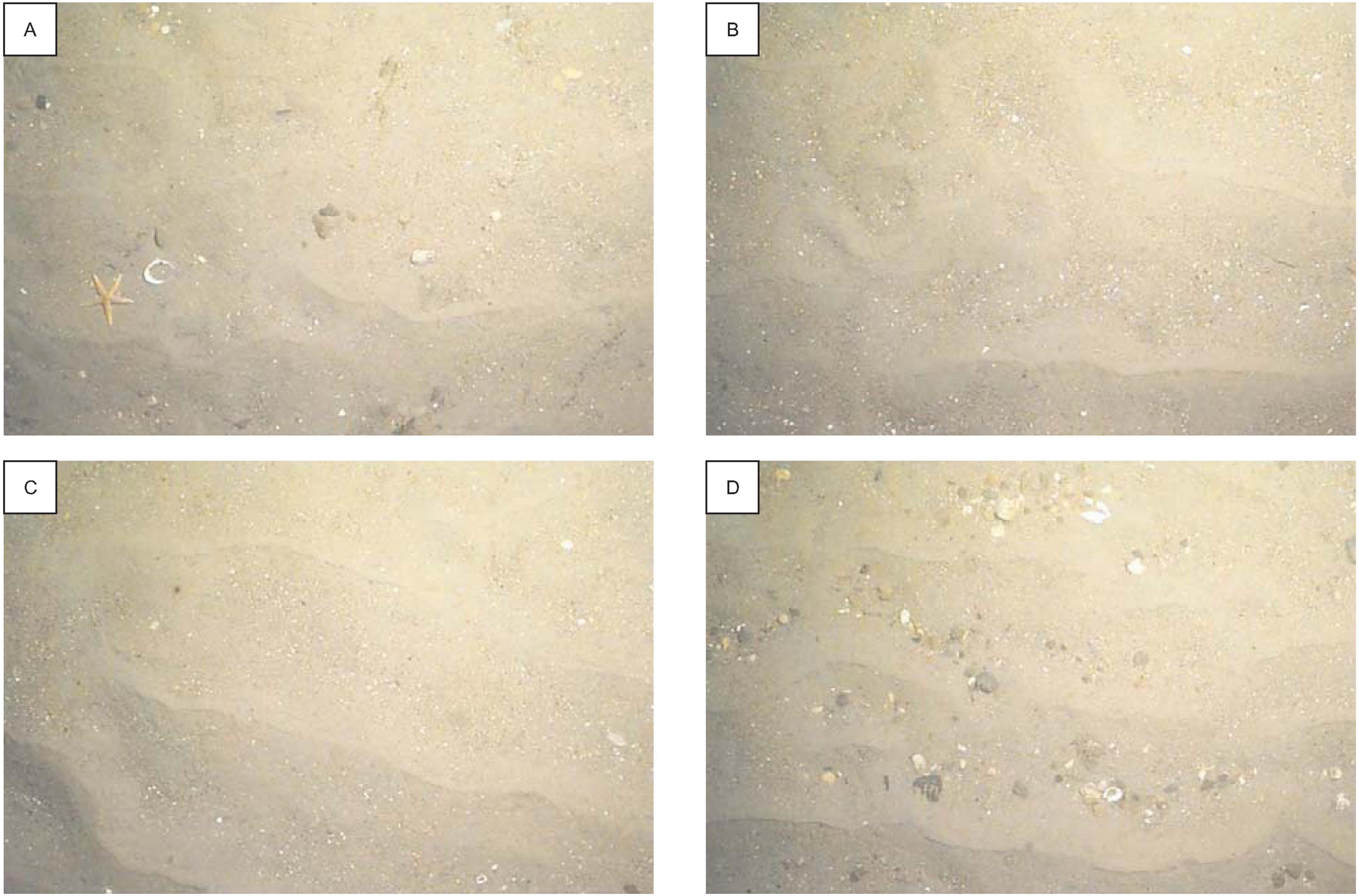



*Figure 6.11. Underwater photographic images taken from within the area of low dredging intensity at Area 408 in 2003*


***Figure 6.12. Underwater photographic images taken within Reference Box 1 at Area 408 in 2003***

## 6.2.3. Macrofaunal assemblage structure

Overall, a total of 296 species were found at Area 408 from the 90 samples collected between 2001 and 2003 (208 species in 2001, 188 species in 2002 and 195 species in 2003).

***Univariate Analyses***

Figure 6.13 shows a comparison of various univariate measures at each sampling site in 2001, 2002 and 2003. A one-way ANOVA detected significantly

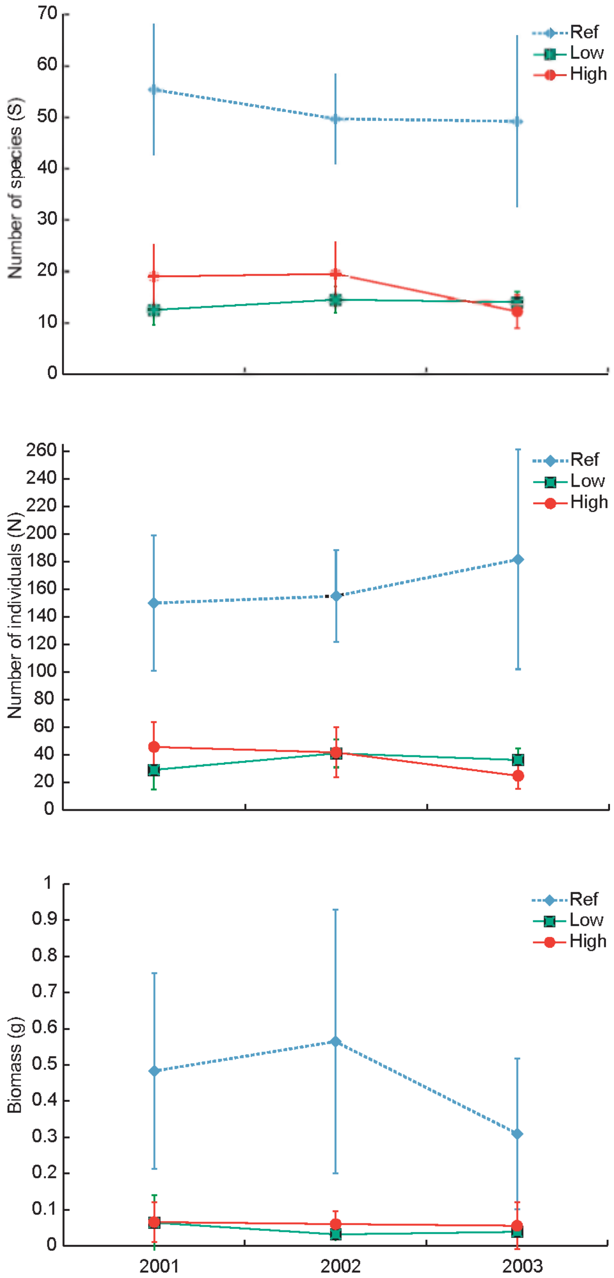



***Figure 6.13. Summary of means and 95% confidence intervals for number of species (S), number of individuals (N) and biomass (AFDW) from sites of high and lower levels of dredging intensity and two nearby reference sites at Area 408 in 2001-2003***

($p<0.05$) higher numbers of species, individuals and biomass (AFDW) at the reference sites compared to the dredged sites over time. However, there was no difference ($p>0.05$) in the numbers of species, number of individuals or benthic biomass found at either the high or low dredging intensity sites in all years.

In general, differences between the dredged and reference sites were due to a lower range of macrofaunal species at the dredged sites (Figure 6.14). These species included the amphipods *Urothoe elegans* and *U. marina*, the polychaete *Notomastus* sp., the bivalve *Mysella bidentata*, ACTINARIA and NEMERTEA.

***Multivariate analyses***

The output from non-metric multi-dimensional scaling ordinations of data from the Hamon grab surveys at Area 408 (Figure 6.15) shows that samples from the areas of high and lower dredging intensity and reference sites are separated. Replicate samples from the area of high dredging intensity also tend to be more diffusely separated on the ordination and there is some overlap with the samples obtained from the area of lower dredging intensity.

The comparative Index of Multivariate Dispersion (IMD) has been calculated in order to contrast the multivariate variability amongst samples taken from the dredged sites with samples from the reference locations. In Table 6.4 IMD values are compared between each of the sites in each year. Comparisons between the area of high dredging intensity and the reference sites give the most extreme values of IMD. However, the results provide some indication that the degree of dispersion of samples obtained from the area of high dredging intensity decreases over time relative to values at the reference site. In comparison, there is little difference between the low dredging intensity and reference samples in terms of variability in multivariate structure.

***Table 6.4. Index of Multivariate Dispersion (IMD) between all pairs of conditions***

| Year | Site | IMD |
|---|---|---|
| 2001 | High/ Reference Site | +0.535 |
| | High /Low | +0.334 |
| | Low/Reference Site | +0.276 |
| 2002 | High/ Reference Site | +0.477 |
| | High /Low | +0.493 |
| | Low/Reference Site | -0.023 |
| 2003 | High/ Reference Site | +0.428 |
| | High /Low | +0.263 |
| | Low/Reference Site | +0.087 |

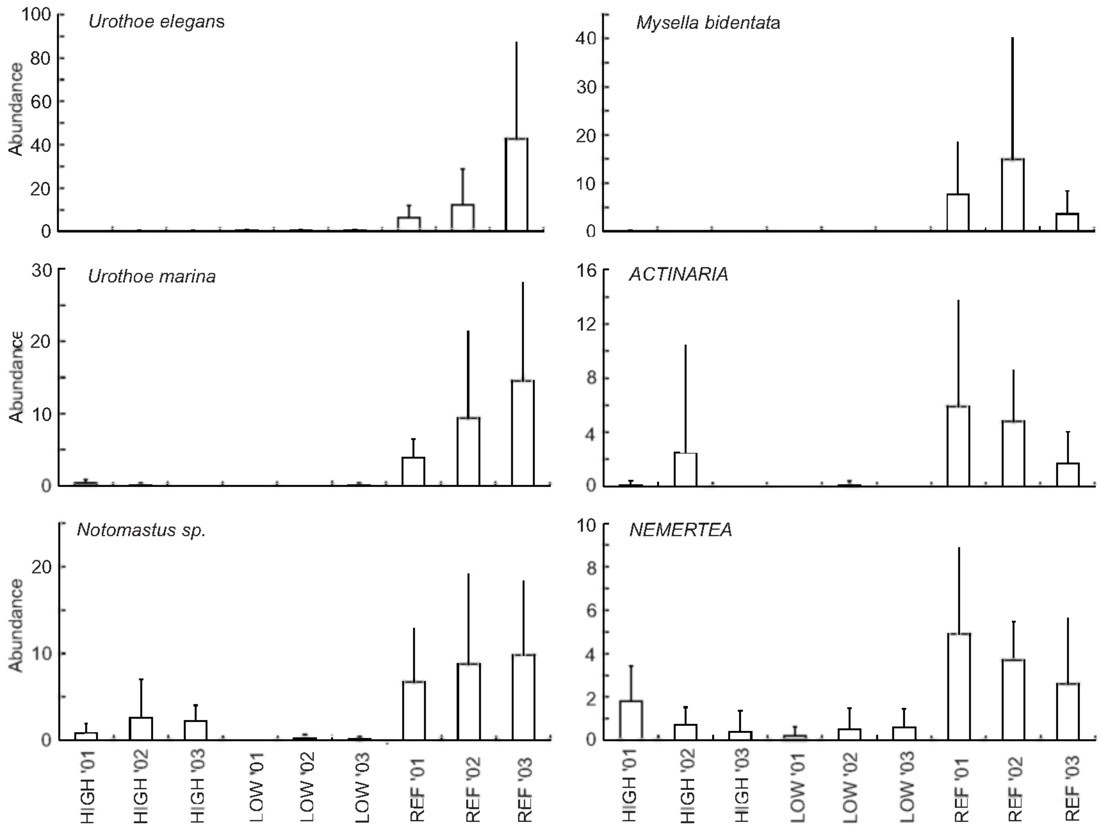



***Figure 6.14.*** ***Means (±SD) of abundances of selected macrofaunal species sampled in 2001-2003 at sites of high and lower levels of dredging intensity and at two reference sites (codes as in Table 6.2)***

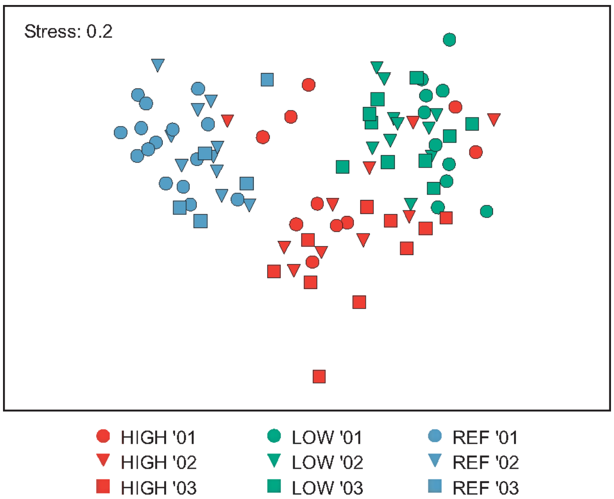



***Figure 6.15.*** ***MDS of Bray-Curtis similarities from 4th root transformed species abundance data 2, 3 and 4 years (2001-2003) after the cessation of dredging at high and low levels of dredging intensity and at the reference sites***

Table 6.5 confirms the above conclusions, i.e. that there is a greater variability in community composition from the area of high dredging intensity in comparison with other sampled locations.

***Table 6.5.*** ***Relative Index of Multivariate Dispersion (r.IMD) in each year***

| Year | Site | r.IMD |
|---|---|---|
| 2001 | High intensity | +1.339 |
| | Low intensity | +1.049 |
| | Reference site | +0.791 |
| 2002 | High intensity | +1.27 |
| | Low intensity | +0.734 |
| | Reference site | +0.759 |
| 2003 | High intensity | +1.249 |
| | Low intensity | +0.955 |
| | Reference site | +0.853 |

Comparison of ANOSIM R values between the dredged and references sites shows a decline between 2001 and 2002 at both the high and the low dredging intensity sites (Table 6.6). Overall the differences between the low dredging intensity and the reference site were greater than between the high dredging intensity and the reference site.

As for the biological data collected at Area 222 and Hastings sites, the community groupings were explored further using the similarity percentages programme SIMPER (Table 6.7). Results revealed similar findings to those from Area 222, namely that the average similarity between replicate samples collected from within each treatment and reference box was relatively low. Again, the lowest values of average similarity are found at the high dredging intensity site in all years. This is a result of the relatively few shared species recorded in replicate samples from the area of high dredging intensity. Dredged sites at Area 408 are numerically dominated by relatively few, tolerant, sand dwelling polychaete worms such as *Ophelia borealis*. Reference samples share some of the species found at the dredged sites including *O. borealis*. However, reference samples are characterised by a greater range of species including the polychatete worms *Polycirrus* sp., *Notomastus* sp., the crustacean *Urothoe elegans* and the mollusc *Mysella bidentata*.

## 6.3 Comparison with other studies undertaken at Area 408

In 2000, a survey of the benthos and sediments was undertaken within and surrounding the Area 408 extraction area (Newell *et al.*, 2002). The purpose of this study was to provide a quantitative description of the benthic fauna and associated sediments over an area encompassing predicted effects of dredging activity. The design was spatially extensive and took account of predicted dispersal pathways for fine sediments released during dredging operations. Sample stations were grouped into a number of different categories including areas of 'current dredging', 'abandoned areas', 'non-dredged areas' and 'control sites'. Their study showed, based on a multivariate analysis of benthic assemblage structure, that there was limited evidence of the effects of dredging on the macrobenthos within actively dredged areas or in areas liable to the effects of increased sedimentation from screening operations. They did, however, detect a shift in the relative dominance of a number of polychaete worms within the boundaries of actively dredged sites and in seabed sediments considered vulnerable to the effects of screening operations relative to deposits sampled elsewhere. Based on these results, they concluded that in 2000, the rates of recolonization by macrobenthic organisms from surrounding deposits were sufficiently rapid to allow the restoration of densities and numbers of macrofaunal species even within areas of active dredging.

Unlike densities and species composition, benthic biomass was found to be depressed in both zones of active dredging and in adjacent areas thought to be affected by screening operations. Newell *et al.* (2002) also concluded from their results that restoration of benthic biomass in dredged zones of Area 408 could be achieved within 12 months of cessation of dredging.

In contrast, the current study employed a stratified random sampling design targeting areas of the seabed, identified from EMS records, that had been subjected to different levels of dredging intensity. This design was chosen to establish the nature and rate of recolonization of benthic invertebrates following the cessation of extraction, in areas exposed to high and lower levels of dredging intensity. Although the aims of these two studies differ, a comparison of the results obtained is useful since it provides the opportunity to (1) place the findings from the current study into a wider geographical setting, (2) check the appropriateness of selected reference locations and (3) explore the reasons for the disparity in some of the findings.

***Table 6.6. R-values derived from the ANOSIM test for macrofaunal assemblages from locations of high and low dredging intensity and from the Reference sites in 2001, 2002 and 2003 at Area 408. * denotes significant difference at p <0.1; ** denotes significant difference at p < 0.05***

| | HIGH '01 | LOW '01 | REF '01 | HIGH '02 | LOW '02 | REF '02 | HIGH '03 | LOW '03 |
|---|---|---|---|---|---|---|---|---|
| LOW '01 | 0.387** | | | | | | | |
| REF '01 | 0.830** | 1.000** | | | | | | |
| HIGH '02 | 0.099* | 0.324** | 0.814** | | | | | |
| LOW '02 | 0.514** | 0.053 | 0.998** | 0.293** | | | | |
| REF '02 | 0.694** | 0.998** | 0.179** | 0.668** | 0.991** | | | |
| HIGH '03 | 0.234** | 0.584** | 0.956** | 0.086 | 0.553** | 0.854** | | |
| LOW '03 | 0.285** | 0.078 | 0.987** | 0.280** | 0.196** | 0.966** | 0.481** | |
| REF '03 | 0.457** | 0.983** | 0.434** | 0.426** | 1.000** | 0.325** | 0.670** | 0.922** |

***Table 6.7.*** ***Results from SIMPER analysis of macrofauna data from Area 408 (all taxa excluding colonial species, 4th root transformed), listing the main characterising species from samples subject to differing levels of dredging impact from 2001-2003. Average abundance, average similarity and the % contribution to similarity made by each characterising species is shown. Also listed is the cumulative percentage and the overall average similarity between replicate samples from within each group***

| Group | Taxon | Average Abundance | Average Similarity | % Contribution | Cumulative % | Overall Average Similarity |
|---|---|---|---|---|---|---|
| HIGH '01 | *Ophelia borealis* | 6.10 | 7.76 | 25.00 | 25.00 | **31.05%** |
| | *Polycirrus* sp. | 1.50 | 3.67 | 11.81 | 36.81 | |
| | NEMERTEA | 1.80 | 2.73 | 8.79 | 45.60 | |
| LOW '01 | *Nephtys cirrosa* | 2.50 | 9.79 | 26.74 | 26.74 | **36.62%** |
| | *Ophelia borealis* | 5.30 | 9.72 | 26.53 | 53.27 | |
| REF '01 | *Polycirrus* sp. | 15.00 | 2.83 | 6.79 | 6.79 | **41.69%** |
| | *Urothoe elegans* | 31.53 | 2.30 | 5.52 | 12.31 | |
| | *Urothoe marina* | 9.33 | 2.20 | 5.29 | 17.60 | |
| | *Notomastus* sp. | 6.13 | 2.18 | 5.24 | 22.84 | |
| | NEMERTEA | 3.93 | 1.54 | 3.70 | 26.54 | |
| | ACTINARIA | 4.80 | 1.42 | 3.40 | 29.94 | |
| | *Pholoe inornata* | 2.53 | 1.39 | 3.34 | 33.28 | |
| | *Mysella bidentata* | 6.80 | 1.17 | 2.82 | 36.10 | |
| | *Eumida sanguinea* | 1.93 | 1.05 | 2.53 | 38.63 | |
| | *Polinices pulchellus* | 1.73 | 1.02 | 2.45 | 41.07 | |
| HIGH '02 | *Ophelia borealis* | 8.20 | 8.09 | 26.38 | 26.38 | **30.68%** |
| | *Polycirrus* sp. | 3.30 | 3.06 | 9.97 | 36.35 | |
| | *Notomastus* sp. | 2.60 | 2.43 | 7.92 | 44.27 | |
| LOW '02 | *Ophelia borealis* | 13.60 | 11.20 | 26.65 | 26.65 | **42.04%** |
| | *Polycirrus* sp. | 10.00 | 10.26 | 24.41 | 51.05 | |
| REF '02 | *Polycirrus* sp. | 9.00 | 3.34 | 8.06 | 8.06 | **41.43%** |
| | *Mysella bidentata* | 15.00 | 2.61 | 6.30 | 14.35 | |
| | *Notomastus* sp. | 8.80 | 2.55 | 6.16 | 20.51 | |
| | NEMERTEA | 3.70 | 2.24 | 5.42 | 25.93 | |
| | ACTINARIA | 4.80 | 2.02 | 4.87 | 30.80 | |
| | *Urothoe elegans* | 12.30 | 1.84 | 4.44 | 35.24 | |
| | *Ophelia borealis* | 8.80 | 1.79 | 4.32 | 39.55 | |
| | *Thracia* sp. | 1.80 | 1.54 | 3.72 | 43.27 | |
| HIGH '03 | *Ophelia borealis* | 3.10 | 6.18 | 18.88 | 18.88 | **32.72%** |
| | *Notomastus* sp. | 2.20 | 5.24 | 16.01 | 34.89 | |
| | *Thracia* sp. | 1.40 | 4.86 | 14.86 | 49.76 | |
| LOW '03 | *Ophelia borealis* | 14.00 | 12.18 | 31.80 | 31.80 | **38.30%** |
| | *Polycirrus* sp. | 4.40 | 5.86 | 15.31 | 47.10 | |
| REF '03 | *Notomastus* sp. | 14.60 | 4.97 | 13.30 | 13.30 | **37.37%** |
| | *Ophelia borealis* | 4.20 | 3.75 | 10.04 | 23.34 | |
| | *Urothoe elegans* | 3.40 | 3.17 | 8.48 | 31.82 | |
| | NEMERTEA | 3.20 | 3.11 | 8.32 | 40.14 | |

Both investigations employed similar sampling techniques, although the timing of surveys was separated by a period of 1 year. Figure 6.16 shows a comparison of the numbers of benthic species and individuals recorded from both studies.

An analysis of variance shows that there is no significant difference ($p>0.05$) in either the number of species or individuals recorded from the reference locations between surveys. This is despite enhanced sampling of reference conditions during the Newell *et al.* (2002) survey in comparison to that undertaken for the current investigation. The lack of marked differences between the reference locations gives further confidence that the reference sites sampled during the current study are representative of wider environmental conditions. Furthermore, it suggests that annual variability in benthic populations at Area 408 reference areas is of minor consequence. There is, however, disparity in the conclusions reached in each study based on the results of benthic sampling at the dredged locations. For example Newell *et al.* (2002) found no difference in terms of the numbers of species and individuals found in 2000 at sites classified as 'abandoned' stations compared to reference locations. These abandoned stations were sampled in four different zones of Area 408. Even when only the 'abandoned' stations from Zone 2, the zone where the CEFAS high and low sampling boxes are located, are

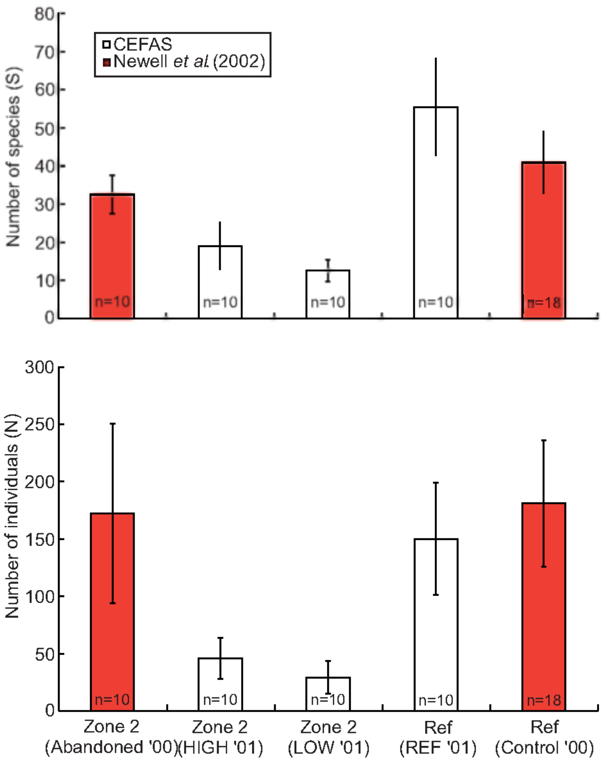



***Figure 6.16. Comparison of the number of species (S) and individuals (N) found by Newell et al. (2002) and in this study. Raw data from Newell et al. (2002) has been adjusted to allow comparison with CEFAS data***

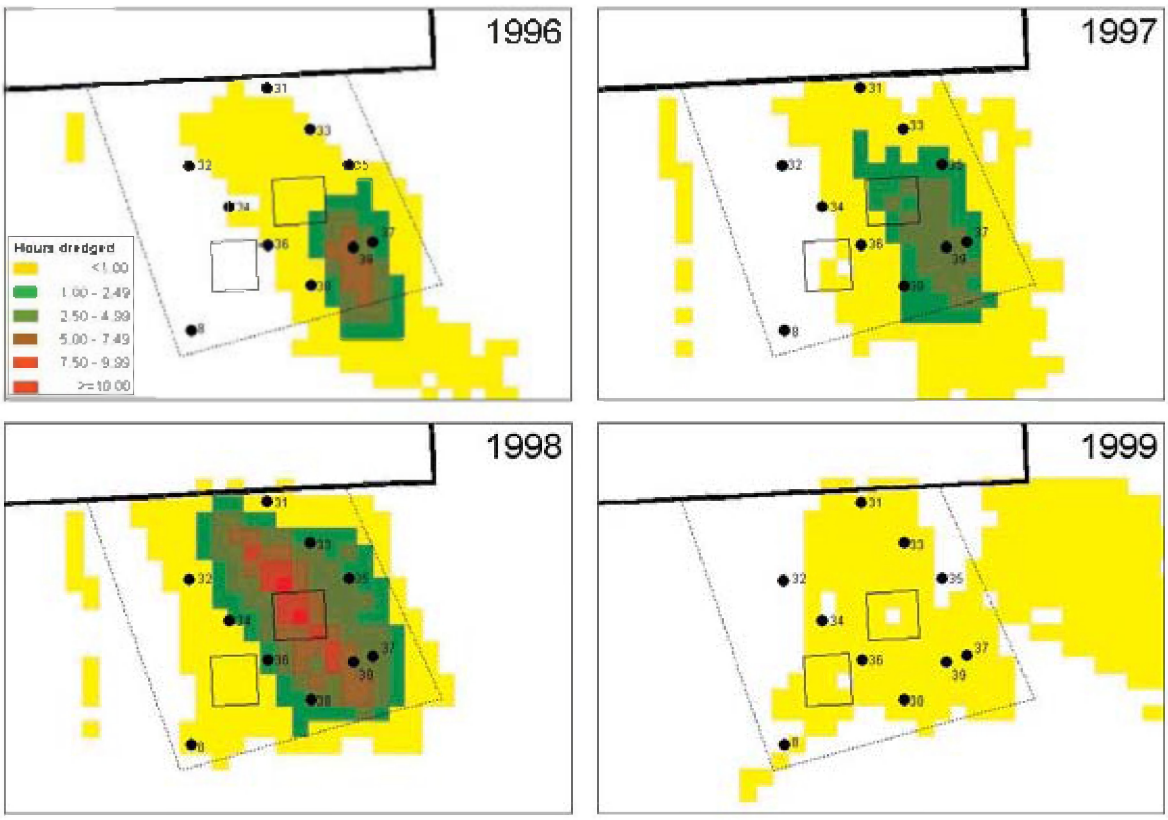



***Figure 6.17. Location of sampling positions in Zone 2 sampled as part of the study reported by Newell et al. (2002) overlain on EMS data from 1996 to 1999***

considered the outcome is the same. This contrasts with the results of the current study which found significantly ($p<0.05$) lower numbers of species and individuals at 'abandoned' sites located in Zone 2 compared to the reference site, at least 4 years after the cessation of dredging. The disparity in the numbers of species and individuals found within Zone 2 between both studies requires further exploration. One possible explanation lies in the different locations sampled in each study. Sampling positions from both studies are shown in relation to the location and intensity of dredging (Figure 6.17) and the distribution of sediments across Zone 2 (Figure 6.18).

Clearly, the high sampling box targets the highest levels of dredging intensity within Zone 2 and would therefore be expected to have lower numbers of species and individuals than undredged areas of the seabed. Furthermore, there is a clear transition across Zone 2 from more gravelly sediments in the east to more sandy sediments in the west. The area of low dredging intensity, positioned in the west of zone 2, is characterised by mobile sandy sediments and would therefore be expected to have lower values for numbers of species and individuals. In contrast, many of the samples taken during the Newell *et al.* (2002) study from within Zone 2 target the coarser sediments in the east of the zone in areas of the seabed which may have only experienced limited exposure to the direct effects of extraction.


***Figure 6.18. Location of sampling positions in Zone 2 sampled as part of the investigation reported in Newell et al. (2002) overlain on sidescan sonar data from 2002 collected as part of the current study***

# 7. SPATIAL INVESTIGATIONS OF AREA 222

## 7.1 Introduction

Traditionally, benthic ecologists have relied on point sampling techniques such as grabs, cores and dredges to provide information on the physical nature of the substrata and its associated benthic fauna (e.g. Holme, 1961, 1966; Cabioch, 1968). Samples collected using such techniques allow detailed descriptions of the benthic assemblages, which can be directly referenced to variations in the particle size distribution of the substrata. However, information of this nature only relates to the specific point on the seabed from which the sample was collected and inferences regarding the wider distribution of substrata and associated fauna may be unreliable, especially in patchy environments. Intensive point sampling must be carried out if a detailed description of the benthic environment is required (e.g. Larsonneur *et al.*, 1982; Sanvicente-Añorve *et al.*, 1996). Surveys of this type are time consuming and expensive and interpolation between the data points must be undertaken if maps of the spatial distribution of benthic habitats are to be produced. The use of remote acoustic techniques offers the possibility of overcoming such problems by producing a continuous record of the physical status of the seabed.

Several remote acoustic techniques such as multibeam bathymetry/backscatter (Kostylev *et al.*, 2001) and AGDS (Greenstreet *et al.*, 1997; Service, 1998; Hamilton *et al.*, 1999; Foster-Smith *et al.*, 2001; Morrison *et al.*, 2001; Anderson *et al.*, 2002; Ellingsen *et al.*, 2002) have recently been employed to infer the biological status of the seabed. This investigation addresses the utility of bathymetric and sidescan sonar techniques, used in conjunction with appropriate groundtruthing to map the status of the seabed within and in the vicinity of Area 222 in relation to the historic effects of extraction activity.

Bathymetric surveys undertaken using single beam sounders provide high-resolution vertical and along-track data which relate to the depth of the water directly beneath the survey vessel. These data can be interpolated between survey lines to generate a continuous bathymetric basemap of the seabed upon which other data layers can be placed. High-resolution bathymetric information can be collected using multibeam bathymetry techniques. Such systems provide a continuous horizontal swath of data, with a vertical resolution of up to 10 cm, which can be collected simultaneously across a section of the seabed measuring up to 7 times the water depth. Sidescan sonar uses acoustic backscatter to provide information on the texture and fine scale morphology of seabed sediments and, from this, it is possible to predict the physical and, to a degree, the biological nature of the seabed environment (Service, 1998; Schwinghamer *et al.*, 1998; Wildish and Fader, 1998; Fenstermacher *et al.*, 2001; Brown *et al.*, 2001; Cochrane and Lafferty, 2002). The use of such data is of particular value when assessing anthropogenic effects in areas of known habitat heterogeneity. For example, conventional environmental monitoring at aggregate extraction sites is often complicated by the presence of a wide range of substratum types (sometimes ranging from sand through gravel to outcropping bedrock) which may be present as a variety of morphological features. This can cause significant problems for the generation of effective, quantitative sampling designs which in turn makes it difficult to draw generalisations concerning the status of the seabed. Acoustic basemaps therefore greatly assist this process through the provision of detailed information concerning the physical nature of the seabed. The wider application of techniques such as sidescan sonar and bathymetry therefore has the potential to aid, supplement or even replace ongoing environmental assessment employing conventional approaches (Rowlatt *et al.*, 1987, 1994; Rees *et al.*, 2000; Saward, 2000; Desprez, 2000; Brown *et al.*, 2001; Boyd *et al.*, 2003).

Thus, to complement the previous time-series investigations (see Section 4), a 'once-off' spatial evaluation of the status of the seabed within and in the vicinity of Area 222 was conducted. The main objectives of this investigation were to provide an indication of the spatial distribution of sediments and macrofauna in the wider area encompassing the dredged site, to evaluate the scope for the effects of marine aggregate extraction to extend beyond the boundaries of the site and to provide a wider geographical context for time-series investigations.

## 7.2 Methods and materials

A spatial grid of thirty 0.1 $m^2$ Hamon grab samples was collected for the analysis of the sediments and the benthic macrofauna (Figure 7.1). Samples were processed and analysed following the procedures described in Section 3.0 and in Boyd (2002). This approach affords single geographically separated points of data across the area of the seabed under investigation. Interpolation of these data points has the potential to overlook discrete seabed features and/or biological assemblages that may lie between sampling stations. To ameliorate this potential limitation to the sampling design, a number of acoustic surveys were also conducted. A series of eight sidescan sonar lines were surveyed (see Section 3.3). This resulted in coverage of the extraction site, an area of disturbed sediment to the north of the site, and two reference sites to the north and east of the extraction area (see Figure 7.2). In addition, a bathymetric survey was conducted using an Elac model LAZ4800 200kHz hydrographic sounder with TSS320 digitiser/heave compensator and

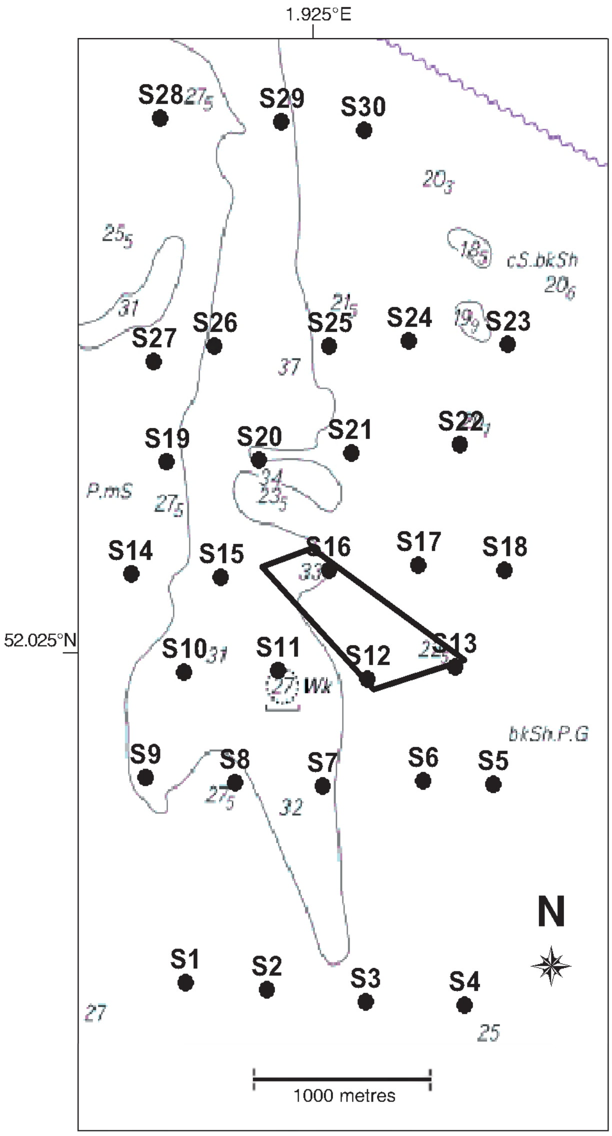



***Figure 7.1. Map showing the location of sample positions in the vicinity of Area 222 collected in 2001***

the data were processed using Geografix Sextant™ survey software and the Surfer® 8 contouring package. This survey covered a similar area to that surveyed using sidescan sonar. Results from the bathymetric survey provided three-dimensional information relating to the larger morphological features at the seabed (Figure 7.3). In 2003, a multibeam bathymetry survey was also undertaken over the same area that was surveyed in 2001 using single beam bathymetry and sidescan sonar (Figure 7.4). Acoustic surveys of this type give an indication of the seabed morphology (e.g. sediment transport features, banks, depressions and dredging derived features) and sediment texture characteristics (e.g. soft or hard sediments) across the survey area, which can then be presented as a continuous record.

## 7.3 Results

The distribution of sediments and seabed features within, and in the vicinity of Area 222 identified from the 2001 sidescan sonar survey are consistent with those described in Section 4.2.2.

The data from the single beam and multibeam bathymetric surveys are presented in Figures 7.3a and 7.4. These show that Area 222 is located on the eastern flank of a channel whose axis runs roughly north-west/south-east through the northern part of the site, with a maximum depth of approximately 35 m. The south-eastern part of the site is situated on a plateau at the top of the channel slope in water depths of approximately 22 m, whereas the north-western part of the site is in the deeper water at the base of the channel. Along its length the channel slope rises approximately 10 m over a horizontal distance of 250 m. Figure 7.3b shows the backscatter data, derived from the sidescan sonar survey draped over the interpolated single beam bathymetric 3D surface map. This image provides a comparison of the seabed texture and the major topographic features present and aids in the determination of any relationships between the datasets. It should be noted that these two datasets are not precisely georeferenced with each other as the positional information for the sidescan sonar data is subject to possible layback errors of up to a few tens of metres. However, comparison of the single beam and multibeam bathymetry and the sidescan sonar image does allow general spatial relationships to be assessed.

Despite the apparent intensity of historic dredging activity both to the north of the site and within the northern part of the licensed extraction area, the bathymetric data do not suggest a substantial overall lowering of the seabed in either of these two areas when compared to the surrounding seabed. To the north of the extraction site there is a discrete bathymetric feature measuring approximately 400 m by 200 m which rises roughly 10 m from the surrounding seabed (Figure 7.5, B1). The sidescan sonar record indicates that this is a series of sand waves located at the southern extent of the zone of 'out of area dredging'. A bathymetric depression, up to approximately 4 m deep, located to the east of the site is evident from both the single and multibeam bathymetric datasets. The single beam data identify this as an isolated feature (Figure 7.3a), but the higher resolution multibeam data suggest that it is an elongated feature which extends north-westwards and joins the zone of out-of-area dredging to the north of Area 222 (Figure 7.6, C2). This feature is almost coincident with an area of disturbed sediments observed from the sidescan sonar record (Figure 7.2) and is possibly a consequence of dredging activity. This might then suggest that 'out of area dredging' had also been carried out in this easterly location prior to the introduction of EMS in 1993.

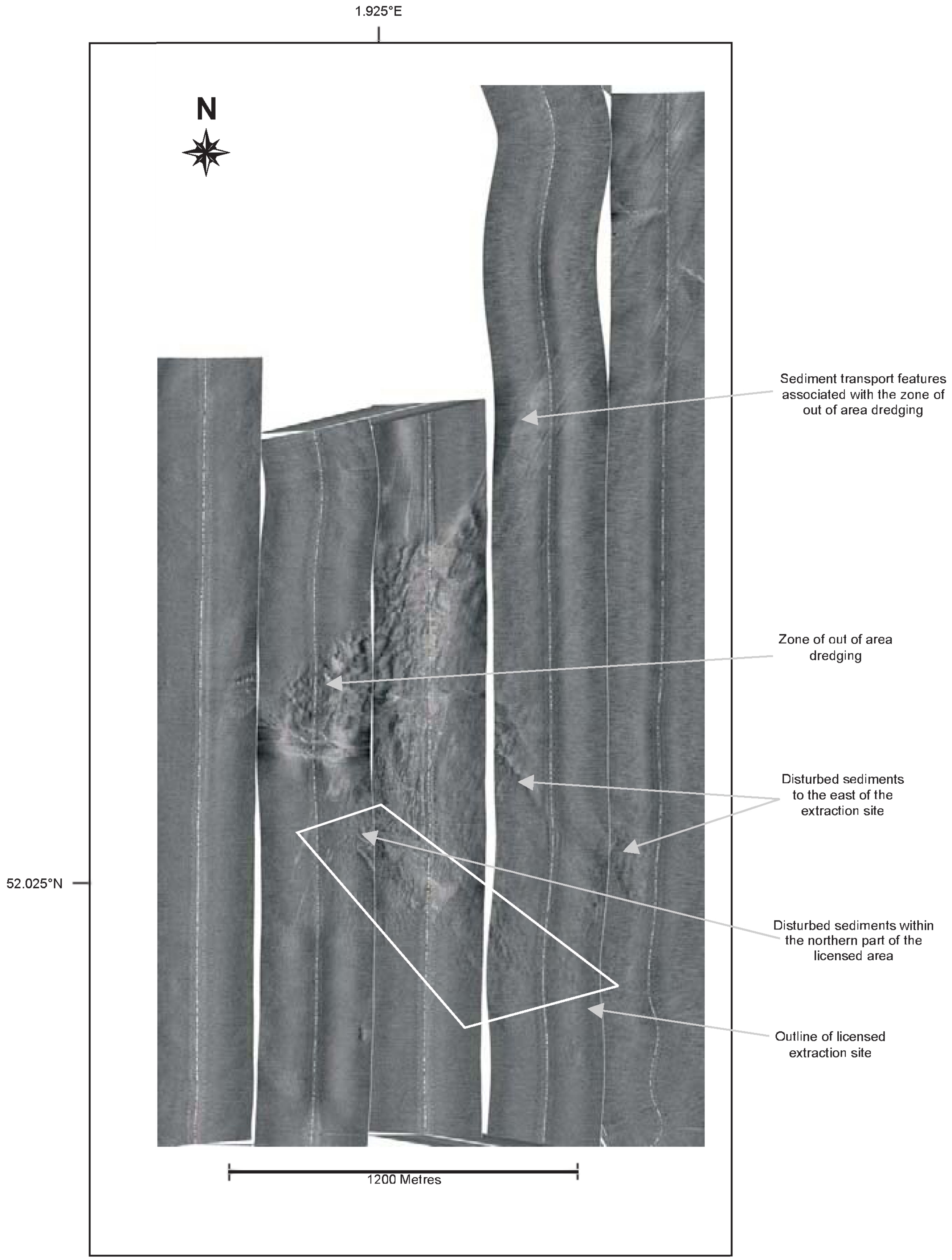
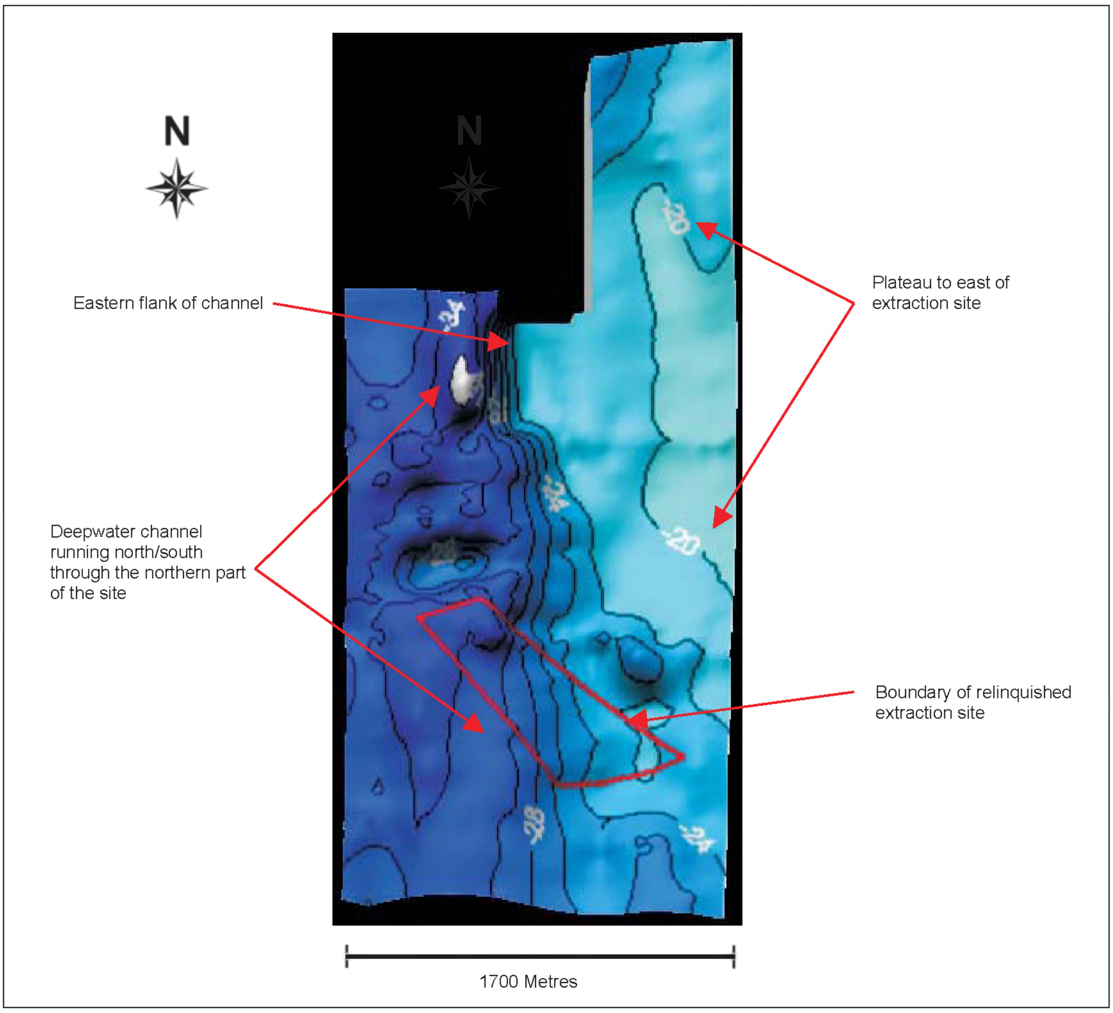



***Figure 7.2. Sidescan sonar mosaic of the survey carried out at Area 222 in 2001 showing major seabed features***

(a)




(b)

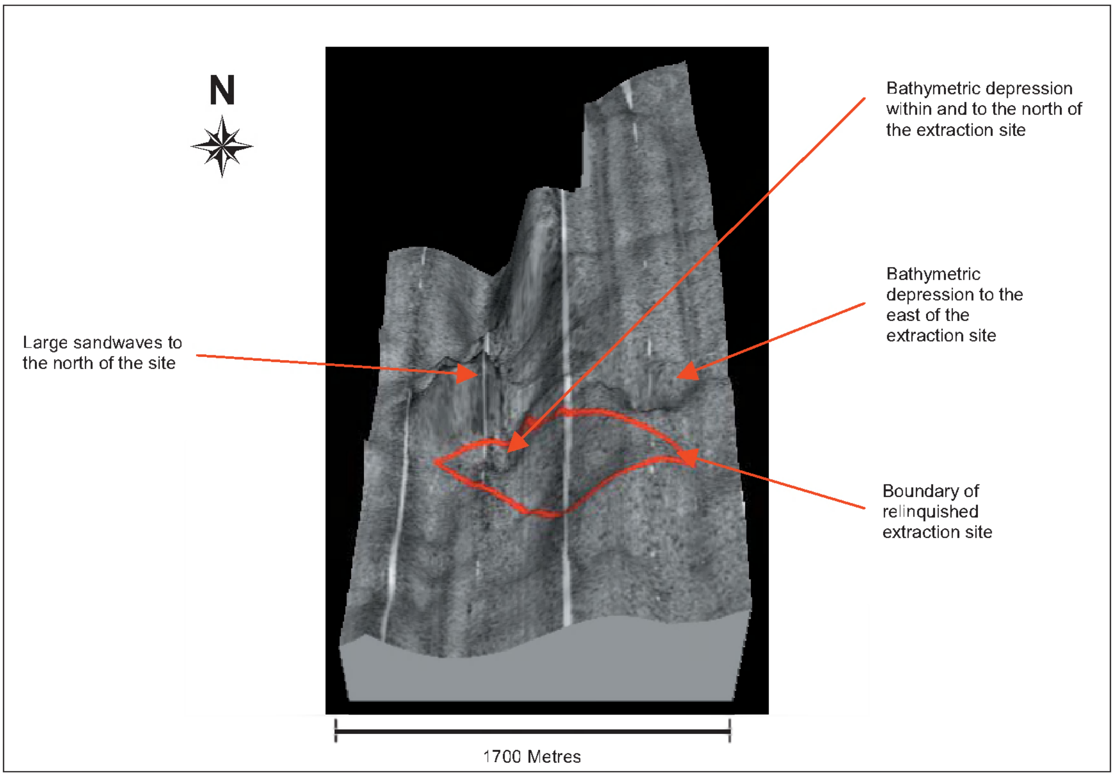



***Figure 7.3.** a) Three dimensional contoured plot derived from the single line bathymetric survey carried out in 2001 at Area 222. b) Three dimensional contoured plot of the 2001 bathymetric survey overlain by the sidescan sonar backscatter data collected in the same year*

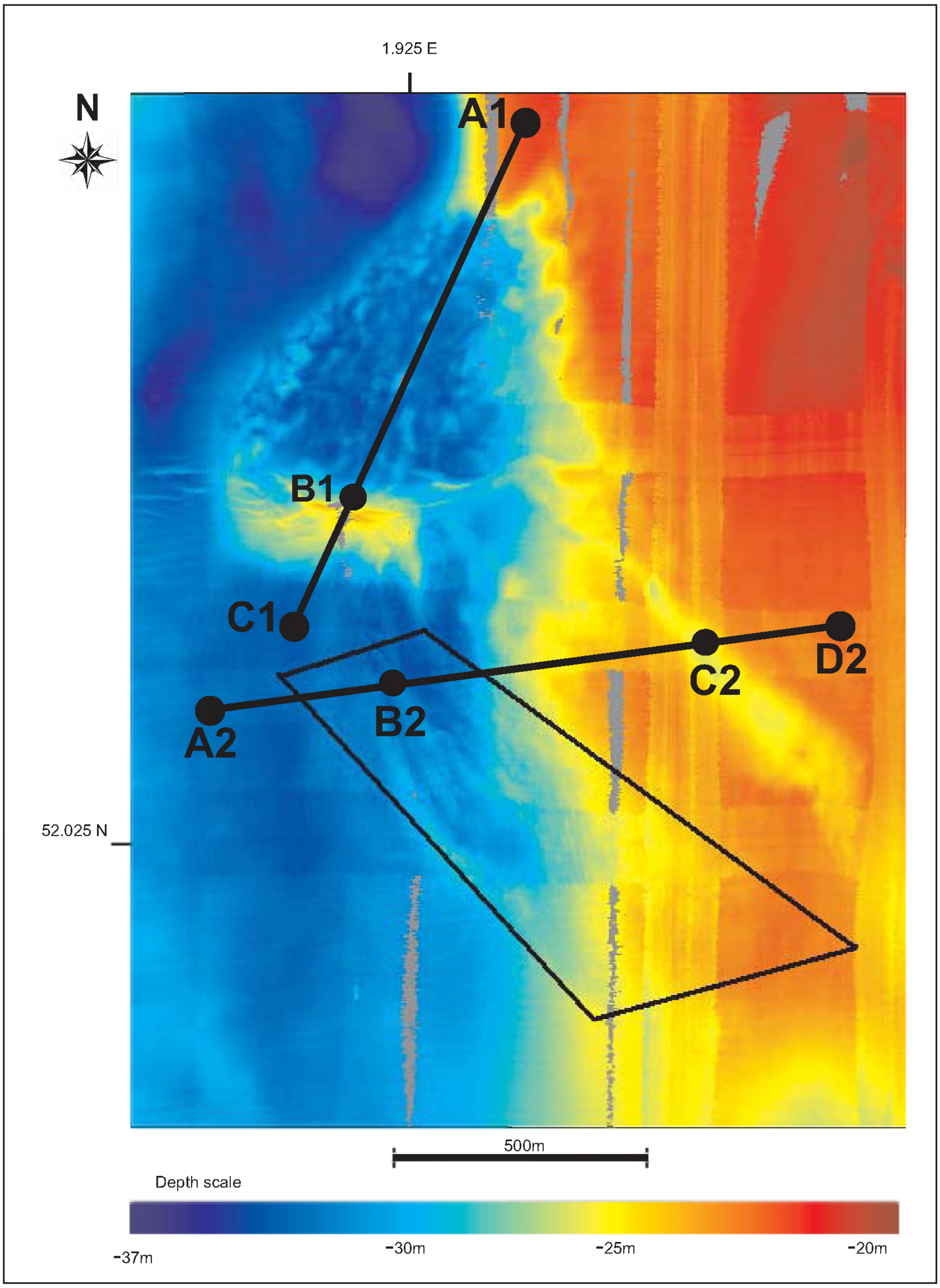



***Figure 7.4. Multibeam bathymetry image of Area 222 collected in 2003. Transects A1 – C1 and A2 – D2 relate to the bathymetric profiles presented in Figures 7.5 and 7.6***

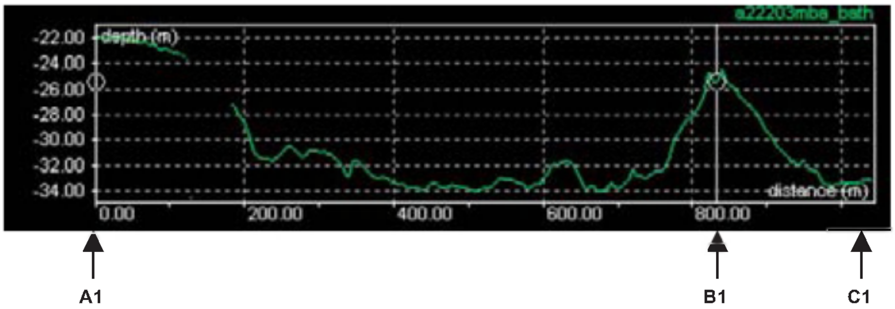



*Figure 7.5. Bathymetric profile across the disturbed area to the north of Area 222 (derived from multibeam data)*

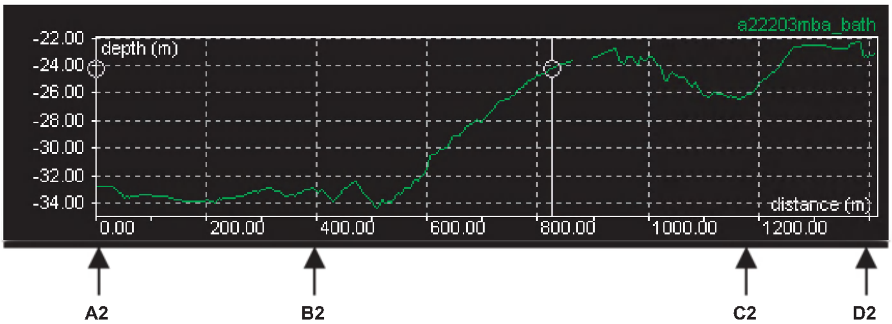



*Figure 7.6. Bathymetric profile across the northern part of Area 222 (derived from multibeam data)*

Figure 7.7 shows the sediment particle size data presented as pie charts and superimposed over the 2001 sidescan sonar image. This demonstrates that sediments over the eastern two thirds of the survey area are composed of varying quantities of sand and gravel with little fine material present. The spatial extent of these sediments encompasses the shallow plateau to the east of Area 222 and the eastern flank and base of the deepwater channel that runs through Area 222. Sediments in the western part of the survey area contain substantially higher proportions of fine (silt/clay) material than sediments located elsewhere. These sediments are present on the deeper parts of the western flank of the deepwater channel feature.

A total of 102 taxa were identified from the 30 Hamon grab samples collected from across the survey area. A group average sorting dendrogram showing the percentage similarity of macrofauna at each of the stations sampled in 2001 is presented in Figure 7.8. This suggests that the sediments in the vicinity of Area 222 support 3 macrofaunal assemblages. These comprise a 'Group A' assemblage, a 'Group B' assemblage and a smaller group of two stations from dredged locations designated as the 'Group C' assemblage. One exception to this grouping is station S9 which is separated from the other sampled stations in the dendrogram on account of elevated (approx. 80%) levels of silt/clay in the sediment. This has facilitated the development of a different benthic assemblage. The groups identified as discrete assemblages from the dendrogram have been colour coded and the corresponding colours are superimposed on to the 2001 sidescan sonar mosaic of the survey area (Figure 7.9).

From the distribution of the 3 faunal groups, there appears to be a roughly east/west separation of the 2 main assemblages (Group A and Group B) which correspond to increasing water depth and a fining of the sediments to the west of the survey area. In general, the separation of these two broad assemblages accords with the location of the bathymetric feature running through the northern part of the extraction site. Thus, it appears that this bathymetric feature, mediated through its effect on substratum characteristics, influences the distribution of benthic assemblages in the area.

Dredged locations represented by stations S16 and S21 also form a distinct group on the dendrogram and are located within the northern extent of the extraction site and within a disturbed area of seabed to the north.

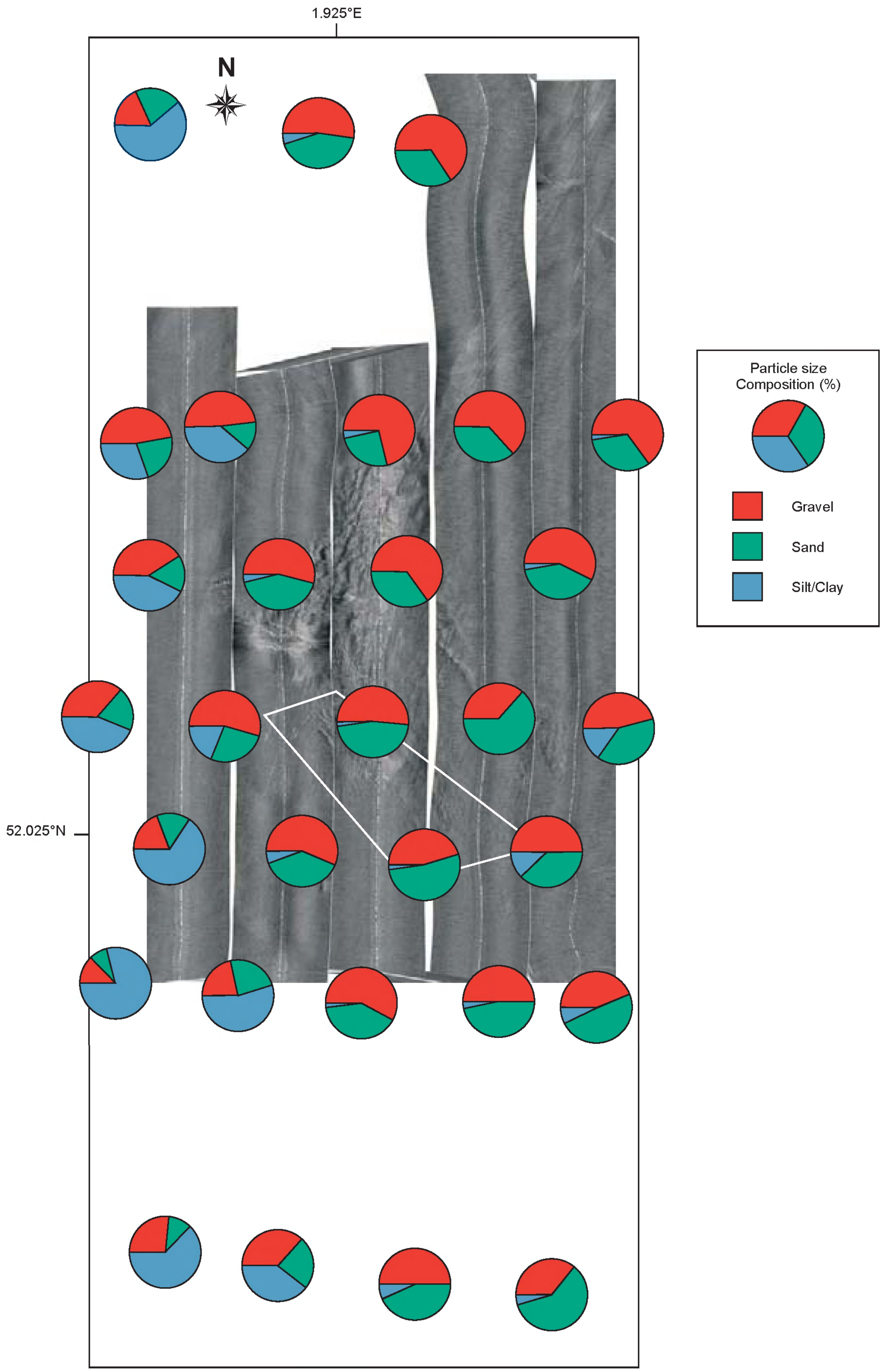



*Figure 7.7. The results of sediment particle size analysis of samples collected from the 2001 survey. The data have been presented as pie charts and superimposed on a sidescan mosiac obtained in the same year of sample collection*

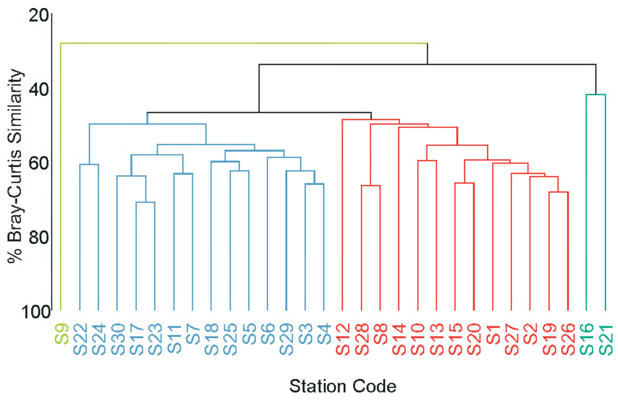



***Figure 7.8. Dendrogram of group average clustering of Bray-Curtis similarities based on log-transformed abundance data from the Area 222 spatial grid survey sampled in 2001***

The corresponding two dimensional MDS ordination is shown in Figure 7.10, together with the same MDS but with superimposed circles proportional in diameter to values of percentage silt/clay. The MDS ordination also indicates that samples collected from the areas of most intensive dredging activity are clearly separated from samples obtained elsewhere confirming that the assemblage structure of macrofaunal samples from these dredged locations is very different to that which exists in the surrounding sediments. Samples collected in the vicinity of dredged areas (e.g. S11-12, & S22-24) are also slightly set apart from the other samples on the MDS ordination which may suggest that subtle effects of dredging are present at distance from the centres of extraction activity.

The relatively high stress value of 0.16 for the ordination is a consequence of the high dimensional data-set and the large number of samples included in the analysis. However, stress values between 0.1 and 0.2 are still considered to provide a useful 2 dimensional illustration of the relationships between samples (Clarke and Warwick, 1994).

## 7.4 Discussion

A comparison of the sidescan sonar and bathymetric surveys has provided further insights in terms of the distribution of sediments and their associated seabed features within and in the vicinity of Area 222. The sandy sediments that lie within and to the north of the extraction site are situated at the base of a gently rising bank whose axis runs northwest/southeast through the site. This feature lies almost at right angles to the local tidal axis (NNE – SSW) (HR Wallingford, 2002) and its presence may trap sand that arrives here either as a result of anthropogenic or natural processes, and may also delay or impede movement further to the northeast along the predicted net bed sediment transport pathway. It is notable that the sandier sediments are located predominantly within areas of known historic dredging activity and accumulations of fine material are not distributed more widely along the base of the bank outside of the areas of impact. Therefore, it seems possible that the sandy sediments were mobilised during the dredging process and their subsequent transport away from the site has been assisted by hydrodynamic processes and/or local bathymetric features.

Coincident with increasing depth is an apparent fining of sediment to the west of the extraction site and these factors appear to influence the distribution of benthic assemblages in the area.

The nature of the substrata and their associated features are key elements in determining the distribution of faunal communities (Glémarec, 1973; Künitzer *et al.*, 1992). The use of sidescan sonar and bathymetric techniques in the current study enabled the discrimination of such features and has aided the interpretation of the faunal distributions. The employment of these geophysical techniques to map the bathymetric features and the extent of dredging disturbance have proved essential for the interpretation of wider cause and effect relationships. Furthermore, this investigation has demonstrated that the combination of conventional grab sampling, and remote acoustic techniques provides a robust approach to mapping the physical status of the seabed. The facility to map the distribution of habitats and their associated biological assemblages is essential to evaluations of the acceptability of proposed, ongoing or historic dredging activity. This may be achieved using conventional grab sampling techniques (Newell *et al.*, 2001), but cost considerations invariably limit the degree of spatial resolution in areas of habitat complexity.

When the outcomes of the above studies are considered in combination, they indicate that the effects of extraction on the benthic fauna and sediments may persist over time within dredging areas (see earlier sections) and may also extend some distance beyond. It is also evident from these findings that it is essential to understand how the biological patterns relate to the environmental setting in order to distinguish between anthropogenic impacts and changes associated with topographic features.

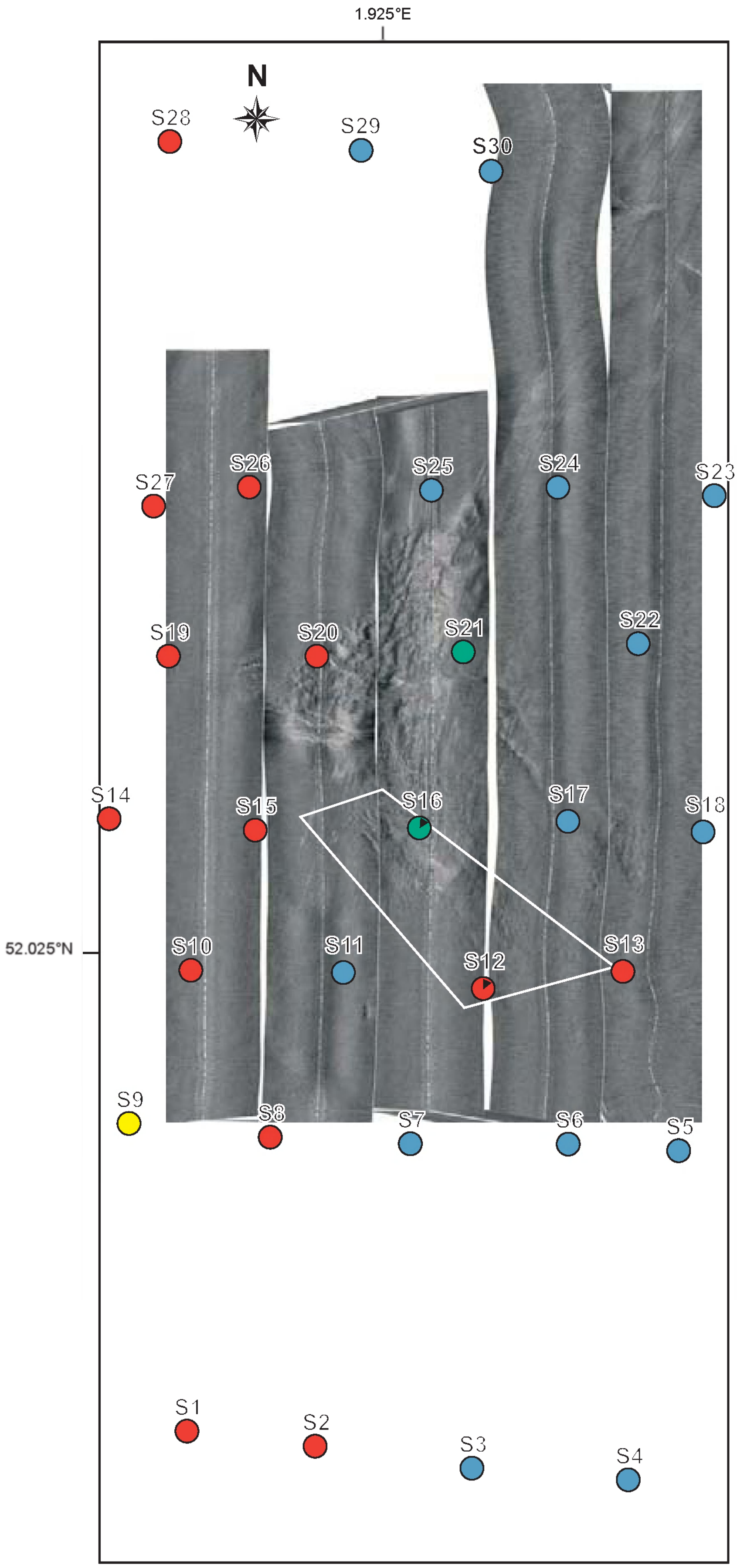



*Figure 7.9. Sites sampled as part of the 2001 spatial survey of Area 222 superimposed on the sidescan sonar mosaic produced in the same year. Red symbols represent 'Assemblage A', blue symbols are 'Assemblage B' and green symbols represent 'Assemblage C'*

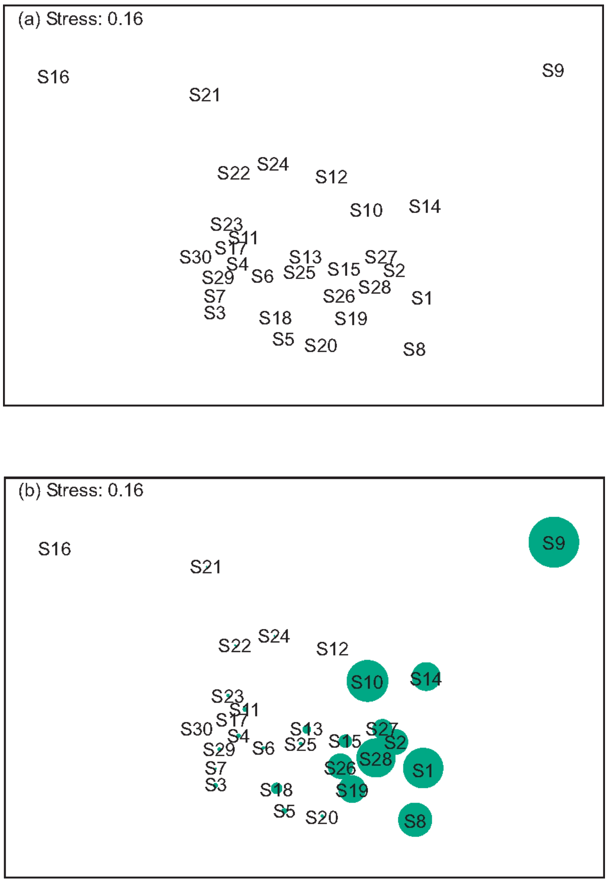



***Figure 7.10. a) MDS of Bray-Curtis similarities from log-transformed species abundance data from samples collected within and in the vicinity of Area 222 in 2001 (Codes as in Figure 7.9), b) the same MDS ordination but with superimposed circles proportional in diameter to values of % silt/clay***

# 8. SPATIAL INVESTIGATIONS OF HASTINGS SHINGLE BANK

## 8.1. Methods

### 8.1.1. Sampling design

A spatial investigation of conditions at the current and relinquished sectors of the Hastings extraction sites was conducted. The design of this spatial study was based on the methods developed by Brown *et al.* (2001). Initially, using this approach, the site of interest is intensively surveyed using acoustic methods (see also Limpenny *et al.*, 2002). In the current study, sidescan sonar was adopted as the primary tool for generating an acoustic basemap. However, comparable approaches using AGDS and multibeam technology have also been employed elsewhere (Service, 1998; Foster-Smith, 1999; Kostylev *et al.*, 2001; Anderson *et al.*, 2002). The output from the sidescan sonar survey (i.e. a sidescan sonar mosaic) carried out in 2002 was divided into acoustically distinct regions which, following groundtruthing using conventional grabbing (0.1 $m^2$ Hamon grab) and photographic techniques, results in the physical and biological characterisation of the acoustic regions. At this stage, the sidescan sonar mosaic can also be used to detect the effects of dredging on the seabed. An AGDS survey was also conducted across the region in 2002. The following year, a multibeam bathymetric survey was carried out to generate a 100% coverage map of the area. In order to construct a validated 'biotope map' the relationships between the physical habitat characteristics, biological assemblages and acoustic regions were tested using a range of univariate and multivariate statistical techniques. In addition, information from the EMS was employed to give an indication of the intensity of dredging activity across the region.

### 8.1.2. Sidescan sonar surveys

A sidescan sonar survey was undertaken using a Datasonics™ SIS 1500 digital chirp sidescan sonar system in July 2002. The purpose of this survey was to identify the spatial distribution of sediments and bedforms across the current and relinquished zones of the Hastings Shingle Bank extraction areas and also across the wider region (Boyd, 2002). Thirteen survey lines (approximately 5 km long) were surveyed in a north/south orientation using a 400 m line spacing in order to achieve 100% coverage of the survey area. The digital data were acquired and post-processed using the Triton Isis™ and Delphwin™ software packages, producing a geo-referenced, on-screen mosaiced image of the survey lines (see Section 3.3). The sidescan sonar record was used to delineate acoustically distinct regions (see Brown *et al.*, 2001).

A QTC AGDS survey was carried out at the same time as the sidescan sonar survey. This allowed a comparison of the two acoustic datasets and hence an examination of the utility of the AGDS output when compared to the sidescan sonar output (Figure 8.4).

In 2003 a multibeam bathymetry survey was carried out over the Hastings Shingle Bank. Multibeam technology allows the dual collection of acoustic backscatter information (similar to sidecan sonar data) and also very detailed bathymetric information. The output is then used to generate very detailed maps of the seabed showing the distribution of sediment in relation to seabed topography and allows the discrimination of comparatively small seabed features such as rippled sand and trailer suction dredge tracks.

### 8.1.3. The use of Electronic Monitoring System (EMS) data

Annual records showing the location and intensity of dredging at the Hastings Shingle Bank were obtained from Posford Haskoning Limited. These records were based on block analysis of the EMS data and were provided in digital format. Records from 1993 to 2001 were input onto a GIS and the images were geo-referenced. A 100 m x 100 m grid was superimposed onto each EMS record and the total annual hours of dredging for each grid square was recorded. These values were then summed across all years in order to calculate the cumulative dredging intensity in each 100 m x 100 m grid square. This output was categorised by dredging intensity to provide a map of the cumulative dredging effort at the Hastings Shingle Bank from 1993 to July 2001. This plot allows inferences to be drawn concerning the relationships between faunal distributions and the cumulative dredging intensity that the region has been exposed to between 1993 and 2001.

### 8.1.4. Benthic Survey

A 0.1 $m^2$ Hamon grab was used to sample sediments and benthos within each of the acoustic regions identified from the sidescan sonar image. Sampling positions were located randomly within each of the regions and the numbers of samples were determined in proportion to the total area of each acoustic region (see also Brown *et al.*, 2001).

## 8.2. Results

Samples from the 2002 Hastings Area X and Area Y time-series investigations (see Section 5) along with those generated during the more spatially extensive survey carried out in the same year were used in the following analyses.

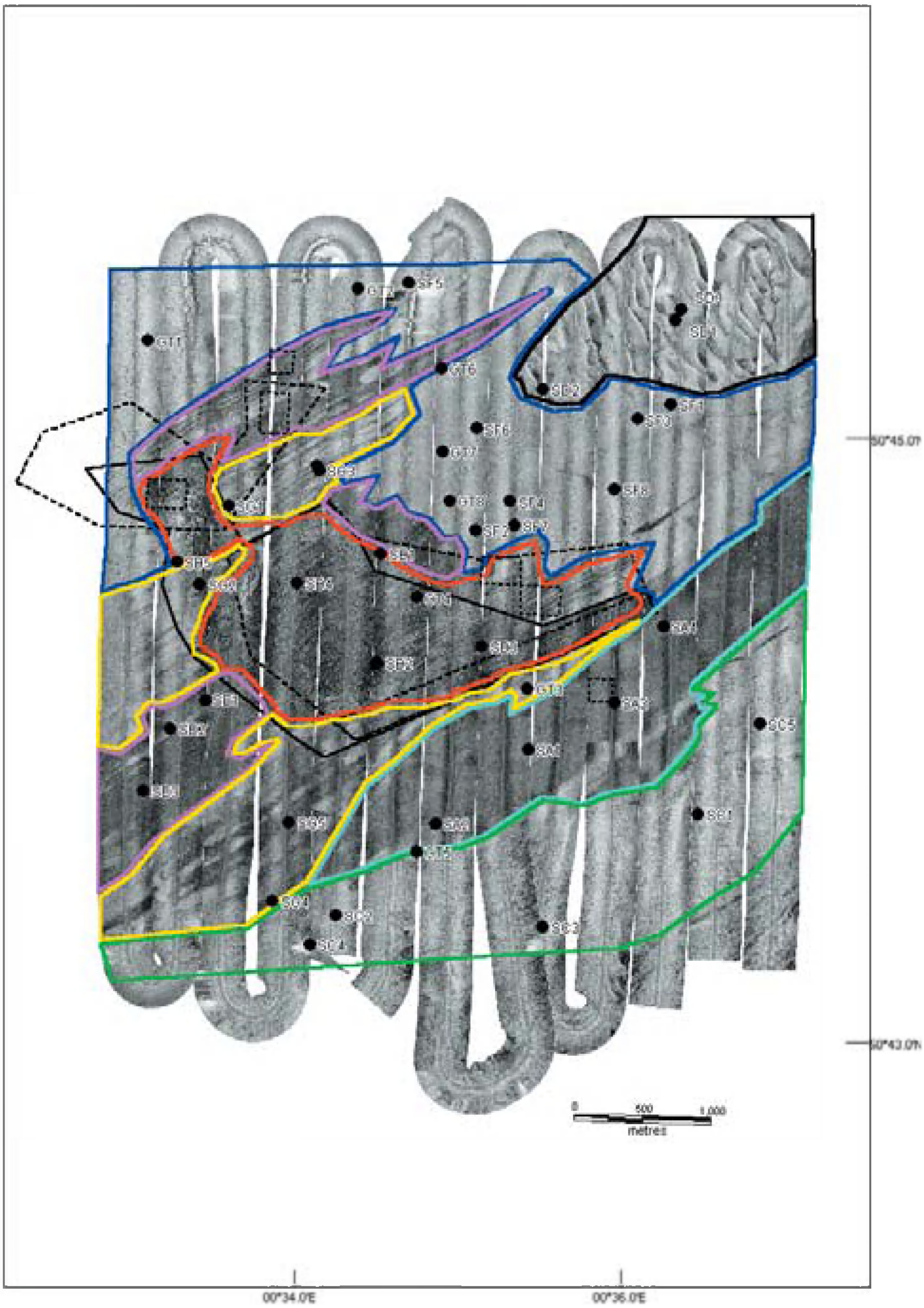


*Figure 8.1. Sidescan sonar mosaic of the Hastings spatial survey showing boundaries between acoustically distinct regions and positions of grab sampling*

### 8.2.1. Sidescan sonar survey

The substrata over the survey area fall into three broad categories, namely sands, sandy gravels, and sand veneers of varying thickness overlying coarser substrata. Following the interpretation of the sidescan sonar images collected in 2002, the survey area was divided into seven acoustically distinct areas. The spatial distribution of these areas is presented in Figure 8.1 and examples of sidescan sonar images from each area are given in Figure 8.2.

Acoustic Region A located in the shallowest water of the Hastings Shingle Bank (Figure 8.2) and Region E, present in two discrete locations to the west and north of the extraction licence, have similar substrata which are characterised by uniform, stable sandy gravels (Figure 8.3). The presence of trawl marks suggests that these areas are fished using demersal towed gear. Region A forms a distinct acoustic boundary with Region C, which is located in deeper water to the south (Figure 8.2), and is predominantly composed of strongly rippled sands (Figure 8.3) interspersed

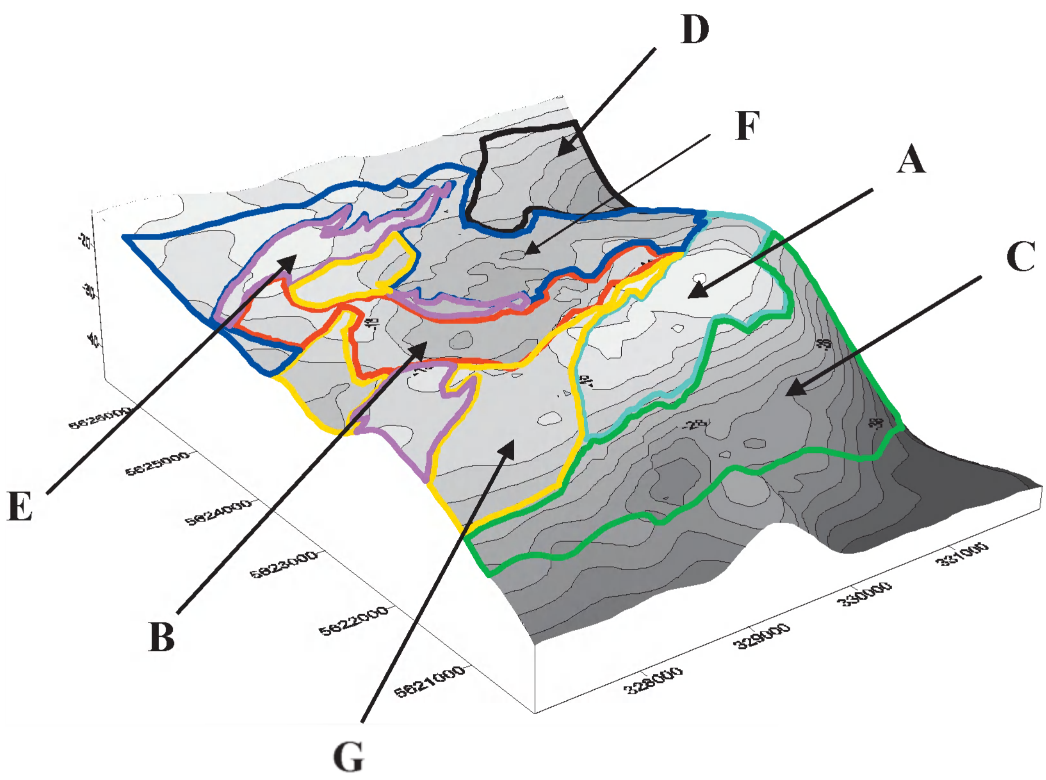



*Figure 8.2. Bathymetric plot of the survey area showing the seven acoustically distinct regions (A, B, C, D, E, F and G) determined from the sidescan sonar data.*

with coarser patches of sediment, again with evidence of trawling activity. The sand ripples suggest that bed sediment transport is aligned along a NE/SW axis, which is consistent with existing hydrodynamic information. Acoustic Region F is a sandy area (Figure 8.3) located to the east and north of the Hastings Shingle Bank. The sands are not as strongly rippled as those in acoustic region C. In addition, the sands within acoustic region F are not rippled over the full extent of the region. There is some evidence to suggest that the sand in acoustic region F forms a veneer of varying thickness overlying coarser substrata. To the east of this region, the sandy substratum is formed into large sand waves and this area was defined as acoustic Region D. Here, coarser material (gravel and shell) is present in the troughs between the sand waves (Figure 8.3). Acoustic Region G consists of a thin, discontinuous veneer of rippled sand covering a gravelly sediment (Figure 8.3). Within the licensed extraction sites (Acoustic region B), the gravelly sediments are intensively furrowed by tracks caused by the actions of suction hopper trailer dredgers. In general, the dredged tracks were infilled with sandy material and are separated by coarser deposits. The results of this survey are in broad agreement with those reported in Brown *et al.* (2001), although the current survey was able to distinguish a larger number of distinctive acoustic classes. Brief descriptions of the acoustic regions derived from underwater video and sidescan sonar data are given in Table 8.1.

***Table 8.1. Descriptions of acoustic regions derived from underwater video and sidescan sonar data***

| Acoustic region | Description from Underwater Video/sidescan sonar data |
|---|---|
| A | Undisturbed slightly sandy gravel with attached epifauna |
| B | Sandy gravel disturbed by aggregate dredging. Few conspicuous epifauna |
| C | Veneer of clean, mobile sand of varying thickness overlying gravel. Possibly impacted by trawling action |
| D | Coarse/medium shelly sand formed into sandwaves interspersed with patches of gravel and coarse shell |
| E | Sandy gravel |
| F | Comparatively thick veneer of mobile sand overlying gravel |
| G | Thin veneer of slightly gravelly sand overlying gravel |

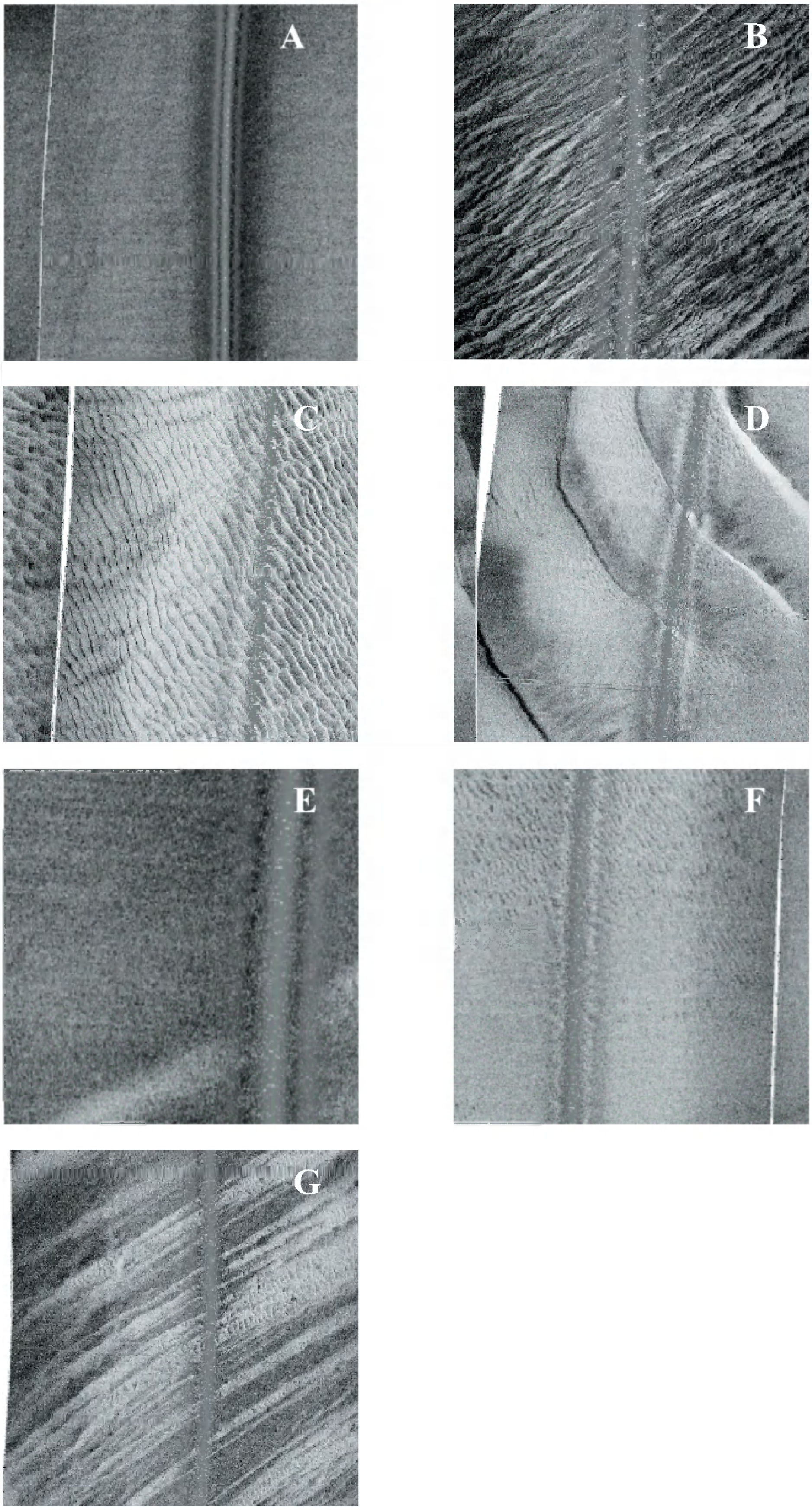



***Figure 8.3. Examples of sidescan images from each of the seven identified acoustic regions (A-G)***

### 8.2.2. QTC AGDS survey

Post-processing of the AGDS data produced a number of acoustic clusters which are represented in Figure 8.4 as different colour classes. There is some broad agreement between the output of the AGDS and sidescan sonar surveys with the offshore sands and the undisturbed gravels, defined using sidescan sonar, falling into separate AGDS classes. Other more heterogeneous substrata appear to be less well defined by AGDS than by sidescan sonar. For example, the acoustic returns from the intensively dredged zone

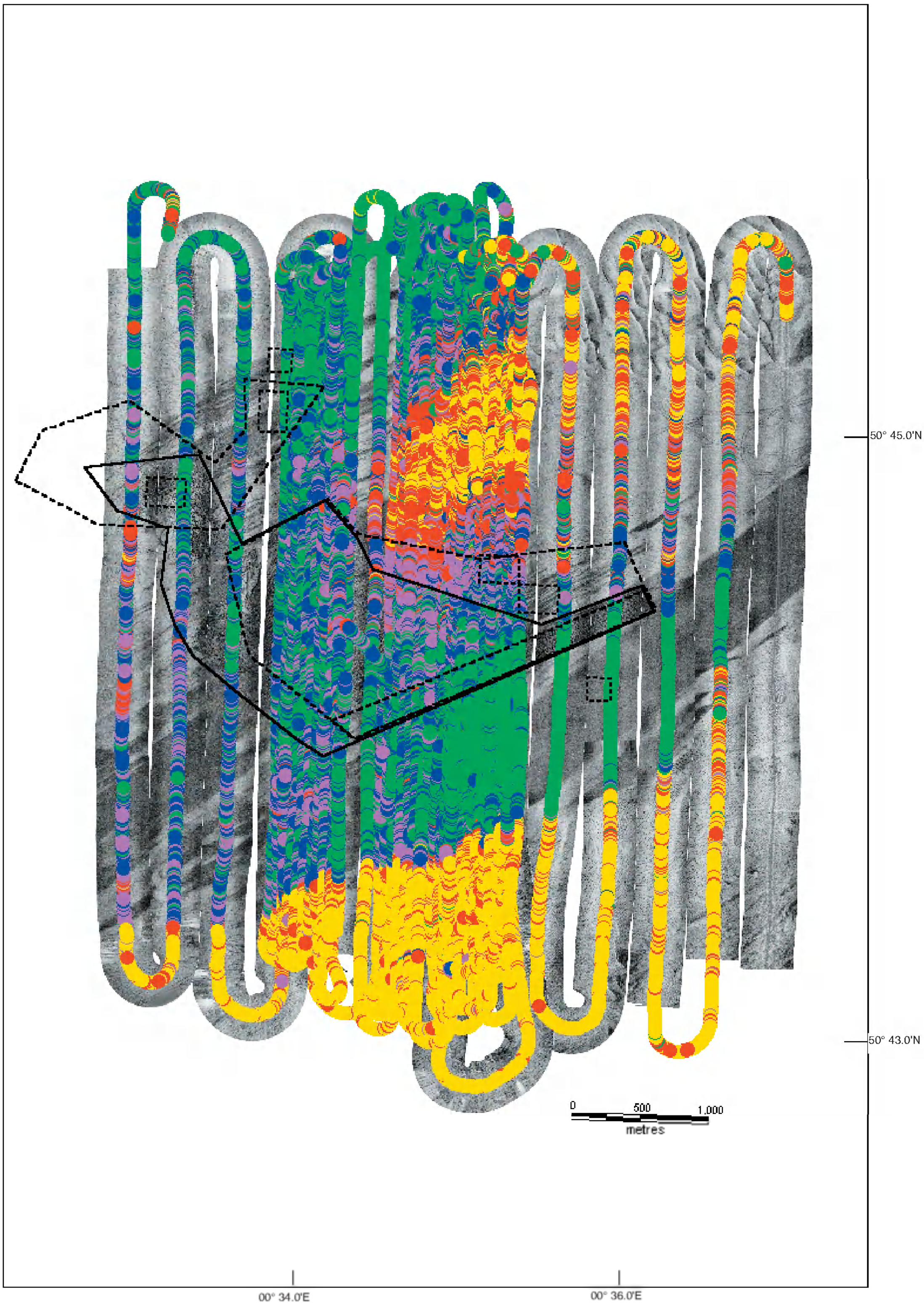



***Figure 8.4. Classified output from a 50 kHz Quester Tangent™ survey carried out at the Hastings Shingle Bank in 2002 superimposed on the sidescan sonar mosaic. The positions of extraction licences (current and historic) and the temporal survey boxes from Area X and Area Y are also shown***

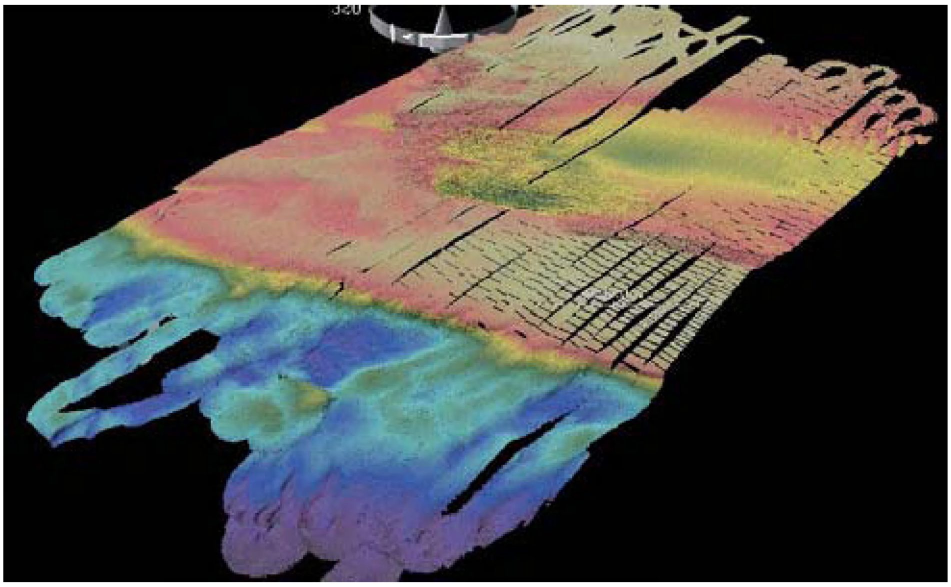


***Figure 8.5. Multibeam bathymetry of the Hastings shingle bank (2003 survey). The colours represent varying depths of water and the colour scale, from deep water to shallow water, is as follows: Purple – Blue – Green – Yellow – Orange – Red***

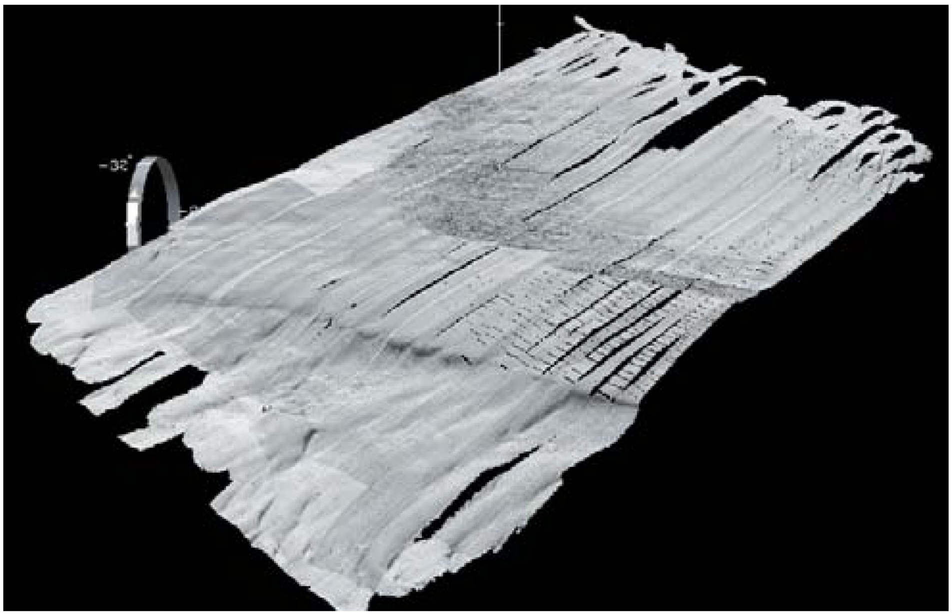


***Figure 8.6 Acoustic backscatter draped over the multibeam bathymetry from 2003***

within the relinquished sector of Hastings Area Y, fall into a number of different acoustic classes and it is not readily apparent why this should be the case. It is possible that AGDS is reacting to features of the substrate that are not identifiable using sidescan sonar techniques such as thickness of sand veneers, or other geophysical properties. Further work is required to fully assess the utility of this technique at marine aggregate extraction sites.

### *8.2.3. Multibeam bathymetry survey*

Figures 8.5 and 8.6 show the output from the multibeam survey carried out across the Hastings Shingle Bank in 2003. Figure 8.5 is a colour scaled digital terrain model (DTM), showing the varying depths of water over the area surveyed. Figure 8.6 is a sun-illuminated representation of the same DTM, with the associated acoustic backscatter data superimposed over the surface of the image. Deeper water offshore (purple and green shading) rapidly gives way to shallower water (yellow and orange shading) on reaching the southern edge of the Hastings Shingle Bank that runs east/west across the image. The impacts of trailer suction dredging activity within Hastings Areas X and Y can be clearly discerned as areas of rough uneven topography. Water depths in the areas affected by dredging activity show broad agreement with surveys carried out by the aggregate industry (Coastline Surveys, 2003).

### 8.2.4 Sediment characteristics and environmental variables

A group average sorting dendrogram based on the particle size distribution of sediment samples was produced and this was used to identify groups of samples with similar particulate composition (Figure 8.7). This analysis indicates that the spatial and temporal samples collected in 2002 could be broadly divided into two groups according to their particle size distribution. The first group, on the left of the plot, contained all the samples from acoustic regions C, D and F, three samples from the site of low dredging intensity at Area Y and one sample from the Area X low dredging intensity site. All other samples were found in a separate cluster to the right of the plot. Results from ANOSIM indicate that there is no significant difference ($p>0.05$) between the sediments at reference site 2 and acoustic region A. Therefore, this confirms that sediments from this reference site are representative of the wider region of undisturbed gravelly substrata. Similarly, there was no significant difference ($p>0.05$) identified between sediments at reference site 1 and acoustic region A. However, the extent of the difference appeared to be minor as reflected in the very low ANOSIM R-value (Clarke, 1993).

SIMPER analysis grouped the acoustic regions and temporal sites into three broad substrate types: sandy gravels, gravelly sands and sands (Figure 8.8) and the proportion of the total survey accounted for by each acoustic region is shown in Figure 8.9.

### 8.2.5. Macrofaunal assemblage structure

**Univariate Analyses**

A total of 245 taxa were identified from 33 Hamon grab samples. Figure 8.10 shows the number of species found within each acoustic region and also from the Hastings Area X and Area Y temporal sites. Acoustic regions A, E and G have significantly ($p<0.05$) higher numbers of species than regions C, D and F. Region B was not significantly different ($p>0.05$) from either of these two broad groups. Regions C, D and F are characterised by low densities of macrofauna, whilst regions A and G have higher numbers of individuals. Acoustic regions B and E have intermediate numbers of individuals. Interestingly, gravelly deposits found within the area of high dredging intensity at Hastings Area X supported the lowest number of species and densities of benthic invertebrates of any of the sandy gravel sediments present in the region. This reflects the impact of recent dredging activity in this area. In contrast, the numbers of species found within the area

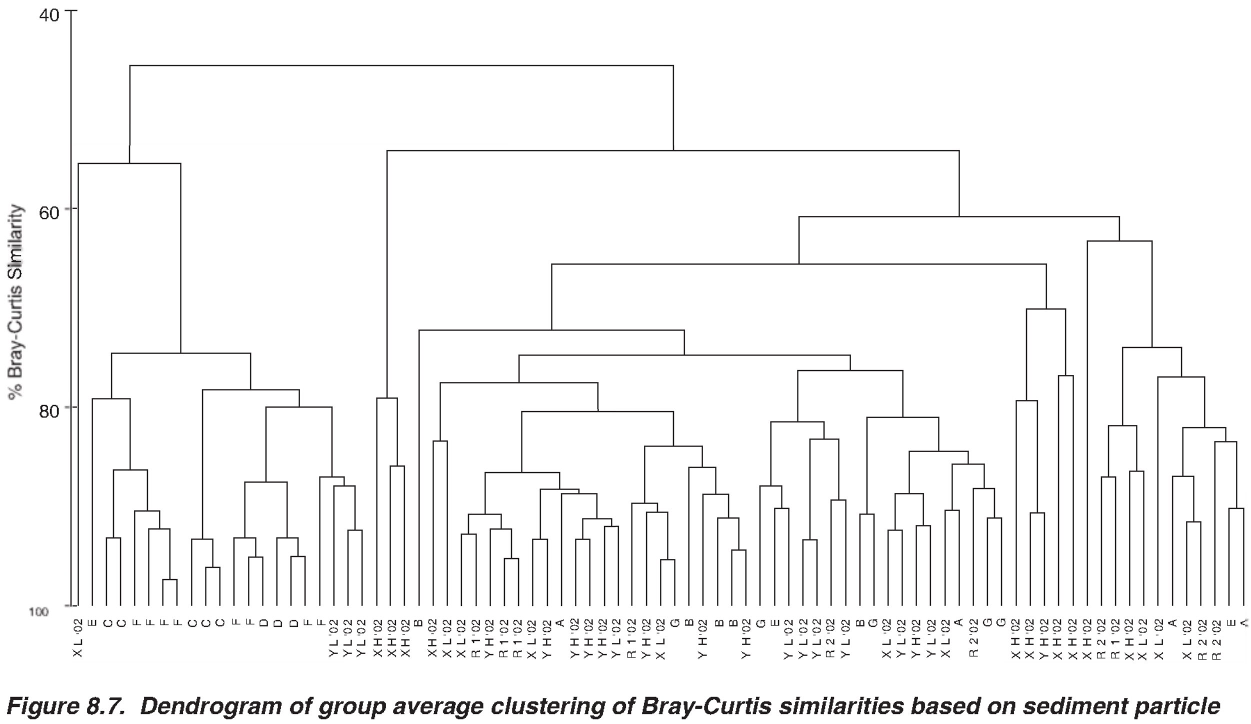



***Figure 8.7. Dendrogram of group average clustering of Bray-Curtis similarities based on sediment particle size distribution data in phi classes from samples collected from the Hastings region in 2002***

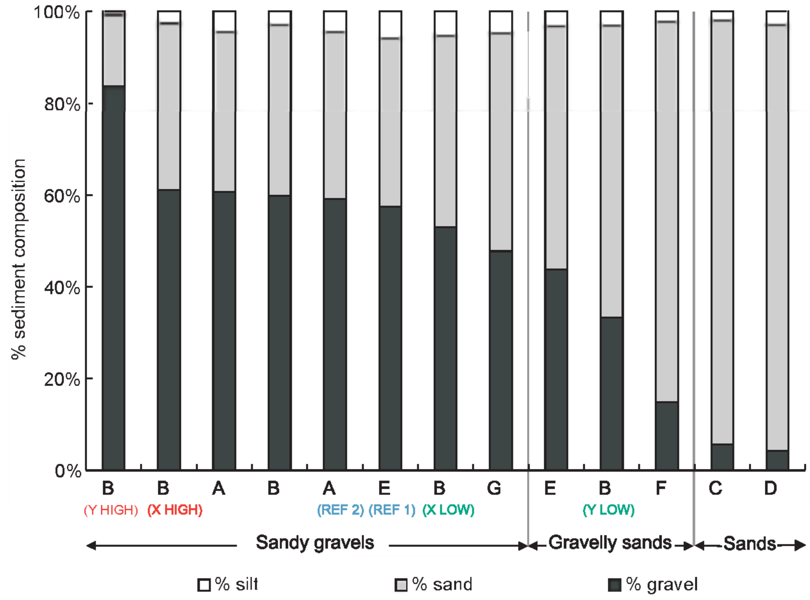



*Figure 8.8. Particle size composition of samples from different areas based on results from a SIMPER analysis*

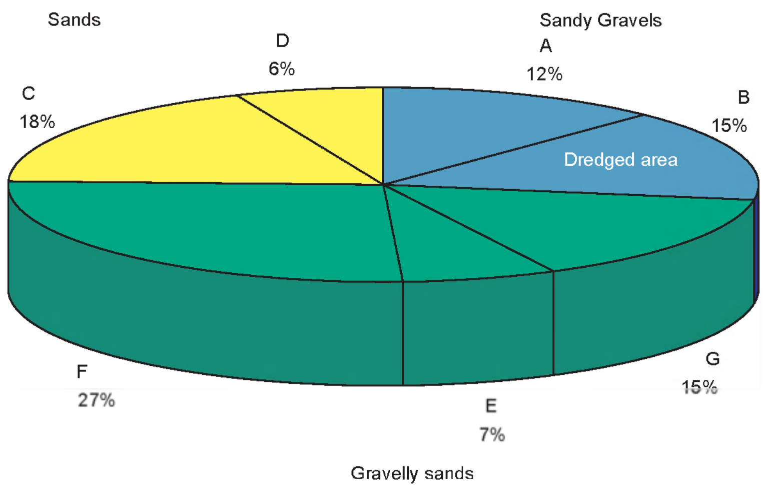



*Figure 8.9. Pie chart showing proportion of Hastings survey area accounted for by each acoustic region*

of low dredging intensity at Area X were either higher than, or not significantly different to, the values found in the undisturbed sandy gravels regions (Areas A and G). In common with areas of low dredging intensity at Area X, deposits from the relinquished sectors of Hastings Area Y support a similar species variety and population density of benthic invertebrates to those found in comparable undisturbed sediments in regions A and G but not in region E. This implies that the rate of recolonization has been sufficient within the period following cessation of dredging to allow restoration of species variety and population density to levels consistent with those found in the undisturbed sandy gravel regions A and G. Samples from the area of low intensity at Hastings Area Y were found to contain a similar number of species and individuals to that recorded in analogous gravelly sands.

**Multivariate Analysis**

A group average sorting dendrogram identifies sample groupings based on the percentage similarity of macrofaunal samples (Figure 8.11). This dendrogram shows some parallels with the dendrogram arising from the analysis of particle size data. For example, samples

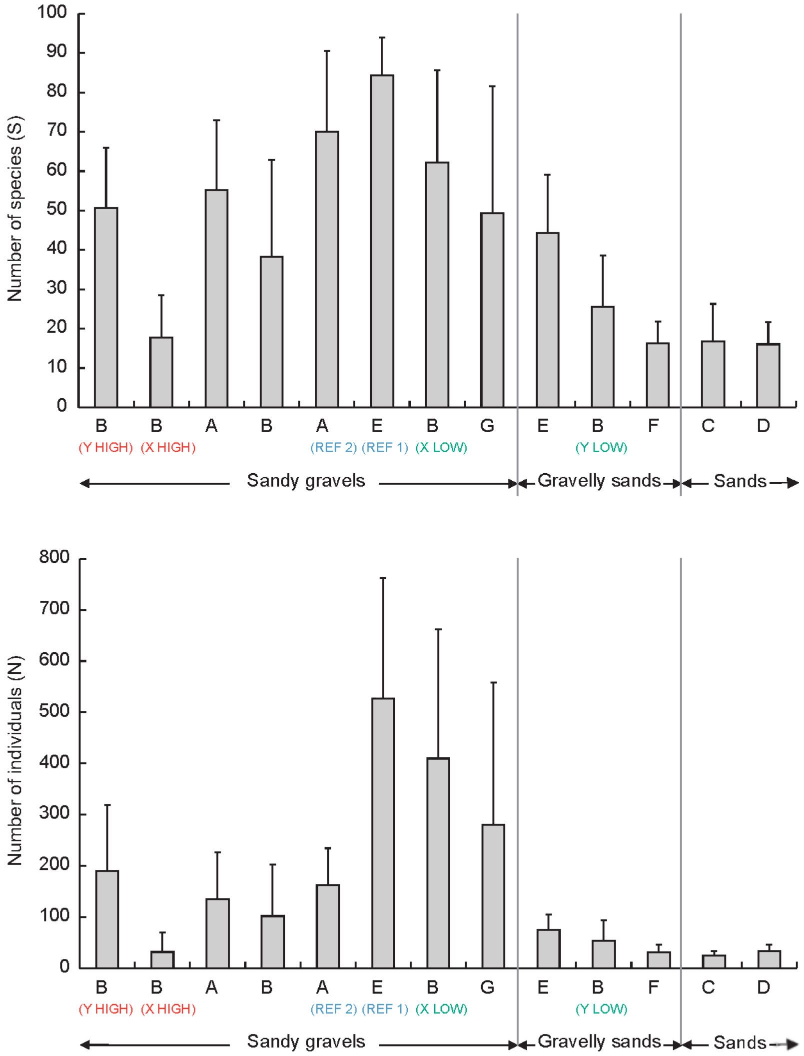



***Figure 8.10. Summary of means (±S.D.) for numbers of species (S) and number of individuals (N) from within each sampled location***

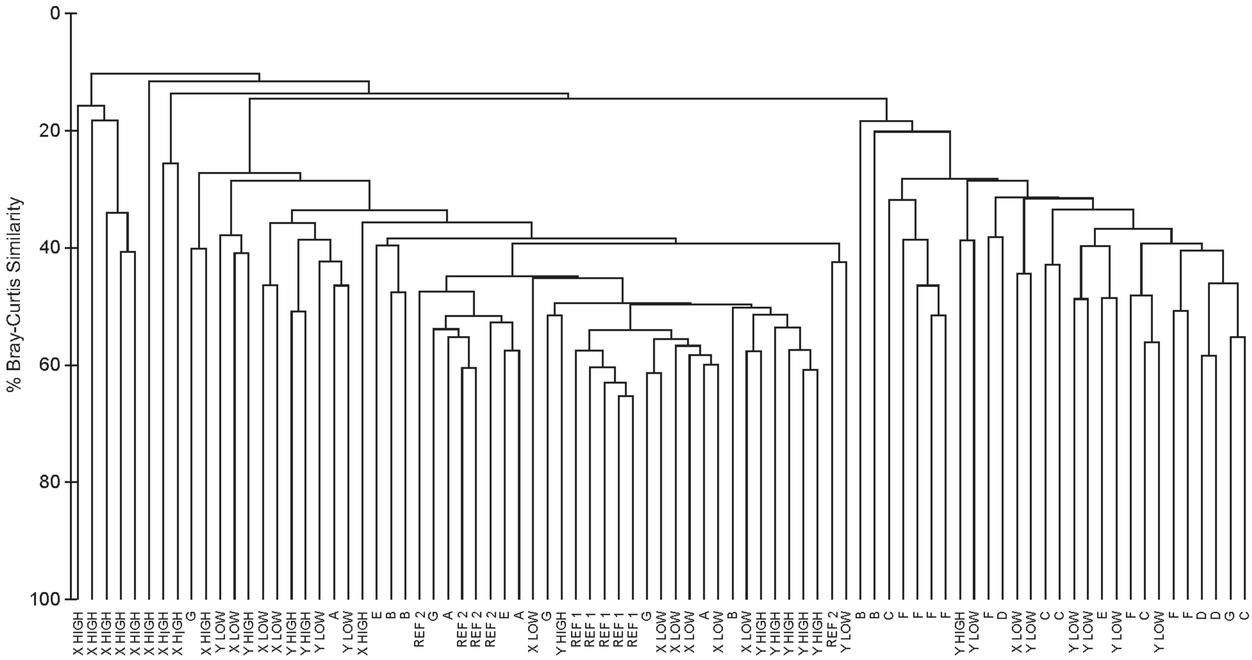



***Figure 8.11. A group average sorting dendrogram of Bray-Curtis similarities based on 4th root transformed macrofauna abundance data collected over the Hastings survey area in 2002***

from regions C, D and F have formed one cluster to the right of the plot, whilst samples from regions A, E and G have formed another. However, a number of samples from the Area X high dredging intensity site showed very little similarity with all other samples. This area coincides with the resumption of dredging activity in this year. Samples from acoustic region B are loosely affiliated to both of the main groups.

An ANOSIM test was conducted to determine if the assemblages from each of the acoustic regions were faunistically distinct. Results show that the greatest differences exist between the gravelly sediments of acoustic regions A and E and the sandy sediments of acoustic regions D and C (Table 8.2). Interestingly,

***Table 8.2. ANOSIM results between assemblages (colonial excluded) from acoustically distinct regions based on 4th root transformed data (* denotes significant difference at the p <0.1; ** denotes significant difference at p <0.05).***

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| B | 0.119 | | | | | |
| C | 0.856** | 0.436** | | | | |
| D | 0.944** | 0.149 | 0.138 | | | |
| E | -0.037 | -0.015 | 0.723** | 0.889* | | |
| F | 0.47** | 0.576** | 0.289** | -0.048 | 0.47** | |
| G | -0.106 | 0.008 | 0.568** | 0.395* | -0.077 | 0.592** |

***Table 8.3. Results from SIMPER analysis of macrofaunal data (colonial taxa excluded, 4th root transformed), listing the main characterising species from each acoustically distinct region***

| Acoustic Region | Taxon | Average Abundance | % | Cumulative % | Average similarity |
|---|---|---|---|---|---|
| A | *Lumbrineris gracilis* | 3.50 | 5.79 | 5.79 | **40.01%** |
| | *Upogebia* (juv.) | 4.25 | 5.68 | 11.48 | |
| | *Balanus crenatus* | 14.00 | 5.64 | 17.10 | |
| | *Polycirrus* sp. | 2.00 | 5.18 | 22.28 | |
| | *Sabellaria spinulosa* | 4.00 | 5.07 | 27.35 | |
| | *Glycera lapidum* (agg.) | 2.25 | 4.87 | 32.22 | |
| B | *Notomastus* sp. | 3.20 | 7.58 | 7.58 | **22.36%** |
| | *Polinices pulchellus* | 0.80 | 6.64 | 14.22 | |
| | *Balanus crenatus* | 27.60 | 5.44 | 19.65 | |
| | *Ampelisca spinipes* | 1.80 | 4.99 | 24.65 | |
| | *Spisula* (juv.) | 1.40 | 4.29 | 28.93 | |
| | *Ampelisca brevicornis* | 1.20 | 4.29 | 33.22 | |
| C | *Nephtys cirrosa* | 2.80 | 21.46 | 21.46 | **33.70%** |
| | *Spiophanes bombyx* | 1.60 | 19.90 | 41.35 | |
| | *Bathyporeia elegans* | 2.60 | 18.14 | 59.50 | |
| | *Diastylis bradyi* | 0.80 | 10.43 | 69.92 | |
| | *Gastrosaccus normanii* | 1.40 | 8.67 | 78.60 | |
| | *Glycera oxycephala* | 1.00 | 5.15 | 83.75 | |
| D | *Gastrosaccus spinifer* | 2.67 | 15.24 | 15.24 | **48.13%** |
| | *Diastylis bradyi* | 3.00 | 14.79 | 30.03 | |
| | *Nephtys cirrosa* | 4.33 | 14.70 | 44.73 | |
| | *Spiophanes bombyx* | 2.67 | 13.34 | 58.07 | |
| | *Abra prismatica* | 1.00 | 12.43 | 70.50 | |
| | *Lumbrineris gracilis* | 1.00 | 12.43 | 82.93 | |
| E | *Sabellaria spinulosa* | 6.33 | 9.56 | 9.56 | **36.37%** |
| | *Notomastus* sp. | 4.67 | 9.46 | 19.02 | |
| | *Aonides paucibranchiata* | 3.00 | 9.23 | 28.25 | |
| | *Echinocyamus pusillus* | 2.00 | 7.37 | 35.62 | |
| | *Dendrodoa grossularia* | 3.00 | 7.37 | 42.98 | |
| | *Lumbrineris gracilis* | 2.33 | 7.37 | 50.35 | |
| F | *Bathyporeia elegans* | 3.75 | 16.78 | 16.78 | **33.82%** |
| | *Ophelia borealis* | 2.50 | 14.66 | 31.44 | |
| | *Nephtys cirrosa* | 1.38 | 12.64 | 44.08 | |
| | *Gastrosaccus spinifer* | 1.63 | 10.45 | 54.53 | |
| | *Notomastus* sp. | 4.00 | 6.49 | 61.02 | |
| | NEMERTEA | 1.25 | 3.68 | 64.69 | |
| G | NEMERTEA | 3.60 | 8.36 | 8.36 | **27.68%** |
| | *Caulleriella alata* | 3.20 | 8.29 | 16.65 | |
| | *Notomastus* sp. | 5.20 | 5.14 | 21.79 | |
| | *Poecilochaetus serpens* | 8.60 | 4.97 | 26.76 | |
| | *Lumbrineris gracilis* | 3.80 | 4.52 | 31.28 | |
| | *Polycirrus* sp. | 3.00 | 4.44 | 35.72 | |

there was no significant difference ($p>0.05$) between the assemblages present within the dredged gravels of region B and the sandy substrata of region D.

SIMPER analysis was used to identify the characteristic species from each of the acoustic regions. Table 8.3 reveals that most of the characterising species from the acoustic regions are typical of the sediment types found within these areas. For example, the polychaetes *Ophelia borealis*, and *Nephtys cirrosa*, are typical inhabitants of sandy substrates, and these were found in acoustic regions C, D and F. Species characteristic of coarser substrata such as the crustaceans *Balanus crenatus* and *Upogebia* and the sea squirt *Dendrodoa grossularia*, were associated with acoustic region A. Acoustic regions B, E and G had species typical of both sands and gravels.

## 8.3. Discussion

The results of this study and other spatially extensive surveys carried out at the Hastings Shingle Bank (e.g. Brown *et al.*, 2001; Hewer *et al.*, 2002; Brown *et al.*, 2004) have provided insights into the distribution of sediments and their associated assemblages within the aggregate extraction area and across the wider region. The purpose of this investigation was to check the 'representativeness' of selected treatment and reference sites sampled as part of time-series investigations. The application of an integrated approach using a suite of destructive (e.g. grabs) and non-destructive (photographic and acoustic) techniques was successful in characterising the nature and extent of substrata and their associated assemblages. Reference locations were physically almost indistinguishable from both dredged and undredged gravelly substrata present within the wider region. Therefore, this supports the selection of these sites as appropriate reference points against which the effects of marine aggregate extraction may be judged over time.

The current study showed that dredged gravelly deposits within the area of high dredging intensity at Hastings Area X supported an assemblage similar to those recorded in sandy substrata in the region. In U.K. waters, gravels typically support a richer assemblage than sandy substrata (e.g. Eleftheriou and Basford, 1989; Brown *et al.*, 2002). Therefore, the fact that assemblages from the area of high dredging intensity at Hastings Area X are indistinguishable from those in sandy deposits suggests that the gravels are impoverished. This observation lends some support to the conceptual models erected early in the project and which are discussed in Section 10.

In contrast, the deposits from within the area of low dredging intensity at Hastings Area X support a similar number of benthic species and individuals to those undisturbed sandy gravel sediments in the region.

Samples from the high dredging intensity site at Area Y show similar numbers of species and individuals to undisturbed sandy gravel deposits within the region with the exception of reference site 1 within acoustic region E. However, the area within which samples were collected for an analysis of the effects of low levels of dredging intensity at Area Y may be less useful as a long-term monitoring site, since it is located across the boundary between two distinct sediment types. Therefore, samples collected from this area will be subject to the confounding effects of variability arising from natural and anthropogenic factors. This illustrates the importance of having a wider appreciation of the distribution of habitats in relation to study sites. The selection of this treatment site was constrained by the limited area of seabed subjected to low levels of dredging intensity that was relinquished by the aggregate extraction industry in 2001. Whilst this situation is not ideal, sampling at this site may still have some value in assessing the recolonization of dredged sites at the Hastings Shingle Bank.

Analysis of EMS data indicates that areas of seabed selected as treatment sites for time-series investigations are not representative of the highest cumulative levels of dredging intensity recorded within the current extraction licence (see Figure 8.12). Dredging intensity has been shown to be a factor in determining the rate at which the seabed 'recovers' following the cessation of dredging (Boyd *et al.*, 2003). Therefore, areas of the seabed subjected to higher levels of dredging intensity than those represented within the time-series investigations are likely to require longer periods of time for the re-establishment of similar benthic populations.

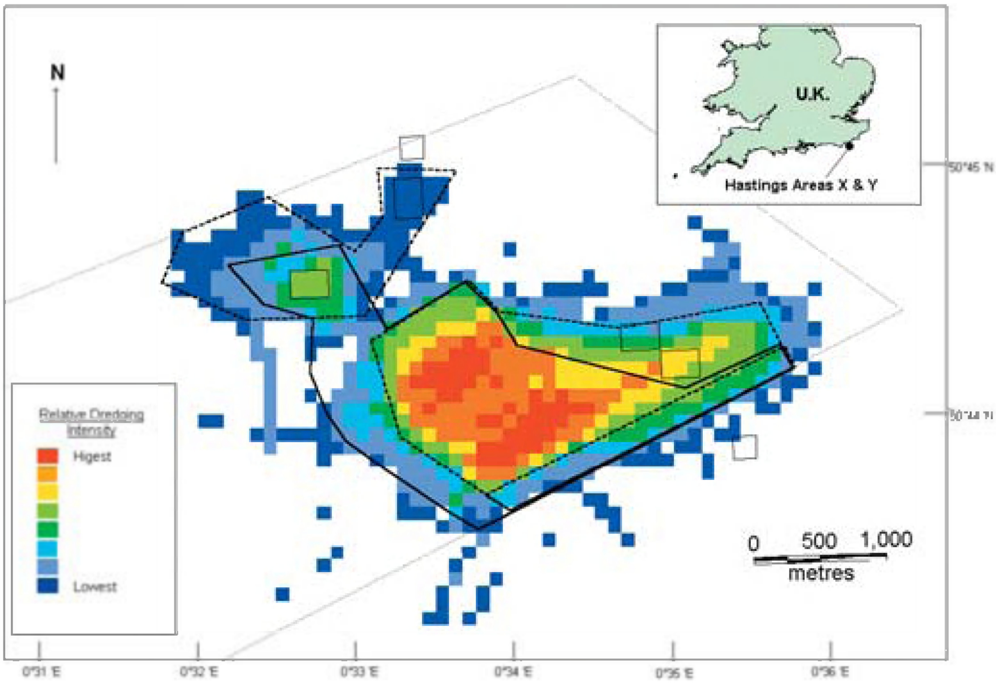



*Figure 8.12. Cumulative area dredged presented as relative levels of dredging intensity, over the period 1993 to July 2002 (data derived from EMS records)*

# 9. SYNTHESIS OF FINDINGS FROM TEMPORAL INVESTIGATIONS

Following the site-specific analysis of each study area, multivariate statistical techniques were employed on the entire Hamon grab data-set obtained from the 2001 time-series investigations from all four extraction sites. This data-set was used in preference to others, because of the availability of a complementary data-set of values of dredging intensity extracted from the EMS. This latter data-set consisted of values of the actual dredging intensity in hours (for each year since 1993) corresponding to the 10,000 $m^2$ square blocks where ten Hamon grab samples were collected, in 2001 from each area (see Table 9.1).

The aim of the data analyses presented in this section is to establish whether there are any generic findings on the environmental effects of dredging activity and/or processes involved in recolonization which may have applicability for managing current or prospective extraction sites elsewhere.

The MDS ordination of macrofaunal assemblage composition from Hamon grab samples collected in 2001 at all four extraction sites, in areas of high and lower levels of dredging intensity and reference sites, is presented in Figure 9.1. Although replicate samples are not strongly clustered in the ordination, samples from dredged areas tend to be spatially separated from the reference locations. Furthermore, despite the variability in the data, ANOSIM results indicate that there is a statistically significant difference ($p<0.01$) between the assemblage structure of samples collected from dredged locations and those obtained from reference sites. Results of ANOSIM also reveal that the differences between the assemblage structure of samples collected from areas of high dredging intensity and reference sites are more pronounced than between the low intensity and reference sites. This is interesting as it suggests that, despite the varying time-interval that has elapsed since cessation of dredging, the differing dredging histories and the variable geological and biological setting of extraction sites (see Section 2), there appears to be some aspect of the selected dredging treatments which makes them distinctive in terms of their species composition. Whether this is because of any dredging induced change brought about by the level of intensity which serves to unify the macrofaunal assemblage structure, or a natural feature of deposits targeted for extraction, remains to be established.

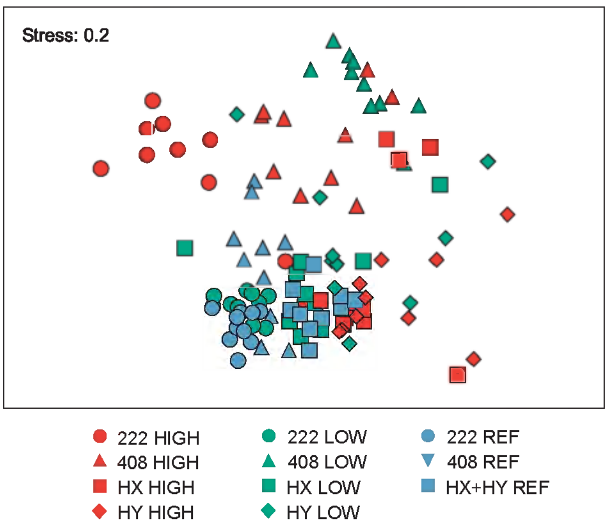



***Figure 9.1. Multi-Dimensional scaling ordination of Bray-Curtis similarities from double square root transformed species abundance data of samples collected from all extraction areas sampled in 2001***

There is also some grouping of samples on the MDS according to region. This is to be expected since samples that are more distant spatially are likely to be less similar biologically, although the similarity of biological samples will also depend on the nature of habitat variability. Clustering of samples from each region may therefore reflect biogeographical differences in the fauna. Analysis of similarities (ANOSIM, Clarke, 1993), confirms that there are significant differences ($p<0.01$) in macrofaunal assemblage structure between all sampled regions. As would be expected, differences in species composition from samples obtained from Hastings Areas X and Y are less distinct than those between other regions.

Further insights into the recovery of fauna following the cessation of extraction can be gained through an examination of the relationships between the assemblage structure and measured environmental variables. Variables investigated in this respect included: sediment particle size characteristics, hours of recorded dredging per annum (1993-2001 inclusive), maximum recorded dredging in any year, total hours of dredging (1993-2001 inclusive), water depth, latitude and longitude. The latter two measures were employed as a proxy for the regional setting. These variables have been correlated with the biological data singly and in combination using the Spearman ranked correlation coefficient (Clarke and Warwick, 1994). The highest few coefficients at each level of complexity identified from BIO-ENV analysis are shown in Table 9.2. This shows the extent of improvement or deterioration in the match between the biota and environmental variables as further variables are added. The best fit between macrofauna species composition and a single environmental variable is achieved with the % fine sand. Other environmental variables considered important for explaining the observed patterns in the macrofaunal assemblage structure were latitude and the % sand. The fit is improved by the addition of other

**Table 9.1. Maximum number of hours of recorded dredging at each sampling location, within a 100 m by 100 m block, for each year (data extracted from the EMS and provided by Posford Haskoning Ltd)**

| Extraction site | Intensity | Year of recorded dredging | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
| Area 408 | HIGH | | | | <0.25 | 1.99 | 9.24 | <0.25 | | |
| | | | | | 0.49 | 2.24 | 8.74 | <0.25 | | |
| | | | | | <0.25 | 1.99 | 9.24 | <0.25 | | |
| | | | | | <0.25 | 1.99 | 9.24 | <0.25 | | |
| | | | | | 0.74 | 2.74 | 6.99 | <0.25 | | |
| | | | | | <0.25 | 1.99 | 9.24 | <0.25 | | |
| | | | | | 0.49 | 2.74 | 10.49 | | | |
| | | | | | <0.25 | 1.99 | 9.24 | <0.25 | | |
| | | | | | 0.49 | 2.24 | 8.74 | <0.25 | | |
| | | | | | 0.74 | 2.74 | 6.99 | <0.25 | | |
| | LOW | | | | | | <0.25 | <0.25 | | |
| | | | | | | <0.25 | <0.25 | <0.25 | | |
| | | | | | | <0.25 | <0.25 | <0.25 | | |
| | | | | | | | <0.25 | <0.25 | | |
| | | | | | | <0.25 | <0.25 | <0.25 | | |
| | | | | | | <0.25 | 0.99 | | | |
| | | | | | | | 0.49 | | | |
| | | | | | | <0.25 | 0.74 | <0.25 | | |
| | | | | | | | 0.49 | | | |
| | | | | | | | 0.49 | <0.25 | | |
| Area 222 | HIGH | 9.99 | 12.49 | 19.24 | 1.24 | | | | | |
| | | 9.99 | 12.49 | 19.24 | 1.24 | | | | | |
| | | 0.74 | 1.24 | 0.99 | | | | | | |
| | | 2.74 | 14.74 | 7.24 | | | | | | |
| | | 8.74 | 39.49 | 15.99 | <0.25 | | | | | |
| | | 9.99 | 12.49 | 19.24 | 1.24 | | | | | |
| | | 9.99 | 12.49 | 19.24 | 1.24 | | | | | |
| | | 1.99 | 16.24 | 11.74 | 11.74 | | | | | |
| | | 11.99 | 24.24 | 17.99 | 1.24 | | | | | |
| | | 13.24 | 31.74 | 16.99 | 0.74 | | | | | |
| | LOW | 0.99 | 3.49 | <0.25 | <0.25 | | | | | |
| | | 0.49 | 2.99 | <0.25 | <0.25 | | | | | |
| | | | <0.25 | | | | | | | |
| | | 1.49 | 2.74 | <0.25 | <0.25 | | | | | |
| | | 0.49 | 1.74 | <0.25 | <0.25 | | | | | |
| | | 1.49 | 2.74 | <0.25 | <0.25 | | | | | |
| | | <0.25 | 1.24 | | | | | | | |
| | | <0.25 | 1.24 | | <0.25 | | | | | |
| | | 1.49 | 2.74 | <0.25 | <0.25 | | | | | |
| | | 0.49 | 1.74 | <0.25 | <0.25 | | | | | |
| Hastings X | HIGH | | | | 7.49 | | | | | |
| | | | | | 28.49 | | | | | |
| | | | | | 28.49 | | | | | |
| | | | | | 7.74 | | | | | |
| | | | | | 7.74 | | | | | |
| | | | | | 13.49 | | | | | |
| | | | | | 5.49 | | | | | |
| | | | | | 7.74 | | | | | |
| | | | | | 7.74 | | | | | |
| | | | | | 13.49 | | | | | |
| | LOW | | | | 0.49 | | | | | |
| | | | | | <0.25 | | | | | |
| | | | | | 0.49 | | | | | |
| | | | | | 0.49 | | | | | |
| | | | | | 0.74 | | | | | |
| | | | | | 0.49 | | | | | |
| | | | | | 0.49 | | | | | |
| | | | | | <0.25 | | | | | |
| | | | | | <0.25 | | | | | |
| | | | | | 0.74 | | | | | |
| Hastings Y | HIGH | <0.25 | 1.49 | 0.99 | 6.24 | 8.24 | 7.49 | 2.24 | 0.49 | 0.49 |
| | | 0.49 | 2.74 | 0.74 | 9.74 | 8.74 | 9.49 | 2.74 | 0.99 | 0.74 |
| | | 0.74 | 4.24 | 0.74 | 9.99 | 10.24 | 10.24 | 3.49 | 1.24 | 0.74 |
| | | 0.49 | 2.74 | 0.74 | 9.74 | 8.74 | 9.49 | 2.74 | 0.99 | 0.74 |
| | | 1.74 | 4.49 | 0.49 | 6.74 | 7.49 | 8.24 | 2.99 | 0.49 | <0.25 |
| | | 1.74 | 4.49 | 0.49 | 6.74 | 7.49 | 8.24 | 2.99 | 0.49 | <0.25 |
| | | 0.99 | 4.74 | 0.74 | 9.74 | 9.99 | 10.24 | 3.24 | 0.74 | 0.49 |
| | | 1.24 | 4.99 | 0.74 | 8.49 | 8.99 | 10.49 | 3.24 | 0.49 | 0.49 |
| | | 1.24 | 4.74 | 0.74 | 8.49 | 8.99 | 10.49 | 3.24 | 0.49 | 0.49 |
| | | 0.99 | 4.74 | 0.74 | 9.74 | 9.99 | 10.24 | 3.24 | 0.74 | 0.49 |
| | LOW | <0.25 | <0.25 | | <0.25 | <0.25 | <0.25 | <0.25 | | |
| | | <0.25 | 1.49 | <0.25 | 0.74 | 0.99 | 0.74 | 0.74 | <0.25 | |
| | | <0.25 | 1.49 | <0.25 | 0.74 | 0.99 | 0.74 | 0.74 | <0.25 | |
| | | 0.49 | 0.99 | <0.25 | <0.25 | 0.49 | <0.25 | | | |
| | | <0.25 | <0.25 | | <0.25 | <0.25 | <0.25 | <0.25 | | |
| | | 0.74 | 1.99 | 0.49 | 1.49 | 0.99 | 0.74 | 0.49 | <0.25 | |
| | | 0.99 | 2.49 | 0.74 | 1.74 | 1.24 | 0.49 | 0.49 | <0.25 | <0.25 |
| | | 0.74 | 1.99 | 0.49 | 1.49 | 0.99 | 0.74 | 0.49 | <0.25 | |
| | | <0.25 | <0.25 | | <0.25 | <0.25 | <0.25 | <0.25 | | |
| | | <0.25 | <0.25 | | <0.25 | <0.25 | <0.25 | <0.25 | | <0.25 |

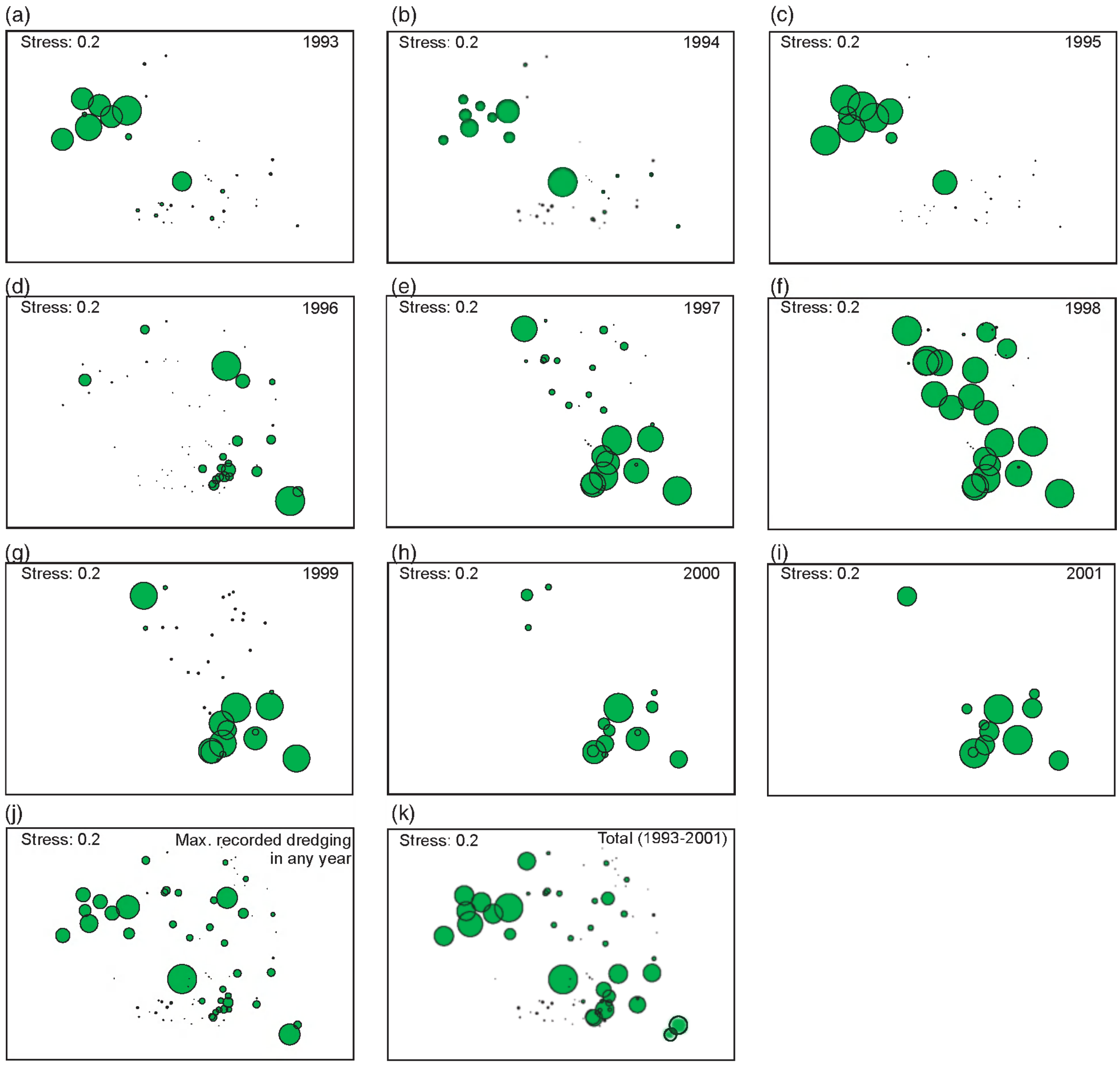



***Figure 9.2. The same MDS as Figure 9.1 with superimposed circles representing values of: (a-i) hours of recorded dredging derived from EMS for each year, (j) maximum recorded dredging in any year, and (k) total hours of recorded dredging intensity 1993-2001***

combinations of variables, the highest correlation being 0.568 with a combination of % fine sand, % medium sand and latitude. Thus it appears that sediment particle size characteristics, particularly the proportion of sands, and the regional setting best explain the macrofaunal assemblage structure. Figures 9.2 (a)-(k) and 9.3 (a)-(e) provide a visual expression of the relationships between the macrofaunal data obtained from Hamon grab samples in 2001 and a number of environmental variables.

The r.IMD has been calculated in order to detect whether there is a difference in the community composition in terms of a higher variance at dredged sites in comparison with reference conditions (Somerfield *et al.*, 1993), since this is often suggestive of disturbed conditions (see for example Warwick and Clarke, 1993; Kenny and Rees, 1994). Inspection of Figure 9.4 suggests that there is a tendency for a higher variance in community composition at dredged areas compared with reference sites and this trend was evident in all years of study. However, this trend should be treated with some caution, because of the limited number of extraction areas involved. An examination of the value of this index obtained at the site of low dredging at Hastings Area Y, serves as a useful reminder that variance can be enhanced as a consequence of inherent substrate variability and patchiness. It is also of interest to note that in 2003, the index was highest overall at Hastings Area X in an area exposed to active dredging, indicating its sensitivity to ongoing disturbance. Despite the scope for this index to be affected by both natural and anthropogenic effects, it offers the potential to rank extraction areas according to variability in community composition which evidence suggests is a property with universal utility.

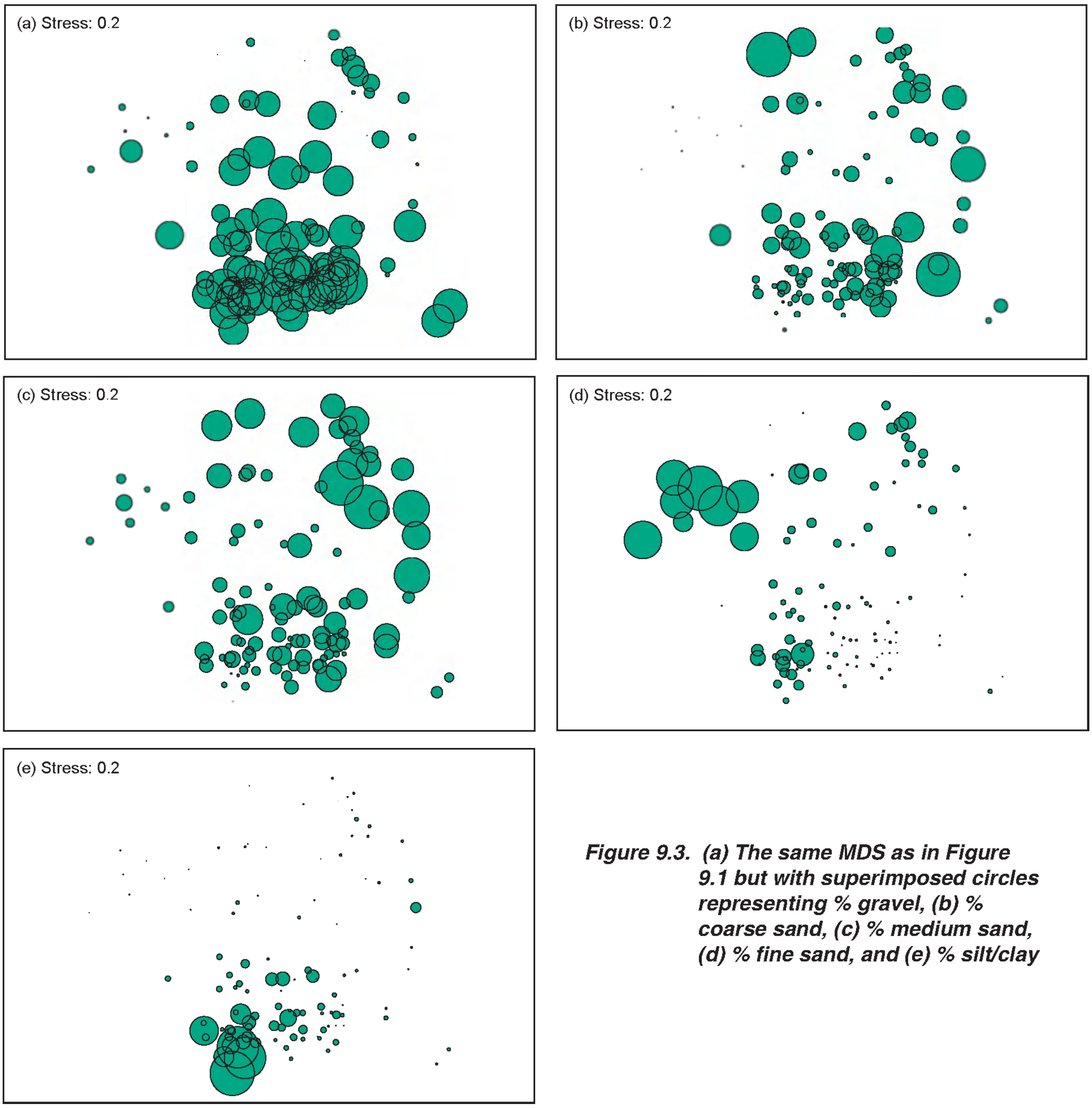



***Figure 9.3.** (a) The same MDS as in Figure 9.1 but with superimposed circles representing % gravel, (b) % coarse sand, (c) % medium sand, (d) % fine sand, and (e) % silt/clay*

***Table 9.2.** Summary of results from BIO-ENV showing the environmental variables that give the best correlation with the trends in the biotic data as identified by multivariate statistical techniques. Lower correlations are omitted from the table. The highest correlation is highlighted in bold*

| Number of variables | Best Variable combination | Spearman rank correlation |
|---|---|---|
| 1 | % Fine Sand | 0.399 |
| 1 | Latitude | 0.383 |
| 1 | % Sand | 0.323 |
| 2 | *Hrs in 1995, Latitude | 0.503 |
| 2 | % Fine Sand, Latitude | 0.494 |
| 2 | % Sand, Latitude | 0.483 |
| **3** | **% Fine Sand, % Medium Sand, Latitude** | **0.568** |
| 3 | % Fine Sand, % Sand, Latitude | 0.561 |
| 3 | *Hrs in 1995, % Sand, Latitude | 0.551 |

**Hrs in 1995 is the hours of recorded dredging from the EMS in 1995.*

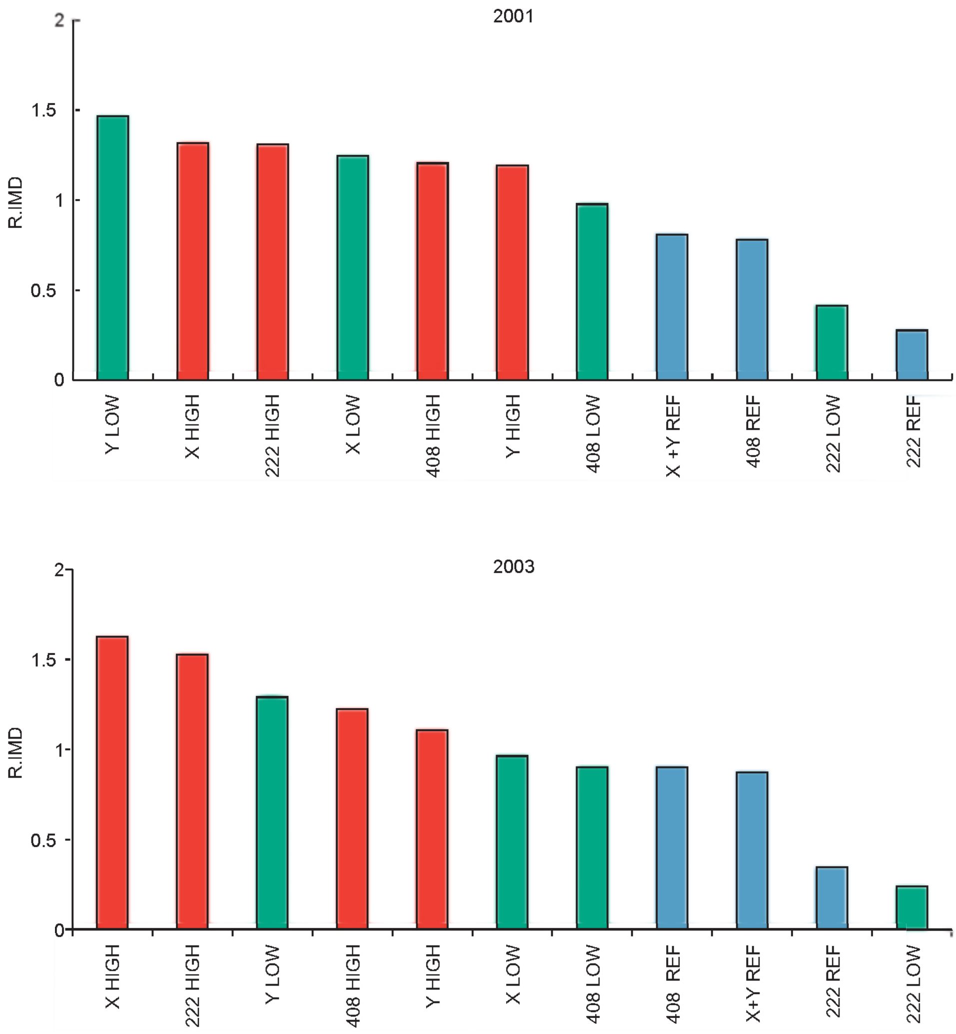



***Figure 9.4. Relative Index of Multivariate Dispersion (Somerfield et al., 1993) calculated from ten Hamon grab samples at each site based on (a) samples collected in 2001 and (b) those collected in 2003***

# 10. DISCUSSION OF THE OUTCOME OF FIELD SURVEYS

Although the absence of comprehensive baseline data at the dredged areas and the lack of reliable historical records (pre-1993) on the location of dredging activity are constraining factors in assessing the potential for and mode of benthic recolonization, reference sites studied alongside the former dredging sites were selected to represent conditions in the wider environment and allow an evaluation of the effects of aggregate extraction. 'Once off' spatial evaluations at Area 222 and at the Hastings Shingle Bank (see Sections 7 and 8), together with the results of previous investigations at Area 408 (Evans, 2000; Newell *et al.*, 2002; Coastline Surveys Europe Limited, 2002) have also provided information on environmental conditions in each region which has helped to provide a wider geographical context for time-series investigations. Furthermore, such studies have provided a check on the 'representativeness' of selected reference sites.

**Rates of biological and physical recovery**

The outcome of sidescan sonar surveys indicates that the physical effects (i.e. presence of weathered dredge tracks) can be detected at least 3 years at Hastings Area Y, 7 years at Hastings X, and 4 years at Area 408 after the cessation of extraction. There was, however, some evidence to suggest that, at these locations, tracks were being eroded and/or infilled by natural sediment transport processes over time. In contrast to these observations, and those from other studies that have demonstrated the rapid degradation of dredge tracks after cessation of dredging (Millner *et al.*, 1977; Kenny *et al.*, 1998; Coastline Surveys Europe Ltd, 2002), it appears that substantially longer periods, (i.e. >10 years), are required at Area 222 for the complete erosion of dredge tracks/pits. This accords with observations at Area 107, another extraction site in the southern North Sea where dredge tracks were still detectable using sidescan sonar records 7 years after their creation (Limpenny *et al.*, 2002). Based on the water depth, tidal current and wave data, Areas 222 and 107 are considered to be sites of 'moderate' energy (see also Annex I). This conclusion is important since it implies that many years, possibly decades will be required for the complete erosion of dredge tracks and hence the return to conditions approximating to the pre-dredged state of dredged habitats in areas classed as 'low energy'. Differences in the persistence of dredge scarring are also likely to influence the biological recovery potential of extraction sites in the longer term, and may also have implications for interference with other activities such as beam trawling (de Groot, 1986).

In general, sediments collected from areas previously exposed to high levels of dredging intensity tended to contain proportionately more sand and less gravel than other sampled sediments. As discussed in Section 2, alterations to the sediment as a consequence of dredging could occur in a number of ways, including as a result of screening activities. Screening of dredged cargoes was carried out at Areas 222 and 408, but not at Hastings Shingle Bank. At Areas 222 and 408 broad areas of gravelly sands and sands coincided with the location of recent recorded dredging activity and the position of weathered dredge tracks detected using sidescan sonar techniques. During extraction operations, significant quantities of gravel were removed from both these areas, accompanied by a return of sands via screening. After repeated dredging (and screening of dredged cargoes), the transport of sands out of an area by waves and tides may not keep pace with the considerable quantities generated during dredging, particularly if elevated levels of intensity are sustained over many years. In such circumstances, it is anticipated that physical recovery of the habitat would be postponed until sediments have either consolidated and/or the burden of sand has moved out of the area. Recent work by Newell *et al.* (2002) suggests that biomass of benthic invertebrates is suppressed in deposits up to distances of 500 m away from active dredging as a consequence of the remobilisation of sediment introduced by the screening process at Area 408. Therefore, it is suggested that the potential for biological recovery will be prolonged until such time as sands have dispersed out of these areas and a greater degree of physical stability of habitats (i.e. approaching the pre-dredged state) are achieved. Without further evidence, however, it is not possible to definitely conclude whether the sandy substrates observed at Areas 222 and 408 are natural in origin or as a result of the fining of sediments due to previous dredging activity.

Interestingly, a number of samples classed as 'gravelly sands' were also recorded at both of the sampled extraction licences on the Hastings Shingle Bank in each year of sampling within areas exposed to high dredging intensities. Furthermore, weathered dredged tracks in coarse gravel were observed to be infilled with sand at Hastings Area Y. In this case, since screening was not practised at either Hastings extraction site, sandy sediments present in the dredged furrows may have resulted from a combination of plume settlement and from the transport and trapping of bedload sediments. In contrast, at Hastings Area X sediments appeared to become coarser over time after the resumption of dredging activity in 2002. This is consistent with the findings from an experimental study off North Norfolk which reported the coarsening of seabed sediments, as a result of the exposure of deeper gravelly deposits, following dredging (Kenny and Rees, 1996).

Evidence from this study suggests that the fauna remains in a perturbed state in areas previously subjected to high levels of dredging intensity at least

4 years at Areas 222 and 408 and 3 years at Hastings Area Y after the suspension of dredging. These findings, particularly those obtained at Area 222 and 408, appear to conflict with a body of case studies which together suggest that substantial progress towards restoration of the fauna could be expected within 2-3 years following cessation of marine sand and gravel extraction (Millner *et al.*, 1977; Kenny *et al.*, 1998; ICES, 2001; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; Newell *et al.*, 2002). Evidence from the present study indicates that the 'recovery' period may be more prolonged, especially for sites dredged repeatedly. Indeed, observations at Area 222 indicated that the fauna remains in a perturbed state some 7 years after the cessation of dredging in the northern sector of the extraction site. In sites where extraction has been suspended more recently e.g. in the relinquished sectors of Hastings Area Y and at Zone 2 in Area 408, full recolonization in all areas does not appear to have been attained. This discrepancy between the data obtained in this investigation and other studies may partly reflect differences in the magnitude of dredging disturbance, since many of the studies reported in the literature have been concerned with the effects of relatively short lived dredging campaigns i.e. periods of up to 1 year (Kenny *et al.*, 1998; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; van Dalfsen and Essink, 2001). For example, most of the reported studies are the results of controlled field experiments which are often designed around 'once-off' dredging events. Thus, by their nature, these studies cannot address the effects of the annual dredging intensity over the life-time of a typical commercial extraction site. In contrast, the extraction sites targeted in this study were dredged repeatedly over many years and, in the case of Area 222, over a 25 year period. This latter situation is the more usual scenario for historic sites in the U.K. in terms of the lifetime of a typical dredging licence (Singleton, 2001). Such dredging periods are also consistent with current Government policy, where it is usual for dredging licences to be issued for a period of up to 15 years, with the possibility for extensions beyond this time-frame (ODPM, 2002).

Another factor that may have contributed to the observed differences with reported studies is the location of sampling stations in relation to the intensity of dredging operations. This is clearly illustrated by the comparison of reported rates for biological recovery given by Newell *et al.* (2002) with the results of our own sampling at Zone 2 of Area 408 (see Section 6). By precisely targeting deposits indicated by EMS records that had been dredged at various levels of intensity, we were able to demonstrate a possible effect of dredging on the numbers of species, individuals and biomass at least 4 years after cessation. Less targeted sampling in the same area (one year earlier) was, in contrast, unable to discriminate any effect of dredging in terms of the species variety and population densities within 12 months of the suspension of dredging operations (Newell *et al.*, 2002). This discrepancy in the results clearly has implications for the design of future monitoring surveys, at this and other aggregate extraction sites, where the aim is to establish the effects of dredging activity and the subsequent rate of recolonization (see below).

Interestingly, in 2003, deposits within areas of lower dredging intensity at Area 222 and Hastings Area X are almost indistinguishable from the surrounding deposits in terms of all univariate measures of community structure. This implies that at the intensities recorded in these areas, re-establishment of the benthic fauna occurs within a period of six years at Area 222 and seven years at Hastings Area X, following the cessation of dredging. However, the 7 year recovery period observed at Hastings Area X low dredging intensity site relates to relatively low culmulative levels of dredging. Therefore this recovery period may not be applicable i.e. the period is likely to be longer in more intensively dredged areas of the Hastings Shingle Bank.

A number of studies have attempted to identify and explain distribution trends in benthic assemblages following the cessation of marine dredging (Cressard, 1975; Kenny and Rees, 1994; 1996; Kenny *et al.*, 1998; Desprez, 2000; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; van Dalfsen and Essink, 2001). Effects on the benthos and sediments identified in such studies show some parallels with the findings observed in this investigation. For example, Desprez (2000) showed that for an industrial extraction site off Dieppe, France the structure of the benthic community changed from one of coarse sands characterised by the lancelet *Branchiostoma lanceolatum* to one of fine sands composed of the infaunal polychaetes *Ophelia borealis*, *Nephtys cirrosa* and *Spiophanes bombyx*. Thus the change in the assemblage structure reflected a change in sediment composition due to dredging. Significant changes in particle size composition, resulting in a net fining of the sediment within extraction sites, have also been reported by van Dalfsen *et al.* (2000) and Sardá *et al.* (2000) following sand extraction. At Area 222, gravelly sands in the area of high dredging intensity were largely composed of juvenile animals suggesting that these individuals are unable to reach adulthood due to the unstable sediments.

A general feature of all the case studies examined during this investigation was the higher than average variability in the composition of sediments within sites exposed to high dredging intensities. Presumably, this represents the uneven impact of the dredger draghead on the seafloor. Further evidence of the patchy nature of substrata is provided by sidescan sonar and photographic images of the dredged locations. This was particularly evident at Hastings Area Y where dense dredge tracks in gravel were observed to be infilled with sand. Furthermore, this variability among replicate samples was also evident in biological samples collected from within dredged locations and, in particular, within areas exposed to elevated levels of dredging intensity. A high variability in the composition of sediments and benthic assemblages at dredged locations has also been reported by Kenny and Rees (1994) and Sardá *et al.* (2000). Such observations lend further support to the hypothesis of Warwick and Clarke (1993), namely that variability in assemblage structure may be an identifiable symptom of perturbed conditions. However, this propensity for extraction sites to exhibit variability in terms of sediment characteristics and species composition has to be referenced against a high degree of natural variability and small-scale sediment patchiness that can be encountered in benthic ecosystems, even at locations which appear superficially to be relatively homogeneous. For example, in Zone 2 at Area 408 there appeared to be a tendency for sandier sediments to be located within the western part of the zone. Whether this was on account of natural or dredging induced variability was difficult to ascertain. At Area 222 a bathymetric feature running north/south was coincident with differences in the sedimentary characteristics of the area and appears to be responsible for determining large scale community patterns. The area of low intensity at Hastings Area Y also straddled the boundaries of two sediment facies and therefore samples collected from this area will be subject to the confounding effects of variability arising from natural and anthropogenic factors.

The above examples also serve to highlight the site specific nature of individual extraction areas in terms of the biological and geological environment, the dredging history and the extraction practices employed (see also Section 2).

Nevertheless, the observation of higher than average variability (quantified using the index r.IMD) within some dredged areas shows promise in an indicator context and merits further testing for its utility in discriminating changes associated with marine aggregate extraction. Environmental indicators have a potentially important role in enabling policy makers to understand ecosystem changes (Rees *et al.*, 2003) and have also recently been used to monitor changes in Dutch sand extraction sites (Kabuta and Hartgers, 2003).

Rates and patterns of colonization are also affected by a variety of biotic factors including the availability of larvae (Zajac and Whitlatch, 1982), competition (Rhoads *et al.*, 1977), life histories (Grassle and Sanders, 1973), the presence of conspecifics, interspecific relationships including predation (Davoult and Richard, 1990) and sediment microbes (Gray, 1974). Therefore, we cannot assume that the same biological and physical responses to dredging will occur in all environments. Indeed, we know that regional differences in the macrofauna in gravelly substrates in the U.K can be explained by site-specific differences in the amount of sediment disturbance (Kenny, 1995; Greening and Kenny, 1996, 1997). The results from the current investigation also indicated that the location of the extraction sites in terms of their latitude and the % sand explained regional differences in the fauna (see Section 9). Furthermore, this study provided evidence of a relationship between the prevailing tidal current strengths and the associated mobility of sand and the composition of epifaunal species in each region (see Annex II). Therefore, the 'scale' of the effects of marine dredging, and by inference the time-scale for successful regeneration of benthic assemblages, appears to depend not only on the severity of the dredging operation itself (ICES, 1993), but also on the 'natural status' of the macrobenthic community.

McCauley *et al.* (1977) found that the density of infauna returned to pre-disturbance levels within 28 days after maintenance dredging. They attributed this high resilience to the initial dominance of species with opportunistic life-history strategies (see also Rosenberg, 1977). Thus it appears that re-establishment of a community is likely to be more rapid in areas which are largely composed of early successional species that are adapted to physical disturbance, e.g. in areas off Lowestoft, U.K., than in areas where communities are composed of mature colonies of bryozoans and long-lived species such as the bivalves *Pecten* sp., *Chlamys* sp., *Arctica islandica* and *Mya arenaria* (Rosenberg, 1977; Rees, 1987; Van Moorsel, 1994; Newell *et al.*, 1998; van Dalfsen *et al.*, 2000). The latter species must undergo a longer succession of many seral stages, taking up to 15 years to mature (Rosenberg, 1973; van Dalfsen *et al.*, 2000).

**The nature of recolonization of dredged sites following cessation**

From the results of this investigation, together with previous studies of dredged sites (Cressard and Dubyser, 1975; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000; van Dalfsen *et al.*, 2000; Sardá *et al.*, 2000; van Dalfsen and Essink, 2001; Boyd *et al.*, 2003) and observations following defaunation as a consequence of storm disturbance (Rees *et al.*, 1977), a general pattern of recolonization is emerging (see also ICES, 2001). The first stage involves the settlement of a few opportunistic species, which are able to take advantage of the dredged and sometimes unstable sediments (Hily, 1983; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000; van Dalfsen *et al.*, 2000; van Dalfsen and Essink, 2001). At Hastings Areas X and Y, this role was assumed by the barnacle *Balanus crenatus*, which appears to have opportunistically colonised gravel substrates exposed after dredging. This accords with similar observations made by Boyd and Rees (2003), where relatively high densities of this species were found within and in the vicinity of active trailer dredging in the central

English Channel. In contrast, at Areas 408 and 222, polychaete worms typical of sandy substrates were the primary colonisers e.g. *Ophelia borealis* at Area 408 and *Glycera lapidum* at Area 222. Mobile epifaunal decapod crustaceans such as the hermit crab *Pagurus bernhardus* and the shrimps *Pandalus montagui* and *Pandalina brevirostris* may also invade dredged deposits at this stage.

Recolonization can either be by adults or larvae from the surrounding area if the sediments of the disturbed area are similar to the original substrata (Cressard and Dubyser, 1975) or by larvae from more distant sources if the sediment is markedly different (Hily, 1983; Santos and Simon, 1980). These species can substantially increase the overall abundance and the diversity during the early stages of post-dredging recolonization (Hily, 1983; Lopéz-Jamar and Mejuto, 1988; Kenny and Rees, 1994; 1996; Kenny *et al.*, 1998; Desprez, 2000; van Dalfsen *et al.*, 2000). A second phase is characterised by a reduced community biomass which can persist for a number of years (Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000). There is a natural expectation that biomass will remain reduced, while new colonisers 'grow on' to maturity comparable with the pre-dredging age/size profile (Rees, 1987; van Dalfsen *et al.*, 2000; Newell *et al.*, 2002). A reduced biomass may also be caused by the abrasive effects of increased sediment (mainly sand) in transport inhibiting the growth and survivorship of epifauna such as hydroids and bryozoans. Paradoxically, it is this sandy sediment that is also responsible for the infilling of dredge tracks (Kenny *et al.*, 1998; ICES, 2001; Limpenny *et al.*, 2002) which in the longer term may promote physical stability. Over time, it may be expected that, at some sites, the bedload transport will approach the pre-dredged equilibrium, allowing the restoration of community biomass (Kenny *et al.*, 1998). A similar model of response has been represented schematically by Hily (1983) and includes a further stage in which opportunists are replaced by a greater number of species. It was suggested that this replacement was the result of increasing levels of interspecific competition. However, this model was based on observations following the dredging of a sandy mud (Hily, 1983), and further evidence is required to establish whether such oscillations occur in more stable gravel habitats during the latter stages of succession.

**Findings from 'once off' spatial surveys**

Two spatially extensive surveys of the macrofauna and sediments were conducted at Area 222 and at the Hastings Shingle Bank (see Sections 7 and 8). The Hastings survey revealed the distribution of sediments and associated assemblages across the region and was characterised by broad areas of sandy gravels, gravelly sands and sands. Reference locations were almost physically indistinguishable from both dredged and undredged gravelly substrata present within the region. This finding supports the selection of these sites as appropriate reference points against which the effects of marine aggregate extraction may be judged over time. The area within which samples were collected for an analysis of the effects of low levels of dredging intensity at Hastings Area Y may be less useful as a long-term monitoring site, since it is located across the boundary of two sediment facies.

At Area 222, a comparison of sidescan sonar and bathymetric surveys has provided further insights in terms of the distribution of substrata and their associated seabed features within and in the vicinity of the historic extraction site. A gently rising bank lies almost at right angles to the local tidal axis and this may impede the movement of sand away from the extraction site. The separation of the two main macrofaunal assemblages in the area also accords with the location of this bathymetric feature. In addition, there was evidence of dredging effects in terms of a difference in assemblage structure of some samples from within dredged locations compared with those from surrounding sediments.

**Lessons for future monitoring studies**

The concentration of effort into the sampling of a limited number of stations has several advantages in time-series investigations, but the adoption of such a strategy requires good knowledge of the local environment and of the impacts of the disturbance activity. In the context of marine aggregate extraction, this information is often somewhat deficient, since studies of the effects of marine aggregate extraction on benthic populations span a period of less than 10 years. Nevertheless, good information exists on the location and intensity of dredging activity since 1993 from EMS records. This type of information was used to good effect to design time-series investigations during the current study, but also has wider utility for interpreting the results of monitoring programmes conducted as part of licence conditions (see also Boyd, 2002). Results from the current study also suggest that sampling designs conducted as part of 'ongoing' monitoring programmes will need to be sufficiently flexible to accommodate changes in dredging patterns within extraction areas.

It is also important that evaluations of the effects of aggregate extraction at a location are made against suitable 'reference' points which are (as far as possible) distinctive only in terms of their distance from the site of extraction, in order to minimise the confounding effects of variability arising from natural and other man-made factors (Skalski and McKenzie, 1982; Underwood, 1990). In a heterogeneous environment, it may be very difficult to locate reference stations which closely resemble those within the sphere of influence. In addition, after dredging has taken place for many years, the benthos (and sediments) may have been structurally altered as a consequence of dredging

(Dickson and Lee, 1972; Shelton and Rolfe, 1972; Bonsdorff, 1983; van der Veer *et al.*, 1985; Kenny and Rees, 1994; 1996; Kenny *et al.*, 1998; Desprez, 2000). In this situation, it is difficult to reach a judgement as to whether a suitably located reference station, in the near vicinity of the dredged site, is representative of the likely pre-dredged status. The reference sites in these studies were chosen by taking account of both sidescan sonar and video images of the seabed, in an attempt to select a site representative of the wider environment. In all cases, the 'representiveness' of annually sampled sites requires periodic checking against the outcome of spatially extensive surveys and this was the main purpose of studies reported in Sections 7 and 8.

**Measures to enhance the potential for the rehabilitation of dredged areas**

In recent years, greater consideration has been given to identifying mitigation measures to reduce the impact of extraction such as zoning of dredged areas. Intuitively, it would be predicted that by zoning areas and minimising the area affected by dredging at any one time, the potential for recolonization would increase, since there is less distance for prospective colonisers to travel. The size of area that is affected by disturbance can also influence the relative contribution of larval, post-larval or adult stages to the recolonization process (Santos and Simon, 1980; Smith and Brumsickle, 1989; Günther, 1992; Whitlatch *et al.*, 1998). The larger the disturbed site, the more important is the colonization route via larvae and post-larvae (Smith and Brumsickle, 1989; Günther, 1992; Thrush *et al.*, 1996; Whitlatch *et al.*, 1998). For example, if the area that is dredged is small, there is a greater potential for the area to be repopulated by adults migrating in from the edges, than by settlement of planktonic larvae (Santos and Simon, 1980). However, if the dredged area is large, recolonization via adult migration to the centre of the area may be a less viable route, in the short-term, than colonization via larval recruitment from the water column (Santos and Simon, 1980). This may also influence the composition of initial recruits, as it is known that colonizing strategies employed by different organisms are species-specific (Santos and Simon 1980). Currently, there is no information on the optimum size of an extraction area in terms of its recolonizing potential.

If the same rates of extraction as at present are to be permitted, minimising the size of dredging sites will, in all probability increase the dredging intensity per unit area. This study examined the potential of different levels of dredging intensity to affect the nature and rate of recolonization of benthic assemblages following the cessation of dredging. Higher dredging intensities may eliminate a greater proportion of species (Boyd and Rees, 2003) which may prolong the time-scale for re-establishment of the benthic community. This would suggest that the level of dredging intensity determines the starting point for recovery. Differences in the rates of recolonization in areas exposed to high and lower levels of dredging intensity were apparent at Area 222.

Furthermore, differences in the composition of the fauna in the areas exposed to higher and lower levels of dredging intensity were evident from an analysis of all the Hamon grab samples collected at the four extraction sites in 2001.

In commercial deposits, trailer dredging leads to the creation of furrows along the seabed (ICES, 1992). This results in undisturbed deposits located between dredged furrows and thus the immediate effect on the benthos is one of local depletion rather than uniform reduction (Van Moorsel, 1994). Therefore, discrepancies in the rates of recovery at higher and lower levels of intensity may be because of the increased proportion of undisturbed deposits between dredged furrows at sites dredged at lower intensities. Such undisturbed areas may provide an important source of colonising species (Van Moorsel, 1994; Newell *et al.*, 1998), allowing recolonization to proceed more rapidly in less heavily dredged sediments than in areas of intensive dredging. In a local context, controlling the level of dredging intensity and allowing undisturbed deposits to act as refugia between dredged furrows may therefore prove to be an effective measure for enhancing the rehabilitation of dredged areas.

The effect of extraction activity appears not only to depend upon the intensity of the dredging activity itself, but also upon the 'type' of gravel assemblage present in an area. Thus, it is likely that upper limits of dredging intensity would be most effective, if set on a site-specific basis. Presently, there are insufficient data at contrasting locations to determine what constitutes an appropriate threshold of intensity in every environmental setting. Further work is therefore required to establish the boundaries for acceptable change before upper limits of dredging intensity can be set to ensure maximum management value. It will also be important to further elucidate the nature of the link between dredging intensity and the effects on sediments and biota, to be confident about the sequence of events before setting absolute threshold levels. Furthermore, since controlling the level of dredging intensity in an area has the potential to increase the size of the area dredged, it will be important to establish the impact of this measure on other ecosystem components such as fish/shellfish populations, associated fisheries and other legitimate interests such as conservation and recreation. It will also be important that such measures allow efficient resource production.

Rates of faunal re-establishment in commercial extraction sites are also likely to depend on whether deposits have been dredged regularly or more sporadically over time, i.e. the frequency of dredging-related disturbance. The time interval between successive dredging events determines how long the habitat has had to recover before it is affected by another disturbance. The degree of 'recovery' will be influenced by whether the time interval is sufficient to allow the settlement of new recruits and allow the organisms to reproduce (Essink, 1999). The resumption of dredging at the area of high dredging intensity at Hastings Area X allowed the opportunity to trace the consequences of intermittent dredging activity. In this case, the benthic fauna appeared to have almost re-established after a 'fallow' period of 6 years before the resumption of dredging significantly reduced the densities, biomass and species variety of benthic invertebrates. Whether in the longer-term the practice of intermittent dredging at extraction areas increases the potential for rehabilitation of dredged areas remains to be established. However, it is conceivable that there may be environmental benefits from rotating dredging operations across different zones and leaving 'fallow' areas to rehabilitate over a period of several years prior to reworking. The wider environmental and operational cost-benefit implications of adopting this practice would, again need to be closely examined prior to its introduction.

Following the cessation of commercial aggregate extraction, there has been a general acceptance of the need to ensure that the surface of the sea bed is left in a comparable state to that prevailing before dredging i.e. with a similar sediment type and evenness profile (Campbell, 1993; ODPM, 2002). For example, at some gravelly locations, it is to be expected through licence conditions that comparable coarse deposits to a depth of at least 50 cm will remain in relatively smooth profile after the event of dredging in order to maximise the chance of recovery to the pre-dredged state. Such licence conditions are designed to permit natural recolonization by benthic organisms to proceed both at the surface and at depth, and to ensure minimal interference with commercial fishing practices. Clearly, the exposure of underlying bedrock or clay in breach of such conditions would result in a significant shift in the topographical and ecological status and would be unacceptable. Recently, however, Seiderer and Newell (1999) have contended that because of relatively low correlations between selected % particle size categories and sub-groups of the benthic fauna which they identified in their study (but, interestingly, not for the data set as a whole, where the correlation is, in ecological terms, very high), then this alone provides justification for dredging-related alterations to sediments within 'broad limits'. Evidence from this study suggests that, where there are significant changes to the topography and/or composition of the sediments as a result of dredging activity, the maintenance of a biological community at an early developmental stage over many years can be expected. There is also a substantial body of literature which has demonstrated the existence of a dynamic equilibrium in any given locality as a result of a number of interacting environmental influences, which finds partial expression through the outcome of conventional particle size analyses (Cabioch, 1968; Rees *et al.*, 1999). Thus, the management aim should be in favour of minimal substratum alterations in order to maximise the prospects for rehabilitation of sediments following cessation of dredging. This position has the advantage of being both precautionary and scientifically sound.

**Framework for future studies**

This is the first time that co-ordinated studies on a wide geographical scale investigating the physical and biological status of commercial aggregate extraction have taken place in the U.K. One consequence of the limited available information on the effects on the benthos of marine aggregate extraction is the difficulty it creates for the establishment of reliable empirical models for predictive management purposes. A further difficulty in generalising about the effects of extraction is the variability in both the dredging history and the particular dredging practices which different extraction sites are exposed to i.e. a typology of dredging disturbance doesn't exist. Consequently, when seeking to develop and then apply predictive models, generalisations about the effects of marine aggregate extraction must be qualified by local information regarding the nature of dredging activity and the conditions under which extraction activity occurs. Based on existing evidence from this and other studies, however, the two most commonly encountered scenarios following marine aggregate extraction in the U.K. are:

a) *sites where the substratum has changed from a sandy gravel to a gravelly sand;*
b) *sites where the substratum has remained unchanged.*

This is not to exclude the possibility of other consequences such as the exposure of clay depending on local circumstances as observed at Area 222. In the first of the scenarios, there are a number of ways in which alterations to the sediment as a consequence of dredging could result. These include, but may not be limited to the exposure of an underlayer of finer sediments (Dickson and Lee, 1972), discharge of finer sediments from spillways (Hitchcock and Drucker, 1996, van Dalfsen *et al.*, 2000;) or screening (Newell *et al.*, 2002; Coastline Surveys Europe Limited, 2002) and the trapping of bedload in dredged furrows (Desprez, 2000; Sardá et al., 2000; ICES, 2001). The degree of change appears to depend both on the local circumstances (van Dalfsen *et al.*, 2000; Desprez, 2000; Boyd and Rees, 2003), and on the magnitude of perturbation, i.e. differences in the intensity, type of dredging or length of extraction period (van Dalfsen *et al.*, 2000; Boyd *et al.*, 2003; Boyd and Rees, 2003). The colonising fauna also appear to reflect this change to the substrata, through a shift in the proportions of sandy versus gravelly fauna (Desprez, 2000). Accompanying this, it appears that

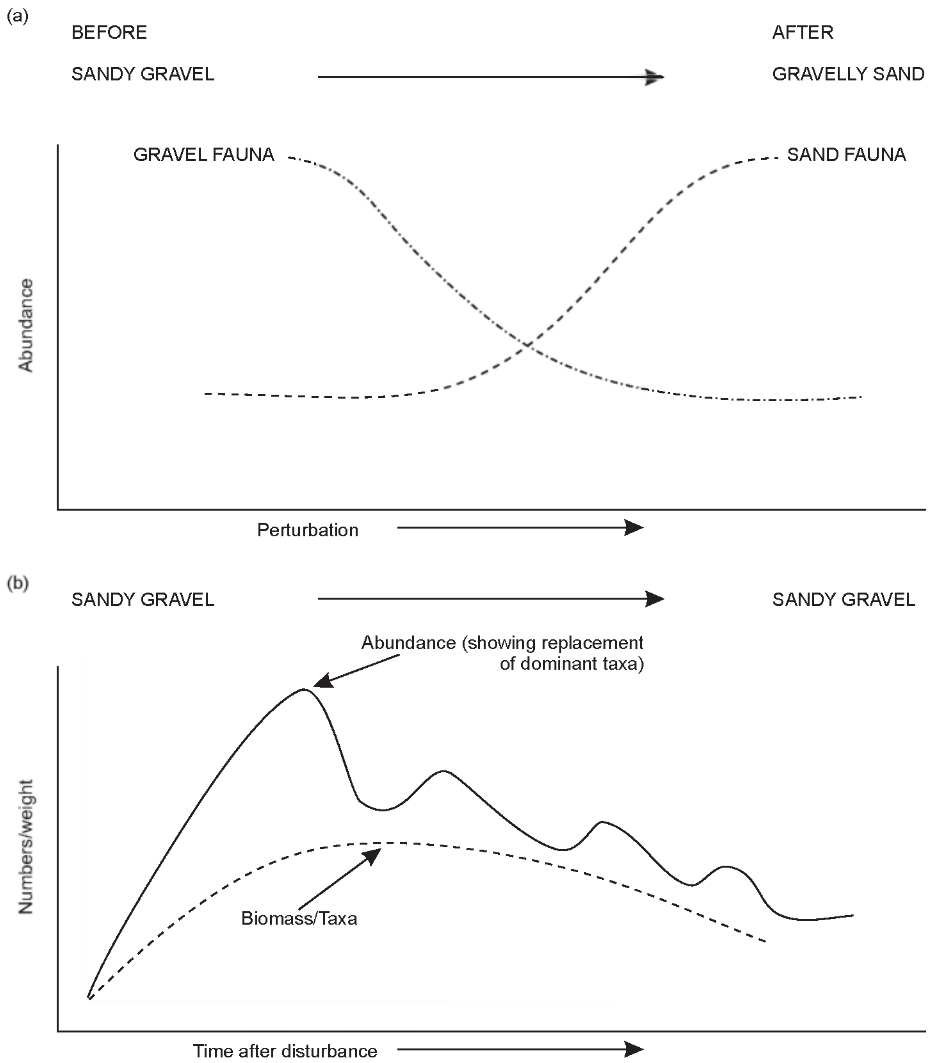



***Figure 10.1. (a) Simplified diagram of changes in the proportions of gravelly fauna in response to a change in sediment type as a consequence of marine aggregate extraction. (b) Simplified model of changes in the benthos after the cessation of marine aggregate extraction***

there is a net decline in biomass. This model of response is schematically portrayed in Figure 10.1. A similar model of response could account for changes at some sand extraction sites where the seabed substrata have changed from coarse to fine sands (Sardá *et al.*, 2000; van Dalfsen *et al.*, 2000).

In the second scenario, sediments present at the seabed following the cessation of marine aggregate extraction are similar to those which existed prior to disturbance, i.e. sandy gravels. This scenario accords with current expectations regarding seabed status following licensed dredging and may be the common one. This appeared to be the case at the low intensity areas at Area 222 and Hastings Area X where a sandy gravel habitat remained following dredging. From the limited available data from this and existing studies concerning the effects of marine gravel extraction (Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998), it is reasonable to postulate that the fauna recolonizing such sites will follow classical successional dynamics (e.g. Grassle and Sanders, 1973).

This scenario was postulated in connection with the disposal of dredged coarse material arising from a port expansion or channel deepening (see Anon, 1996). Although such simplified models require further validation and/or refinement, they provide a useful framework for evaluating the outcome of post-cessation recolonization studies and recovery rates and eventually could provide a reliable predictive capability that could be used to set limits for acceptable change. A body of case studies on the consequences of marine aggregate extraction over sufficiently long time-scales from sites exposed to commercial extraction practices is required to underpin the derivation of reliable and scientifically credible models of response. Such a need applies equally to many other human activities which take place in the marine environment.

# 11. CONCLUSIONS AND RECOMMENDATIONS

At the outset of this study, we set out to better understand the rate at which the seabed recovers following marine aggregate extraction and outlined our intention to conduct field programmes to address whether different levels of dredging intensity affected the rate and nature of recolonization following cessation. It was also our stated aim to use the outcome of surveys to suggest ameliorative measures for enhancing the rehabilitation of dredged areas. The following conclusions and recommendations can be drawn from the results of this study:

**Rates of physical and biological recovery**

- Results indicate that the physical effects of extraction (e.g. the presence of weathered dredge tracks or pits) can be detected at least 3 years after the cessation of extraction at Hastings Area Y, 7 years after at Hastings Area X, 4 years after at Area 408 and >10 years after at Area 222.
- In general, sediments collected from areas previously exposed to high levels of dredging intensity contained proportionally more sand and less gravel than other sampled sediments, within the surveyed extraction sites, reflecting the patchy nature of the substrata encountered there. There was also significant variability among replicate samples in some of the biological samples from dredged locations, which may be an identifiable symptom of perturbed conditions.
- The absence of comprehensive baseline (i.e. pre-dredging) data for each of the extraction areas precludes definitively attributing cause and effect relationships. Despite this, evidence from this study suggests that the fauna remains at a perturbed state in areas previously subjected to 'high' levels of dredging intensity at least 3 years at Hastings Area Y, 4 years at Area 408 and 7 years at Area 222. Therefore, relatively rapid 'recovery' rates, commonly cited as 2-3 years for European coastal gravelly areas, should not be assumed to be universally applicable.
- Sediments from within the areas of lower dredging intensity at Area 222 and Hastings Area X are now almost indistinguishable from the surrounding deposits in terms of all univariate measures of community structure. This implies that, at the intensities of dredging recorded at these sites, re-establishment of the benthic fauna occurs within a period of 6 years at Area 222 and 7 years at Hastings X following the cessation of dredging.
- It may be concluded that there is strong circumstantial evidence to suggest that dredging intensity, or an associated variable, is an important factor in determining differences in the composition of benthic assemblages. The elucidation of which facet of the dredging activity affects the benthic assemblage structure, beyond that which can be ascribed to intensity *per se*, cannot be answered directly by this study. Further work is therefore required to test appropriate impact hypotheses in the field and improve the understanding of the physical processes determining recoverability.
- Results also indicate that the geographical location of the extraction sites and the percentage of sand explained regional differences in the fauna i.e. the results tend to be site-specific. This site-specificity which will also include variability in the dredging history and any particular extraction practices employed can complicate the prediction of likely effects at both extant and prospective extraction areas. This must be taken into account in attempts to generalise about the potential effects of dredging activity.
- When the outcome of the results of surveys are considered in combination, they indicate that the effects of extraction on the benthic fauna and sediments persist over time within dredging areas and that the period for benthic 'recovery' appears to depend on the local environment and the magnitude of disturbance.

**The nature of recolonization of dredged sites following cessation**

- Prior to the resumption of dredging in 2002 at Hastings Area X, sediments from the dredged locations supported significantly ($p<0.05$) fewer species than sediments from the reference sites. This is due to some of the sandier samples from dredged locations supporting fewer numbers of species than deposits containing higher proportions of gravels. Differences in the total counts of macrofauna are less distinct at this site, and also at Hastings Area Y, and this is attributable to elevations of the barnacle *Balanus crenatus* at the dredged locations which masked the reductions in abundance of many other species.
- Following the resumption of dredging in the area of high dredging intensity at Hastings Area X, significantly lower numbers of species, individuals and biomass were detected in comparison with the areas of low intensity and local reference sites.
- At Area 408, significantly lower numbers of species, individuals and biomass were found within dredged locations compared to reference sites 4 years after the cessation of dredging. This contrasts with the findings of previous reported studies conducted in the area which showed no significant effects of extraction in terms of species variety and population density within 12 months of cessation. The discrepancy is considered a consequence of different sampling strategies employed in both investigations.

- Observations at Area 222 indicated that the fauna remains in a perturbed state at least 7 years after the cessation of dredging within the area representative of high dredging intensities. Furthermore, the gravelly sands found within this area tended to support juvenile animals suggesting that these species were prevented from reaching maturity.

**Findings from 'once off' spatial investigations**

- The once-off spatial surveys conducted at Area 222 and the Hastings Shingle Bank using conventional grab sampling in conjunction with swathe acoustic systems (sidescan sonar and multibeam bathymetric techniques) and visual techniques (underwater photography) provided a robust approach to assessing the site-specific effects of marine aggregate extraction in relation to the wider distribution of faunal assemblages and sediments. Furthermore, such an approach has proved essential for the better understanding of cause and effect relationships and for placing the findings from time-series investigations into a wider geographical context.

**Lessons for future monitoring studies.**

- EMS information proved to be very useful for precisely targeting locations of varying dredging intensity during the design of seabed surveys. This approach assisted the evaluation of the recovery of dredged areas after cessation. It is recommended that, where appropriate, EMS information is taken into account in the design and interpretation of ongoing monitoring surveys carried out by industry at current aggregate extraction areas. Sampling designs agreed as part of monitoring programmes should also have sufficient flexibility to respond to shifts in dredging patterns over time.
- The techniques and approaches adopted in this study are suitable for use in ongoing monitoring programmes where the emphasis is on monitoring temporal trends before, during and after dredging activity. Furthermore, there is a need for such programmes to include a spatial component in order to check the 'representativeness' of annually sampled sites. It is also evident from the results of spatial investigations conducted during this study that such surveys must be sufficiently extensive to encompass the entirety of predicted effects.
- Complementary surveys of epifauna populations using trawls provided additional information, beyond that obtained from conventional grab sampling, about the status of the disused extraction areas. This included observations both on the range and relative abundance of species present and the distribution of biomass across different size classes (see Annex II). There was no evidence of a shift to smaller sized epifaunal specimens at the dredged sites at any of the extraction areas, rather an absence or reduction in the abundance in the smaller size classes, equating to a decline in productivity. This study also provides evidence of a relationship between tidal current strength, the mobility of sand and the composition of epifaunal species.
- As a further complement to field surveys a new measure indicative of the prevailing hydrographic conditions in the vicinity of centres of dredging activity has been developed through a synthesis of existing and new data (see Annex I). Such information has provided an important means to interpret biological data (see Annex II) obtained during this study and further refinement of this hydrodynamic index may improve predictive capability with regard to environmental effects of dredging activity, whether recently ceased, ongoing or planned.

**Measures to enhance the potential for rehabilitation of dredged areas**

- A number of management strategies for minimising the environmental consequences of ongoing dredging activity and maximising the prospects for rehabilitation of sediments following the cessation of dredging have been proposed, following consideration of the outcome of field surveys. Further work is required to increase the capability to link changes in these measures, e.g. levels of dredging intensity, to some underpinning cause/effect rationale prior to their effective application. It is also recommended that the wider environmental and operational cost-benefits of adopting such measures, including the impacts on other ecosystem components and/or other users of the marine environment, are closely examined prior to their routine application.

**Framework for future studies**

- Many of the field studies reported in the literature are the results of investigations on the impacts of short-term dredging events and these have proved useful in determining the rates and processes leading to benthic re-establishment following aggregate extraction. From such studies and those undertaken at sites exploited for commercial interests, a general pattern of response to marine aggregate extraction is emerging. This needs to be tested to establish its general validity in all environments, particularly in areas which have been exposed to industrial scale dredging operations over many years. From this work and from the limited information from existing studies, it is clear that re-establishment of a community similar to that which existed prior to dredging can only be attained if the topography and original sediment composition are restored and the natural hydrodynamic regime has not been changed. Should physical stability of the sediments comparable to the pre-dredged state not be attained, communities will develop towards a significantly altered state.

- This study also resulted in the development of two conceptual models to describe the effects of commercial aggregate extraction which require further testing for their general applicability. Presently, they provide a useful framework for interpreting biological responses following the cessation of dredging, but appear to have the potential to provide a reliable predictive capability that could be used to determine limits for acceptable change.
- This study is unique in that it has provided the beginnings of a consistent time-series of data at contrasting extraction areas around the U.K. The value of consistent time-series information at impacted and reference stations should be emphasised, since it is essential for:
  i) elucidating cause/effect relationships and their amelioration over time, so contributing to better management and monitoring practices.
  ii) providing a reliable means to evaluate the significance of aggregate extraction impacts relative to other human (and natural) influences on the seabed biota.
  iii) retrospective testing of the utility and robustness of potential indicators prior to their application in routine environmental management and for understanding the processes involved in recolonization.

**Publications arising from this research programme.**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**Posters arising from this research programme**


Boyd, S. E., Limpenny, D. S., Kilbride, R., Cooper, K. M. and Meadows, W. (2003). Assessment of the rehabilitation of the seabed following marine aggregate extraction. CEFAS Burnham.

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# 12. FUTURE WORK

This project is aimed at assessing the physical and biological impacts of marine aggregate extraction at a range of sites around the U.K. coast. It has progressed our understanding of the ecological effects of marine extraction and allowed, for the first time, an examination of the likely factors responsible for observed differences in the recovery of licensed extraction sites. Results indicate that information on the nature and rate of physical and biological recovery from one site cannot be uncritically applied to others. Therefore, there is a need to establish the long-term consequences and the scale of impact of marine aggregate extraction following cessation, in a greater range of habitats and historically subject to different dredging practices. In particular, research is needed to better understand the physical processes that drive recoverability (see also Section 14.3) and the factors responsible for observed differences in the rates of recolonization. More attention also needs to be directed at establishing the effects of dredging intensity and the consequences for recolonization of different spatial and temporal scales of dredging disturbance.

This study has also resulted in the development of two simplified models of response which are considered to most plausibly reflect the specific circumstances at aggregate extraction sites around the English coastline. Presently, these need empirical validation and/or refinement to account for the full range of physical and biological responses that may be expected at marine aggregate extraction sites in order to enhance their future utility. Empirical validation of these and other existing conceptual models is not straightforward. This is because the results from different studies may be incomparable or are presently insufficient to account for all the various dredging scenarios, which have occurred or are currently practised in UK waters. This does not make the task impossible. The challenge is to devise robust sampling strategies for a suite of locations representative of habitats and/or different effective dates of cessation of dredging, not already accounted for by this or other similar studies, for follow-up field sampling. These relinquished licences (and/or zones) should, as far as possible, be selected to represent a range of geographical conditions around the coastline. In parallel, strategies need to be devised for enhancing comparisons between studies and for synthesising existing data suitable for the development of generic models of response.

Also evident from this study was the need for strategically placed reference stations, against which the effects of local and wider scale impacts may be assessed. Data arising from the present study have provided the beginnings of a consistent time-series of data within and in the vicinity of contrasting extraction areas around the U.K. However, there is also a need to augment this with other data series from coarse ground habitats at both impacted and reference stations. Such time-series data-sets can be used to determine the likely time-scales for seabed recovery following the cessation of dredging and provide consistent data for evolving and testing 'indicators' of change.

Additional research is needed to identify dredging practices or remedial actions, which promote the rehabilitation of dredged sediments. This study has demonstrated that there is the potential for long-term changes (i.e. >10 years) to the seabed as a result of marine aggregate extraction. Therefore there may be a requirement for practical measures to actively rehabilitate or restore damaged habitats in areas of particular sensitivity or in areas where the affected areas would otherwise fail to recover naturally. As yet, there is no science to underpin such actions or to determine how best to approach this in a cost-effective manner and this is being investigated as part of an ongoing CEFAS investigation. In parallel, there is a need to establish clear goals for any restoration efforts that may be deemed necessary, in terms of the structural and functional properties of the marine environment.

Finally, further work is required to improve our understanding of the inter-relationships between gravelly and other marine habitats through the production of high-resolution broadscale habitat maps for the UK offshore environment. This could have benefits for policy making and for regulatory decisions on the licensing of aggregate extraction and, indeed, of human activities generally i.e., it would provide a better basis for marine spatial planning.

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# 14. ANNEX I - INDICES OF NATURAL ENVIRONMENTAL VARIABILITY

## 14.1 Introduction

As part of this study HR Wallingford was commissioned to consider the hydrodynamic conditions at a number of dredging sites.

This study relied mostly on existing data for tidal flows and wave activity. These were used to compare and categorise each of the sites and to calculate the potential mobility of sand at each in the form of a mobility index. The index is a nominal measure representing the potential for sand to be moved at the site.

Additional tests were made to determine which factors are most important in determining mobility and sensitivity analyses were undertaken to assess the comparative significance of tidal currents, waves and water depth.

In additional tests the variation in the direction of the movement of material during the tidal cycle was assessed at three of the sites, and the effect of aggregate extraction on the seabed sediments was assessed by comparing the size grading of bed material in areas where the dredging activity varied in intensity.

Full details of the results of the HR Wallingford study are provided in Section 14.2 of this Annex. Section 14.3 gives some details of recent developments in modelling that may be applied to further our understanding of the transport mechanisms at a dredging site and to develop the mobility index into a measure of actual sediment transport. Section 14.4 provides conclusions of the study.

## 14.2 The HR Wallingford study

### *14.2.1 Aims*

This section lists the sites selected for analysis and their main hydrodynamic characteristics, namely tidal currents, waves and water depths. It considers typical bed shear stresses caused by waves and currents and relates this to the potential for sediment transport.

Finally some sensitivity analyses were undertaken to assess the potential limitations in the current and wave data used, and the net direction of transport over a tidal cycle was considered. The effect of dredging on the bed material at three of the sites has been considered by comparing dredged and reference locations.

### *14.2.2 Selection of sites*

The sites (Table 14.1) were selected to include locations where CEFAS bed sampling has been undertaken as part of this project. Additional sites were included to extend the coverage around the south and east coasts of England. At each of the Hastings, Southwold and Great Yarmouth sites two locations were selected.

***Table 14.1. Site names and ID for this study***

| Site Name, Number | ID for this study |
|---|---|
| Owers Bank, Area 396 | 1 |
| Hastings Bank, Area X | 2a |
| Hastings Bank, Area Y | 2b |
| Outer Thames, Area 327 | 3 |
| Outer Thames, Area 222 | 4 |
| Southwold, Boundary of Areas 221 and 229 | 5a |
| Southwold, Boundary of Areas 282 and 305/2 | 5b |
| Great Yarmouth, Intersect of Areas 202, 254, 319 and 240 | 6a |
| Great Yarmouth, Intersect of Areas 328, 242, 361 and 360 | 6b |
| Coal Pit/Sole Pit, Area 408 | 7 |

### *14.2.3 Tidal currents*

Due to resource constraints no new current data were collected from the sites listed in Table 14.1, but the data used was extracted from information already available to HR Wallingford.

Mean spring tidal currents were extracted at each of the locations from existing flow models. These models are depth averaged and are based on a finite element grid. They are typically calibrated against Admiralty Tidal Diamonds. There are some limitations in the current data generated from these models. These include:

- The resolution in each of the model areas varies across the sites and from model to model.
- The model output was stored every 20-30 minutes and therefore peak currents may not be represented fully.
- Mean spring tidal currents have been used for this study. These are reasonably representative of conditions for long term sediment transport predictions, but they will not include the higher flows on the larger spring tides which occur for about 15% of the year.

The main limitation of the analysis is that the peak flows at the sites may not be fully represented. This limitation is considered further in Section 14.2.7.

The models used for the different sites were as follows:

1 - Bassurelle model, HR Wallingford 2000.
2a, 2b – Hastings model, HR Wallingford 1999
3, 4 – Outer Thames model, HR Wallingford 1998
5a, 5b, 6a, 6b, 7 – Southern North Sea studies, HR Wallingford 2001

The results in terms of percentage exceedence (the portion of time that currents exceed the specified values over a year) of mean spring tidal currents for the ten sites identified above are shown in Table 14.2.

The strongest currents (in excess of 1.5 m $s^{-1}$) are found at the inshore location at Great Yarmouth. Peak flow speeds exceed 1 m $s^{-1}$ at Hastings Area Y, Outer Thames (Area 327), Outer Thames (Area 222), Southwold (Area 282) and Great Yarmouth (Area 328) and Great Yarmouth (Area 202). The remaining four sites: Owers Bank (Area 396), Hastings X, Southwold (Area 221), Great Yarmouth (Area 202) and Coal Pit (Area 408) all have peak flows lower than 1 m $s^{-1}$.

### 14.2.4 Wave climates

Wave climates at some of the selected locations were available through earlier HR investigations. However, there was no consistent data set for the sites where data existed. It was therefore decided to generate new wave climates using the United Kingdom Meteorological Office (UKMO) European Wave Model (Golding, 1981). The UKMO model covers European waters on a 25-30km grid. The model archive provides good quality synthetic sequential wind and wave data, in consistent format, from October 1986 onwards. It is a reliable and inexpensive source of information on deep water wave conditions and over-water wind conditions. The model is run twice daily, driven by wind fields extracted from operational global weather forecasting models, which produce wave forecasts from 12 hours prior to the datum time (T) up to 36 hours ahead, at 3 hourly intervals.

At a grid spacing of 25-30km the model cannot represent islands, headlands or bathymetric features less than about 30 km in size. The data for grid points close to land should be regarded as representative of offshore conditions just outside the influence of coastal features, in 20-30 m depth. On open, relatively deep nearshore areas, this may mean 10-20 km from the coast, but in more complex areas, it may be better to assume 40-50 km offshore. Reliability should be considered for each potential coastal application in turn, with a common sense attitude to what a 25-30 km grid could achieve. Nearshore wave transformation modelling will nearly always be required before using UKMO wave data as input to coastal design calculations.

As well as noting the time, date, latitude and longitude, each forecast gives the wind speed and direction, significant wave height (Hs) and mean wave period (Tm), for the separate wind-sea, swell components and overall. The data from T – 12 hours to T + 0 hours are permanently stored in an archive, whilst the data from T + 0 to T + 36 hours are immediately disseminated for forecasting purposes.

***Table 14.2. Exceedence of tidal currents at the sites selected***

| Current (m $s^{-1}$) | 1 | 2a | 2b | 3 | 4 | 5a | 5b | 6a | 6b | 7 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 0.1 | 97.4 | 96.2 | 96.2 | 97.4 | 94.9 | 94.7 | 92.1 | 100 | 100 | 100 |
| 0.2 | 94.9 | 92.3 | 88.5 | 87.2 | 92.3 | 92.1 | 89.5 | 92.1 | 94.7 | 94.7 |
| 0.3 | 84.6 | 76.9 | 80.8 | 82.1 | 82.1 | 81.6 | 81.6 | 86.8 | 84.2 | 76.3 |
| 0.4 | 79.5 | 76.9 | 73.1 | 69.2 | 79.5 | 76.3 | 78.9 | 84.2 | 78.9 | 68.4 |
| 0.5 | 69.2 | 65.4 | 65.4 | 61.5 | 66.7 | 65.8 | 71.1 | 78.9 | 73.7 | 60.5 |
| 0.6 | 66.7 | 57.7 | 57.7 | 59.0 | 64.1 | 60.5 | 68.4 | 73.7 | 65.8 | 44.7 |
| 0.7 | 53.8 | 34.6 | 42.3 | 48.7 | 56.4 | 50.0 | 57.9 | 71.1 | 60.5 | 26.3 |
| 0.8 | 41.0 | 15.4 | 15.4 | 38.5 | 48.7 | 34.2 | 50.0 | 65.8 | 55.3 | 2.6 |
| 0.9 | 25.6 | 11.5 | 11.5 | 28.2 | 41.0 | 15.8 | 42.1 | 63.2 | 47.4 | |
| 1.0 | 0.0 | 0.0 | 3.8 | 15.4 | 28.2 | | 26.3 | 55.3 | 36.8 | |
| 1.1 | | | | | 10.3 | | | 52.6 | 18.4 | |
| 1.2 | | | | | | | | 44.7 | | |
| 1.3 | | | | | | | | 42.1 | | |
| 1.4 | | | | | | | | 31.6 | | |
| 1.5 | | | | | | | | 18.4 | | |

***Table 14.3. Exceedence of wave height (Hs) at the sites selected***

| Height Hs (m) | 1 | 2a/2b | 3 | 4 | 5a/5b | 6a/6b | 7 |
|---|---|---|---|---|---|---|---|
| 0.0 | 100.0 | 100 | 100 | 100 | 100 | 100 | 100 |
| 0.5 | 85.1 | 87.4 | 82.3 | 87.0 | 87.5 | 88.7 | 91.5 |
| 1.0 | 53.3 | 50.0 | 43.5 | 51.8 | 52.2 | 54.7 | 62.8 |
| 1.5 | 30.6 | 26.2 | 18.8 | 26.6 | 26.7 | 28.7 | 37.1 |
| 2.0 | 18.1 | 14.8 | 8.0 | 14.1 | 13.7 | 14.6 | 21.2 |
| 2.5 | 10.3 | 8.1 | 2.7 | 6.4 | 6.1 | 6.5 | 10.8 |
| 3.0 | 5.7 | 4.4 | 0.6 | 2.3 | 2.2 | 2.2 | 5.2 |
| 3.5 | 2.8 | 2.0 | 0.1 | 0.7 | 0.7 | 0.7 | 2.1 |
| 4.0 | 1.2 | 0.9 | <0.01 | 0.2 | 0.2 | 0.2 | 0.9 |
| 4.5 | 0.6 | 0.4 | | < 0.1 | < 0.1 | < 0.1 | 0.3 |
| 5.0 | 0.2 | 0.1 | | <0.01 | | | 0.1 |
| 5.5 | 0.1 | < 0.1 | | | | | < 0.1 |
| 6.0 | < 0.1 | <0.01 | | | | | < 0.1 |
| 6.5 | <0.01 | | | | | | < 0.01 |
| 7.0 | < 0.01 | | | | | | |

Sea state observations from fixed buoys, oil platforms, Ocean Weather Ships, and more recently satellite measurements, are used for real-time calibration of the model, and also for periodic calibration exercises.

The closest points on the UKMO grid for seven of the sites (one site only for Hastings, Southwold and Great Yarmouth) were identified and the full record from the archive downloaded. An appropriate grid point was chosen to represent wave conditions offshore of each of the seven sites of interest. For each point chosen, the full data record back to October 1986 was extracted from the wave model archive, to form the basis of the offshore wave climate intended as representative of that location. Scatter plots of Hs and direction and Hs and Tm were produced.

The results in terms of percentage exceedence of Hs for the seven sites are shown in Table 14.3.

Maximum wave heights off the East Anglian coast are less than those found off the South Coast and off the Humber.

## 14.2.5 Bed shear stresses

The results presented in the preceding sections broadly describe the hydrodynamics at the ten sites selected. They can be used to infer sediment mobility at the site and provide an initial indicator of natural variability. However, sediment mobility is more properly described by the concept of bed shear stress, which is the force acting on the seabed surface and the particles on that surface. Estimates of bed shear stress induced by currents and waves at each of the sites have been made based on assumptions about roughness length scales on the bed and on grain size.

The parameterisation of the bed roughness used by the numerical models was optimised by comparison with the observed tidal propagation in the various areas of interest. Both the choice of friction law and the relevant coefficient are chosen as part of this calibration process. For each model this process is further described in the references for the model study. For the four models used to provide data for the present study the Hastings model (HR Wallingford, 1999), the Bassurelle model (HR Wallingford, 2000) and the Southern North Sea model (HR Wallingford, 2001) all used a Nikuradse roughness law with a coefficient of 0.01 m. The model of the Outer Thames Estuary (HR Wallingford, 1998) used a Chezy parameterisation of the bed roughness with a coefficient of 70.

Bed shear stresses for currents and waves are shown in Tables 14.4 and 14.5.

The data represented in Tables 14.4 and 14.5 demonstrate that the generation of bed shear stresses up to about 1.0 $N/m^2$ is dominated by tidal currents at all sites, but it is the large, infrequent waves which are responsible for maximum potential movement of bed material.

*Table 14.4. Exceedence of current induced bed shear stress at the ten sites selected*

| Bed shear stress ($N/m^2$) | 1 | 2a | 2b | 3 | 4 | 5a | 5b | 6a | 6b | 7 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 0.1 | 84.6 | 80.8 | 84.5 | 82.1 | 82.1 | 81.6 | 81.6 | 89.5 | 84.2 | 76.3 |
| 0.2 | 79.5 | 73.1 | 73.1 | 79.5 | 69.2 | 76.3 | 78.9 | 84.2 | 76.3 | 65.8 |
| 0.3 | 69.2 | 65.4 | 65.4 | 66.7 | 61.5 | 68.4 | 71.1 | 79.0 | 73.7 | 55.3 |
| 0.4 | 66.7 | 57.7 | 57.7 | 64.1 | 59.0 | 63.2 | 68.4 | 76.3 | 65.8 | 44.7 |
| 0.5 | 56.4 | 53.9 | 53.9 | 56.4 | 51.3 | 60.5 | 60.5 | 71.1 | 63.2 | 34.2 |
| 0.6 | 53.9 | 34.6 | 34.6 | 53.8 | 48.7 | 50.0 | 57.9 | 71.1 | 60.5 | 13.2 |
| 0.7 | 46.2 | 15.4 | 23.1 | 48.7 | 41.0 | 47.4 | 52.6 | 65.8 | 55.3 | 5.3 |
| 0.8 | 41.0 | 15.4 | 15.4 | 43.6 | 35.9 | 39.5 | 50.0 | 65.8 | 50.0 | 2.6 |
| 0.9 | 30.8 | 11.5 | 11.5 | 41.0 | 33.3 | 31.6 | 42.1 | 63.2 | 47.4 | |
| 1.0 | 23.1 | 11.5 | 11.5 | 35.9 | 25.6 | 23.7 | 36.8 | 60.5 | 42.1 | |
| 1.1 | 7.7 | 7.7 | 11.5 | 28.2 | 20.5 | 5.3 | 28.9 | 57.9 | 36.8 | |
| 1.2 | 2.6 | | 3.9 | 17.9 | 12.8 | | 18.4 | 55.3 | 31.6 | |
| 1.3 | | | | 12.8 | | | 5.3 | 55.3 | 23.7 | |
| 1.4 | | | | 10.3 | | | | 52.6 | 18.4 | |
| 1.5 | | | | 5.1 | | | | 50.0 | | |
| 1.6 | | | | | | | | 47.4 | | |
| 1.7 | | | | | | | | 44.7 | | |
| 1.8 | | | | | | | | 42.1 | | |
| 1.9 | | | | | | | | 42.1 | | |
| 2.0 | | | | | | | | 42.1 | | |
| 2.1 | | | | | | | | 34.2 | | |
| 2.2 | | | | | | | | 31.6 | | |
| 2.3 | | | | | | | | 31.6 | | |
| 2.4 | | | | | | | | 29.0 | | |
| 2.5 | | | | | | | | 21.1 | | |
| 2.6 | | | | | | | | 18.4 | | |
| 2.7 | | | | | | | | 10.5 | | |
| 2.8 | | | | | | | | 7.9 | | |

*Table 14.5. Exceedence of wave induced bed shear stress at the sites selected*

| Bed shear stress ($N/m^2$) | 1 | 2a/2b | 3 | 4 | 5a/5b | 6a/6b | 7 |
|---|---|---|---|---|---|---|---|
| 0.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 0.1 | 18.1 | 14.8 | 14.1 | 2.7 | 26.7 | 6.4 | 10.8 |
| 0.2 | 10.3 | 8.1 | 6.4 | 2.7 | 13.7 | 0.7 | 5.2 |
| 0.3 | 5.7 | 4.4 | 6.4 | 0.6 | 6.1 | 0.2 | 2.1 |
| 0.4 | 5.7 | 4.4 | 2.3 | 0.1 | 6.1 | 0.2 | 2.1 |
| 0.5 | 2.8 | 2.0 | 2.3 | 0.1 | 6.1 | <0.1 | 0.9 |
| 0.6 | 2.8 | 2.0 | 0.7 | <0.1 | 2.2 | | 0.9 |
| 0.7 | 2.8 | 2.0 | 0.7 | <0.1 | 2.2 | | 0.3 |
| 0.8 | 1.2 | 0.9 | 0.7 | | 2.2 | | 0.3 |
| 0.9 | 1.2 | 0.9 | 0.2 | | 0.7 | | 0.3 |
| 1.0 | 1.2 | 0.9 | 0.2 | | 0.7 | | 0.1 |
| 1.2 | 0.6 | 0.4 | 0.2 | | 0.2 | | <0.1 |
| 1.4 | 0.6 | 0.4 | <0.1 | | 0.2 | | <0.1 |
| 1.6 | 0.2 | 0.1 | <0.1 | | 0.2 | | <0.1 |
| 1.8 | 0.2 | 0.1 | <0.1 | | <0.1 | | <0.1 |
| 2.0 | 0.1 | <0.1 | | | <0.1 | | <0.01 |
| 2.2 | 0.1 | <0.1 | | | <0.1 | | |
| 2.4 | 0.1 | <0.1 | | | | | |
| 2.6 | <0.1 | <0.01 | | | | | |
| 2.8 | <0.1 | | | | | | |
| 3.0 | <0.1 | | | | | | |
| 3.2 | <0.1 | | | | | | |
| 3.4 | <0.1 | | | | | | |
| 3.6 | <0.1 | | | | | | |
| 3.8 | <0.01 | | | | | | |
| 4.0 | <0.01 | | | | | | |
| 4.2 | <0.01 | | | | | | |

## 14.2.6 Sand mobility

### 14.2.6.1 Representation of currents and waves

In the second year of the study, the representation of currents and waves at each of the ten sites was modified so that the data could be used to estimate the potential mobility of sand on the bed.

The tidal currents were plotted in terms of exceedence graphs (Figure 14.1). These graphs have been used to extract mean flow speeds in 10% bands. These flows are shown in Table 14.6 below.

Similarly, the wave data were used to extract wave heights in 10% bands and the exceedence curves for the seven distinct locations are shown in Figure 14.2. The curves have been used to extract mean wave heights and periods in 10% bands. The wave data are shown in Table 14.7 below.

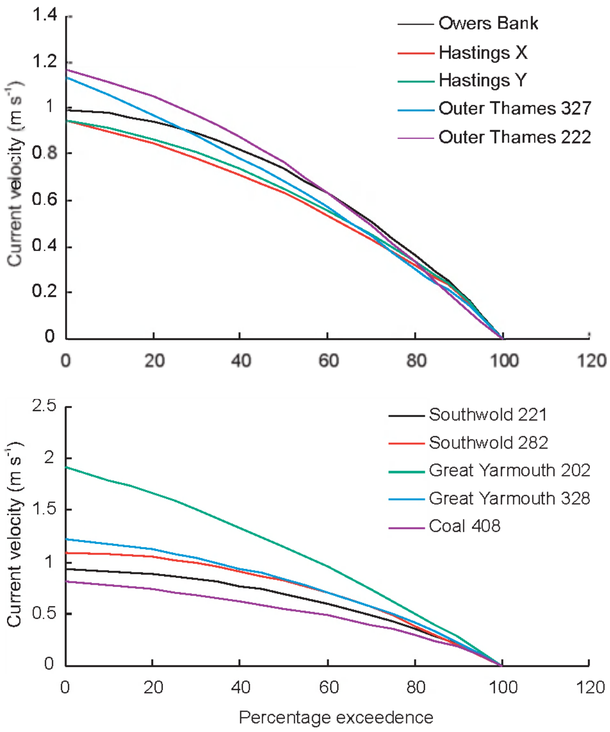


***Figure 14.1. Current velocities at the extraction sites***

***Table 14.6. Distribution of tidal currents at the sites selected***

| % band | Current velocity at each location (m s$^{-1}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2a | 2b | 3 | 4 | 5a | 5b | 6a | 6b | 7 |
| 100-90 | 0.12 | 0.13 | 0.13 | 0.14 | 0.06 | 0.13 | 0.14 | 0.16 | 0.14 | 0.13 |
| 90-80 | 0.29 | 0.26 | 0.27 | 0.27 | 0.24 | 0.28 | 0.33 | 0.40 | 0.32 | 0.24 |
| 80-70 | 0.44 | 0.38 | 0.39 | 0.40 | 0.41 | 0.42 | 0.49 | 0.63 | 0.49 | 0.34 |
| 70-60 | 0.57 | 0.49 | 0.50 | 0.52 | 0.56 | 0.54 | 0.64 | 0.85 | 0.64 | 0.44 |
| 60-50 | 0.68 | 0.58 | 0.61 | 0.63 | 0.70 | 0.64 | 0.76 | 1.05 | 0.77 | 0.52 |
| 50-40 | 0.78 | 0.67 | 0.69 | 0.73 | 0.82 | 0.73 | 0.87 | 1.24 | 0.89 | 0.60 |
| 40-30 | 0.86 | 0.75 | 0.77 | 0.83 | 0.92 | 0.80 | 0.96 | 1.42 | 0.99 | 0.66 |
| 30-20 | 0.92 | 0.82 | 0.84 | 0.93 | 1.01 | 0.86 | 1.02 | 1.57 | 1.08 | 0.71 |
| 20-10 | 0.96 | 0.88 | 0.89 | 1.02 | 1.08 | 0.90 | 1.07 | 1.57 | 1.15 | 0.76 |
| 10-0 | 0.98 | 0.92 | 0.93 | 1.10 | 1.14 | 0.92 | 1.09 | 1.57 | 1.20 | 0.79 |

***Table 14.7 . Distribution of wave height (Hs) at the sites selected***

| % Band | Wave Height/Period at each location | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 a&b | 3 | 4 | 5 a&b | 6 a&b | 7 |
| 100-90 | 0.35/4.5 | 0.30/4.4 | 0.20/4.0 | 0.30/4.0 | 0.30/4.1 | 0.30/4.1 | 0.40/4.2 |
| 90-80 | 0.60/4.6 | 0.60/4.5 | 0.50/4.1 | 0.60/4.1 | 0.63/4.3 | 0.60/4.3 | 0.66/4.4 |
| 80-70 | 0.75/4.7 | 0.70/4.6 | 0.65/4.3 | 0.75/4.2 | 0.75/4.4 | 0.80/4.5 | 0.83/4.6 |
| 70-60 | 0.90/4.8 | 0.83/4.6 | 0.78/4.4 | 0.88/4.3 | 0.88/4.5 | 0.90/4.6 | 1.05/4.8 |
| 60-50 | 1.05/4.9 | 1.00/4.7 | 0.90/4.5 | 1.03/4.4 | 1.05/4.7 | 1.10/4.7 | 1.20/5.0 |
| 50-40 | 1.25/5.1 | 1.10/4.8 | 1.05/4.7 | 1.20/4.5 | 1.23/4.9 | 1.28/4.9 | 1.40/5.1 |
| 40-30 | 1.50/5.4 | 1.30/5.0 | 1.20/4.8 | 1.38/4.6 | 1.38/5.0 | 1.40/5.0 | 1.65/5.3 |
| 30-20 | 1.85/5.7 | 1.55/5.3 | 1.40/5.0 | 1.60/4.7 | 1.60/5.2 | 1.70/5.3 | 1.90/5.5 |
| 20-10 | 2.20/6.5 | 2.00/5.7 | 1.65/5.2 | 2.00/4.9 | 2.00/5.6 | 2.00/5.5 | 2.30/6.0 |
| 10-0 | 3.50/7.0 | 2.90/6.5 | 2.25/5.8 | 2.70/5.2 | 2.65/6.3 | 2.70/6.4 | 3.00/6.6 |

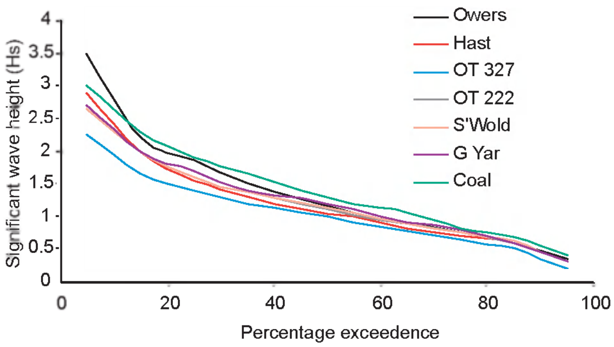


***Figure 14.2. Wave climates at the extraction sites***

## 14.2.6.2 Mobility index

The flow and wave conditions together with representative water depths for each site have been used to calculate the potential mobility of sand in terms of a 'mobility index' at each of the ten sites. The calculations have used standard sediment transport equations such as those described in Soulsby (1997). They have been carried out for a standard bed sediment type (fine sand with a $D_{50}$ of 0.1 mm) with all other factors and coefficients constant between sites. This allows a direct comparison to be made between each of them, and they can in effect be ranked from most dynamic to least dynamic.

The mobility index is a nominal quantity (in tonnes) of fine sand moved across a section of seabed over a period of one year. Direction is not taken into account, so the index is the total quantity of sand moving to and fro across the site through a metre width across the tidal flow.

For comparison, the indices for medium and coarse sand have also been calculated and are shown in Table 14.9 below.

The tables show that by far the most dynamic site is 6a, Great Yarmouth (Area 202) with a mobility index of 5312 (fine sand). At the other end of the scale is the Coal/Sole Pit site (Area 408) where the index is only 135. The most significant difference between these two extreme sites is the peak spring tide current velocities, which are included in the table below. The maximum value at the Yarmouth site (6a) is 1.57 m $s^{-1}$ and at Area 408 offshore of the Humber (7) only 0.79 m $s^{-1}$. Peak spring tide currents are shown in Table 14.10 below.

There is a positive correlation between the maximum current velocity at the site and the total potential mobility (Figure 14.3). This is independent of any other factor such as water depth, and wave height.

Depth may be expected to be an important factor, but there is little correlation between the total mobility of a site and the water depth at that site. This is probably because all of the sites are relatively deep (16 m and over) and there is not a great deal of difference between them (depths range from 16 m to 28 m).

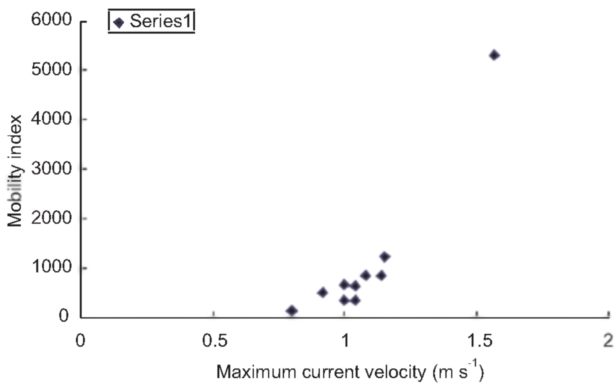


***Figure 14.3 Maximum current velocity against mobility index***

***Table 14.8. Mobility Index for fine sand ($D_{50}$ = 0.1 mm)***

Potential mobility of fine sand in one year

| 1 | 2a | 2b | 3 | 4 | 5a | 5b | 6a | 6b | 7 |
|---|---|---|---|---|---|---|---|---|---|
| 648 | 347 | 357 | 613 | 837 | 506 | 859 | 5312 | 1209 | 135 |

***Table 14.9. Mobility Index for three sand sizes***

| Sand size | 1 | 2a | 2b | 3 | 4 | 5a | 5b | 6a | 6b | 7 |
|---|---|---|---|---|---|---|---|---|---|---|
| Fine ($D_{50}$ = 0.1 mm) | 648 | 347 | 357 | 613 | 837 | 506 | 859 | 5312 | 1209 | 135 |
| Medium ($D_{50}$ =0.3 mm) | 278 | 148 | 152 | 263 | 358 | 218 | 367 | 2321 | 520 | 56 |
| Coarse ($D_{50}$ = 1 mm) | 44 | 18 | 18 | 42 | 61 | 33 | 60 | 635 | 100 | 3 |

***Table 14.10. Peak spring tide current velocities***

Current speed exceeded for 10% of the time

| 1 | 2a | 2b | 3 | 4 | 5a | 5b | 6a | 6b | 7 |
|---|---|---|---|---|---|---|---|---|---|
| 0.98 | 0.92 | 0.93 | 1.10 | 1.14 | 0.92 | 1.09 | 1.57 | 1.20 | 0.79 |

### 14.2.7 Sensitivities

#### 14.2.7.1 Flowspeeds

As stated in the last section, the defining factor in terms of potential sediment transport at the locations considered in this study is the current flow at the ten sites. Current speeds for the main calculations were based on single tide information from existing models at HR Wallingford. On the whole, the method used represents the peak flow reasonably well. As stated in Section 14.3 the highest value is not always included but with data from a single tide only it is not reasonable to allocate a percentage occurrence to a speed recorded for a very brief period. Additional measured flow data were supplied by CEFAS for Site 4 and Site 7. The Area 222 data were from October and November 1992, and were for two heights above the bed. Those from Area 408 were for two periods in 1976 (07.07.76 – 31.08.76 and 04.09.76 to 38.10.76).

The comparisons of the current speeds at the two sites are shown in terms of percentage exceedence graphs (as in Figures 14.1 and 14.2) in Figure 14.4.

In the first of the two plots (Area 222) the two sets of CEFAS data fall either side of the HR Wallingford model predictions. The most significant difference is in the E1-1 data which show generally higher flows than the Wallingford data, and more significantly have a peak velocity in excess of 1.6 m $s^{-1}$ compared with under 1.2 m $s^{-1}$. Using the CEFAS data in the bed transport calculations gives mobility indices of 1533 for the E1-1 data and 669 for El-2. This compares with the HR Wallingford index of 837.

In the case of the Area 408 data (Figure 14.4, lower plot) the CEFAS velocities are generally lower than the HR Wallingford values, except inasmuch as the peaks are greater. The peak flow of 1.2 m $s^{-1}$ in the later data (September/October, D6-1) compensates for the otherwise lower flows with the net result that the mobility index of 139 is much the same as the HR Wallingford data (135). The earlier data (July and August, D5-1) had a lower maximum of just over 1 m $s^{-1}$, and the mobility index is calculated at 67.

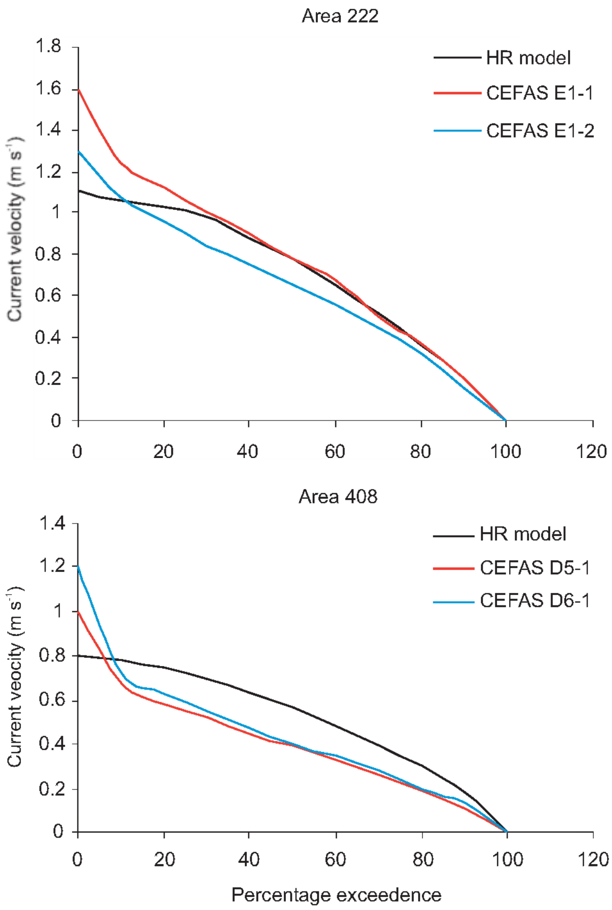


***Figure 14.4. Tidal currents - comparison of HR model and CEFAS measurements***

#### 14.2.7.2 Wave climate

In the case of waves, much higher peaks are potentially ignored in the process of grouping them into 10% bands. For example at Owers Bank where the wave climate indicates a very small proportion of waves with significant height 7 m, the greatest value used for the mobility calculation was 3.5 m (Table 14.3). To check on the significance of this effect the calculations were updated for the Owers and Coal Pit sites.

At Owers Bank the additional waves, in excess of the 3.5 m used in the main calculation, were between 4 m and 7 m significant wave height. The full distribution, with percentage occurrence is shown below:

***Table 14.11. Owers Bank wave heights***

| Wave Height (m) | Wave Period (s) | Percentage Occurrence |
|---|---|---|
| 4 | 7.6 | 0.650 |
| 4.5 | 8.0 | 0.330 |
| 5 | 8.3 | 0.140 |
| 5.5 | 8.9 | 0.070 |
| 6 | 9.0 | 0.020 |
| 6.5 | 9.1 | 0.002 |
| 7 | 9.3 | 0.008 |

Using these figures (with their relevant percentage occurrence) in the calculation of the mobility index (allowing for the small reduction in the effect of the 3.5 m wave – which was previously assumed to be the highest) gives a new value of 672 (previously 648). This represents an increase of about 4% compared with the calculation which omitted the higher waves.

The additional waves at Coal Pit, in excess of the 3.0m used in the main calculation, were between 3.5 m and 6.5 m significant wave height. The full distribution, with percentage occurrence is shown below:

***Table 14.12. Coal Pit wave heights***

| Wave Height (m) | Wave Period (s) | **Percentage Occurrence** |
|---|---|---|
| 3.5 | 7.1 | 1.230 |
| 4.0 | 7.5 | 0.530 |
| 4.5 | 7.9 | 0.180 |
| 5.0 | 8.1 | 0.120 |
| 5.5 | 8.3 | 0.015 |
| 6.0 | 8.5 | 0.010 |
| 6.5 | 8.5 | 0.005 |

Using this figure gives a new value for the mobility index of 146, an increase of nearly 8% compared with calculations which omitted the higher waves (135).

### 14.2.7.3 Flow direction

In this section the net direction of flow, and consequently transport is considered for three of the sites considered in this study.

***Hastings Y***
The flood flow at this site is towards 50°N with the slightly more variable ebb tide flowing between 230°N and 250°N. The flood tide is stronger than the ebb (with peaks of just over 1 m $s^{-1}$ and 0.75 m $s^{-1}$ for flood and ebb respectively. This is reflected in the net potential transport quantities with about 3½ times as much being transported on the flood as on the ebb. (Diamonds D and E on Admiralty Chart 536 confirm stronger flood flows.)

***Area 222***
Again flows at this site are reasonably aligned with the ebb direction being around 25°N and the flood about 200°N. The ebb flow peak of around 1.2 m $s^{-1}$ is stronger than the flood (just over 1 m $s^{-1}$) and this makes a big difference to potential sand transport with the ebb tide moving twice the amount as the flood.

***Area 408***
The flows at 408 are more complex with quite a variation as the tide tends to turn quite slowly. The strongest flows are towards 340°N and 150°N, but tend to be around high and low water. (The closest Admiralty diamond shows peak spring tide flows of 0.7 m $s^{-1}$ at high water and 0.6 to 0.65 at low water.) The "main" flood direction is about 320°N and ebb 140°N. The predicted ebb potential transport is 2 to 2½ times that on the flood.

### 14.2.7.4 Discussion

Whilst the potential mobility index clearly does not provide all details of the actual sediment transport at a site it does provide a basis for comparison from one site to another. Even relatively simplistic representation of the hydrodynamics is adequate for this purpose.

Bed material type and bed form at and adjacent to the site of interest will significantly influence the actual transport of material at the site. The importance of bed material distribution at licensed extraction sites is considered in Section 14.2.8.

## *14.2.8 Bed materials*

The following briefly considers the bed material types at the three sample locations used above (Hastings Y, Areas 222 and 408). At each of these sites samples were taken and analysed in three zones defined by CEFAS as "Reference", where no dredging was undertaken and two zones where the historic dredging intensity was defined as "High" and "Low".

***Table 14.13. Bed sample analysis for Hastings Y***

| | Gravel | Sand | Silt | Clay |
|---|---|---|---|---|
| Reference (5 samples) | 55 | 41 | 3 | 1 |
| Low activity (10) | 30 | 67 | 2 | 1 |
| High activity (10) | 44 | 54 | 1 | 1 |

The particle size distribution shows that the gravel fraction is lower at the site of dredging activity and is replaced by sand. In this case there is a higher proportion of sand in the low intensity zone than in the high intensity zone. This potentially increases the mobility of the bed materials at the site of low dredging intensity.

***Table 14.14. Bed sample analysis for Area 222***

| | Gravel | Sand | Silt | Clay |
|---|---|---|---|---|
| Reference (5) | 46 | 21 | 32 | 2 |
| Low activity (5) | 52 | 41 | 7 | <1 |
| High activity (5) | 35 | 65 | <1 | <1 |

Within this area, dredging causes a substantial lowering in the apparent proportion of silt and there is a large increase in the sand content, and potential mobility. Presumably, the disturbance caused by the dredging results in the fines being carried away with the tidal flows, or possibly through the vessel's overflow and/or screening.

***Table 14.15. Bed sample analysis for Area 408***

| | Gravel | Sand | Silt | Clay |
|---|---|---|---|---|
| Reference | 40 | 56 | 3 | <1 |
| Low activity | 47 | 52 | 1 | <1 |
| High activity | 26 | 73 | <1 | <1 |

Between reference and high dredge zones the proportion of gravel is lowered and replaced with sand. Once again this would result in a potential increase in the mobility of bed material at the site.

## 14.3 Future work

If recovery at aggregate dredging sites is directly related to mobility and we wish to be able to predict, quantify, compare and influence recovery rates, then we need to develop a method of converting the indices of potential mobility discussed in the last Section into actual mobility.

Mobility depends to a great extent on the supply of material, and this may include:

- The material that is activated naturally near the site and transported across it under the influence of frequent or occasional hydrodynamic conditions.
- The material exposed by the dredging activity with potentially greater mobility than the original seabed surface.
- The material disturbed, overflowed or screened during the dredging activity.

The work undertaken by HR Wallingford for this study has to some extent been theoretical and is based on sand transport relationships. The means to calculate mobility at a site has been developed but actual mobility has not been calculated. In order to extend the assessment information about the sediment movement at the sites is needed, and sophisticated modelling techniques applied to the transport processes. Recent and ongoing developments in modelling have been specifically designed for use by the dredging industry. These will help enable predictions to be made about the way sediment behaves in the water column after it leaves the dredger, and the form and subsequent behaviour of the footprint of material on the seabed. The models include tidal current models, plume models and particle tracking models. In order to begin to apply them, the following information is required:

- The rate and duration of input of screened material onto the bed.
- The initial distribution of this material for a single dredging cycle and over time as more dredging cycles are completed.
- The quantity of material that is mobile and the changes to this mobility with different tidal, wave and seasonal conditions.
- The nature and mobility of the local seabed material.
- The interaction between the screened deposit and the surrounding seabed.
- The rate of dispersion from the site.
- The nature of any resulting bedforms.
- The thickness of the screened material covering the surrounding seabed, and the variation of this with time.
- The final destination of dispersed material.

## 14.4 Summary and conclusions

CEFAS has undertaken a study designed to investigate the mechanisms of re-habilitation of the seabed following marine aggregate dredging and to identify measures to enhance this re-habilitation. As part of this study HR Wallingford was commissioned to use available data to categorise each of a number of dredging sites. The hydrodynamic conditions at the sites were derived from a combination of computational flow and wave models held at Wallingford. The data was analysed in a systematic manner enabling relative comparisons from one site to another to be made.

Initially the data were presented as raw hydrodynamic data and then as exceedence tables for the different sites. An initial analysis of the contribution of wave and tidal forces on the seabed at the different sites has been made by applying uniform assumptions concerning bedform roughness and grain size across all the sites.

Following this, the hydrodynamic information, together with standard sediment transport equations, were interpreted in terms of the ability of the hydrodynamic forces to mobilise bed material at each of the sites. To compare like with like a uniform size of bed material was used for each site. This resulted in a "mobility index" being calculated for each site. This index is a nominal measure representing the potential for sand to be moved across a section of seabed of width one metre over a period of one year. Direction is not taken into account, so the index is the total quantity of sand that could be moved to and fro across the site.

Sensitivity analysis has shown that within the selected areas the mobility indices are closely related to the current velocities, with maximum potential for sand movement occurring in the areas with highest tidal flows (See Section 14.2.7). At the sites selected transport was relatively insensitive to water depth and wave climate. This conclusion was further emphasised by comparing the indices at two of the selected sites as calculated using HR Wallingford model predictions and with field data measured by CEFAS.

An assessment of the variation in the potential direction of the movement of material during the tidal cycle was made at three of the sites. In each case there was a strong directional bias, with up to 3½ times as much being transported during one phase of the tide than the other.

Also, consideration of the effect of aggregate recovery on the seabed materials was made by comparing the size grading of bed material in zones where the dredging activity varied in intensity. This showed that dredging did affect the nature of the material at the site and that although the percentage of gravel was generally lower in the high intensity zones, it was actually higher at two of the low intensity zones. On the whole when the proportion of gravel is lower the sand content is higher and if silt is present at a site where aggregate is recovered the amount tends to be substantially reduced by the dredging.

The overall aim of this study has been to identify the use of the mobility index to examine the relationships with biological stations, and to evaluate its utility as a predictor of the status of natural and impacted environments. In order to predict, quantify, compare and influence recovery rates it is necessary to develop a method of turning the measure of potential mobility investigated in this study into actual mobility.

To do this, recent developments in modelling that have been specifically designed for use by the dredging industry should be utilised. These will help us to understand and predict the way sediment behaves in the water column after it leaves the dredger, and the form and subsequent behaviour of the footprint of material on the seabed. In order to implement these models much more detail of the sites and the dredging procedures is required. This should include details of the bed material and how this is changed by dredging as well as details of the dredging procedure.

Such detail would enable the perturbation to sediment transport processes caused by dredging at a site to be put into the context of the actual sediment transport at the site. For example, a high net input of sand from dredging at a site with high natural transport rates (high mobility index) might have less of a physical effect than a low input of sand at a site with little natural transport (low mobility index) and small tidal residual.

## 14.5 References

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# 15. ANNEX II - THE EFFECTS OF DREDGING ACTIVITY ON EPIFAUNAL COMMUNITIES – SURVEYS FOLLOWING CESSATION OF DREDGING

## 15.1 Introduction

In recent years approximately 23 Mt per annum of marine sand and gravel has been extracted from sites around the England and Wales coastlines. Sand and gravel extraction has been shown to have a number of environmental effects on the seabed including the removal of sediment and resident fauna, changes to the nature and stability of sediments accompanying the exposure of underlying strata, increased turbidity and redistribution of fine particulates (for review see Newell *et al.*, 1998). As the extraction of marine aggregate has a direct impact at the seabed, assessment of this activity has conventionally targeted bottom substrata and the associated benthic fauna, usually by means of small (0.1 $m^2$) grab samplers (Boyd, 2002). Such biological assessments consist of an analysis of macrobenthic species that are either sessile or mobile within narrow spatial ranges. The level of information on the effect of dredging activity on this component of the fauna is increasing (e.g. Kenny and Rees, 1996; Newell *et al.*, 1998; Seiderer and Newell, 1999; Boyd *et al.*, 2003; Boyd and Rees, 2003), but studies on the effects of dredging on the marine epifauna as sampled using trawls and dredges are more limited (Shelton and Rolfe, 1972; Kenny *et al.*, 1991). The epifauna are those conspicuous macrofaunal species which live on or near the surface of the seabed. Members of the epifauna can be further classified in terms of their permanency in association with the seabed. Some species spend their entire adult life intimately associated with the seabed e.g. hydroids, most crabs and groundfish, whilst others may only be transiently associated, e.g. shrimps and many pelagic fish species.

From a theoretical standpoint, the epifauna possess many ecological characteristics which make this group an important target in environmental assessments (see Rees and Service, 1993; Rees *et al.*, 1990; Boyd, 2002). These include their ability to support a relatively high diversity or biomass of other species e.g. in association with subtidal mussel beds (Magorrian and Service, 1998). Assessment of the epifauna may also be particularly effective in rocky areas or where the environment is so physically disturbed as a result of tidal and wave action that infaunal species composition is very impoverished. Furthermore, many epifaunal species are preyed upon by fish, hence an assessment of the impact of dredging on the epifauna in areas where juvenile fish are present would seem highly appropriate since they provide a refugia and food source for commercial fish species (Jennings and Kaiser, 1998; Bergman and van Santbrink, 2000) and any alteration or reduction in productivity or diversity of the fauna could affect fisheries success (Collie *et al.*, 2000).

Perturbations such as beam trawling (Jennings *et al.*, 2001; 2002) have been linked with a reduction in total community production, so it can be postulated that aggregate extraction activity may affect community production. Jennings *et al.* (2002) employed conventional size-based analyses in production estimation. Comparisons between the distribution of species biomass in communities impacted by aggregate extraction and reference locations may therefore prove to be a useful additional tool in evaluating the impact of aggregate extraction on the epifauna.

In addition, sessile benthic epifaunal species such as Ascidians provide a direct route for carbon from the water column via filter feeding. Finally, complementary surveys of the epifauna may provide additional information beyond that obtained from traditional infaunal investigations. Therefore increasingly, this component of the fauna is being employed as a means of detecting environmental perturbation (Kaiser and Spencer, 1994; Veale *et al.*, 2000; Brown *et al.*, 2001) and hence is also being incorporated into national and international monitoring programmes (Rees *et al.*, 1999; Ellis *et al.*, 2000; Callaway *et al.*, 2002).

Recent work has indicated that there is a correlation between diversity of epifaunal communities and factors such as the nature of substrata, near-bed tidal current velocity, water depth and temperature (Rees *et al.*, 1999; Callaway *et al.*, 2002; Freeman and Rogers, 2003). Physical disturbance and the destabilisation of the sediment as a result of marine aggregate extraction is therefore likely to be a significant factor in terms of the potential for recolonization of this component of the benthos following cessation of dredging.

A number of other factors may also influence the effect of marine aggregate extraction on epibenthic assemblages and their ensuing restoration. These include the types of organisms which remain in the vicinity following sediment extraction (Thrush *et al.*, 1991, 1992), the life histories and mechanisms of dispersal of different fauna (Levin, 1984), the patchiness of the environment (Hall *et al.*, 1994), the spatial and temporal variability of dredging disturbance (Hall *et al.*, 1994) and the effects of existing or new recruits on the substratum (Dean and Hurd, 1980). Thus the effects of marine aggregate extraction will not only depend upon the type of dredging but also the nature of the assemblage present prior to dredging.

The aim of this study was to investigate the status of epifaunal assemblages within and outside areas where marine aggregate extraction had ceased and to investigate whether different levels of historical dredging affected the subsequent nature of epifaunal recolonization. The epifauna was sampled at the same four extraction areas (namely Area 408, Area 222, Hastings X and Y; see Figure 15.1) selected for time-series investigations (see below for further information on these extraction areas).

## 15.2 Methodology

Four aggregate extraction sites were selected for the purposes of this study. Whilst inherent variability associated with the dredging history of each study site inevitably confounds the geographical comparison of effects, the selected sites account for current dredging practices employed in the UK and are representative of several habitats where dredging is occurring. In addition, all the study sites vary in the time-interval since cessation of dredging and therefore have the potential to represent different stages in the 'recovery' process. Two of these sites are located on the east coast, one offshore of Harwich in the region of the Thames (Area 222) and the other, offshore from the Humber estuary (Area 408). On the South coast, two extraction areas were sampled, located at Hastings Shingle Bank (Hastings X and Y).

***Site descriptions***
Area 222 is located approximately 20 miles east of Felixstowe in the Southern North Sea (Figure 15.1), and was first licensed for dredging in 1971. Historical records indicate that annual rates of extraction peaked in 1974 at 872,662 t and extraction was maintained at a lower level still in excess of 100,000 t per annum until 1995. It is located in water depths of between 22 m and 33 m. Dredging was carried out using trailer suction hopper dredgers with cargoes screened for gravel, and unwanted sediments, usually sands, being returned to the sea. Dredging using static hopper suction dredgers is also thought to have been carried out at the site. Boyd *et al.* (2003) have studied macrofauna at Area 222 and found that macrofaunal communities within the dredged areas had a reduced number of species when compared with a reference location. There was also a positive correlation between intensity of dredging activity and changes in the macrofaunal community structure.

Area 408 is located 60 miles east of the Humber estuary, also in the Southern North Sea (Figure 15.1). Aggregate extraction in zone 2 of Area 408 commenced relatively recently in 1996, reaching a peak in 1998 with the extraction of 948,459 tonnes of sand and gravel (Newell *et al.*, 2002), but dredging has been temporarily suspended in this zone since 1999. Water depths at Area 408 range from 22-33 metres with an average depth of approximately 25 metres and depths within zone 2 ranging from 20-24 metres. Screening of trailer-dredged cargoes has been routinely carried out at this site with sand the main sediment fraction that was returned to the seabed.

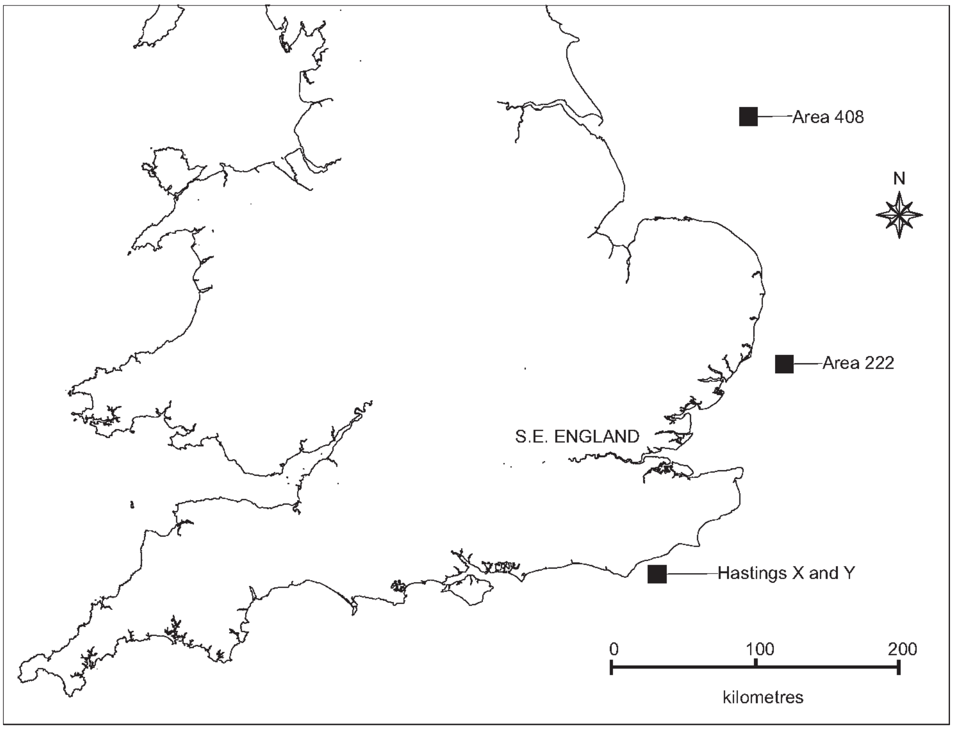


***Figure 15.1. Map showing location of aggregate extraction area surveyed between 2001-2003***

The remaining two sites, Hastings X and Y, are located in the Eastern English Channel on the Hastings Shingle Bank, 7 miles South of Hastings (Figure 1). Extraction licences on the South coast such as those at Hastings Shingle Bank tend to exploit discrete deep deposits of coarser aggregate. The cargoes dredged from such sites are usually retained entire rather than being screened on-site to reduce the proportion of fine material, and collected using trailer suction hopper techniques. Depths at the extraction site range from approximately 15-25 metres, deepening from north to south as a result of the natural topography of the Shingle Bank.

Although the two sub areas X and Y surveyed here are within the same extraction area, they have very different extraction histories. Sub area Y was licensed for dredging from 1988 until 2001, with extraction activity at its peak between 1996-1998. Over 7 million tonnes of material was removed during this period. However, at sub area X, dredging was only carried out during 1996 and resumed again in 2002 at one of the study sites. Unfortunately, it is not possible to separate quantities of material extracted between the two sub-areas so a figure for extraction in 1996 at sub-area X cannot be provided. Work carried out by Rees (1987) at the then proposed extraction site at Hastings Shingle Bank provides useful baseline community data, showing that the epifauna was dominated by motile crustacean and echinoderm species with a range of erect hydroid and bryozoans attached to stones. This would indicate relatively stable conditions at the seabed. A previous survey by Shelton and Rolfe (1972) showed similar faunal species present in the area, further indicating pre-dredging sediment stability.

The dredging histories of each study site since 1993 were ascertained with the use of an Electronic Monitoring System (EMS) which records the geographical location and duration of dredging activity on board each vessel (see Table 15.1 for minimum and maximum hours of dredging derived from EMS data). These data were used to assign treatments of high and lower dredging intensity and also a nearby reference location considered representative of the wider environment at each study site. For Hastings X and Y, one reference site was utilised for both extraction areas due to the proximity of the licensed areas to each other.

All epifaunal samples were collected during July and August, aboard the survey vessels *RV CIROLANA* in 2001 and 2002, and *RV CEFAS ENDEAVOUR* in 2003. In each of these three years, a modified 2 m Jennings beam trawl with a heavy-duty steel beam, chain mat and a 4 mm mesh liner fitted inside the net (see Jennings *et al.*, 1999 for design specification) was deployed four times at each treatment and reference site with the exception of the high treatment at Hastings X in 2003 where dredging had recommenced and epifaunal samples could not be obtained. This provided a total of 128 samples for epifaunal analysis over the three years of the study. The beam trawl was deployed with a 3:1 ratio of warp length to depth and towed at a speed of approximately 0.5 $ms^{-1}$. Tow lengths were affected by variations in local current and sea state and operational constraints (see Table 15.2 for overview of trawl lengths).

***Sample processing***

On retrieval of the beam trawl, sample volume was measured and the sample was washed over a 5 mm square mesh to retain smaller and rarer free living species which may provide important information on geographical distribution (Callaway *et al.*, 2002). All specimens were identified to species level using a range of standard taxonomic keys and enumerated with the exception of colonial and encrusting taxa, which were recorded on a presence/absence basis. Representative specimens of each taxon encountered at sea were preserved in 4-6% formaldehyde solution and identification confirmed in the laboratory. Where

***Table 15.1. Dredging histories in maximum and minimum hours of dredging per year at high and low treatments since inception of Electronic Monitoring System (EMS) data from 1993-2003***

| Year | Area 222 HIGH | | Area 222 LOW | | Area 408 HIGH | | Area 408 LOW | | Hastings Y HIGH | | Hastings Y LOW | | Hastings X HIGH | | Hastings X LOW | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. |
| 1993 | 0.50 | 13.25 | 0.00 | 1.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 1.75 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1994 | 0.50 | 39.50 | 0.00 | 3.50 | 0.00 | 0.00 | 0.00 | 0.00 | 1.25 | 6.00 | 0.00 | 2.50 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1995 | 0.75 | 19.25 | 0.00 | <0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.75 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1996 | 0.00 | 11.75 | 0.00 | <0.25 | 0.25 | 0.75 | 0.00 | 0.00 | 6.00 | 10.00 | 0.25 | 1.75 | 5.25 | 28.50 | 0.00 | 0.75 |
| 1997 | 0.00 | 0.00 | 0.00 | 0.00 | 1.75 | 2.75 | 0.00 | <0.25 | 7.25 | 10.25 | 0.00 | 2.50 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1998 | 0.00 | 0.00 | 0.00 | 0.00 | 6.75 | 14.25 | 0.00 | 1.00 | 7.25 | 10.25 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1999 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | <0.25 | 0.00 | <0.25 | 7.25 | 10.50 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2000 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 1.25 | 0.00 | <0.25 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2001 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.75 | 0.00 | <0.25 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2002 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.50 | >10.00 | 0.00 | 0.00 |
| 2003 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.50 | >10.00 | 0.00 | 0.00 |

samples visibly contained large numbers of a particular taxon, for example the echinoderm *Psammechinus miliaris* at Area 222, a sub-sampling procedure was used. This involved measuring the total volume of the sample using a graduated bucket. The sample was then thoroughly mixed and a sub sample of a suitable volume (usually between 4-10 litres depending on the volume of the total sample) was removed and examined for all specimens. If the numbers of individuals of one taxon reached 100 or more, this taxon was no longer counted in any subsequent sub-samples and a note was made of the volume in which the initial count was determined. Values of each taxon subsampled were then raised in order to estimate the total abundance in the whole sample. Any taxon that did not reach 100 or more in each sub-sample continued to be counted until 100 was reached or until the entire sample had been processed. In the following account, the epifaunal data are reported as numbers per tow i.e. their densities are not adjusted for tow length.

In 2003, one replicate sample from each extraction area and treatment box underwent biomass determination, following an unpublished CEFAS procedure (J. Ellis, *pers. comm.*) This was carried out at sea using a Pols heave compensated balance with a resolution of 0.1 g and minimum accuracy of 0.2 g. These samples did not undergo sub-sampling as all specimens were required for weighing to enable a full assessment of the distribution of species size ranges. Samples were sorted into separate species, and individuals weighed and assigned to $\log_2$ size classes. Hermit crabs were removed from their shells prior to weighing. Specimens weighing less than 0.6 g were discounted from the subsequent biomass analyses as sorting over a 5 mm mesh would have removed a large proportion of specimens from the smaller size classes and have the potential to bias the interpretation of results. All fish species were also removed, catch efficiency for most are likely to have been low and variable using a 2 metre Jennings Beam trawl.

***Derivation of hydrodynamic indices***
Please refer to ANNEX 1 - INDICES OF NATURAL ENVIRONMENTAL VARIABILITY for information on the methodology and derivation of these indices.

***Data analysis***
Samples were analysed according to the procedures described above and according to the guidelines given in Boyd (2002). Further details are also provided below.

***Univariate analyses***
Total abundance and numbers of all taxa were calculated for each treatment box to show any trends of decreasing or increasing numbers over time and between extraction areas.

The significance of differences between each of the treatment boxes was tested using one-way ANOVA. This analysis was carried out using the software package STATGRAPHICS plus, Version 4.1.

***Multivariate analysis***
All multivariate analyses were performed using PRIMER v.5 (Clarke and Gorley, 2001). Colonial taxa were removed from the data matrix. This approach was used in order to test whether there were any significant differences in community composition between samples collected from treatments subjected to different levels of dredging intensity. All non-colonial community data was standardised and a 4th root transformation was applied, to reduce the effect of dominant taxa and take account of rarer taxa. Standardisation was applied, as data arising from beam trawl samples are considered at best semi-quantitative due to the differing volumes of material retained in each trawl tow (Holme and McIntyre, 1984).

Further insights into the recolonization of dredged sediments may be obtained from an examination of the inter-relationships between the observed biological patterns and derived 'indices of natural environmental variability' (see ANNEX I). Such indices have been generated to give an indication of the prevailing environmental conditions at each of the extraction sites, which bear upon the natural status of sediments and associated biota. Thus values of hydrodynamic indices (peak spring tide current velocities and potential mobility of fine sand year$^{-1}$) at each site were compared with the ranked dissimilarity matrix of faunal abundance data using the BIO-ENV routine in PRIMER v5 (Clarke and Gorley, 2001).

Biomass by $\log_2$ size class was calculated for each sample as the sum of all species for that sample. These values were then sequentially added to produce a cumulative curve. Linear regression was applied and the residual variation ($r^2$) calculated to provide an indication of the strength of the relationship between size and cumulative biomass, and any similarities in distribution of biomass across the size classes between high, low and reference treatments at each extraction area. Differences between treatments were also assessed by comparing the size class in which biomass peaked in each treatment. This has been shown to be a useful indicator of changes due to the impact of sand extraction in meiofaunal communities (Vanaverbeke *et al.*, 2003) and may be valid in assessing changes in biomass in epifaunal communities at extraction sites.

***Table 15.2. The average length in metres of beam trawl tows over three years (2001-2003) at study sites following a tow of 5 minutes duration***

| | Area 222 | Area 408 | Hastings X | Hastings Y |
|---|---|---|---|---|
| HIGH | 152.5 ± 27.5 m | 220 ± 40 m | 157 ± 30 m | 167.5 ± 27.5 m |
| LOW | 147.5 ± 22.5 m | 222.5 ± 22.5 m | 182.5 ± 32.5 m | 255 ± 65 m |
| REF | 167.5 ± 17.5 m | 220 ± 20 m | 170 ± 30 m | 170 ± 30 m |

## 15.3 Results

The average trawl tow lengths over the 3 years are shown for each study site (Table 15.2). Studies of epifaunal communities by Rees *et al.* (1999) found that tow length did not significantly influence numbers and densities of taxa. Therefore, the low variability between tow lengths in the present study is not considered to be a significant source of error between stations. A total of 201 taxa were recorded from the survey of the four extraction areas of which 53 were colonial species (largely hydroids and bryozoans). The results from both univariate and multivariate statistical analyses establish that there are significant differences ($p<0.05$) between epifaunal communities previously subjected to dredging activity (high and low treatments) and the reference treatment.

At Area 222 (Figure 15.2a) numbers of species at one or both dredged treatments compared to the reference treatment are significantly reduced ($p<0.05$) over the three years of the study with the exception of the high intensity treatment in 2002, and the low intensity treatment in 2003. Numbers of individuals varied greatly over time at Area 222 (Figure 15.2b) but these differences were not statistically significant ($p>0.05$) except during 2001, when numbers at the high treatment were significantly reduced ($p<0.05$) in comparison to the low and reference treatments. Over the three years of the study, numbers of species at Area 408 (Figure 15.3a) were significantly reduced ($p<0.05$) at both dredged treatments when compared to the reference, whilst numbers of individuals (Figure 15.3b) are seen to be significantly reduced ($p<0.05$) within the dredged treatments in 2001 and 2003, but in 2002, numbers of individuals are not significantly different between the three treatments due to large numbers of individuals being found at the low intensity treatment. At the Hastings X extraction area, numbers of species (Figure 15.4a) at each treatment were not significantly different ($p>0.05$) temporally. Numbers of individuals (Figure 15.4b) were significantly reduced ($p<0.05$) at the high treatment compared to the low and reference treatments in 2001, and significantly greater ($p<0.05$) at the low treatment compared to the reference in 2003, but otherwise, differences between dredged and reference treatments were not significant ($p>0.05$). At Hastings Y in 2001, numbers of species (Figure 15.5a) at the dredged treatments were significantly reduced ($p<0.05$) in comparison to the reference, but in 2002 and 2003 there was no significant difference ($p>0.05$) in species numbers between any of the dredged and reference treatments. At Hastings numbers of individuals at Hastings Y (Figure 15.5b) were significantly reduced ($p<0.05$) at the dredged treatments compared to the reference in 2001, whilst in 2002, there were a significantly greater number of individuals at the high treatment than either the low or reference treatments. In 2003, numbers of individuals at each of the three treatment were not significantly different ($p>0.05$) from each other. Overall, these results (Figures 15.2-5) demonstrate that there appears to be no trend of increasing or decreasing numbers of species or individuals over time either within or between extraction areas.

The MDS ordinations of epifaunal assemblages collected at high, low and reference treatments over the three year study (Figure 15.6 a-d) indicate that at all extraction areas, samples from each of these remain separate from each other. Samples from the high and low treatments at Area 222 appear to become more similar to the reference treatments over time. However, this is not reflected at Area 408 or the two Hastings extraction areas where the reference samples from all years remain clustered away from the high and low treatment samples. A further MDS ordination of all samples from all years (Figure 15.6e) shows that there is good discrimination between samples collected from different geographical areas which may reflect biogeographical differences in the fauna. In addition to this graphical representation, ANOSIM confirms that there is a statistically significant difference ($p<0.05$) between the assemblage structure of samples collected from dredged locations compared with those obtained from reference sites for all combinations with the exception of the high and low treatment at Hastings Y in 2001 (Tables 15.3-15.6). These tables also show that there is greater dissimilarity between dredged and reference treatments than between treatments.

The differences observed between samples collected from the high treatment and those elsewhere are due to the reduced abundance or absence of a range of epifaunal species (Tables 15.7-15.10). However, elevated numbers of mobile adult decapod crustaceans and fish species such as the hermit crabs *Pagurus bernhardus* in 2001, *Anapagurus laevis* in 2002 and the shrimp *Pandalus montagui* in 2001 and 2003 were present in the high treatment at Area 222. At Area 408, when compared with the reference site, the sand eel *Ammodytes* spp. were consistently recorded in

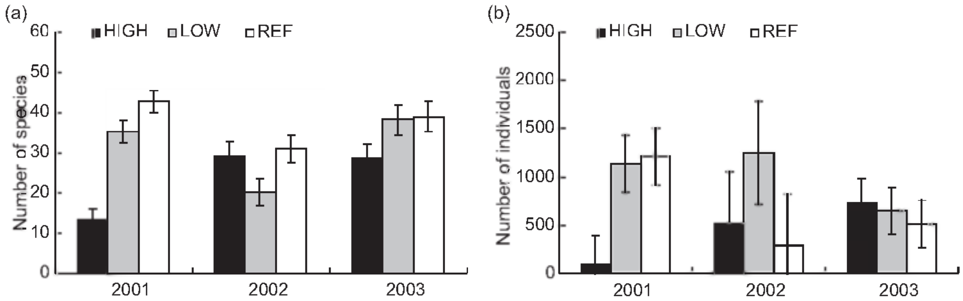


***Figure 15.2.*** ***(a) Numbers of species at high, low and reference treatments 2001-2003 Area 222 (b) Numbers of individuals at high, low and reference sites 2001-2003 Area 222***

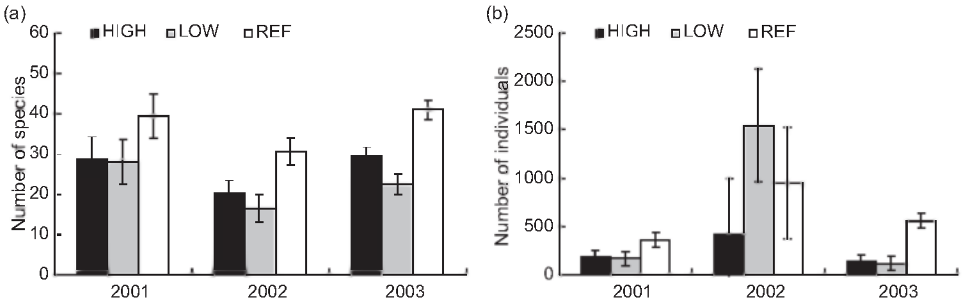


***Figure 15.3.*** ***(a) Numbers of species at high, low and reference treatments 2001-2003 Area 408 (b) Numbers of individuals at high, low and reference sites 2001-2003 Area 408***

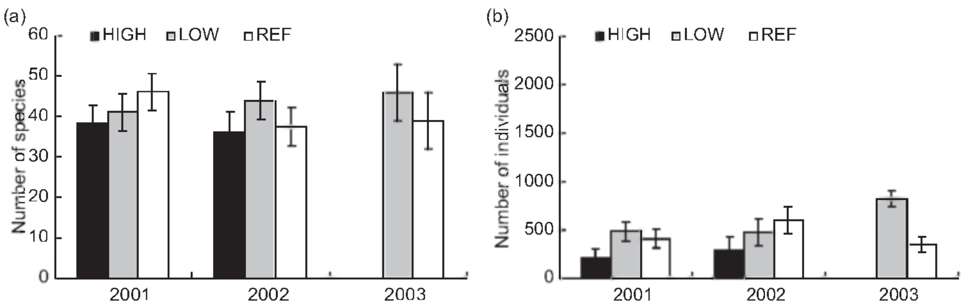


***Figure 15.4.*** ***(a) Numbers of species at high, low and reference treatments 2001-2003 Hastings X (b) Numbers of individuals at high, low and reference sites 2001-2003 Hastings X***

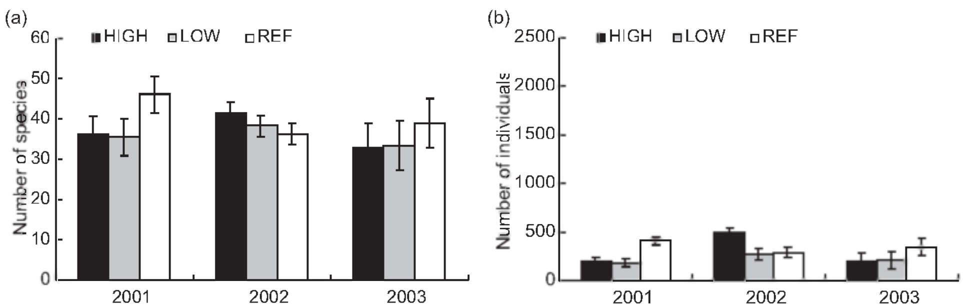


***Figure 15.5.*** ***(a) Numbers of species at high, low and reference treatments 2001-2003 Hastings Y (b) Numbers of individuals at high, low and reference sites 2001-2003 Hastings Y***

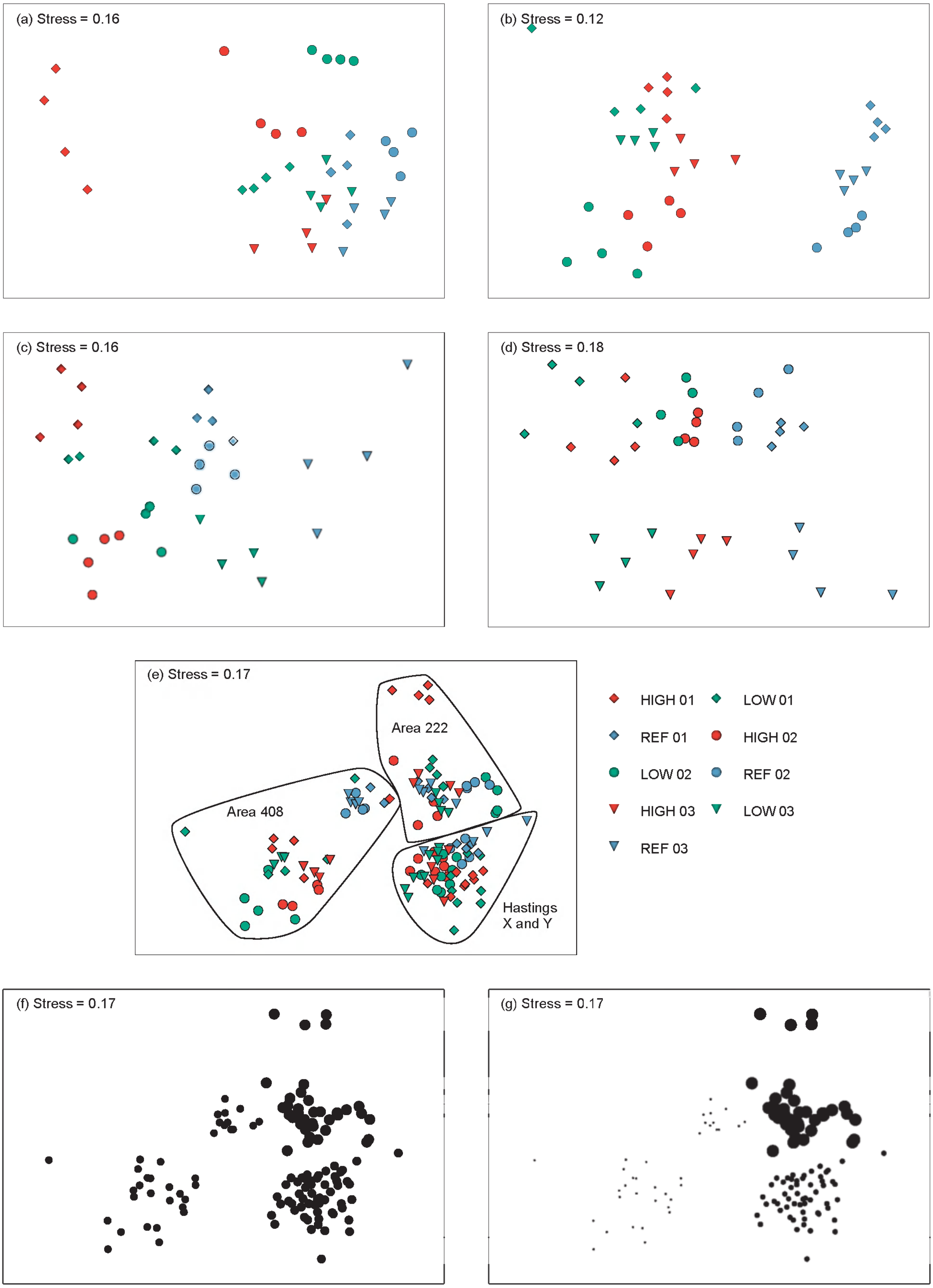


***Figure 15.6.*** ***Multi-Dimensional Scaling ordinations of: (a) All samples collected from Area 222 2001-2003 (b) All samples collected from Area 408 2001-2003 (c) All samples collected from Hastings X 2001-2003 (d) All samples collected from Hastings Y 2001-2003 (e) All samples collected from all extraction areas 2001-2003 (f) The same as (e) but superimposed with peak current (g) The same as (e) but superimposed with sand mobility***

**Table 15.3. Table of % dissimilarities between high low and reference treatments over all years at Area 222 based on 4th root transformed non-colonial species abundance data**

| | HIGH 01 | LOW 01 | REF 01 | HIGH 02 | LOW 02 | REF 02 | HIGH 03 | LOW 03 |
|---|---|---|---|---|---|---|---|---|
| LOW 01 | 62 | | | | | | | |
| REF 01 | 68 | 38 | | | | | | |
| HIGH 02 | 62 | 52 | 51 | | | | | |
| LOW 02 | 70 | 51 | 52 | 53 | | | | |
| REF 02 | 75 | 55 | 42 | 50 | 51 | | | |
| HIGH 03 | 69 | 48 | 49 | 49 | 58 | 52 | | |
| LOW 03 | 73 | 44 | 43 | 46 | 50 | 47 | 34 | |
| REF 03 | 74 | 51 | 41 | 51 | 60 | 41 | 51 | 37 |

*All are significant at $p<0.05$*

**Table 15.4. Table of % dissimilarities between high low and reference treatments over all years at Area 408 based on 4th root transformed non-colonial species abundance data**

| | HIGH 01 | LOW 01 | REF 01 | HIGH 02 | LOW 02 | REF 02 | HIGH 03 | LOW 03 |
|---|---|---|---|---|---|---|---|---|
| LOW 01 | 40 | | | | | | | |
| REF 01 | 67 | 74 | | | | | | |
| HIGH 02 | 49 | 53 | 74 | | | | | |
| LOW 02 | 59 | 60 | 85 | 38 | | | | |
| REF 02 | 70 | 78 | 44 | 60 | 76 | | | |
| HIGH 03 | 47 | 52 | 66 | 45 | 57 | 61 | | |
| LOW 03 | 40 | 47 | 77 | 48 | 53 | 75 | 34 | |
| REF 03 | 70 | 76 | 45 | 66 | 79 | 44 | 57 | 66 |

*All are significant at $p<0.05$*

**Table 15.5. Table of % dissimilarities between high low and reference treatments over all years at Hastings X based on 4th root transformed non-colonial species abundance data**

| | HIGH 01 | LOW 01 | REF 01 | HIGH 02 | LOW 02 | REF 02 | LOW 03 |
|---|---|---|---|---|---|---|---|
| LOW 01 | 38 | | | | | | |
| REF 01 | 47 | 39 | | | | | |
| HIGH 02 | 45 | 44 | 47 | | | | |
| LOW 02 | 47 | 37 | 43 | 35 | | | |
| REF 02 | 47 | 42 | 35 | 41 | 37 | | |
| LOW 03 | 51 | 43 | 42 | 45 | 41 | 43 | |
| REF 03 | 60 | 53 | 46 | 59 | 57 | 48 | 44 |

*All are significant at $p<0.05$*

**Table 15.6. Table of % dissimilarities between high low and reference treatments over all years at HastingsY based on 4th root transformed non-colonial species abundance data**

| | HIGH 01 | LOW 01 | REF 01 | HIGH 02 | LOW 02 | REF 02 | HIGH 03 | LOW 03 |
|---|---|---|---|---|---|---|---|---|
| LOW 01 | *38 | | | | | | | |
| REF 01 | 42 | 49 | | | | | | |
| HIGH 02 | 39 | 44 | 42 | | | | | |
| LOW 02 | 43 | 43 | 44 | 31 | | | | |
| REF 02 | 46 | 50 | 35 | 37 | 36 | | | |
| HIGH 03 | 45 | 49 | 46 | 42 | 41 | 44 | | |
| LOW 03 | 46 | 49 | 55 | 45 | 44 | 52 | 39 | |
| REF 03 | 57 | 63 | 46 | 55 | 58 | 48 | 46 | 54 |

*All are significant at $p<0.05$ except * significant at $p<0.1$*

**Table 15.7. The average abundance of the top 10 ranked non-colonial species contributing to the dissimilarity between high low and reference treatments at Area 222, derived from SIMPER analysis of 4th root transformed data from 2001, 2002 and 2003; species are ordered in decreasing contribution**

| Species | LOW 01 | HIGH 01 |
|---|---|---|
| *Pagurus bernhardus* | 13.75 | 56.25 |
| *Pandalus montagui* | 527.50 | 6.25 |
| *Pisidia longicornis* | 30.25 | - |
| *Sabellaria spinulosa* | 0.25 | 1.00 |
| *Liocarcinus holsatus* | 22.00 | 0.25 |
| *Asterias rubens* | 5.75 | - |
| *Aequipecten opercularis* | 3.50 | - |
| *Gibbula* spp. | 3.25 | - |
| *Philocheras trispinosus* | 1.75 | 3.00 |
| *Anapagurus laevis* | 2.00 | - |

| Species | REF 01 | HIGH 01 |
|---|---|---|
| *Pisidia longicornis* | 135.75 | - |
| *Pagurus bernhardus* | 19.75 | 56.25 |
| *Pandalus montagui* | 276.25 | 6.25 |
| *Asterias rubens* | 16.00 | - |
| *Anomia* spp. | 13.50 | - |
| *Liocarcinus holsatus* | 30.00 | 0.25 |
| *Aequipecten opercularis* | 9.00 | - |
| *Echinus esculentus* | 8.25 | - |
| *Pilumnus hirtellus* | 7.25 | - |
| *Buccinum undatum* | 5.75 | - |

| Species | REF 01 | LOW 01 |
|---|---|---|
| *Pandalus montagui* | 276.25 | 527.50 |
| *Echinus esculentus* | 8.25 | - |
| *Ebalia* spp. | 3.75 | - |
| *Pilumnus hirtellus* | 7.25 | 0.25 |
| *Trisopterus minutus* | 16.50 | 0.75 |
| *Ophiothrix fragilis* | 4.50 | 0.25 |
| *Pandalina brevirostris* | 12.00 | 1.50 |
| *Pisidia longicornis* | 135.75 | 30.25 |
| *Liocarcinus depurator* | 46.75 | 7.75 |
| *Buccinum undatum* | 5.75 | 0.75 |

| Species | LOW 02 | HIGH 02 |
|---|---|---|
| *Crangon allmani* | - | 12.50 |
| *Anapagurus laevis* | 6.75 | 23.50 |
| *Gobiidae* | - | 7.25 |
| *Ammodytes* | - | 5.75 |
| *Leptochiton asellus* | 14.50 | - |
| *Pisidia longicornis* | 68.75 | 3.25 |
| *Gibbula* | 15.50 | 0.75 |
| *Liocarcinus pusillus* | 5.25 | - |
| *Sagartia* | - | 3.25 |
| *Trisopterus minutus* | - | 3.75 |

| Species | REF 02 | HIGH 02 |
|---|---|---|
| *Pisidia longicornis* | 35.75 | 3.25 |
| *Pilumnus hirtellus* | 7.50 | - |
| *Anapagurus laevis* | 0.25 | 23.50 |
| *Echinus esculentus* | 10.00 | 1.00 |
| *Gobiidae* | - | 7.25 |
| *Ammodytes* | - | 5.75 |
| *Hinia* | 2.75 | - |
| *Pandalina brevirostris* | 12.25 | 2.50 |
| *Ocenebra erinacea* | 3.50 | 0.25 |
| *Crangon allmani* | 0.50 | 12.50 |

| Species | REF 02 | LOW 02 |
|---|---|---|
| *Echinus esculentus* | 10.00 | - |
| *Calliostoma zizyphinum* | 12.75 | 2.25 |
| *Pilumnus hirtellus* | 7.50 | - |
| *Galathea* | - | 14.50 |
| *Hinia* | 2.75 | - |
| *Leptochiton asellus* | - | 14.50 |
| *Pandalus montagui* | 5.00 | 0.50 |
| *Trisopterus minutus* | 2.25 | - |
| *Ophiothrix fragilis* | 1.75 | - |
| *Sagartia* | 4.00 | - |

| Species | LOW 03 | HIGH 03 |
|---|---|---|
| *Liocarcinus pusillus* | 2.75 | - |
| *Gibbula* spp. | 3.25 | 0.75 |
| *Liparis liparis* | - | 1.75 |
| *Anapagarus laevis* | 0.50 | 4.25 |
| *Trisopterus minutes* | 3.75 | 0.50 |
| *Ophiura albida* | 16.25 | 4.50 |
| *Pisidia longicornis* | 5.25 | 1.75 |
| *Crangon allmani* | 20.75 | 35.75 |
| *Callionymus lyra* | 1.75 | 0.50 |
| *Atelecyclus rotundatus* | 3.50 | 2.50 |

| Species | REF 03 | HIGH 03 |
|---|---|---|
| *Pilumnus hirtellus* | 25.00 | - |
| *Necora puber* | 4.00 | - |
| *Gobiidae* | 3.50 | 0.25 |
| *Pisidia longicornis* | 11.00 | 1.75 |
| *Pandalus montagui* | 66.50 | 333.25 |
| *Echinus esculentus* | 14.00 | 2.25 |
| *Crangon allmani* | 10.50 | 35.75 |
| *Ophiura albida* | - | 4.50 |
| *Pandalina brevirostris* | 37.00 | 10.75 |
| *Isopoda* | 1.50 | - |

| Species | REF 03 | LOW 03 |
|---|---|---|
| *Ophiura albida* | - | 16.25 |
| *Pilumnus hirtellus* | 25.00 | 0.75 |
| *Echinus esculentus* | 14.00 | 0.25 |
| *Gibbula* spp. | - | 3.25 |
| *Necora puber* | 4.00 | 0.50 |
| *Ciliata mustela* | 2.75 | - |
| *Ocenebra erinacea* | 2.00 | - |
| *Isopoda* | 1.50 | - |
| *Scyliorhinus canicula* | - | 1.00 |
| *Atelecyclus rotundatus* | 2.00 | 3.50 |

**Table 15.8. The average abundance of the top 10 ranked non-colonial species contributing to the dissimilarity between high low and reference treatments at Area 408, derived from SIMPER analysis of 4th root transformed data from 2001, 2002 and 2003; species are ordered in decreasing contribution**

| Species | LOW 01 | HIGH 01 |
|---|---|---|
| *Ophiura albida* | 5.75 | 0.25 |
| *Sgartia sp.* | 0.25 | 1.75 |
| *Ophiura ophiura* | 2.00 | - |
| *Callionymus sp.* | 5.50 | 12.25 |
| *Pomatoschistus minutus* | 6.25 | 13.00 |
| *Trachninidae* | 1.50 | 1.00 |
| *Hydrozoa* | 1.25 | - |
| *Macropodia sp.* | 1.00 | 2.50 |
| *Agonus sp.* | 2.00 | 2.25 |
| *Philocheras trispinosus* | 2.75 | 1.25 |

| Species | REF 01 | HIGH 01 |
|---|---|---|
| *Ammodytidae* | - | 56.25 |
| *Pandalus montagui* | 132.75 | 0.25 |
| *Pisidia longicornis* | 22.50 | - |
| *Liocarcinus depurator* | 22.25 | - |
| *Anomia sp.* | 11.00 | - |
| *Buglossidium luteum* | 0.75 | 8.75 |
| *Limanda limanda* | - | 3.75 |
| *Ophiothrix fragilis* | 10.75 | 0.25 |
| *Cancer pagurus* | 5.75 | - |
| *Liocarcinus holsatus* | 0.25 | 3.75 |

| Species | REF 01 | LOW 01 |
|---|---|---|
| *Ammodytidae* | - | 81.25 |
| *Pandalus montagui* | 132.75 | 0.25 |
| *Pisidia longicornis* | 22.50 | - |
| *Buglossidium luteum* | 0.75 | 16.25 |
| *Ascidiella aspersa* | 15.75 | - |
| *Liocarcinus depurator* | 22.25 | 0.25 |
| *Ophiothrix fragilis* | 10.75 | - |
| *Anomia sp.* | 11.00 | - |
| *Sagartia sp.* | 18.25 | 0.25 |
| *Liocarcinus holsatus* | 0.25 | 6.50 |

| Species | LOW 02 | HIGH 02 |
|---|---|---|
| *Ascidiella scabra* | 11.75 | 72.25 |
| *Asterias rubens* | 10.50 | 28.50 |
| *Pagurus bernhardus* | 0.25 | 1.75 |
| *Arnoglossus laterna* | - | 2.25 |
| *Spisula* | 0.50 | 2.00 |
| *Gobiidae* | 3.25 | 3.75 |
| *Philocheras trispinosus* | 0.50 | 1.50 |
| *Agonus cataphractus* | 1.75 | 1.75 |
| *Onchidoris* | 1398.75 | 243.75 |
| *Macropodia* | 0.50 | 1.25 |

| Species | REF 02 | HIGH 02 |
|---|---|---|
| *Onchidoris* | 3.50 | 243.75 |
| *Sagartia* | 115.00 | - |
| *Ammodytes tobianus* | - | 24.75 |
| *Pandalus montagui* | 36.25 | - |
| *Buglossidium luteum* | - | 10.25 |
| *Ascidiella scabra* | 619.75 | 72.25 |
| *Limanda limanda* | - | 4.75 |
| *Anomia* | 9.50 | - |
| *Pisidia longicornis* | 21.50 | 0.25 |
| *Liocarcinus depurator* | 7.25 | - |

| Species | REF 02 | LOW 02 |
|---|---|---|
| *Onchidoris* | 3.50 | 1398.75 |
| *Ascidiella scabra* | 619.75 | 11.75 |
| *Sagartia* | 115.00 | - |
| *Ammodytes tobianus* | - | 81.25 |
| *Pandalus montagui* | 36.25 | - |
| *Pisidia longicornis* | 21.50 | - |
| *Anomia* | 9.50 | - |
| *Buglossidium luteum* | - | 10.50 |
| *Liocarcinus depurator* | 7.25 | - |
| *Taurulus bubalis* | 6.50 | - |

| Species | LOW 03 | HIGH 03 |
|---|---|---|
| *Limanda limanda* | 11.75 | 1.75 |
| *Ascidiella scabra* | - | 1.50 |
| *Crangon allmani* | 2.50 | 0.25 |
| *Spisula sp.* | 0.50 | 4.00 |
| *Ophiura albida* | 0.25 | 1.50 |
| *Hyperoplus lanceolatus* | 1.25 | - |
| *Liocarcinus depurator* | - | 1.00 |
| *Balanus sp.* | - | 0.75 |
| *Macropodia* | 2.25 | 8.75 |
| *Echichthys vipera* | 3.00 | 1.25 |

| Species | REF 03 | HIGH 03 |
|---|---|---|
| *Pandalus montagui* | 199.75 | - |
| *Buglossidium luteum* | - | 12.50 |
| *Ammodytes marinus* | - | 11.50 |
| *Liocarcinus depurator* | 66.75 | 1.00 |
| *Spisula sp.* | - | 4.00 |
| *Ophiura albida* | - | 1.50 |
| *Gobiidae* | 15.75 | 0.50 |
| *Pisidia longicornis* | 25.75 | 0.50 |
| *Crangon allmani* | 14.00 | 0.25 |
| *Liocarcinus holsatus* | 2.00 | 9.50 |

| Species | REF 03 | LOW 03 |
|---|---|---|
| *Pandalus montagui* | 199.75 | - |
| *Ammodytes marinus* | - | 16.00 |
| *Liocarcinus depurator* | 66.75 | - |
| *Buglossidium luteum* | - | 13.25 |
| *Limanda limanda* | 0.50 | 11.75 |
| *Pisidia longicornis* | 22.75 | - |
| *Ascidiella scabra* | 17.00 | - |
| *Gobiidae* | 15.75 | - |
| *Pleuronectes platessa* | - | 2.25 |
| *Liocarcinus holsatus* | 2.00 | 13.00 |

**Table 15.9. The average abundance of the top 10 ranked non-colonial species contributing to the dissimilarity between high low and reference treatments at Hastings X, derived from SIMPER analysis of 4th root transformed data from 2001, 2002 and 2003; species are ordered in decreasing contribution**

| Species | LOW 01 | HIGH 01 |
|---|---|---|
| *Crepidula fornicata* | 173.00 | 1.25 |
| *Pandalus montagui* | 1.50 | 18.50 |
| *Psammechinus miliaris* | 43.75 | - |
| *Gibbula spp.* | 4.00 | - |
| *Anapagurus laevis* | 3.50 | 7.50 |
| *Pisidia longicornis* | 1.25 | 5.50 |
| *Adamsia carciniopados* | 11.75 | 0.75 |
| *Philocheras trispinosus* | 0.50 | 1.50 |
| *Galathea sp.* | 3.50 | 11.25 |
| *Molgula* spp. | 2.75 | 1.75 |

| Species | REF 01 | HIGH 01 |
|---|---|---|
| *Psammechinus miliaris* | 131.75 | - |
| *Gibbula spp.* | 31.50 | - |
| *Pandalus montagui* | 0.75 | 18.50 |
| *Anapagurus laevis* | 0.50 | 7.50 |
| *Calliostoma zizyphinum* | 32.50 | 1.00 |
| *Polinices pulchellus* | 0.50 | 3.50 |
| *Leptochiton asellus* | 3.50 | - |
| *Philocheras trispinosus* | - | 1.50 |
| *Onchidoris* spp. | 2.75 | - |
| *Ophiura albida* | 30.75 | 1.50 |

| Species | REF 01 | LOW 01 |
|---|---|---|
| *Crepidula fornicata* | 1.50 | 173.00 |
| *Psammechinus miliaris* | 131.75 | 43.75 |
| *Calliostoma zizyphinum* | 32.50 | 0.50 |
| *Onchidoris* spp. | 2.75 | - |
| *Ophiura albida* | 30.75 | 4.25 |
| *Gibbula* spp. | 31.50 | 4.00 |
| *Leptochiton asellus* | 3.50 | 0.25 |
| *Urticinia felina* | 6.25 | 0.25 |
| *Polinices pulchellus* | 0.50 | 6.50 |
| *Dendrodoa grossularia* | 6.75 | 0.50 |

| Species | LOW 02 | HIGH 02 |
|---|---|---|
| *Crepidula fornicata* | 264.75 | 17.75 |
| *Philocheras trispinosus* | 2.00 | 12.75 |
| *Trisopterus minutus* | 1.50 | 4.50 |
| *Ophiura ophiura* | 0.50 | 4.00 |
| *Echiichthys vipera* | 0.50 | 2.50 |
| *Psammechinus miliaris* | 15.25 | 1.50 |
| *Crangon allmani* | 0.50 | 6.75 |
| *Aphroditidae* | - | 3.25 |
| *Sagartia* | 2.00 | 11.50 |
| *Anomia* | 14.00 | 2.50 |

| Species | REF 02 | HIGH 02 |
|---|---|---|
| *Psammechinus miliaris* | 45.50 | 1.50 |
| *Philocheras trispinosus* | - | 12.75 |
| *Calliostoma zizyphinum* | 7.25 | 0.25 |
| *Gibbula* | 3.25 | - |
| *Trisopterus minutus* | - | 4.50 |
| *Ophiura albida* | 16.00 | 3.00 |
| *Echiichthys vipera* | - | 2.50 |
| *Ophiura ophiura* | - | 4.00 |
| *Crangon allmani* | 0.25 | 6.75 |
| *Asterias rubens* | 0.50 | 11.00 |

| Species | REF 02 | LOW 02 |
|---|---|---|
| *Crepidula fornicata* | 4.25 | 264.75 |
| *Ophiura albida* | 16.00 | 1.25 |
| *Anapagurus hyndmanni* | 4.50 | - |
| *Calliostoma zizyphinum* | 7.25 | 0.25 |
| *Psammechinus miliaris* | 45.50 | 15.25 |
| *Gibbula* | 3.25 | 1.00 |
| *Ascidia conchilega* | 2.00 | 8.75 |
| *Sabellaria* | - | 1.00 |
| *Asterias rubens* | 0.50 | 6.75 |
| *Molgula* | 17.25 | 4.50 |

| Species | LOW 03 | HIGH 03 |
|---|---|---|
| *NO SAMPLES COLLECTED FROM HIGH TREATMENT* | | |

| Species | REF 03 | HIGH 03 |
|---|---|---|
| *NO SAMPLES COLLECTED FROM HIGH TREATMENT* | | |

| Species | REF 03 | LOW 03 |
|---|---|---|
| *Crepidula fornicata* | 2.75 | 206.25 |
| *Anapagurus hyndmanni* | 10.00 | 0.75 |
| *Hinia sp.* | 2.00 | 35.25 |
| *Gobiidae* | - | 11.75 |
| *Diplecogaster bimaculata* | - | 5.75 |
| *Macropodia* | 10.75 | 70.50 |
| *Calliostoma zizyphinum* | 1.75 | - |
| *Gibbula spp.* | 4.00 | 2.00 |
| *Pisidia longicornis* | 0.25 | 11.25 |
| *Atelecylus rotundatus* | 4.75 | 0.50 |

**Table 15.10 . The average abundance of the top 10 ranked non-colonial species contributing to the dissimilarity between high low and reference treatments at Hastings Y, derived from SIMPER analysis of 4th root transformed data from 2001, 2002 and 2003; species are ordered in decreasing contribution**

| Species | LOW 01 | HIGH 01 |
|---|---|---|
| *Anapagurus laevis* | 22.00 | 0.75 |
| *Ascidia conchilega* | 2.75 | 0.25 |
| *Galathea* spp. | 1.50 | 10.50 |
| *Liocarcinus holsatus* | - | 2.25 |
| *Adamsia carciniopados* | 4.50 | 5.75 |
| *Aphrodita aculeata* | 2.00 | 0.25 |
| *Pandalina brevirostris* | 4.75 | 36.75 |
| *Psammechinus miliaris* | 1.50 | 3.75 |
| *Onchidoris* spp. | - | 1.50 |
| *Hyas* spp. | 1.50 | 0.25 |

| Species | REF 01 | HIGH 01 |
|---|---|---|
| *Gibbula* spp. | 31.50 | - |
| *Calliostoma zizyphinum* | 32.50 | 0.25 |
| *Psammechinus miliaris* | 131.75 | 3.75 |
| *Philocheras trispinosus* | - | 4.25 |
| *Polinices pulchellus* | 0.50 | 3.75 |
| *Hyas* spp. | 5.75 | 0.25 |
| *Ebalia* spp. | 2.75 | - |
| *Dendrodoa grossularia* | 6.75 | - |
| *Crepidula fornicata* | 1.50 | - |
| *Ocenebra erinacea* | 3.50 | 0.25 |

| Species | REF 01 | LOW 01 |
|---|---|---|
| *Psammechinus miliaris* | 131.75 | 1.50 |
| *Calliostoma zizyphinum* | 32.50 | - |
| *Anapagurus laevis* | 0.50 | 22.00 |
| *Gibbula* spp. | 31.50 | 1.00 |
| *Polinices pulchellus* | 0.50 | 9.00 |
| *Philocheras trispinosus* | - | 3.00 |
| *Aphrodita aculeata* | - | 2.00 |
| *Onchidoris* spp. | 2.75 | - |
| *Ascidia conchilega* | 0.50 | 2.75 |
| *Urticinia felina* | 6.25 | - |

| Species | LOW 02 | HIGH 02 |
|---|---|---|
| *Trisopterus minutus* | - | 2.00 |
| *Aequipecten opercularis* | 8.75 | 91.75 |
| *Crangon allmani* | - | 1.75 |
| *Pandalina brevirostris* | 5.75 | 27.00 |
| *Ascidia conchilega* | 8.75 | 9.00 |
| *Tritonia hombergii* | 2.25 | 1.50 |
| *Anomia* | 0.50 | 3.50 |
| *Polinices pulchellus* | 3.00 | 1.75 |
| *Sagartia* | 5.25 | 3.50 |
| *Onchidoris* | 1.00 | 0.25 |

| Species | REF 02 | HIGH 02 |
|---|---|---|
| *Gibbula* | 3.25 | - |
| *Anapagurus hyndmanni* | 4.50 | 0.50 |
| *Aequipecten opercularis* | 6.00 | 91.75 |
| *Calliostoma zizyphinum* | 7.25 | 0.75 |
| *Adamsia carciniopados* | 1.75 | 14.00 |
| *Trisopterus minutus* | - | 2.00 |
| *Pagurus prideaux* | 2.50 | 14.00 |
| *Crepidula fornicata* | 4.25 | 29.00 |
| *Hinia* | 4.25 | 49.25 |
| *Sabellaria* | - | 1.00 |

| Species | REF 02 | LOW 02 |
|---|---|---|
| *Gibbula* | 3.25 | - |
| *Calliostoma zizyphinum* | 7.25 | 0.25 |
| *Psammechinus miliaris* | 45.50 | 3.00 |
| *Anapagurus hyndmanni* | 4.50 | 0.25 |
| *Modiolarca* | 0.25 | 3.25 |
| *Ascidia conchilega* | 2.00 | 8.75 |
| *Anomia* | 6.50 | 0.50 |
| *Hinia* | 4.25 | 34.00 |
| *Polinices pulchellus* | 0.50 | 3.00 |
| *Adamsia carciniopados* | 1.75 | 4.50 |

| Species | LOW 03 | HIGH 03 |
|---|---|---|
| *Psammechinus miliaris* | 4.25 | 54.75 |
| *Echichthys vipera* | 2.75 | - |
| *Crangon allmani* | 6.25 | 0.75 |
| *Polinices pulchellus* | 1.25 | 0.25 |
| *Gibbula* spp. | - | 1.00 |
| *Philocheras trispinosus* | 2.50 | 1.00 |
| *Adamsia carciniopados* | 1.25 | 2.00 |
| *Ocenebra erinacea* | 0.50 | 1.00 |
| *Hinia sp.* | 36.25 | 12.25 |
| *Galathea* spp. | 1.25 | 2.25 |

| Species | REF 03 | HIGH 03 |
|---|---|---|
| *Anapagurus hyndmanni* | 10.00 | 0.25 |
| *Hinia sp.* | 2.00 | 12.75 |
| *Atelecylus rotundatus* | 4.75 | - |
| *Gobiidae* | - | 5.00 |
| *Anapagurus laevis* | 0.25 | 2.50 |
| *Calliostoma zizyphinum* | 1.75 | - |
| *Asterias rubens* | 15.75 | 20.25 |
| *Leptochiton sp.* | 1.50 | - |
| *Galathea* spp. | 0.50 | 2.25 |
| *Ebalia* spp. | 2.50 | - |

| Species | REF 03 | LOW 03 |
|---|---|---|
| *Psammechinus miliaris* | 147.50 | 4.25 |
| *Hinia sp.* | 2.00 | 36.25 |
| *Anapagurus hyndmanni* | 10.00 | - |
| *Gibbula* spp. | 4.00 | - |
| *Gobiidae* | - | 4.50 |
| *Echichthys vipera* | - | 2.75 |
| *Atelecyclus rotundatus* | 4.75 | - |
| *Callionymus lyra* | 0.50 | 4.75 |
| *Crangon allmani* | 0.75 | 6.25 |
| *Anapagurus laevis* | 0.25 | 6.50 |

high numbers at the high treatment in all years and the nudibranch *Onchidoris* sp. was 'super-abundant' (i.e. >1000 individuals) in 2002 at the low treatment (present on the bryozoan *Alcyonidium diaphanum* which was also observed to be abundant). The shrimps *Pandalus montagui* and *Pandalina brevirostris* were more abundant in the high and low dredging intensity sites at both Hastings extraction areas in 2001. In 2002 and 2003, the gastropod mollusc *Crepidula fornicata* appears to be the species principally responsible for differences between high, low and reference sites at Hastings X; at Hastings Y, these differences are also attributable to other gastropod mollusc species, namely *Gibbula* sp., *Hinia* sp. and *Calliostoma zizyphinum*.

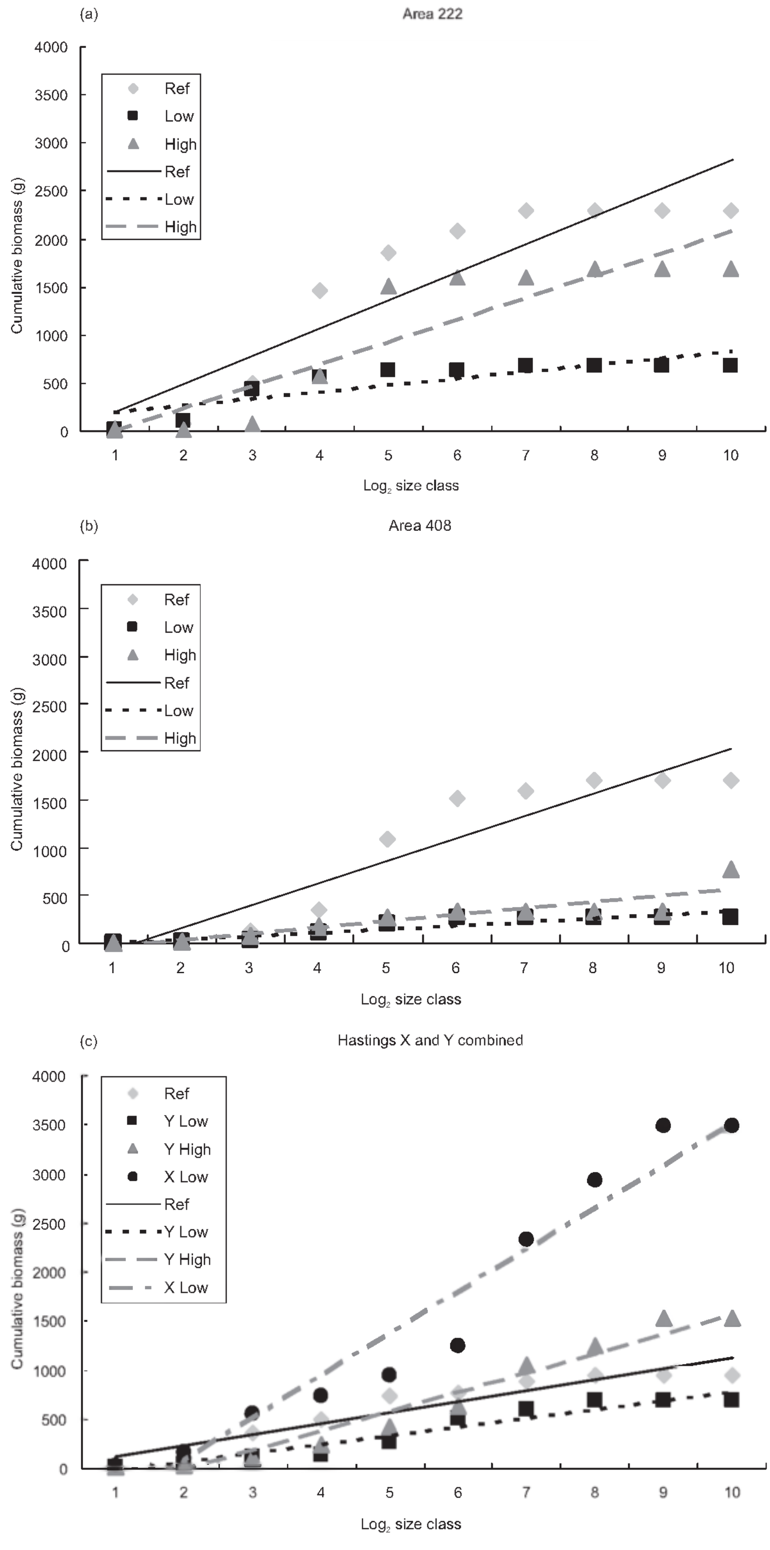


***Figure 15.7. Plots of Cumulative biomass (g) across each size class with linear regression applied for Area 222 (a), Area 408 (b) Hastings X and Y combined (c)***

**Table 15.11. $R_2$ values derived from the application of a linear regression to cumulative curves of biomass data collected in 2003**

| | Area 222 | Area 408 | Hastings X | Hastings Y |
|---|---|---|---|---|
| HIGH | 0.82 | 0.81 | - | 0.95 |
| LOW | 0.73 | 0.85 | 0.94 | 0.94 |
| REF | 0.84 | 0.88 | 0.9 | 0.9 |

BIOENV analysis indicated a relatively strong correlation between species composition and the recently developed 'hydrodynamic indices' of peak tidal current and potential mobility of fine sand ($\rho w=0.666$ for both variables). Figures 15.6f and g provide a visual expression of the relationships between epifaunal data and the two hydrodynamic indices for the 2001-2003 data.

Cumulative biomass over size classes at each of the treatments and extraction areas are shown in Figure 15.7a-c. Results from both Hastings extraction areas are combined onto one graph as only the low treatment was collected in 2003. $R^2$ values(Table 15.11) indicate a good relationship between size classes and cumulative biomass at all extraction areas. At Area 222 and Area 408, biomass across all size classes was higher at the reference treatments compared with the high and low dredging intensity treatments i.e. biomass was reduced within previously dredged areas, with the exception of one large edible crab *Cancer pagurus* which was present in the high treatment site at Area 408. It is worth noting that certain colonial taxa were also present in large quantities at Area 408 which are not included in the analysis as they are colonial taxa. These included the erect bryozoan *Alcyonidium diaphanum* of which there were 6 kg, 3 kg and 4 kg at the high, low and reference treatments respectively. At the reference site, 2 kg of the erect bryozoan *Flustra foliacea* and 20 kg of the soft coral *Alcyonium digitatum* (dead men's fingers) were also recorded.

In contrast, at both Hastings sites, biomass was generally higher at the dredged treatments than the reference site, particularly in the larger size classes. The starfish *Asterias rubens* appears to be the species mainly responsible for these differences between high, low and reference treatments, as it was present in much larger numbers at the previously dredged treatments than the reference site and hence contributed towards increased biomass.

At all four extraction areas, biomass in the high treatments peaked at a larger size class than at the low and reference. There was no evidence of a shift to smaller sized specimens at the dredged treatments at any of the extraction areas, rather an absence or lower abundance in the smaller size classes, equating to a decline in productivity.

## 15.4 Discussion

Whilst the absence of comprehensive 'pre-dredging' data introduces some uncertainty into assessments of progress towards 'recovery' of these epifaunal communities in the dredged treatments, the reference sites are considered to be representative of unimpacted sediments around the extraction areas and therefore provide a sound alternative means for an evaluation of the effects of aggregate extraction. Examination of the epifaunal samples suggests that at the study sites investigated, the numbers and densities of epifaunal taxa within the dredged treatments are typically reduced compared with the nearby reference sites. In addition, enhanced numbers of mobile decapod crustacea, fish and gastropod mollusc species were observed in areas previously exposed to high dredging intensities. This is not entirely unexpected since the invasion of mobile scavengers and predators is a common feature in areas which have been disturbed (Hall, 1994). In such situations, it has been suggested that the disturbance regime is responsible for creating a new a food source which attracts opportunistic scavenging species into the area (Morton, 1996). Comparable results have been obtained during studies of the effects of beam trawling activity on epifaunal populations (Kaiser and Spencer, 1994; Ramsay *et al.*, 1998; Veale *et al.*, 2000). In such studies, predatory species such as the starfish *Asterias rubens* and the hermit crab *Pagurus bernhardus* were observed to move into an area following disturbance of the seabed. However, this is usually documented as a relatively short-term phenomenon observed over relatively short time-scales. In the current study, elevated numbers of certain epifaunal species in areas previously exposed to high dredging intensities appears to have been sustained over a number of years following the cessation of dredging. Recolonization by populations of motile epifaunal browsers and predators will depend on the availability of suitable food, but may also occur opportunistically through migration of adults into the area or via larval recruitment (Rees, 1987).

Not only are species diversity and abundance altered following aggregate extraction activity, biomass of the epifauna within previously dredged treatments is also reduced compared to the reference sites, in particular at Area 222 and Area 408. Such a link between anthropogenic impacts and alteration in community biomass structure has already been shown in studies of the effects on the infauna of trawling disturbance (Lindeboom and de Groot, 1998; Bergman and van Santbrink 2000; Jennings *et al.*, 2001, 2002) and on meiofauna at sand extraction sites (Vanaverbeke *et al.*, 2003). The epifauna at the high and low treatments in this study are undoubtedly reduced in numbers but do not appear to be smaller in size than those found at the reference sites from any of the four extraction areas studied here. This is in contrast to changes observed to occur in size distribution of meiofaunal communities impacted by sand extraction (Vanaverbeke *et al.*, 2003) and for infaunal communities impacted by trawling disturbance (Jennings *et al.*, 2001, 2002). It is therefore suggested that the epifauna respond to such a perturbation in a different way. This may be because of the enhanced capability of motile adults to migrate in and out of an impacted area in response to food resources compared with errant infaunal species. Also, because many motile epifaunal species are scavengers, they are well adapted to move into an area to take advantage of dead or damaged fauna resulting from an activity such as aggregate extraction.

The different results obtained from biomass analysis at the two Hastings extraction areas may be explained by ongoing extraction activity at Hastings Shingle Bank. A renewed licence has meant that extraction recommenced early in 2002 at the Hastings X high intensity treatment and all high, low and reference treatments at Hastings Y are located within 1 km of the active dredging licence. Boyd and Rees (2003) have shown that a footprint of the impact of extraction activity is visible in the form of changes to infaunal community structure up to 1 km away from the actual activity. The differing results obtained at the Hastings extraction areas in comparison with other study sites may be on account of the proximity of sampling locations at Hastings to ongoing dredging activity.

Indirect effects of dredging activity also need to be considered as a possible mechanism for contributing towards the enhancement of numbers and biomass of mobile epibenthic species. For example, Newell *et al.* (1999) suggested that fragmented benthos discharged with the outwash of dredgers can contribute to an enrichment effect. Furthermore, enhanced densities and biomass of benthic invertebrates have been observed on the periphery of dredging operations and beyond in a number of studies (Poiner and Kennedy, 1984; Boyd and Rees, 2003; Newell *et al.*, in press). Whether this enhancement on the boundaries of the extraction areas is a result of deposition of particulate organic matter from the dispersing plume arising from the dredging operation (Newell *et al.*, 1999) or some other feature of disturbance associated with the dredging operation remains to be established. However, it seems highly improbable that such an effect as a consequence of material arising from dredger plumes could be maintained over a number of years following the cessation of extraction activity.

Differing dredging histories of the four extraction areas limits the scope for between-site comparisons. However, the results from this study suggest that screening of cargoes from Area 222 and Area 408 has had a more persistent and acute impact on the epifauna than removal of the sediment as an ‘all-in’ cargo from the Hastings licences. Diversity and biomass is still reduced at the high and low treatments compared to the reference treatment at Area 222 seven years after cessation of dredging activity, and at Area 408 three years after cessation. This could be a function of alteration of the sediment from a gravel to a sandier substratum as discussed for Area 222 by Boyd *et al.* (2003). Such changes may cause destabilisation of the sediment and allow the development of a more specialised fauna. The differences between high, low treatments and reference treatments at the two Hastings study sites are less pronounced, but this may be confounded by the response to renewed activity.

It has been suggested by Kenny (1995) that a relatively impoverished epifauna dominated by ‘resilient’ motile species such as hermit crabs (e.g. *Pagurus* sp.) and *Psammechinus* sp. with a much reduced sessile component persists in areas with a substantial sand content subjected to strong nearbed tidal currents on account of the resuspension and scouring action of the sediments. At Area 222, a greater proportion of sand was observed within the site subject to the highest dredging intensity compared with the reference site (see Boyd *et al.*, 2003). A specialised infauna adapted to mobile sandy sediments may still develop under these conditions (Holme and Wilson, 1985; Kenny *et al.*, 1991; Kenny, 1995) composed of sand dwelling polychaetes (Desprez, 2000; Boyd *et al.*, 2003). Therefore the dominance of a few epifaunal species in the current investigation, in areas previously exposed to high dredging intensities may simply be on account of their resilience to shifting sands in the area and as a result of the opportunistic settlement of species taking advantage of uncolonised sediments (Boyd and Rees, 2003). A further ‘type’ of gravel assemblage with a relatively diverse epifauna may also develop in conditions of high nearbed currents in sediments with a low proportion of sand, although the lack of fine sediment can of course, result in a much reduced infauna (Davoult, 1990).

The present study provides evidence of a relationship between the prevailing environmental conditions tidal current strength and mobility of sand, and the composition of epifaunal species in each region. The importance of tidal action on the distribution of benthic species mediated through its effect on the substratum and natural sediment dynamics was recognised by Cabioch (1968) who conducted large-scale surveys of gravelly substrata of the English Channel. Warwick and Uncles (1980) also correlated the variability in the fauna of the Bristol Channel to bed stresses arising from tidal currents. On the basis of such evidence, Hall (1994) concluded that it is the hydrodynamic regime (mainly the tidal currents) that largely determines the sedimentary characteristics of an area and which is ultimately responsible for determining broad scale community patterns. Later, these conclusions were further supported with the findings of Rees *et al.* (1999) who examined the benthic diversity around the UK coast, and again with the aid of correlation analyses demonstrated a link between the degree of physical disturbance of sediments and broad trends in the numbers and densities of infauna taxa. It is therefore apparent that any changes in the status of benthic assemblages in areas that have been subjected to commercial aggregate extraction will need to be referenced both against variations in particle size and the hydrodynamic regime. It is likely that a combination of direct and indirect effects will be responsible, but these will vary in importance depending upon location, and hence any generic models of cause/effect relationships will require 'ground-truthing', and in all probability, some modification in order to satisfy site-specific needs. With further refinement of the hydrodynamic indices, it is hoped they will improve predictive capability with regard to environmental effects of dredging activity, whether recently ceased, ongoing or planned.

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