Environment Waikato Technical Report 2010/03

Method Development : Assessing the Benthic Impacts of Aquaculture

www.ew.govt.nz
ISSN 1172-4005 (Print)
ISSN 1177-9284 (Online)

Prepared by:
Hilke Giles, National Institute of Water and Atmospheric Research Ltd. (NIWA)

For:
Environment Waikato
PO Box 4010
HAMILTON EAST

December 2009

Document #: 1611953

Approved for release by:
Peter Singleton Date January 2010

Disclaimer

This technical report has been prepared for the use of Waikato Regional Council as a reference document and as such does not constitute Council's policy.

Council requests that if excerpts or inferences are drawn from this document for further use by individuals or organisations, due care should be taken to ensure that the appropriate context has been preserved, and is accurately reflected and referenced in any subsequent spoken or written communication.

While Waikato Regional Council has exercised all reasonable skill and care in controlling the contents of this report, Council accepts no liability in contract, tort or otherwise, for any loss, damage, injury or expense (whether direct, indirect or consequential) arising out of the provision of this information or its use by you or any other party.

Corrigendum

The hardware and software system used to generate the raw data used in this report is a product of Benthic Science Limited, a company separate and not affiliated with the National Institute for Water & Atmospheric Research (NIWA). This sediment profile imaging (SPI) system is manufactured under the Benthic Science Limited trade name of SPI-Scan, not NIWA SPI-SCAN as printed.

Method development: Assessing the benthic impacts of aquaculture

NIWA Client Report: HAM2009-161
December 2009

NIWA Project: EVW09205

Method development: Assessing the benthic impacts of aquaculture

Hilke Giles

Prepared for

Environment Waikato

NIWA Client Report: HAM2009-161
December 2009

NIWA Project: EVW09205

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

Contents

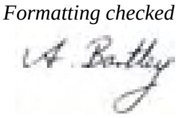
Reviewed by:

Niall Broekhuizen

Approved for release by:

Bob Wilcock

Formatting checked



Executive Summary

In 2006 NIWA began testing the utility of sediment profile imagery (SPI) for resource monitoring of the seafloor near mussel farms in Wilson Bay, Firth of Thames. Sediment Profile Imagery is an underwater technique for photographing the interface between the seabed and the overlying water. The technique is used to measure or estimate biological, chemical, and physical processes occurring on and in the first few centimetres of the sediment. Projects commissioned by Environment Waikato and the Wilson Bay Group A Consortium as well as NIWA funded research have demonstrated the usefulness of SPI. As a consequence, the benthic monitoring component of the Wilson Bay Group A monitoring programme has been modified by substituting the previous video surveys with SPI surveys.

To aid the interpretation of SPI data sets, NIWA proposed to collect additional sediment profile images in the Firth of Thames in reference regions that are not affected by aquaculture and in regions that are affected by different intensities of mussel farming activities. Environment Waikato commissioned NIWA to conduct such a SPI baseline survey within a method development project funded through the Ministry for the Environment's Aquaculture Planning Fund (APF) and Environment Waikato.

This report describes the outcomes of the method development project. Specifically, it presents results of two SPI surveys, demonstrates the potential of SPI to underpin the assessment of benthic impacts and provides suggestions on how to develop a SPI-based benthic habitat quality index for the Firth of Thames, which could inform the development of benthic limits of acceptable change (LACs).

In 2007 and 2009 we collected a total of 174 sediment profile images. We identified a range of attributes in the images, including layers defined from colour parameters that are known to relate to the microbial decomposition of organic matter, and attributes that can be directly identified from the images, such as fauna, mussel faecal pellets or burrows.

The variability of attributes among sites suggests that they provide useful information for the assessment of seafloor functioning and thus the benthic effects of aquaculture. We identified a selection of attributes that we consider useful candidates for a Firth of Thames benthic habitat quality index similar to indices used in the assessment of anthropogenic input overseas. These attributes include the depth of layers identified from colour parameters, scanner penetration depth, annelid worms, *Echinocardium* sp. individuals, epifauna, black/dark patches, shell hash in/on the sediment, mussel faecal pellets and burrows.

A review of advantages and disadvantages of SPI and video surveys, the previously employed method for the assessment of benthic effects of mussel farming in the Wilson Bay Marine Farming Zone, clearly favoured SPI. The key advantages of SPI are the better quality and meaningfulness of data and higher efficiency in data analysis.

Some technical problems experienced during this study were related to the difficulty of scanner penetration under the mussel farms. NIWA has purchased a new SPI device and we are confident that the new device will resolve this problem.

The main conclusions of this method assessment projects were:

(1) Sediment profile imagery is a useful tool for the assessment of benthic aquaculture impacts in the Firth of Thames. It is superior to the previously employed video surveys, primarily due to the better quality and meaningfulness of data and higher efficiency in data analysis.

(2) We believe that the proposed combination of attributes identified from sediment profile images has the potential to form the basis of a SPI-based benthic habitat quality index, which can become a cost-effective and scientifically sound tool for the assessment of benthic habitat quality in the Firth of Thames.

(3) Such a benthic habitat quality index would be independent of the source of impact and could inform the development of benthic limits of acceptable change (LACs).

(4) Future work is required to develop a SPI-based benthic habitat quality index for the Firth of Thames and we suggest the following development process:

   a. The various sources and locations of anthropogenic organic input into the Firth of Thames are identified (e.g., mussel farms, rivers).

   b. The areas affected by these inputs are identified.

   c. In each of these areas transects are generated ranging from maximum organic input to reference areas in which anthropogenic organic input is considered negligible.

   d. Surveys similar to the one conducted in this study are conducted along these transects.

   e. Images are analysed as described in this study and all attributes recommended in this study as being useful for a benthic habitat quality index collated.

   f. Various potential benthic habitat quality indices are calculated from these attributes and examined for their merit in classifying benthic habitats in the Firth of Thames.

   g. The final selection of a benthic habitat quality index is made by Environment Waikato.

1. Introduction

In 2006 NIWA proposed to test the utility of sediment profile imagery (SPI) for resource monitoring of the seafloor near mussel farms in Wilson Bay, Firth of Thames. Sediment Profile Imagery is an underwater technique for photographing the interface between the seabed and the overlying water. The technique is used to measure or estimate biological, chemical, and physical processes occurring on and in the first few centimetres of the sediment. In response to this proposal Environment Waikato and Wilson Bay Groups A and B Consortia commissioned NIWA to test a sediment profile imaging device in Wilson Bay, the SPITwo System (Benthic Science Ltd). The instrument trial demonstrated the great potential of this approach; the instrument was cost-effectively deployed from a small boat and rapidly produced high-resolution images of the sediment profile (Vopel and Funnell 2006).

Following the successful trial Environment Waikato and Wilson Bay Group A Consortium commissioned NIWA to conduct a pilot study of the Wilson Bay seafloor to assess the utility of SPI for the benthic component of the Wilson Bay Group A monitoring programme. The pilot study was completed by NIWA using a modified version of the SPITwo System (referred to as NIWA SPI-SCAN). It demonstrated that SPI is a powerful tool to detect and characterise mussel farm effects and provided recommendations for future resource monitoring of the Wilson Bay seafloor (Vopel et al. 2007).

Environment Waikato, the Wilson Bay Group A consortium and NIWA agreed that further work needed to be done before a suitable long term monitoring programme could be identified. For this purpose, a small scale sediment survey was designed. The aim of this survey was to test a new proposed benthic monitoring programme strategy incorporating recommendations and experience from past monitoring and the SPI studies. The small scale sediment survey enabled us to estimate benthic farm footprints in the Wilson Bay Marine Farming Zone Area A and recommendations were made to adopt the tested benthic monitoring strategy for long term future monitoring (Giles and Budd, 2009). As a consequence, the benthic monitoring component of the Wilson Bay Group A monitoring programme has been modified and the previous video surveys have been substituted with a SPI survey (Wilson et al. 2009).

To aid the interpretation of the new data sets NIWA proposed to collect additional sediment profile images in the Firth of Thames in a reference region that is not affected by aquaculture. Early data indicate a relationship between water depth and the vertical positions of three horizontal layers in the sediment profile images identified from average vertical profiles of the colour parameter saturation and intensity. Such layers result from microbial decomposition of organic matter and solute and particle transport and reaction processes and therefore represent an integrated measure of the seafloor function (Vopel et al. 2007). NIWA proposed to test whether this relationship is generally valid for the Firth of Thames seafloor and, if so, could be used to develop 'Limits of Acceptable Change' (LAC, Zeldis et al. 2006). Following this proposal, Environment Waikato commissioned NIWA to conduct the first part of a SPI baseline survey in the Firth of Thames.

In 2008 Environment Waikato commissioned NIWA to conduct the second part of the SPI baseline survey within a method development project funded through the Ministry for the Environment's Aquaculture Planning Fund (APF) and Environment Waikato. Based on the preliminary analysis of images taken during the first survey and the small scale sediment survey (Giles and Budd, 2009), the initial objective of the method development project (which was to work along the transect of the May 2007 survey) was modified in August 2009. Both studies indicated that there is no significant relationship between water depth and the vertical positions of three horizontal layers in the sediment profile images along the investigated transect. For this reason, the revised aims of the method development project were to:

(1) Collect sediment profile images at a range of sites (~5) to cover a large spectrum of sediment types in the Wilson Bay area (Firth of Thames), e.g., under mussel farms, north and south of Area A, in the navigation channel, and take ~10 replicate images in that area.

(2) Define the vertical boundaries of distinct consecutive layers in the profile images, merge data with those collected in the May 2007 baseline survey and confirm the lack of correlations between water depth and the position of the vertical boundaries of the layer in the sediment profile images.

(3) Identify features in the sediment images from the 2007 and 2009 surveys comparable with those used for benthic habitat indices (e.g., Nilsson and Rosenberg, 1997; Rhoads and Germano, 1986) and additional candidate features that may be useful for the development of a benthic habitat index for the Firth of Thames.

(4) Discuss implications of results for future assessments of benthic impacts of aquaculture and the development of benthic LACs.

2. Methods

2.1 Study design and sites

We visited the Firth of Thames in May 2007 and September 2009 to collect sediment profile images (300 dpi resolution) using the NIWA SPI-SCAN. In 2007 we collected a total of 116 sediment profile images along a 10 km transect (Fig. 1). The transect was located parallel and approximately 2 km from the western boundary of mussel farming Area A. We collected 1–2 sediment profile image every 200 m along the transect starting in the South (37°0.204000 S, 175°26.6356 E) in ~12 m water depth and finishing in the North (36°55.9457 S, 175°22.5039 E) in ~25 m water depth. In addition, we collected images at each of 5 sites along the North–South transect. The sites were 2.5 km apart. At each site, 10–12 replicate sediment profile images were collected at arbitrarily selected locations within a radius of about ~50 m.

In 2009 we collected 58 sediment profile images at five sites (Fig. 1). At each site we took between 10 and 16 replicate images. The sites were located between Area A and Area B in 16.4 m depth (Ref16) and 19.6 m depth (Ref20), between two longlines of one of the farms near the NE boundary of Area A (Farm), in the navigation channel approximately 50 m north of that farm (NavChannel) and approximately 300 m SE of the SE boundary of Area A (SEAreaA).

Appendix I Tables 1 to 3 lists the image identifiers, GPS coordinates and water depths for all images taken. The image identifier reads: Location_Date_Distance along transect_Replicate number for images taken in 2007 and Location_Date_Site_Replicate number for images taken in 2009. The location for this study is represented by WB, referring to Wilson Bay. Replicate number 0 denotes the first image taken at each location. For example, image WB_300507_0000-00 is the first image taken on 30 May 2007 at the beginning of the transect (distance = 0 m). The water depth is the actual water depth measured by the boat's echo sounder at the time of image collection.

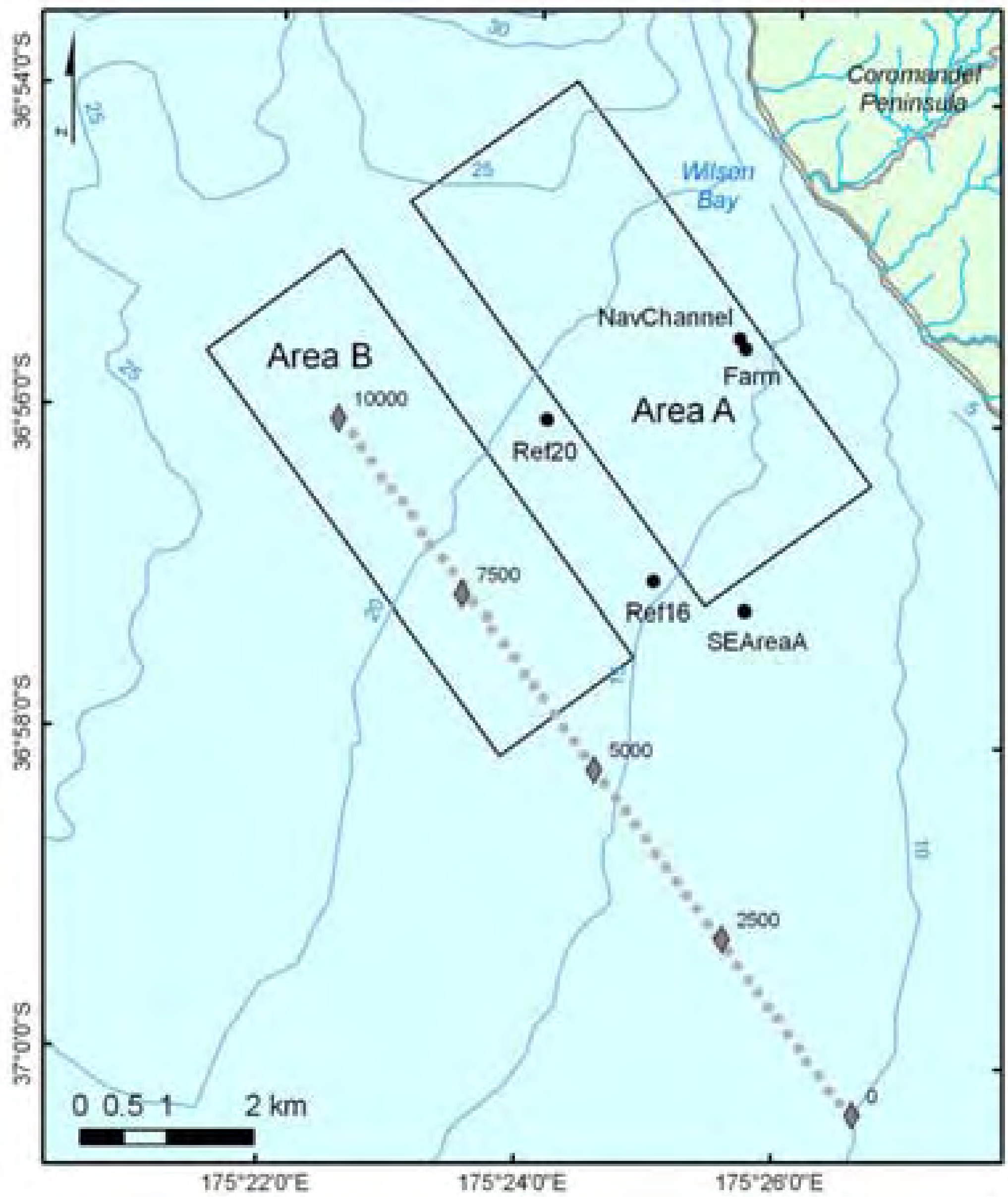


Figure 1: Wilson Bay Marine Farming Areas A (Area A) and B (Area B) in the eastern Firth of Thames and location of sites sampled in the May 2007 survey (grey symbols) and September 2009 survey (black dots). Grey diamonds represent sites on transect where replicate images were taken in 2007. These sites are identified by their distance along the transect.

Figure 2: Photograph showing the NIWA Sediment Profile Imaging device (NIWA SPI-SCAN) deployed from RV Rangatahi in Wilson Bay, Firth of Thames, in September 2009.

2.2 In situ imaging and image analysis

The NIWA SPI-SCAN is a portable device deployed to the seabed in waters up to 40 m depth (Fig. 2). The device communicates sediment profile images to a computer on the vessel via an underwater cable. The acquisition software displays the images, which are later entered into a database for analysis.

Image database

We imported all sediment profile images and associated data such as GPS coordinates, date, time, site, distance on transect into AnalySIS LS (Olympus Soft Imaging Solutions) databases. Two databases were created, one for images collected in 2007 (WB_AreaB_APF.apl) and one for images collected in 2009 (WB_AreaA_APF.apl). Copies of the two databases are provided on DVD with this report. Instructions on how to use the database are provided in Appendix IV.

Sediment colour

All images were X–Y calibrated with the calibration feature of AnalySIS LS and image colour components were separated using the HSI colour model (Hue, Saturation, and Intensity). We produced one average grey-value profile for each of the colour levels: “saturation” and “intensity” and then used these profiles to define the vertical lower boundaries of distinct consecutive layers in each profile image. Layers identified in earlier studies (Giles and Budd, 2009; Vopel et al. 2007) were: (O1) a layer of high colour saturation, (T2) a layer of gradually decreasing colour saturation but maximum colour intensity, (T3) a layer with low colour saturation and gradually decreasing colour intensity, and (R4) a layer of minimum colour saturation and low intensity. The sediment depths of the lower boundaries of these layers are denoted by DO1, DT2, DT3 and DR4.

Detailed background information on these layers is provided in Vopel et al. (2007). Our understanding of these layers is still limited and the focus of ongoing research but we know that layer O1 is associated with oxidised sediment, layers T2 and T3 characterise a gradual transition from oxidising to reducing sediment and layer R4 comprises of reduced sediment.

Surface and subsurface features

Sediment profile images capture a range of physical and biological sediment features. We identified these features visually from each image and compiled them by type and frequency of occurrence. Surface features include epifauna, mussel faecal pellets and Echinocardium spines. Subsurface features include infaunal organisms, burrows, and voids.

2.3 Data analysis

Differences among the depths identified from colour parameters in sediment profile images were analysed using General Linear Models (GLM) with factor Site. Where the GLM analysis revealed significant differences, a Fisher LSD post-hoc test (α = 0.05) was used to elucidate which sites were similar and between which sites differences were statistically significant. Correlation analysis was used to investigate the relationships of layer depths with water depth. All analyses were done using Statistica (Version 8.0).

3. Results

3.1 SPI performance and attributes identified in images

Example sediment profile images from all sites are shown in Appendix II. All attributes identified in the sediment profile images are listed in Table 1. The layers defined from colour saturation and intensity profiles are O1 (oxidised sediment), T2 (an upper redox transition), T3 (a lower redox transition). We could not determine the lower boundary of layer R4 as it extended beyond the penetration depth of the scanner. The scanner penetration depth (SPD) is a relative measure of the sediment compaction since more compact sediments limits the penetration of the scanner.

Table 1: Attributes identified in the sediment profile images, symbols used for their identification, brief description of their link to chemical or ecological properties of the sediment and how they were measured. Presence/absence data were scored relative to the frequency of occurrence: 0 = absent, 1 = low, 2 = intermediate, 3 = high occurrence or as presence/absence only (0, 1). Examples are shown in Appendix III.

Attribute	Symbol	Chemical or ecological interpretation	Measure
Depth of layers defined from colour saturation and intensity profiles:	DO1	Oxidised sediment	Depth (mm)
	DT2	Upper redox transition	Depth (mm)
	DT3	Lower redox transition	Depth (mm)
Scanner penetration depth	SPD	Sediment compaction	Depth (mm)
Black/dark grey patches	BZ	Iron sulphide compounds	Score (0, 1, 2, 3)
Voids	VOID	Voids - gas bubbles or burrow sections	Count
Shell hash in/on sediment	SHELL	Mainly buried broken mussel shells fallen from farm or other epi- or infaunal molluscs	Score (0, 1, 2, 3)
Mussel faecal pellets	MFP	Faecal pellets originating from cultivated mussels	Score (0, 1)
Annelid worms	WORM	Annelid worms inhabiting sediment	Count
Starfish	STAR	Starfish inhabiting sediment	Count
Unspecified infauna	INF	Infauna that could not be specified	Count
Burrows	BUR	Old burrows	Count
Echinocardium sp. individuals	ECH-IND	*Echinocardium* sp. individuals on sediment surface or in sediment	Count
Echinocardium sp. spines	ECH-SP	*Echinocardium* sp. spines on sediment surface or buried into sediment	Score (0, 1)
Unspecified epifauna	EPI	Fauna inhabiting sediment surface	Score (0, 1)

Some attributes directly identified in the sediment profile images were counted, others were quantified by assigning a score relative to the frequency of their occurrence (0: absence, 1: low, 2: intermediate and 3: high occurrence) or a score denoting presence (1) or absence (0) only.

Black or dark grey zones (BZ) were patches surrounded by lighter coloured sediment that indicate high concentrations of iron sulphide compounds. Voids (VOID) in the sediment are typically gas bubbles caused by outgassing of methane and/or hydrogen sulphide. However, some of the voids we identified are more likely parts of empty or collapsed burrows. Shell hash on the sediment surface or in the sediment (SHELL) can originate from mussels that have fallen off the farm structure or from other epifaunal or infaunal molluscs. We were also able to identify mussel faecal pellets on the sediment surface (MFP). These most likely originated from cultivated mussels attached to longlines near the water surface.

We identified annelid worms (WORM) and starfish (STAR) in the sediments as well as other unspecified infauna (INF). In addition we detected and counted old burrows (BUR) in the sediment structure. In some cases it was difficult to distinguish between burrows and fine drag marks of the scanner. In very muddy sediment only few small burrows were visible and we assume that they were destroyed by the scanner. On the sediment surface we identified *Echinocardium* sp. individuals (ECH-IND), *Echinocardium* sp. spines (ECH-SP) and other unspecified epifauna (EPI).

We experienced some problems with the scanner penetration under the farm. The sediment was very muddy and covered by a dense shell layer. To penetrate through this layer we had to add weights to the instrument but, as a consequence, the scanner penetrated rapidly through the muddy sediment, which resulted in smudges on the images. NIWA has recently purchased a new SPI-SCAN device with a pump mechanism, which should solve this problem in future surveys.

3.2 Layers defined from colour parameter

3.2.1 Oxidised sediment layer (O1)

The mean oxidised sediment layer depth ranged from 6.8 mm at site Ref16 to 19.8 mm at site Ref20 (Fig. 3). Differences among some sites were statistically significant (GLM: $p < 0.001$, Table 2) but only few sites were significantly different (Fig. 3).

The five sites on the transect through Area B had similar depths of O1. The five sites in and around Area A were more variable. Directly under the farm the mean depth of the oxidised sediment layer was 8.0 mm, the second lowest observed value. However, no consistent trends emerged related to the proximity to mussel farms or Area A. Furthermore, the correlation between DO1 and water depth was non-significant ($p = 0.896$, Fig. 4).

DO1 values from the five sites in and around Area A generally fell within the range of those derived from sites on the Area B transect in similar water depths (Fig. 4). The depths of the oxidised sediment layers at sites Ref16, SEAreaA and Farm represent the lower range of those measured at the Area B transect sites. At site Ref 20 most values of DO1 were higher than those at the same water depth on the transect.

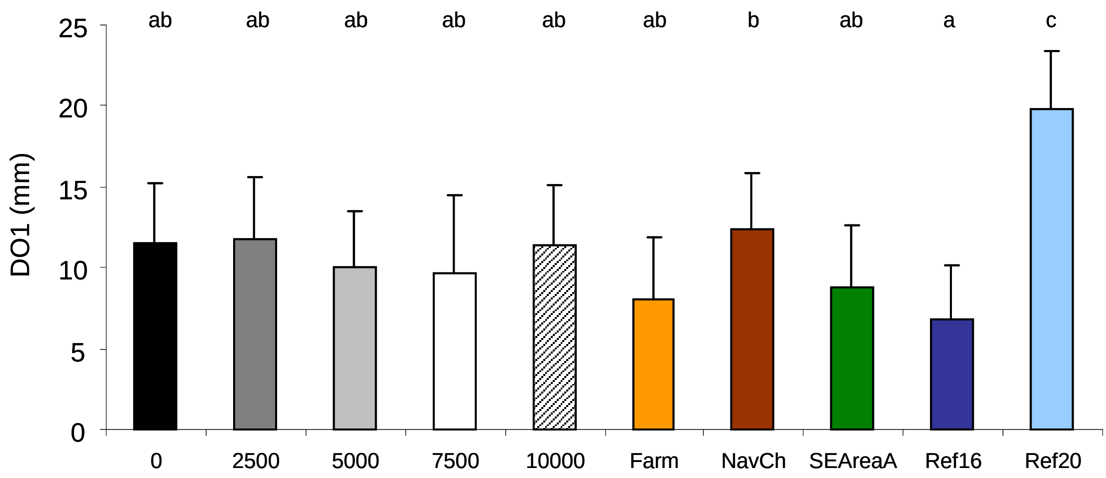


Figure 3: Depth of oxidised sediment layer (DO1) at sites where replicate sediment profile images were collected. Site locations are shown in Fig. 1. Bars denote mean values and error bars denote upper 95 % confidence interval (n = 5–11). Differences between sites labelled with the same letter are not statistically different (post-hoc Fisher LSD, $\alpha = 0.05$).

Table 2: GLM results for parameters derived from image analysis. DOI = depth of oxidised sediment layer, DT2 = depth of upper redox transition layer, SPD = scanner penetration depth.

Parameter	Factor	DF	MS	F	P-value
DO1	Intercept	1	10104	332.55	<0.001
	Site	9	116	3.83	<0.001
	Error	77	30		
DT2	Intercept	1	46909	793.17	<0.001
	Site	9	399	6.75	<0.001
	Error	78	59		
SPD	Intercept	1	1118643	1642.83	<0.001
	Site	9	3660	5.38	<0.001
	Error	87	681		

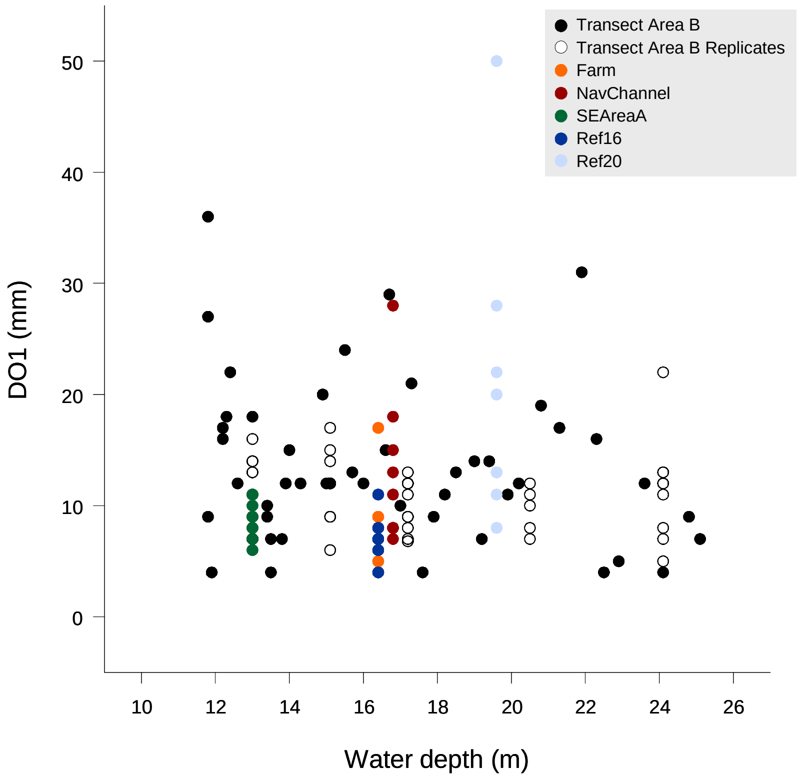


Figure 4: Depth of oxidised sediment layer (DO1) vs. water depth at sites located on transect through Area B and sites in and around Area A. Correlation between DO1 and water depth was non-significant ($p = 0.896$).

3.2.2 Upper redox transition (T2)

The mean depth of the upper redox transition ranged from 13.9 mm at site Ref16 to 36.6 mm at site Ref20 (Fig. 5). Differences among some sites were statistically significant (GLM factor Site: $p < 0.001$, Table 2) but again only site Ref20 was significantly different from all other sites (Fig. 5). DT2 was significantly correlated with DO1 ($p < 0.001$) with a correlation coefficient (r) of 0.78 ($n = 134$).

The five sites on the transect through Area B displayed more variability in DT2 than in DO1 but had larger depths of T2 than all sites in and around Area A, except for site Ref20. Again, no consistent trends emerged related to the proximity to mussel farms or Area A. The correlation between DT2 and water depth was also non-significant ($p = 0.135$, Fig. 6).

As for DO1, the DT2 values from the five sites in and around Area A generally fell within the range of those derived from sites on the Area B transect in similar water depths (Fig. 6). Sites Ref16 and SEAreaA represented the lower range of those measured at the Area B transect sites and most values of DT2 at site Ref 20 were higher than those at the same water depth on the transect.

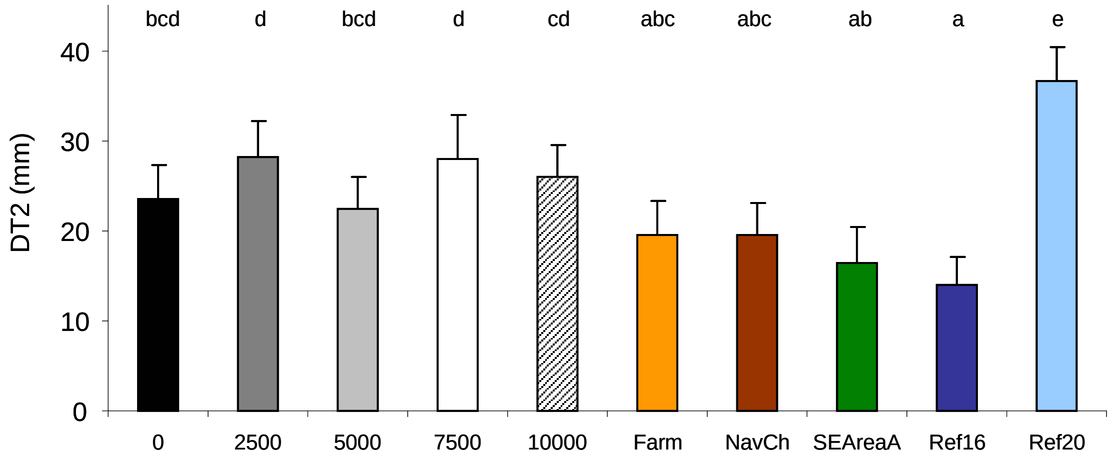


Figure 5: Depth of upper redox transition (DT2) at sites where replicate sediment profile images were collected. Site locations are shown in Fig. 1. Bars denote mean values and error bars denote upper 95 % confidence interval (n = 6–11). Differences between sites labelled with the same letter are not statistically different (post-hoc Fisher LSD, α = 0.05).

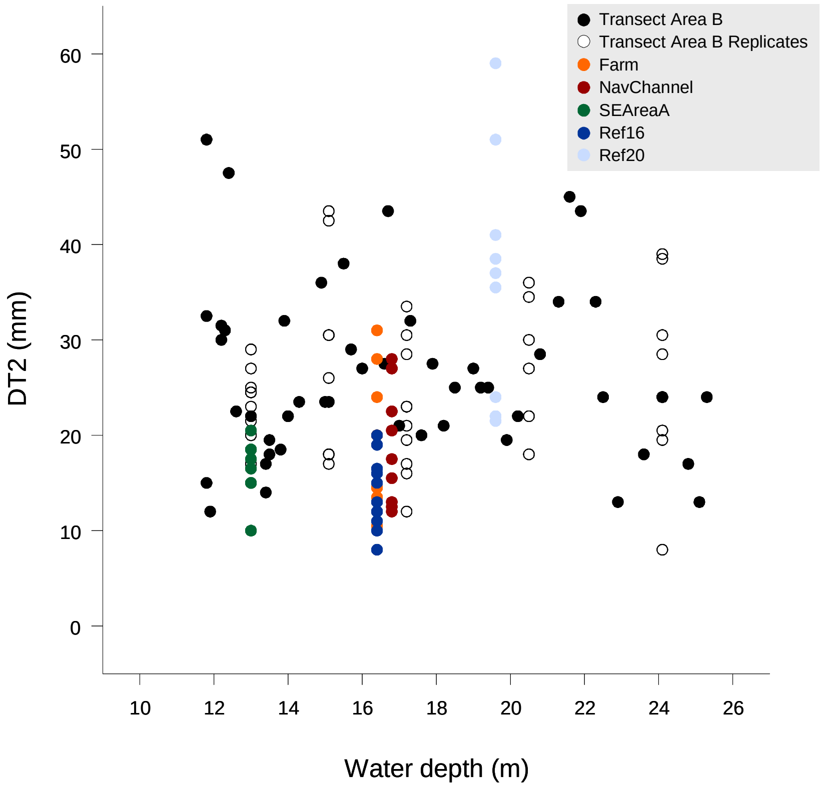


Figure 6: Depth of upper redox transition (DT2) vs. water depth at sites located on transect through Area B and sites in and around Area A. Correlation between DO1 and water depth was non-significant (p = 0.135).

3.3 Lower redox transition (T3)

The depth of the lower redox transition could be determined in only very few images (Fig. 7). This parameter represents a transition to reducing sediment and in locations with relatively low organic input it may be below the penetration depth of our scanner (see 3.4). We were surprised that we could not detect the depth of T3 in the images collected under the farm and in the navigation channel. In a past survey this parameter could be identified in most images under and near farms at the northern and southern boundaries of Area A (Giles and Budd, 2009). We believe that the problem in this survey mainly stemmed from problems with the scanner penetration at the Farm site (see section 3.1) and that we will be able to avoid it in future surveys with our new SPI-SCAN device.

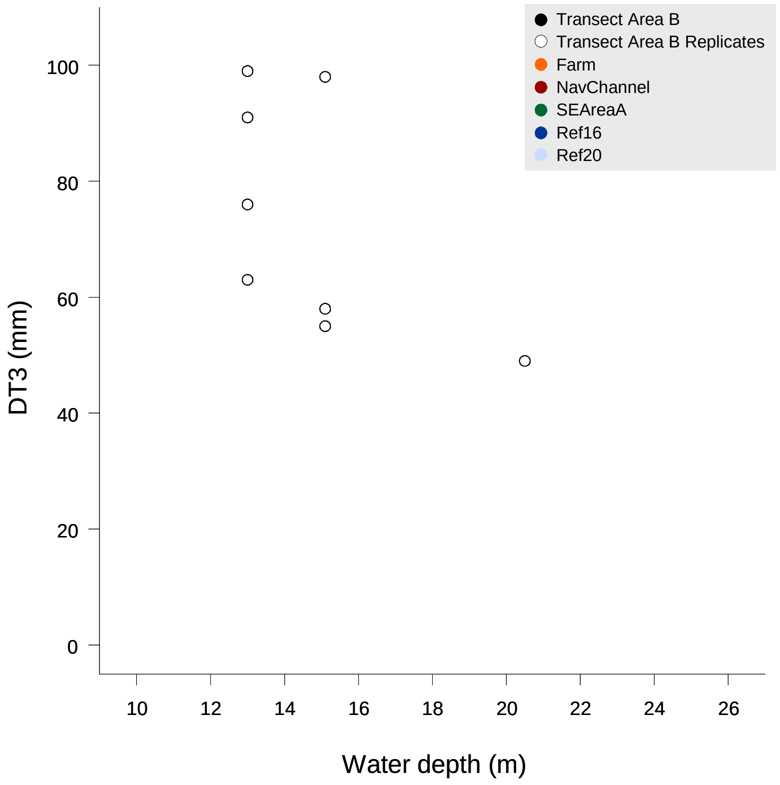


Figure 7: Depth of lower redox transition (DT3) vs. water depth at sites located on transect through Area B and sites in and around Area A.

3.4 Scanner penetration depth

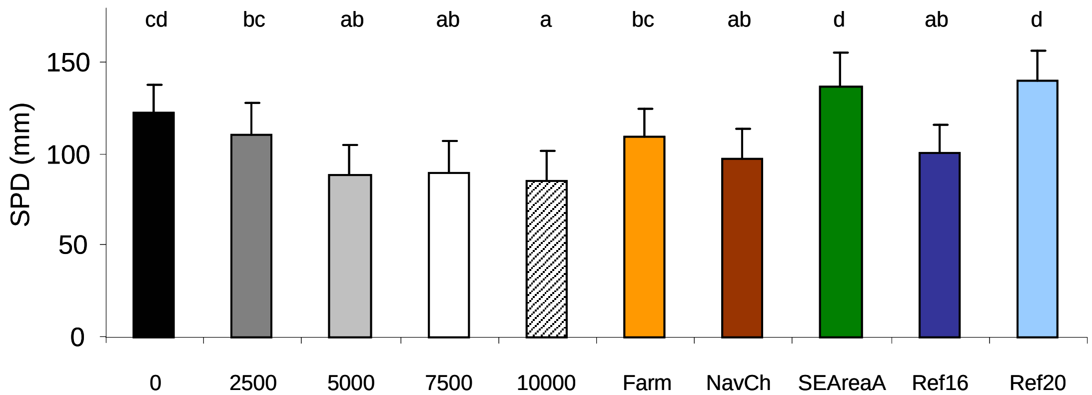


Figure 8: Scanner penetration depth (SPD) at sites where replicate sediment profile images were collected. Site locations are shown in Fig. 1. Bars denote mean values and error bars denote upper 95 % confidence interval (n = 8–11). Differences between sites labelled with the same letter are not statistically different (post-hoc Fisher LSD, $\alpha = 0.05$).

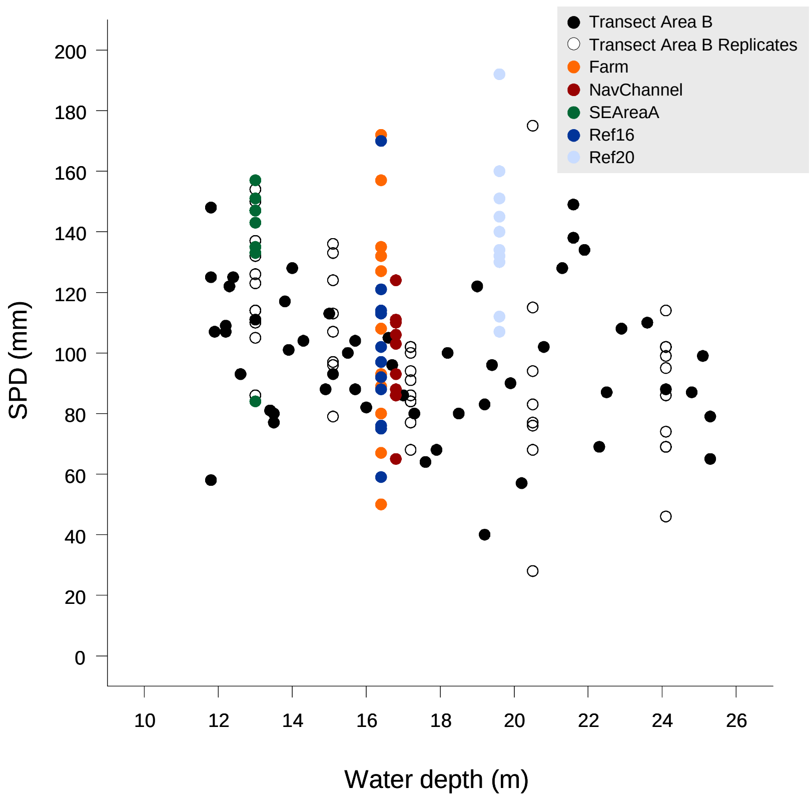


Figure 9: Scanner penetration depth (SPD) vs. water depth at sites located on transect through Area B and sites in and around Area A. Correlation between SPD and water depth was significant ($p = 0.030$, $r = -0.24$).

The scanner penetration depth (SPD) is a relative measure of sediment compaction and therefore can provide useful information on sediment characteristics. SPD was lowest at site 10000 (Fig. 8), the deepest site (24.1 m) and showed a weak correlation with water depth ($p = 0.030$, $r = -0.24$, Fig. 9). While the relationship between SPD and water depth was statistically significant for all combined data, it did not hold for the sites in and around Area A alone ($p = 0.776$), though it did hold for sites from the Area B transect ($p = 0.002$, $r = -0.31$). At some deeper sites the SPD was less than 60 mm, which adversely affects our ability to detect layers defined from colour parameters.

3.5 Attributes directly identified from images

We separated the attributes directly identified from images into ‘fauna attributes’ (Fig. 10) and ‘non-fauna attributes’ (Fig. 11) and present the number of burrows alongside a derived parameter ‘total infauna’ (Fig. 12). These separations were made solely for the purpose of structuring this section. Examples of attributes in images are shown in Appendix III.

3.5.1 Fauna attributes

The most frequently detected attribute were annelid worms (WORM). The mean number of worms ranged from 0.5 to 2.5 worms per image. Numbers were generally lowest at the sites on the Area B transect (with the exception of site 0). The highest numbers were observed in the navigation channel in Area A as well as at sites SEAreaA and Farm.

Starfish (STAR) were rare and only observed at sites 10000 and Ref20. In total only three starfish were identified. Unspecified infauna (INF) were most likely annelid worms or starfish but this could not be determined from the images. Their distribution is similar to that of annelid worms. Individual *Echinocardium* sp. (ECH-IND) were observed at sites NavChannel and Ref20. At these sites a total of six (NavChannel) and eight (Ref20) individuals were identified on the images, which we consider

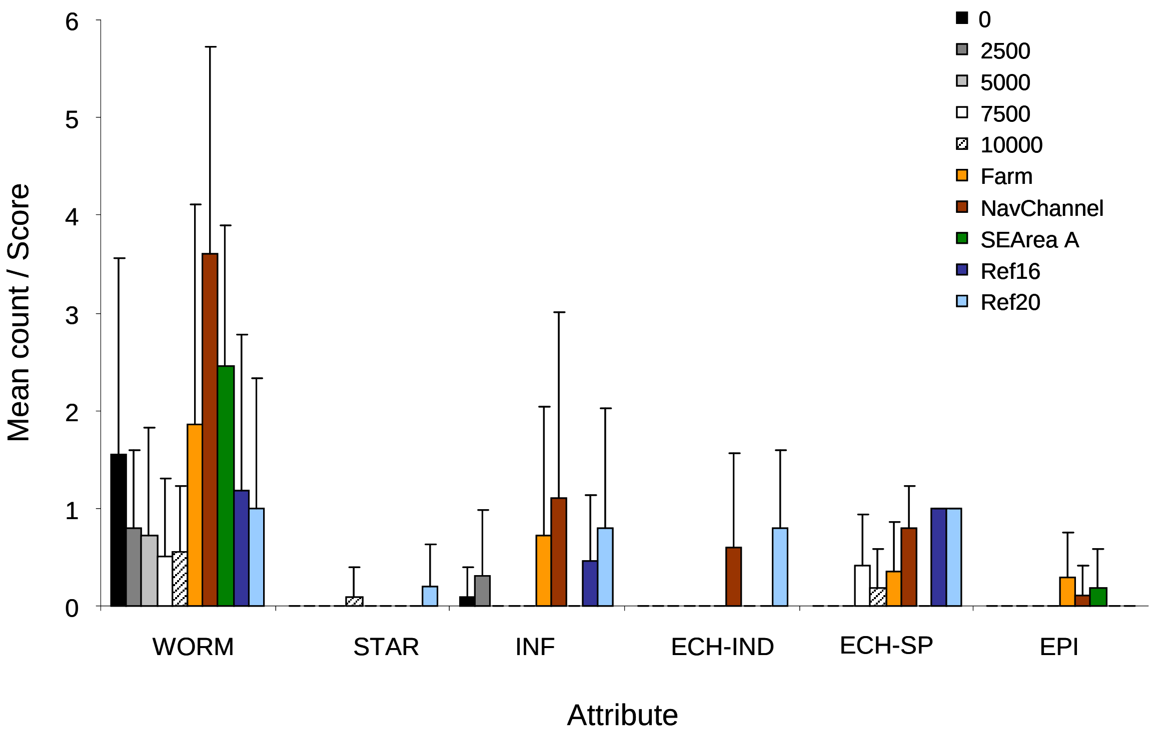


Figure 10: Fauna attributes directly identified from sediment profile images. WORM = annelid worms, STAR = starfish, INF = unspecified infauna, ECH-IND = *Echinocardium* sp. individuals, ECH-SP = *Echinocardium* sp. spines, EPI = unspecified epifauna. Measures and units are described in Table 1. Site locations are shown in Fig. 1. Bars denote mean counts or scores and error bars denote standard deviations.

sufficient to calculate adequate estimates of average numbers. *Echinocardium* sp. spines (ECH-SP) were identified at several sites where no *Echinocardium* sp. individuals appeared in the images. This could be due to the transport of spines into areas not inhabited by *Echinocardium* sp. individuals or it could indicate that *Echinocardium* sp. individuals were present in the area but not captured on the images. Epifauna other than *Echinocardium* sp. individuals (EPI) were present at sites Farm, NavChannel and SEAreaA.

3.5.2 Non-fauna attributes

Most images contained some black or grey patches (BZ) that indicate high concentrations of iron sulphide compounds. The occurrence of these patches is common and not necessarily an indication of organic enrichment. However, the images collected at sites Farm, NavChannel and SEAreaA contained the largest amount of black or grey sediment, indicating that this attribute may be a good indicator of farm influences. In the future this attribute could be better quantified, e.g., by measuring the combined area of dark patches.

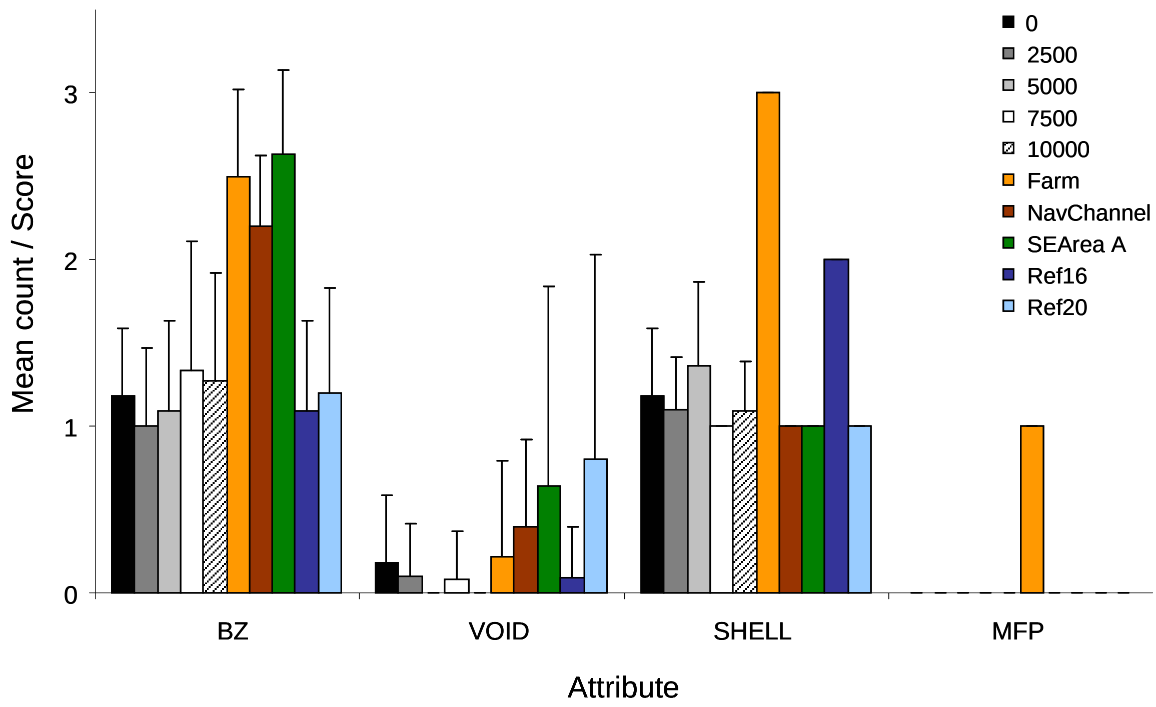


Figure 11: Non-fauna Attributes directly identified from sediment profile images. BZ = black/grey patches, VOID = gas bubbles or burrow sections, SHELL =shall hash in or on sediment, MFP = mussel faecal pellets. Measures and units are described in Table 1. Site locations are shown in Fig. 1. Bars denote mean counts or scores and error bars denote standard deviations.

Voids (VOID) were observed in several images but it was often not possible to distinguish between gas bubbles or burrow sections, which severely limits the usefulness of this attribute. Shell hash (SHELL) in or on the sediment was very common and showed some clear trends, primarily the distinct elevation under the farm and at site Ref16. Mussel faecal pellets (MFP) could be clearly identified under the farm.

3.6 Burrows and total infauna

Burrows (BUR) were visible in most images and showed clear differences among sites. We did not quantify burrow size but, in the future, doing so may increase the usefulness of this attribute in future studies. We derived a parameter 'total infauna' by adding annelid worms, starfish and unspecified infauna. This combined parameter shows some clear trends that, as expected, are similar to the distribution of the number of burrows among sites, providing confidence in our ability to identify burrows in most images. However, no burrows could be identified at site Ref20, demonstrating the problem of destroying small burrows in muddy sediments during scanner penetration (see difficulties discussed in section 3.1).

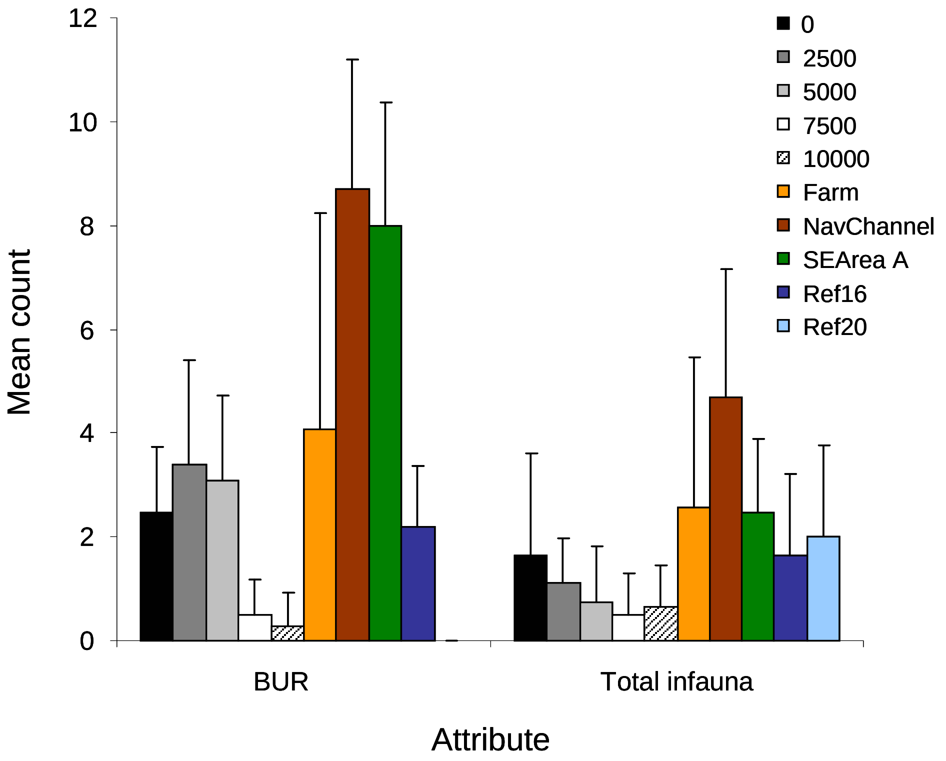


Figure 12: Mean count of burrows and total infauna (annelid worms + starfish + unspecified infauna) identified from sediment profile images. Site locations are shown in Fig. 1. Bars denote mean counts or scores and error bars denote standard deviations.

4. Implications for the future assessments of benthic impact in the Firth of Thames

4.1 Benthic habitat quality indices

A number of indices have been developed using SPI to characterise overall benthic habitat quality and benthic impacts. In general, these indices define a scale for assessing habitat quality based on biogeochemical indicators of benthic condition. The lowest possible index values (highly disturbed/degraded benthic habitat quality) denote black sediments that lack oxygen and have no sign of any active benthic life. The highest possible index values (undisturbed or non-degraded benthic habitat quality) denote well-oxidized sediments having evidence of a mature and well-developed benthic community (NOAA, 2009). These indices are useful for the assessment of changes in benthic habitat quality over time and thus a useful management tool for assessing the effects of anthropogenic inputs into aquatic ecosystems.

One example is the Organism-Sediment Index (OSI; Rhoads and Germano 1986), which aims to characterise the overall quality of the benthic habitat. It is based on several parameters, including the community successional stage, the estimated depth of oxygen penetration and a variety of chemical parameters. Habitat quality is defined relative to an index scale of -10 to +11 (Table 3). In general, OSI values of +6 or greater indicate undisturbed or non-degraded benthic habitats.

Table 3: Method of calculating Organism-Sediment Index (Rhoads and Germano, 1986).

Chemical parameters		Biological parameters	
Mean apparent RPD depth, (cm)	Index value	Successional stage (Primary succession)	Index value
0	0		
>0 – 0.75	1	Azoic	−4
0.76 – 1.50	2	Stage 1	1
1.51 – 2.25	3	Stage 1 – 2	2
2.26 – 3.00	4	Stage 2	3
3.01 – 3.75	5	Stage 2 – 3	4
> 3.75	6	Stage 3	5
Methane present	−2	(Secondary succession)	
No/low O_2	−4	Stage 1 on Stage 3	5
		Stage 2 on Stage 3	

Benthic index = Sum of chemical and biological index values.
Potential index range: −10 to +11.

Table 4: Calculation of the benthic-habitat quality (BHQ) index from sediment profile images. BHQ = ∑A + ∑B + ∑C. (Nilsson and Rosenberg, 2000)

Faunal and sediment structures			BHQ
A: Surface structures			
	Faecal pellets		1
	Tubes	≤2 mm diam.[a]	1
or	Tubes	>2 mm diam.[b]	2
	Feeding pit or mound		2
B: Sub-surface structures			
	Infauna		1
	Burrows	# 1–3	1
or	Burrows	# >3	2
	Oxic void at ≤5 cm depth		1
or	Oxic void at >5 cm depth		2
C: Mean depth of apparent RPD			
		0 cm	0
		0.1–1.0 cm	1
		1.1–2.0 cm	2
		2.1–3.5 cm	3
		3.6–5.0 cm	4
		5 cm	5

[a]e.g. *Euchone* sp., *Polydora* sp.
[b]e.g. *Melinna* sp. Terebellidae sp., Ampharetidae sp., *Rhodine* sp.

Another, example is the Benthic Habitat Quality (BHQ) index developed by Nilsson and Rosenberg (1997). It is similar to the OSI but uses a more quantitative determination of the relative densities of surface and subsurface organisms. The index assigns points to an image based on the type and extent of signatures that animals leave in the sediments (Table 4). High scores are assigned to features that correlate with considerable bioturbation, and the overall score (ranging from 0 to 15) for an image is the sum of the feature scores.

Several other benthic habitat quality indices exist. The variety in approaches and indices used for assessing habitat quality worldwide illustrates two key factors in their development: (1) the disciplinary and methodological preferences of those developing the indices, and (2) regional factors that affect the value of each index and limit its global application (Diaz et al. 2003).

Before applying an index to a particular estuary it has to be calibrated since the thresholds used to assign index values are dependent on regional factors such as natural variability. Furthermore, regional factors may preclude the quantification of some parameters, limiting the usefulness of an existing index. On the other hand regional factors may provide additional features that can be integrated into the index to strengthen its meaningfulness.

4.2 Potential for development of a benthic habitat quality index for the Firth of Thames

We assessed the usefulness of attributes identified in the images for a benthic habitat quality index for the Firth of Thames. The suggestions made in this report are preliminary suggestions that need to be considered in consultation with all stakeholders. The main purpose of this assessment was to demonstrate the potential of the SPI methodology to underpin the development of a benthic habitat quality index in this region.

Attributes identified via image analysis are the depths of layers defined from colour parameters and the scanner penetration depth (Table 5). Attributes DO1, DT2 and DT3 are useful for a benthic habitat quality index for the Firth of Thames as they are directly related to the decomposition of organic matter and sediment transport processes and therefore represent an integrated measure of the seafloor function. The scanner penetration depth (SPD) is related to sediment compaction, thus providing relevant information on the physical sediment characteristics, which will influence the response of the sediment to organic enrichment. For this reason SPD is also a useful attribute for a benthic habitat quality index.

Table 5: Assessment of the usefulness of attributes identified via image analysis of sediment profile images for a benthic habitat quality index for Firth of Thames sediments. DOI = depth of oxidised sediment layer, DT2 = depth of upper redox transition layer, DT3 = depth of lower redox transition layer SPD = scanner penetration depth.

Attribute	Useful	Not useful	Comment / Improvements
DO1	✓		
DT2	✓		
DT3	✓		
SPD	✓		

Table 6: Assessment of the usefulness of attributes directly identified in sediment profile images for a benthic habitat quality index for Firth of Thames sediments. WORM: Annelid worms, STAR: starfish, INF: unspecified infauna, ECH-IND: *Echinocardium* sp. individuals, ECH-SP: *Echinocardium* sp. spines, EPI: epifauna, BZ: black/dark grey patches, VOID: Voids - gas bubbles or burrow sections, SHELL: Shell hash in/on sediment, MFP: mussel faecal pellets, BUR: burrows.

Attribute	Useful	Not useful	Comment / Improvements
WORM	✓		
STAR		✓	Could be used to calculate total infauna
INF		✓	Could be used to calculate total infauna
ECH-IND	✓		
ECH-SP		✓	More research needed on distribution of spines
EPI	✓		Could identify taxonomic level
BZ	✓		Could measure combined area of dark patches
VOID		✓	Need more information on what voids are
SHELL	✓		
MFP	✓		
BUR	✓		

A number of attributes directly identified from sediment profile images have been assessed (Table 6). The considerable differences in annelid worms among sites indicate that they may be a useful attribute to include in a benthic habitat quality index. The low occurrence of starfish in the sediment profile images illustrates that they would not be a useful attribute on their own because of the difficulties in obtaining sufficient replicates. Due to the uncertainty in identifying individuals categorised as unspecified infauna, this attribute should also not be used on its own in a benthic habitat quality index. However, it would be useful to quantify the total number of infaunal organisms and use this parameter for the index.

The numbers of *Echinocardium* sp. individuals were sufficiently high to estimate mean numbers per site but, consistent with the typically low density and patchy distribution of echinoids (e.g., Nebelsick, 1992), abundances were variable. *Echinocardium* sp. play an important role in marine ecosystems (Lohrer et al. 2004) and we believe that they should form an integral part of a benthic habitat quality index. *Echinocardium* sp. spines were more abundant than living individuals but their distribution among sites did not match the distribution of *Echinocardium* sp. individuals well. Such discrepancies can be attributed to transport on the sediment surface or mixing in the sediment by living individuals or other burrowing species

(Nebelsick, 1992). Our understanding of the transport characteristics of the spines and links between spines and living individuals is limited but the inclusion of *Echinocardium* sp. spines into a benthic habitat quality index should be considered.

Epifauna other than *Echinocardium* sp. individuals can be easily identified in images and play important roles in the ecosystem. Despite low numbers they should be incorporated in a benthic habitat quality index. Individuals could be identified to provide taxonomic information.

The attribute BZ should be incorporated into a benthic habitat quality index as high concentrations of iron sulphide compounds are typically associated with organic enrichment. To increase the information obtained from this parameter it might be useful to calculate the total area of grey or black patches in the images. Due to the inability to distinguish between gas bubbles or burrow sections we currently do not suggest including voids into a benthic habitat quality index. Shell hash and mussel faecal pellets showed clear trends. In addition, both attributes are directly linked to the (past or present) presence of animals and should be included in an index.

One problem is that due to the different scanner penetration depths, images represent different depths of the sediment. This creates biases for some parameters. For example, iron sulphide compounds are more common at greater depths. As a consequence, at two similar sites (in terms of iron sulphide compounds) fewer black or grey patches may be identified at the site with lower penetration depth compared to the site with greater penetration depth. This problem could be addressed by normalising relevant parameters in relation to penetration depth or by analysing all images to the same sediment depth.

4.3 Advantages and disadvantages of SPI vs. Sediment Surface Video

In the past the benthic component of the Wilson Bay Group A monitoring programme was accomplished by a combination of video survey and sediment analyses. The video survey component of this monitoring programme has been substituted by SPI in 2008 (Wilson et al., 2009). The two survey methods differ in a number of respects and have advantages and disadvantages, which were collated and discussed in a SPI pilot study carried out in 2007 (Vopel et al., 2007). Due to the relevance of these advantages and disadvantages for the evaluation of the usefulness of SPI for assessing benthic impacts of aquaculture, we present a modified version of the original table in Vopel et al. (2007) in Table 7.

As emphasised in the SPI pilot study, it is important to note that the comparison is focused solely on the applicability of the methods to the seafloor in Wilson Bay and that it does not provide a general comparison of the methods. Furthermore, the comparison is restricted to the actual survey techniques employed, that is, the collection of data by means of the NIWA SPI-SCAN and the NIWA video sled, and the interpretation of such data.

Table 7: Advantages and disadvantages of two survey techniques for the Wilson Bay seafloor, Firth of Thames: Sediment Profile Imagery (SPI) vs. Sediment Surface Video.

Advantages	Disadvantages
1. SPI (NIWA SPI Scan)	
Data quality and speed of data collection	
High image quality	Low spatial coverage of single image
Quality of data not affected by water clarity	
Rapid image collection	
Rapid image processing	
Data interpretation	
Provides clear visual images and impressions, interpretable by laymen	Biogeochemical processes associated with image features are complex
Ground truthing of sediment colour information possible with modern analytical techniques (pore water chemistry)	Interpretation of colour in images is based on the presence few colourful redox active sediment constitutes
Digital and automated image analyses can provide quantifiable parameter that can be standardised	Does not provide quantitative information that direct physical and chemical measurements can provide
Easy to identify attributes that directly relate to ecosystem functioning and structure, such as epifauna, infauna, mussel faecal pellets, burrows	
Information on sediment profile	
Images represent time integrator of biogeochemical processes	
Predictive capabilities when combined with numerical models	

(continued)

Table 7 (continued)

Advantages	Disadvantages
Logistics of data collection / weather dependency	
Easy to use	Deployment impaired under conditions of strong tidal currents
Minimal disturbance of seafloor	No deployment possible when wind from the North, West or South is above 15 knots
Data collection inside farm blocks and directly underneath long lines possible	Deployment during spring tides only under conditions of calm weather
	Scanner penetration may be impaired by sediment compaction
2. Surface Video (NIWA video sled)	
Data quality and speed of data collection	
Large spatial coverage	Video quality not consistent and affected by water clarity
Rapid video collection	Slow video processing
	Water clarity in field of view affected by sediment disturbance of video sled
	Feature recognition dependent on experience of staff
Data interpretation	
Ground truthing of surface features possible using other sampling techniques	Lacks the power that comprehensive analyses of infaunal communities can provide
Predictive capabilities when combined with comprehensive analyses of sediment infaunal communities	No information on sediment profile or vertical colonisation of sediment
	Provides only information on species and physical sediment features that produce marks at the sediment surface
Logistics of data collection / weather dependency	
	No deployment when wind from North, West or South is above 15 knots and when strong wind opposes the tide
	No data collection inside farm blocks
	No deployment during spring tides and after recent rain because both decreases water clarity
	Disturbance of seafloor by video sledge

As reported in Vopel et al. (2007), the main advantages of SPI relating to data interpretation were that images cover a vertical profile of the sediment and represent a time integrator of biological, chemical and physical processes. As demonstrated in this method development study, many attributes that can be directly identified in the images are directly related to ecosystem functioning and structure. For ground truthing of sediment colour information analytical techniques are available and NIWA is currently conducting research to improve our understanding of the layers identified from colour parameters. SPI can be used to collect data inside farm blocks directly underneath mussel long lines. This study demonstrated that these applications can be impaired due to restricted scanner penetration but we are confident that a new SPI device currently being built for NIWA will resolve this problem. The main disadvantages of the use of SPI are the low spatial coverage of a single image. The deployment of the current sediment profile imaging device in Wilson Bay is impaired under conditions of strong currents or wind and, as mentioned earlier, the device penetration may be impaired in compact sediments.

The following paragraph is a direct quote from Vopel et al. (2007), summarising the advantages and disadvantages of the video survey methodology:

> "The video survey used in past monitoring of the Wilson Bay seafloor has a large spatial coverage and video collection is fast. Ground truthing of the video data is possible using additional sampling techniques and this method has predictive capabilities when combined with comprehensive analyses of sediment infaunal communities. The main disadvantages are that the video quality is not consistent and affected by water clarity. The processing of video data is slow and feature recognition depends on staff experience. Only data of the sediment surface is gathered and no information is provided on sediment profile or the vertical colonisation of the sediment. Consequently only information on species and physical sediment features is provided that produce marks on the sediment surface. The deployment of the video sled is impaired under conditions of strong currents, wind and rain".

In conclusion, we believe that for the assessment of benthic impacts of aquaculture, the advantages of SPI over video survey outweigh the disadvantages, primarily due to the better quality and meaningfulness of data and higher efficiency in data analysis.

5. Conclusions

We identified a selection of attributes that we consider useful candidates for a Firth of Thames benthic habitat quality index similar to indices used in the assessment of anthropogenic input overseas. These attributes include the depths of layers identified from colour parameters, scanner penetration depth, annelid worms, *Echinocardium* sp. individuals, epifauna, black/dark patches, shell hash in/on the sediment, mussel faecal pellets and burrows. Due to difficulties identifying starfish and other infauna, these attributes could be used combined as a measure of unspecified infauna. We believe that the combination of these attributes has the potential to form the basis of a cost-effective and scientifically sound assessment tool that can help to assess the benthic habitat quality in the Firth of Thames. Such a tool would be underpinned by meaningful assessments of sediment chemical, biological and physical characteristics and consider locally significant attributes.

One benefit of using a SPI-based benthic habitat quality index is that it is independent of the source of impact. Specifically, it would enable the impact assessment from different types of cultivated aquaculture species (e.g., mussels or finfish) but also from other sources, such as riverine inputs. Benthic habitat quality indices can easily be modified if anthropogenic inputs change. For example, should new aquaculture species be introduced in the Firth of Thames, additional attributes may become visible on sediment profile images (e.g., fish faeces). These could easily be added to the list of parameters used to calculate the index, making it more specific and meaningful for local conditions. In addition to being a stand-alone index for the assessment of benthic habitat quality and aquaculture impacts, a Firth of Thames specific benthic habitat quality index could inform the development of benthic limits of acceptable change (LACs).

A review of advantages and disadvantages of SPI and video surveys, the previously employed method for the assessment of benthic effects of mussel farming in the Wilson Bay Marine Farming Zone, clearly favoured SPI. The key advantages of this methodology are the better quality and meaningfulness of data and higher efficiency in data analysis.

6. Future work

To develop a SPI-based benthic habitat quality index for the Firth of Thames we suggest that:

(1) The various sources and locations of anthropogenic organic input into the Firth of Thames are identified (e.g., mussel farms, rivers).

(2) The areas affected by these inputs are identified.

(3) In each of these areas transects are generated ranging from maximum organic input to reference areas in which anthropogenic organic input is considered negligible.

(4) Surveys similar to the one conducted in this study are conducted along these transects.

(5) Images are analysed as described in this study and all attributes recommended in this study as being useful for a benthic habitat quality index collated.

(6) Various potential benthic habitat quality indices are calculated from these attributes and examined for their merit in classifying benthic habitats in the Firth of Thames.

(7) The final selection of a benthic habitat quality index is made by Environment Waikato.

(8) This preliminary index may be modified based on the results of further studies or the introduction of new anthropogenic inputs in the Firth of Thames.

7. References

Diaz, R.J.; Cutter, G.R.; Dauer, D.M. (2003). A comparison of two methods for estimating the status of benthic habitat quality in the Virginia Chesapeake Bay. *Journal of Experimental Marine Biology and Ecology 285*: 371-381.

Giles, H.; Budd, R. (2009). Small Scale Sediment Survey in the Wilson Bay Marine Farming Zone Area A. NIWA client report HAM2009-010 (Client: Group A Consortium Wilson Bay)

Lohrer, A.M.; Thrush, S.F.; Gibbs, M.M. (2004). Bioturbators enhance ecosystem function through complex biogeochemical interactions. *Nature 431(7012)*: 1092-1095.

Nebelsick, J.H. (1992). Echinoid distribution by fragment identification in the northern Bay of Safaga, Red Sea, Egypt. *Palaios 7(3)*: 316-328.

Nilsson, H.C.; Rosenberg, R. (1997). Benthic habitat quality assessment of an oxygen stressed fjord by surface and sediment profile images. *Journal of Marine Systems 11*: 249-264.

Nilsson, H.C.; Rosenberg, R. (2000). Succession in marine benthic habitats and fauna in response to oxygen deficiency: analysed by sediment profile-imaging and by grab samples. *Marine Ecology-Progress Series 197*: 139-149.

NOAA (2009). How can SPI be used to measure benthic community condition? Characterizing Habitat Quality. Retrieved from http://www.csc.noaa.gov/benthic/mapping/applying/osi5.htm

Rhoads, D.C.; Germano, J.D. (1986). Interpreting long-term changes in benthic community structure: a new protocol. *Hydrobiologia 142*: 291-308.

Vopel, K.; Funnell, G. (2006). Wilsons Bay Sediment Imaging: 1. Instrument test. NIWA Client Report: HAM2006–004. (Client: Environment Waikato).

Vopel, K.; Giles, H.; Budd, R.; Hart, C. (2007). Wilson Bay Sediment Profile Imaging: 2. Pilot Study. NIWA Client Report HAM2007-080. (Clients: Environment Waikato, Wilson Bay Group A and B Consortium).

Wilson, J.; Zeldis, J.; Giles, H. (2009). Environmental monitoring programme for Wilson Bay Marine Farming Zone Area A, revision November 2009. NIWA Client Report: HAM2007-174.

Zeldis, J.; Felsing, M.; Wilson, J. (2006). Limits of acceptable change: a framework for managing marine farming. *Water & Atmosphere 14(2)*: 16-17.

8. Appendix I: Sample log

Table 1: Sample log. Image identifier, GPS coordinates and water depth for images taken along a 10 km transect in the Firth of Thames heading South–North on 30 May 2007. Location_Date_Distance along transect-Replicate.

Image identifier	Longitude	Latitude	Water depth (m)
WB_300507_0000-00	37° 0.204000	175° 26.6356	11.8
WB_300507_0000-01	37° 0.212900	175° 26.6316	11.8
WB_300507_0200-00	37° 0.131000	175° 26.5386	11.8
WB_300507_0200-01	37° 0.131200	175° 26.5393	11.8
WB_300507_0400-00	37° 0.055500	175° 26.4538	11.9
WB_300507_0600-00	36° 59.96060	175° 26.3742	12.2
WB_300507_0600-01	36° 59.95990	175° 26.3698	12.2
WB_300507_0800-00	36° 59.87420	175° 26.2821	12.3
WB_300507_0800-01	36° 59.87280	175° 26.2764	12.3
WB_300507_1000-00	36° 59.79230	175° 26.2115	12.4
WB_300507_1200-00	36° 59.70710	175° 26.1229	12.6
WB_300507_1400-00	36° 59.61290	175° 26.0389	13.0
WB_300507_1600-00	36° 59.54320	175° 25.9661	13.4
WB_300507_1800-00	36° 59.45260	175° 25.8817	13.4
WB_300507_2000-00	36° 59.37000	175° 25.8094	13.5
WB_300507_2000-01	36° 59.37740	175° 25.8073	13.5
WB_300507_2200-00	36° 59.28520	175° 25.7187	13.8
WB_300507_2400-00	36° 59.19920	175° 25.6402	13.9
WB_300507_2600-00	36° 59.11290	175° 25.5542	14.0
WB_300507_2800-00	36° 59.03240	175° 25.4748	14.3
WB_300507_3000-00	36° 58.93840	175° 25.3912	14.9
WB_300507_3200-00	36° 58.85810	175° 25.3056	15.0
WB_300507_3400-00	36° 58.77290	175° 25.2241	15.1
WB_300507_3600-00	36° 58.68540	175° 25.1435	15.3
WB_300507_3800-00	36° 58.60040	175° 25.0629	15.5
WB_300507_4000-00	36° 58.51320	175° 24.9782	15.7
WB_300507_4000-01	36° 58.52020	175° 24.9748	15.7
WB_300507_4200-00	36° 58.42400	175° 24.8935	16.0
WB_300507_4400-00	36° 58.34240	175° 24.8173	16.4
WB_300507_4600-00	36° 58.26060	175° 24.7352	16.6
WB_300507_4800-00	36° 58.17310	175° 24.6443	16.7
WB_300507_5000-00	36° 58.09010	175° 24.5620	17.0
WB_300507_5200-00	36° 58.00050	175° 24.4833	17.3
WB_300507_5400-00	36° 57.91640	175° 24.4032	17.6
WB_300507_5600-00	36° 57.83160	175° 24.3192	17.9
WB_300507_5600-01	36° 57.83810	175° 24.3156	17.9
WB_300507_5800-00	36° 57.74990	175° 24.2439	18.2
WB_300507_6000-00	36° 57.65120	175° 24.1521	18.5

Table 1 (continued)

Image identifier	Longitude	Latitude	Water depth (m)
WB_300507_6200-00	36° 57.57460	175° 24.0764	19.0
WB_300507_6400-00	36° 57.50050	175° 23.9995	19.2
WB_300507_6400-01	36° 57.50410	175° 24.0017	19.2
WB_300507_6600-00	36° 57.40150	175° 23.9179	19.4
WB_300507_6800-00	36° 57.31830	175° 23.8373	19.9
WB_300507_7000-00	36° 57.23220	175° 23.7394	20.2
WB_300507_7200-00	36° 57.15460	175° 23.6966	20.5
WB_300507_7400-00	36° 57.06880	175° 23.5864	20.8
WB_300507_7600-00	36° 56.96260	175° 23.5019	21.3
WB_300507_7800-00	36° 56.88530	175° 23.4200	21.6
WB_300507_8000-00	36° 56.80690	175° 23.3402	21.9
WB_300507_8200-00	36° 56.72300	175° 23.2421	22.3
WB_300507_8400-00	36° 56.64680	175° 23.1717	22.5
WB_300507_8600-00	36° 56.53860	175° 23.0989	22.9
WB_300507_8800-00	36° 56.45420	175° 23.0220	23.1
WB_300507_9000-00	36° 56.37730	175° 22.9279	23.6
WB_300507_9200-00	36° 56.30960	175° 22.8477	24.1
WB_300507_9400-00	36° 56.20650	175° 22.7674	24.8
WB_300507_9600-00	36° 56.12570	175° 22.6836	24.8
WB_300507_9800-00	36° 56.04300	175° 22.6190	25.1
WB_300507_10000-00	36° 55.94570	175° 22.5039	25.3

Table 2: Sample log. Image identifier, GPS coordinates and water depth for images taken along a 10 km transect in the Firth of Thames heading South–North on 31 May 2007. Image identifier reads: Location_Date_Distance along transect-Replicate.

Image code	Longitude	Latitude	Water depth (m)
WB_310507_0000-00	37° 00.26900	175° 26.59370	13.0
WB_310507_0000-01	37° 00.25640	175° 26.58870	13.0
WB_310507_0000-02	37° 00.24960	175° 26.58260	13.0
WB_310507_0000-03	37° 00.24830	175° 26.60050	13.0
WB_310507_0000-04	37° 00.23850	175° 26.61290	13.0
WB_310507_0000-05	37° 00.23150	175° 26.60500	13.0
WB_310507_0000-06	37° 00.23940	175° 26.62420	13.0
WB_310507_0000-07	37° 00.23500	175° 26.63630	13.0
WB_310507_0000-08	37° 00.22520	175° 26.63020	13.0
WB_310507_0000-09	37° 00.22000	175° 26.63480	13.0
WB_310507_0000-10	37° 00.21370	175° 26.62840	13.0
WB_310507_2500-00	36° 59.18590	175° 25.54550	15.1
WB_310507_2500-01	36° 59.18380	175° 25.56640	15.1
WB_310507_2500-02	36° 59.17640	175° 25.59180	15.1
WB_310507_2500-03	36° 59.15910	175° 25.60090	15.1
WB_310507_2500-04	36° 59.15370	175° 25.59650	15.1
WB_310507_2500-05	36° 59.12630	175° 25.58860	15.1
WB_310507_2500-06	36° 59.12850	175° 25.55900	15.1
WB_310507_2500-07	36° 59.14440	175° 25.54390	15.1
WB_310507_2500-08	36° 59.16350	175° 25.54380	15.1
WB_310507_2500-09	36° 59.16530	175° 25.55900	15.1
WB_310507_2500-10	36° 59.14020	175° 25.58170	15.1
WB_310507_5000-00	36° 58.10550	175° 24.54790	17.2
WB_310507_5000-01	36° 58.09560	175° 24.56430	17.2
WB_310507_5000-02	36° 58.07000	175° 24.55680	17.2
WB_310507_5000-03	36° 58.06440	175° 24.54630	17.2
WB_310507_5000-04	36° 58.06960	175° 24.52150	17.2
WB_310507_5000-05	36° 58.07870	175° 24.50860	17.2
WB_310507_5000-06	36° 58.08840	175° 24.51240	17.2
WB_310507_5000-07	36° 58.09660	175° 24.52420	17.2
WB_310507_5000-08	36° 58.08460	175° 24.53610	17.2
WB_310507_5000-09	36° 58.07710	175° 24.55550	17.2
WB_310507_5000-10	36° 58.08120	175° 24.54590	17.2

Table 2 (continued)

Image code	Longitude	Latitude	Water depth (m)
WB_310507_7500-00	36° 57.03460	175° 23.53390	20.5
WB_310507_7500-01	36° 57.02040	175° 23.54980	20.5
WB_310507_7500-02	36° 56.99210	175° 23.52550	20.5
WB_310507_7500-03	36° 56.99620	175° 23.51290	20.5
WB_310507_7500-04	36° 57.00120	175° 23.49910	20.5
WB_310507_7500-05	36° 57.01410	175° 23.49360	20.5
WB_310507_7500-06	36° 57.02260	175° 23.49860	20.5
WB_310507_7500-07	36° 57.03470	175° 23.50930	20.5
WB_310507_7500-08	36° 57.04300	175° 23.50780	20.5
WB_310507_7500-09	36° 57.03770	175° 23.51930	20.5
WB_310507_7500-10	36° 55.95460	175° 22.50990	20.5
WB_310507_7500-11	36° 55.95460	175° 22.50990	20.5
WB_310507_10000-00	36° 55.95460	175° 22.50990	24.1
WB_310507_10000-01	36° 55.95450	175° 22.49260	24.1
WB_310507_10000-02	36° 55.95770	175° 22.51880	24.1
WB_310507_10000-03	36° 55.95630	175° 22.53030	24.1
WB_310507_10000-04	36° 55.93950	175° 22.52840	24.1
WB_310507_10000-05	36° 55.92430	175° 22.50800	24.1
WB_310507_10000-06	36° 55.93070	175° 22.48360	24.1
WB_310507_10000-07	36° 55.93780	175° 22.48210	24.1
WB_310507_10000-08	36° 55.95930	175° 22.49790	24.1
WB_310507_10000-09	36° 55.95230	175° 22.48900	24.1
WB_310507_10000-10	36° 55.94360	175° 22.52300	24.1
WB_310507_10000-11	36° 55.93110	175° 22.51520	24.1

Table 3: Sample log. Image identifier, GPS coordinates and water depth for images taken in September 2009. Replicate images at each site were taken within 50 m of the given GPS coordinates. Image identifier reads: Location_Date_Site-Replicate.

Image identifier	Longitude	Latitude	Water depth (m)
Site Ref16			
WB_070909_R16-00	36° 56.910	175° 24.983	16.4
WB_070909_R16-01	36° 56.910	175° 24.983	16.4
WB_070909_R16-02	36° 56.910	175° 24.983	16.4
WB_070909_R16-03	36° 56.910	175° 24.983	16.4
WB_070909_R16-04	36° 56.910	175° 24.983	16.4
WB_070909_R16-05	36° 56.910	175° 24.983	16.4
WB_070909_R16-06	36° 56.910	175° 24.983	16.4
WB_070909_R16-07	36° 56.910	175° 24.983	16.4
WB_070909_R16-08	36° 56.910	175° 24.983	16.4
WB_070909_R16-09	36° 56.910	175° 24.983	16.4
WB_070909_R16-00	36° 56.910	175° 24.983	16.4
Site Ref20			
WB_070909_R20-00	36° 55.919	175° 24.122	19.6
WB_070909_R20-01	36° 55.919	175° 24.122	19.6
WB_070909_R20-02	36° 55.919	175° 24.122	19.6
WB_070909_R20-03	36° 55.919	175° 24.122	19.6
WB_070909_R20-04	36° 55.919	175° 24.122	19.6
WB_070909_R20-05	36° 55.919	175° 24.122	19.6
WB_070909_R20-06	36° 55.919	175° 24.122	19.6
WB_070909_R20-07	36° 55.919	175° 24.122	19.6
WB_070909_R20-08	36° 55.919	175° 24.122	19.6
WB_070909_R20-09	36° 55.919	175° 24.122	19.6
Site Farm			
WB_070909_F-00	36° 55.447	175° 25.655	16.4
WB_070909_F-01	36° 55.447	175° 25.655	16.4
WB_070909_F-02	36° 55.447	175° 25.655	16.4
WB_070909_F-03	36° 55.447	175° 25.655	16.4
WB_070909_F-04	36° 55.447	175° 25.655	16.4
WB_070909_F-05	36° 55.447	175° 25.655	16.4
WB_070909_F-06	36° 55.447	175° 25.655	16.4
WB_070909_F-07	36° 55.447	175° 25.655	16.4
WB_070909_F-08	36° 55.447	175° 25.655	16.4
WB_070909_F-09	36° 55.447	175° 25.655	16.4
WB_070909_F-10	36° 55.447	175° 25.655	16.4
WB_070909_F-11	36° 55.447	175° 25.655	16.4
WB_070909_F-12	36° 55.447	175° 25.655	16.4
WB_070909_F-13	36° 55.447	175° 25.655	16.4
WB_070909_F-14	36° 55.447	175° 25.655	16.4
WB_070909_F-15	36° 55.447	175° 25.655	16.4

Table 3 (continued)

Image identifier	Longitude	Latitude	Water depth (m)
Site NavChannel			
WB_070909_NC-00	36° 55.383	175° 25.607	16.8
WB_070909_NC-01	36° 55.383	175° 25.607	16.8
WB_070909_NC-02	36° 55.383	175° 25.607	16.8
WB_070909_NC-03	36° 55.383	175° 25.607	16.8
WB_070909_NC-04	36° 55.383	175° 25.607	16.8
WB_070909_NC-05	36° 55.383	175° 25.607	16.8
WB_070909_NC-06	36° 55.383	175° 25.607	16.8
WB_070909_NC-07	36° 55.383	175° 25.607	16.8
WB_070909_NC-08	36° 55.383	175° 25.607	16.8
WB_070909_NC-09	36° 55.383	175° 25.607	16.8
Site SEAreaA			
WB_070909_E-00	36° 57.080	175° 25.697	13.0
WB_070909_E-01	36° 57.080	175° 25.697	13.0
WB_070909_E-02	36° 57.080	175° 25.697	13.0
WB_070909_E-03	36° 57.080	175° 25.697	13.0
WB_070909_E-04	36° 57.080	175° 25.697	13.0
WB_070909_E-05	36° 57.080	175° 25.697	13.0
WB_070909_E-06	36° 57.080	175° 25.697	13.0
WB_070909_E-07	36° 57.080	175° 25.697	13.0
WB_070909_E-08	36° 57.080	175° 25.697	13.0
WB_070909_E-09	36° 57.080	175° 25.697	13.0
WB_070909_E-10	36° 57.080	175° 25.697	13.0

9. Appendix II: Sample sediment profile images

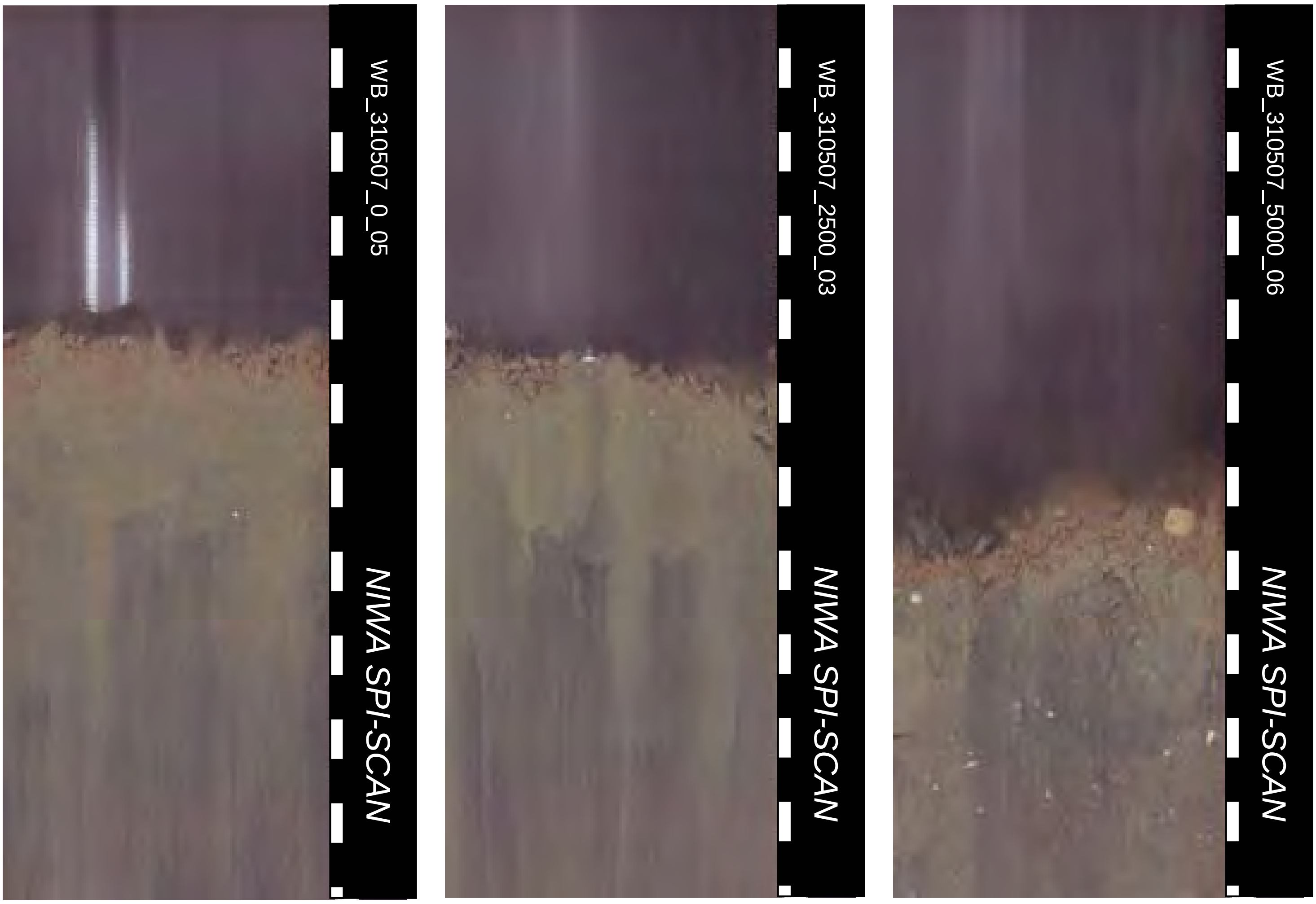


Figure 1: Representative sediment profile image collected at distances 0, 2500 and 5000 m along the transect through Area B. White and black bars on side of image = 1 cm.

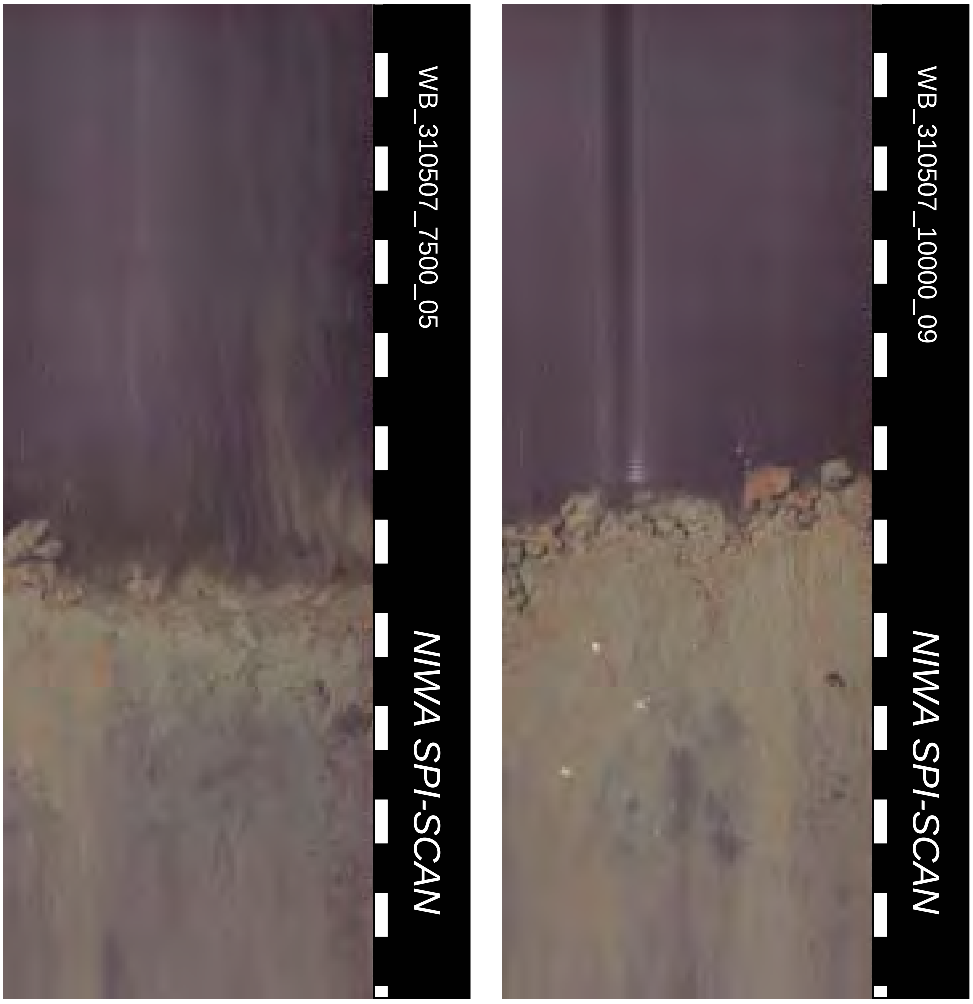


Figure 2: Representative sediment profile image collected at distances 7500 and 10000 m along the transect through Area B. White and black bars on side of image = 1 cm.

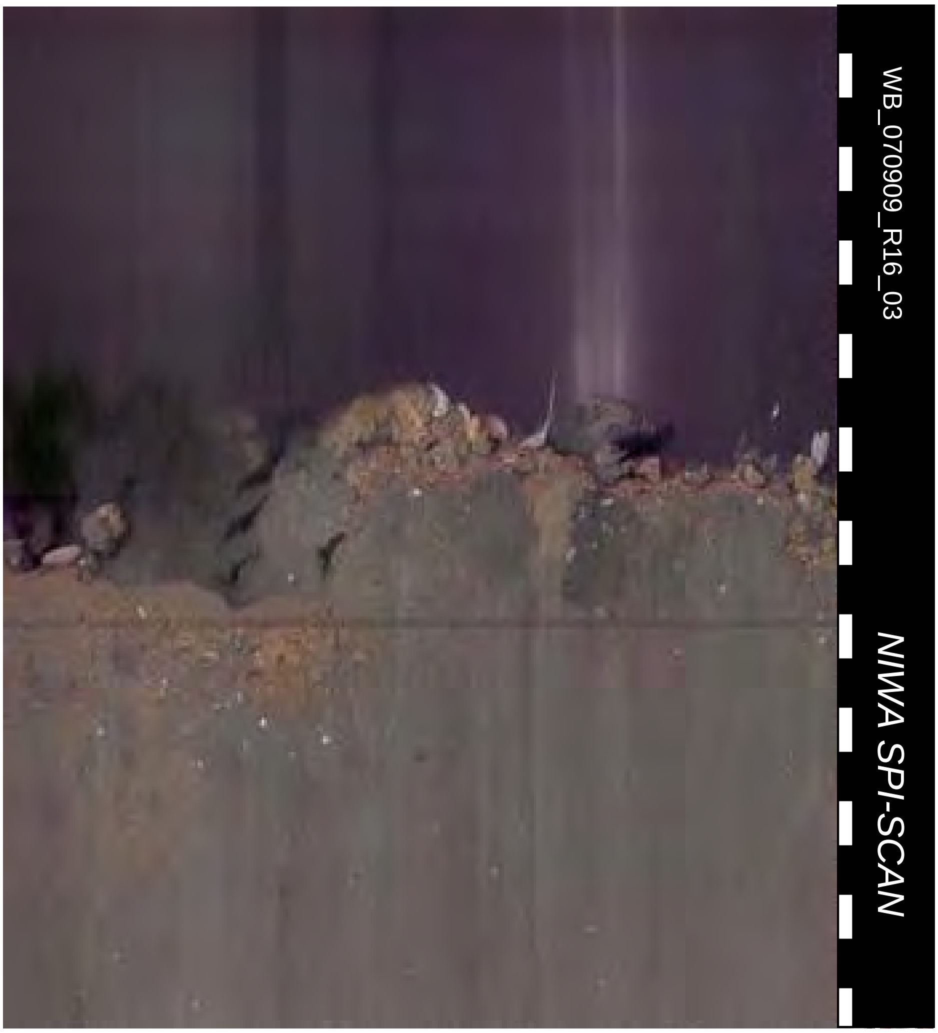


Figure 3: Representative sediment profile image collected at site Ref16. White and black bars on side of image = 1 cm.

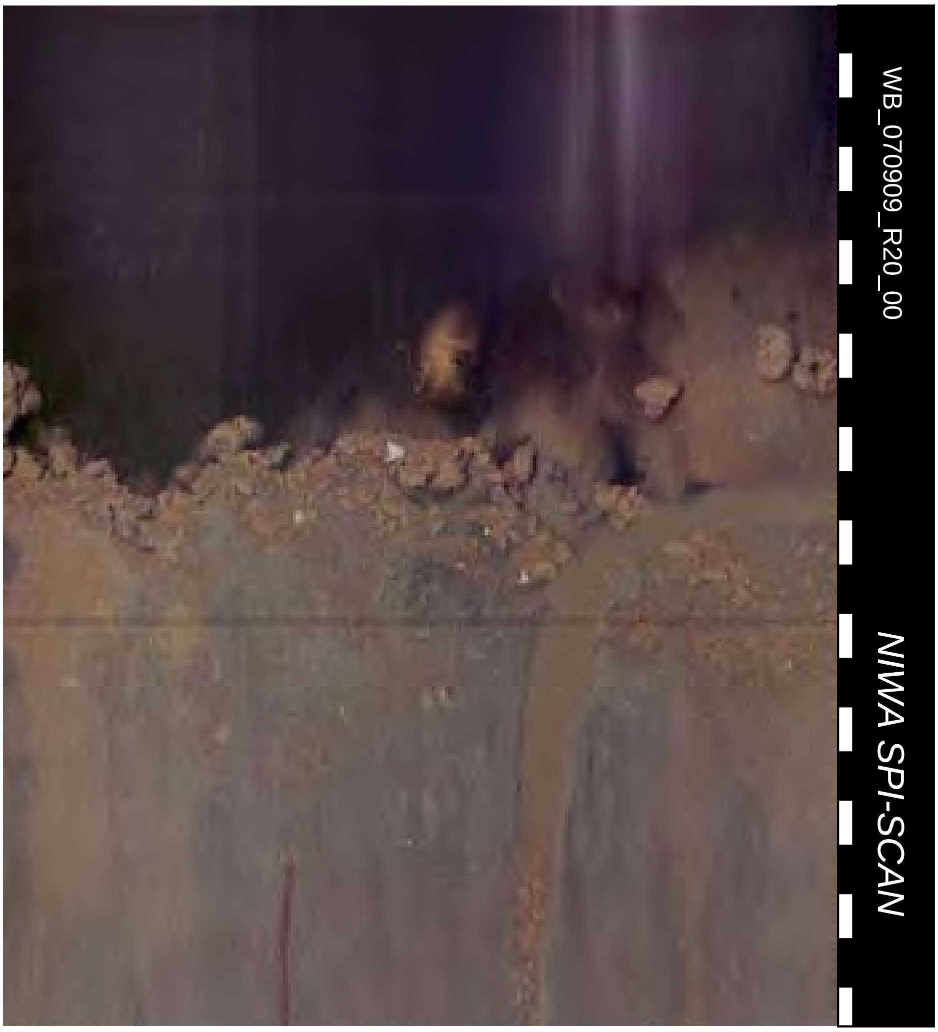


Figure 4: Representative sediment profile image collected at site Ref20. White and black bars on side of image = 1 cm.

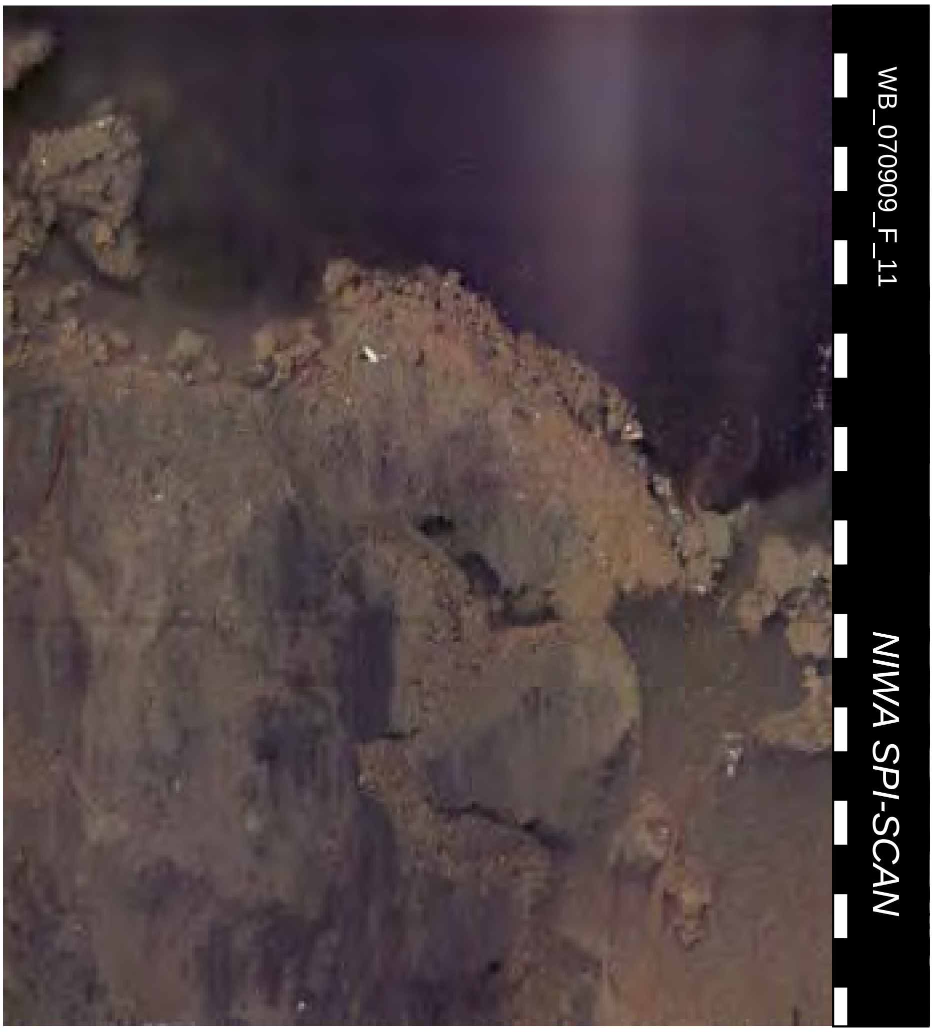


Figure 5: Representative sediment profile image collected at site Farm. White and black bars on side of image = 1 cm.

Figure 6: Representative sediment profile image collected at site NavChannel. White and black bars on side of image = 1 cm.

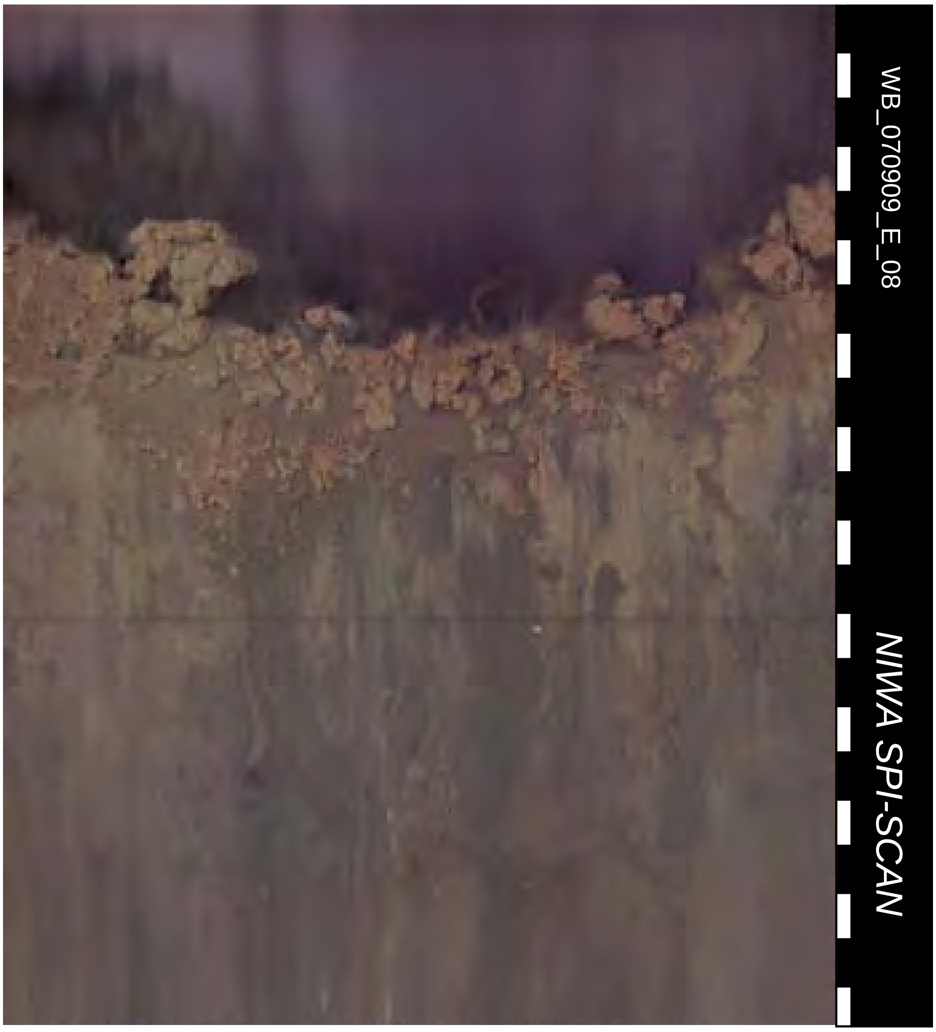


Figure 7: Representative sediment profile image collected at site SEAreaA. White and black bars on side of image = 1 cm.

10. Appendix III: Examples of attributes directly identified in images

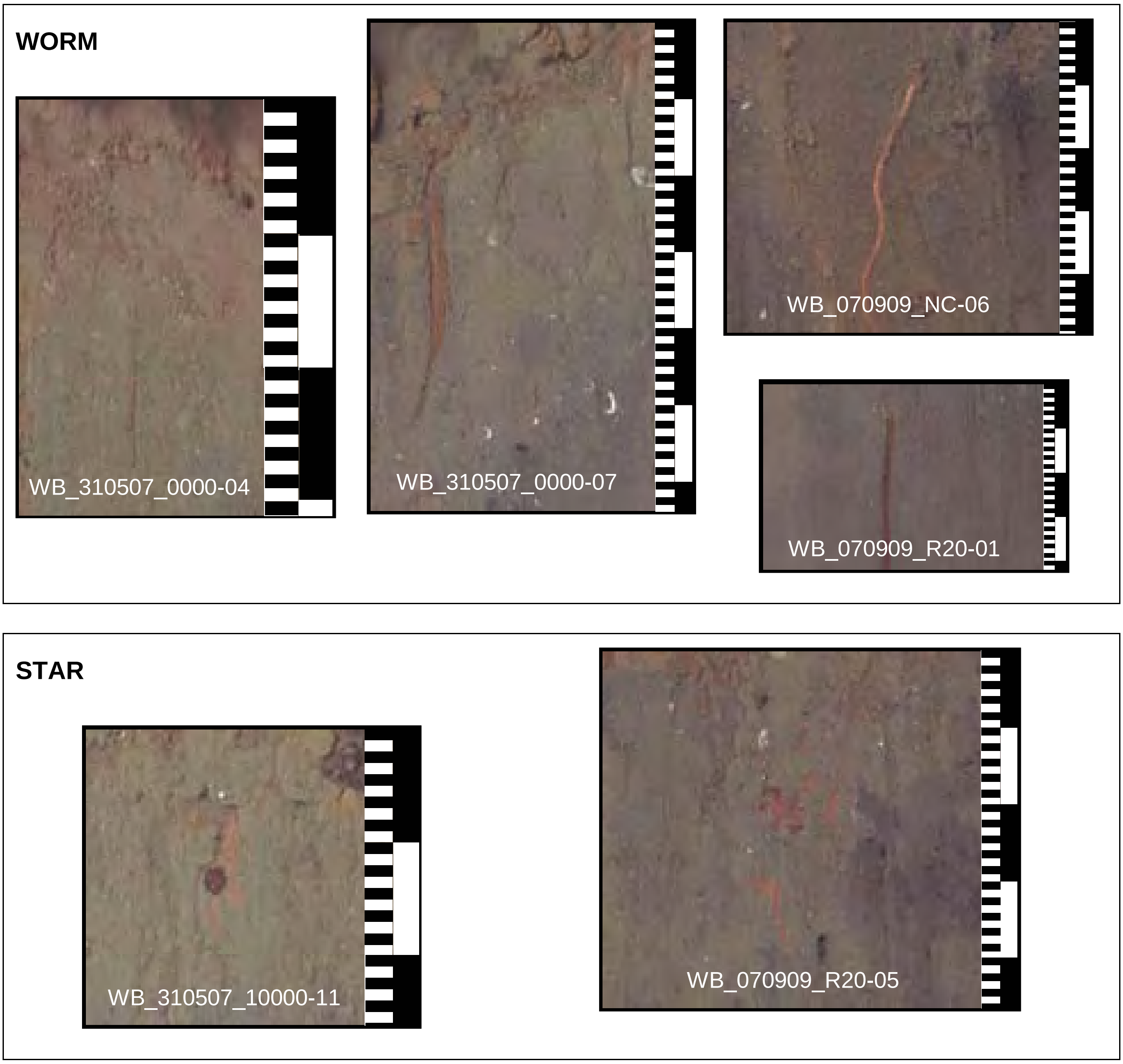


Figure 8: Example annelid worms (WORM) and starfish (STAR) identified in sediment profile images. White and black bars show 1 mm (small bars) and 1 cm (large bars).

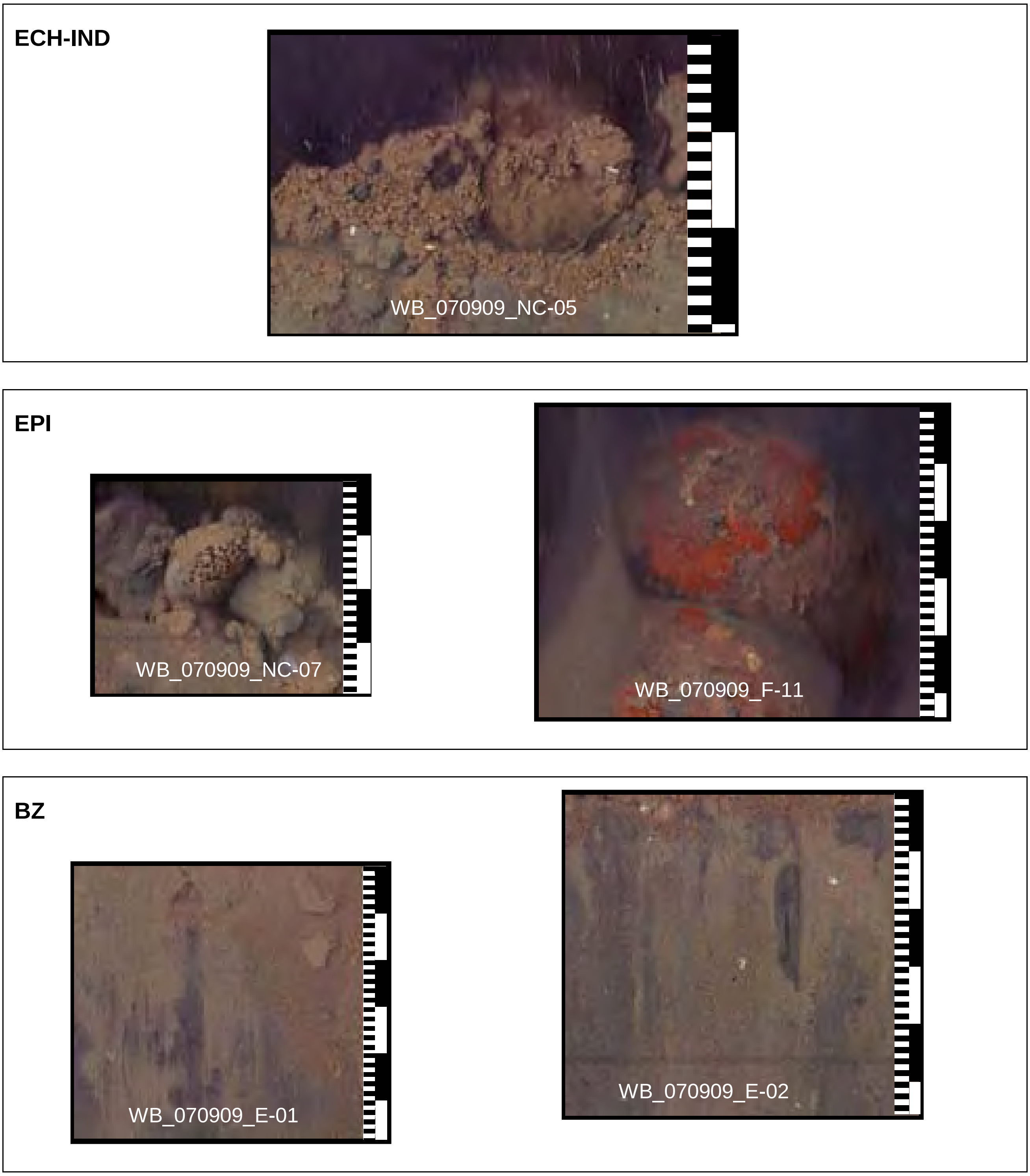


Figure 9: Example *Echinocardium* sp. individual (ECH-IND), other epifauna (EPI) and black and grey patches indicating iron sulphide compounds (BZ) identified in sediment profile images. White and black bars show 1 mm (small bars) and 1 cm (large bars).

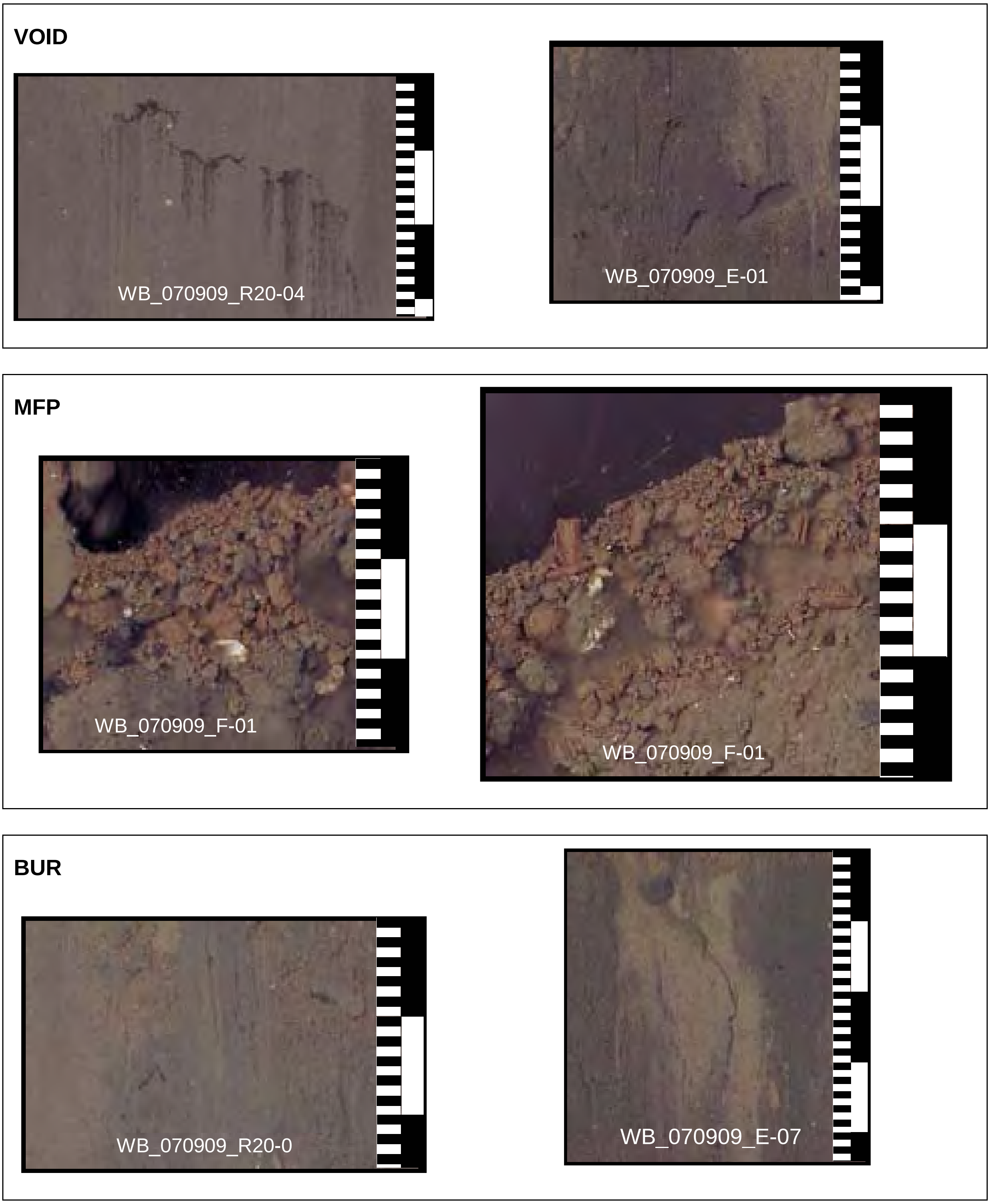


Figure 10: Example voids (VOID), mussel faecal pellets (MFP) and burrows (BUR) identified in sediment profile images. White and black bars show 1 mm (small bars) and 1 cm (large bars).

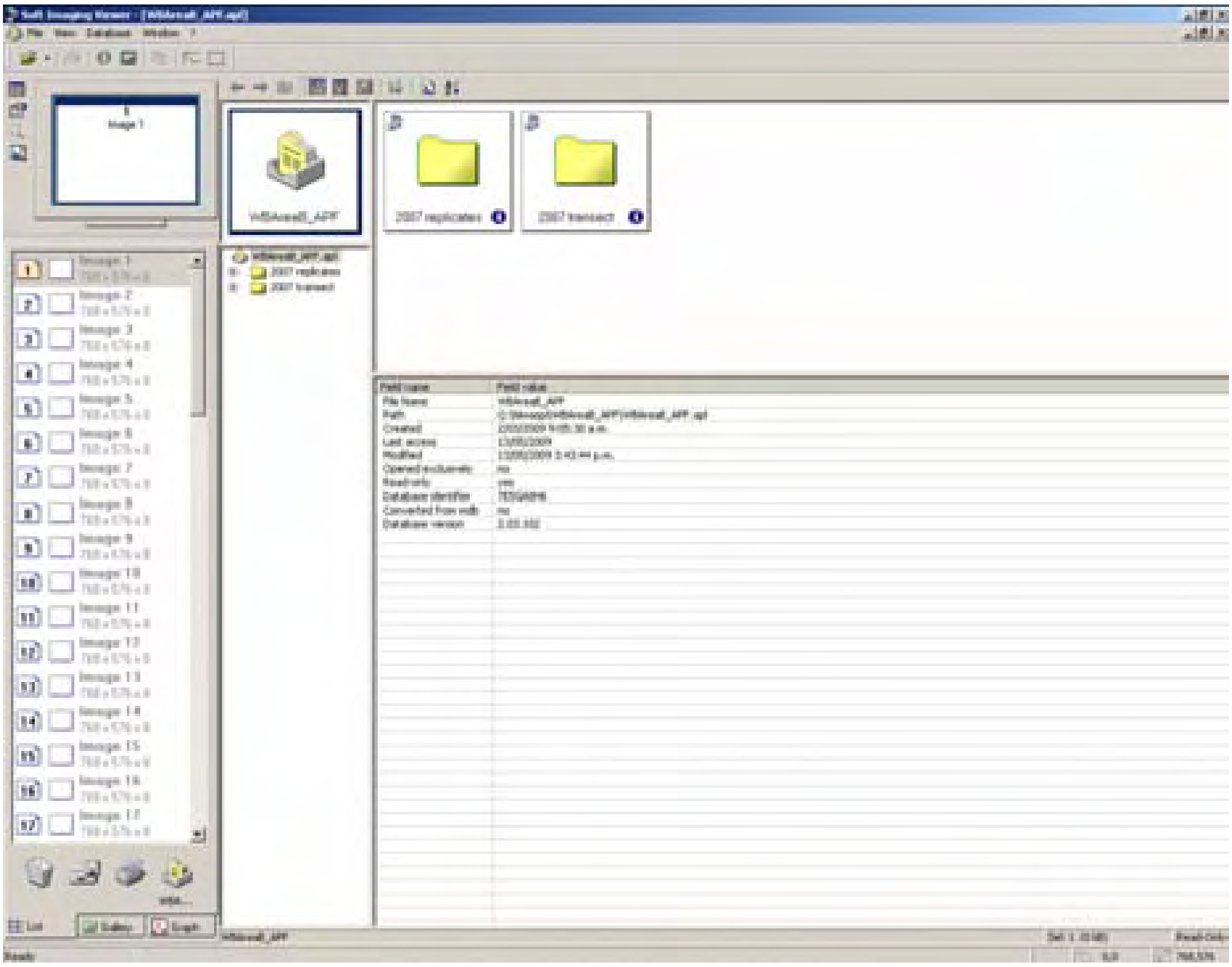
11. Appendix IV: Instructions for use of sediment image database

The sediment image database can be accessed using Soft Imaging Viewer, a free image viewer provided by Soft Imaging System GmbH (www.soft-imaging.net), which is provided on the enclosed DVD.

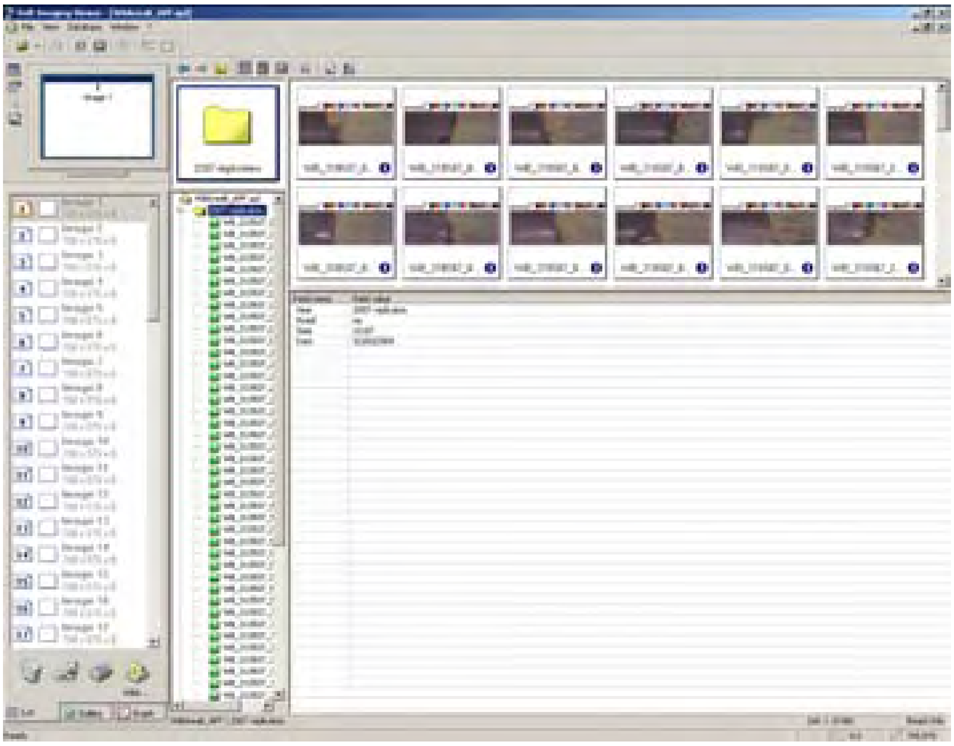
To install the Soft Imaging Viewer double-click Setup_SiViewer.exe. During the installation process select your preference and the STAR (STrucured ARchive) database module.

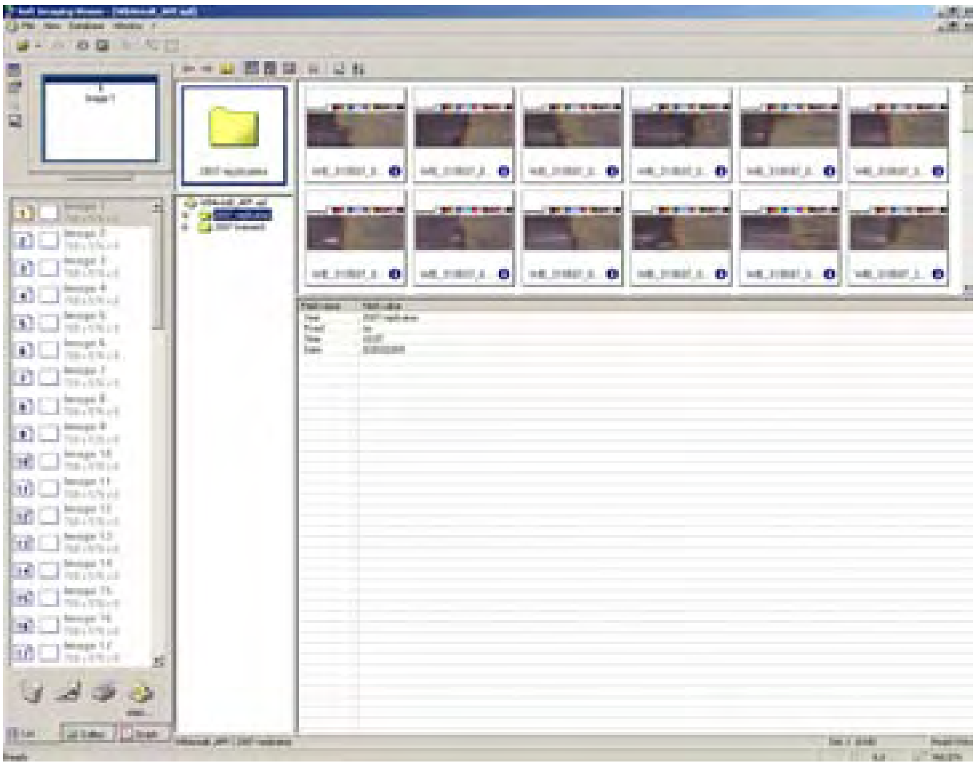
To open the database containing the sediment images taken during the baseline survey in 2007 select *Database* → *Open…*and choose file WBAreaB_APF.apl (images taken in 2009 are saved in database WBAreaA.APF.apl)

View after opening database WBAreaB_APF

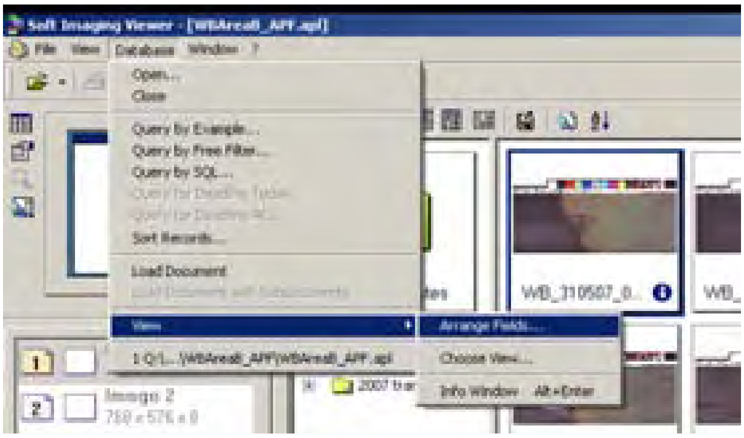


Expand a folder or click on it to bring up thumbnails of the images:

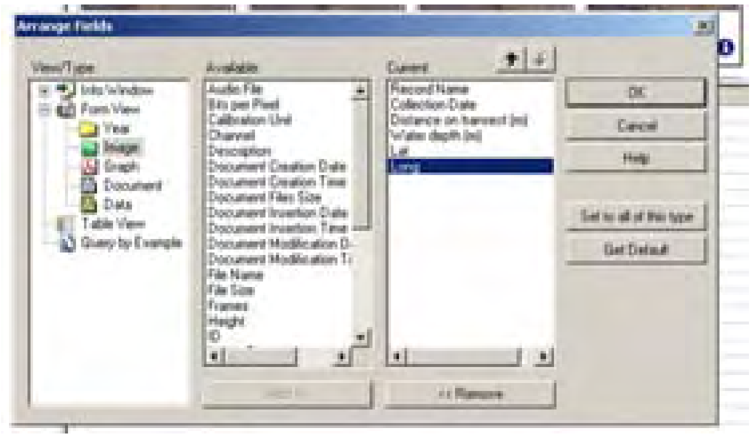




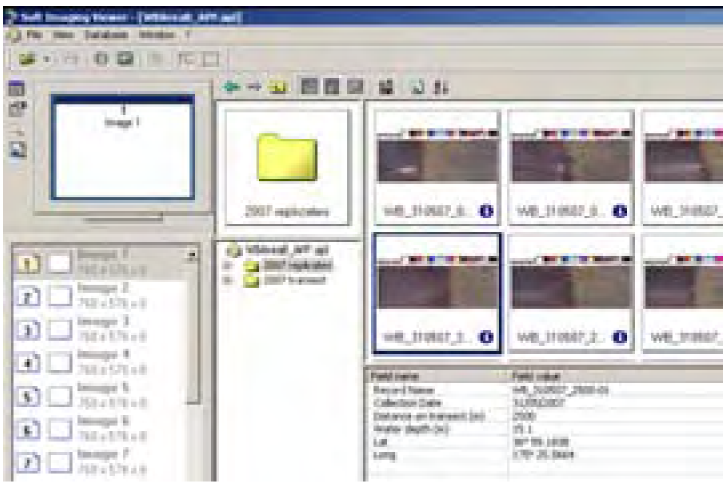
To change the information shown for each image select *View* → *Arrange Fields…*



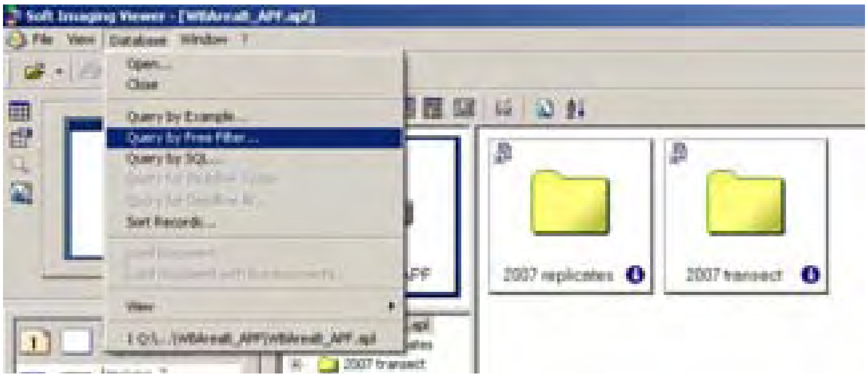
Then select *Image* in the *Form View* folder and select from the available fields those you like to show. You can also remove current fields (they will not be deleted, just won't show anymore).



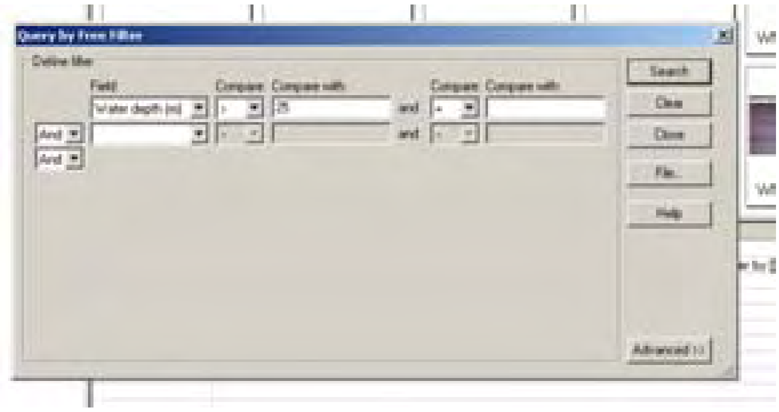
The selected current fields will now show when clicking on an image:



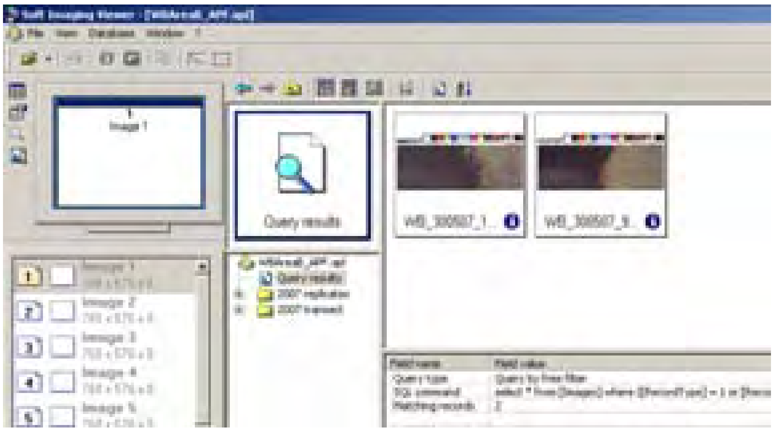
To search for a particular image or images fulfilling particular criteria select *Database → Query by Free Filter…*



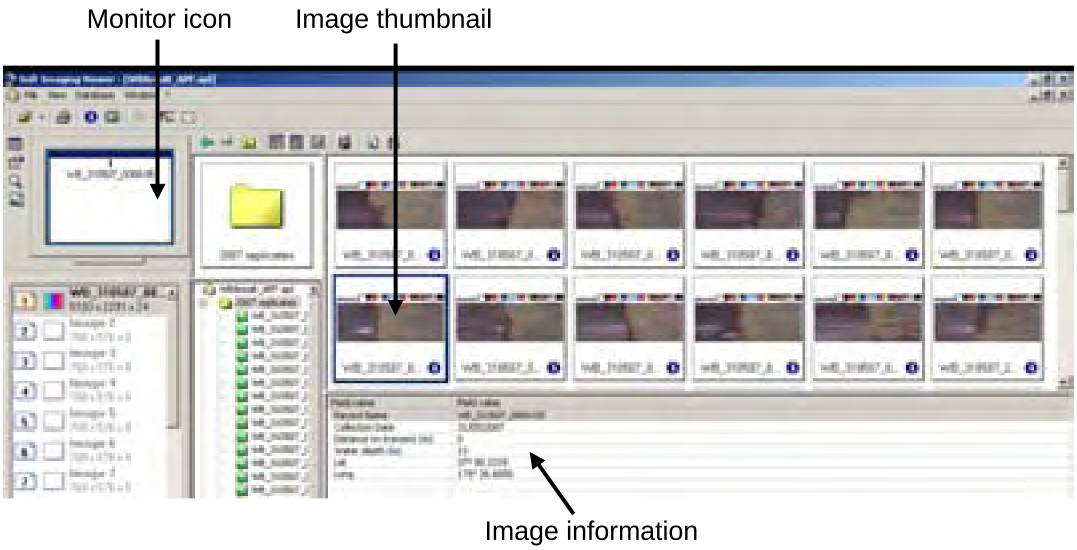
Images can be searched using any combination of stored properties. For example,



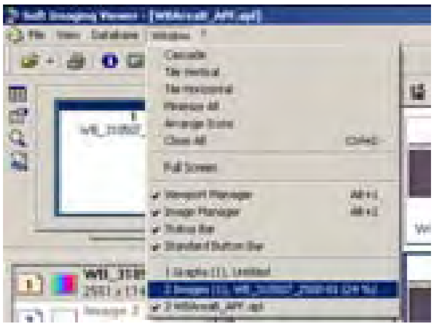
finds the two images taken at sites with water depth greater than 25 m:



View after selecting image (example image WB_310507_0000-05)



To view a specific image double-click on the image. It takes a little while for the image to be read. The image can be viewed by clicking on the monitor icon or by selecting *Window* → *2 Images (1)* …



As images contain a scale bar the overlain scale bar can be removed (Shift F4):