TIERRA SOLUTIONS, INC.

Transmitted Via Electronic Mail & Federal Express

September 29, 2008

U.S. Environmental Protection Agency, Region II
Emergency and Remedial Response Division
290 Broadway, 19th Floor
New York, NY 10007-1866

Attention: Ms. Elizabeth Butler
Remedial Project Manager

Re: Administrative Order on Consent, U.S.E.P.A. Index No. CERCLA-02-2004-2010 for Newark Bay Study Area – *Estimation of the Biologically Active Zone, Newark Bay, New Jersey, Revision 2 (September 2008)*

Dear Ms. Butler:

Tierra Solutions, Inc. [funding and performing, on behalf of Occidental Chemical Corporation, the subject Administrative Order on Consent (Newark Bay AOC)] (Tierra) hereby submits three copies (2 paper, 1 electronic) of the above referenced report. In accordance with the Newark Bay Study Area (NBSA) Remedial Investigation Work Plan (RIWP), Revision 1, September 2005 (Phase I RIWP), Tierra undertook an investigation to determine the depth of the Biologically Active Zone (BAZ), on average, in the NBSA. Results of the investigation were submitted in a November 2005 report entitled *Estimation of Biologically Active Zone, Newark Bay, New Jersey* (BAZ Report). On February 5, 2007, USEPA issued comments to Tierra on the Phase II RIWP, Revision 0; a subset of which specifically related to the BAZ Report. USEPA agreed that certain comments, including those relating to the BAZ Report, would be held for future resolution, putting a priority on those issues that were critical to finalizing and implementing the scope of work in the Phase II RIWP. Following up on and pursuant to the responses included in the Responses to USEPA's Compiled Comments dated March 4, 2008, Tierra revised the BAZ Report and submitted Revision 1 in August 2008 for USEPA's review. Comments received from USEPA regarding Revision 1 are addressed in this most recent revision submitted herein.

Please feel free to contact me if you have any questions regarding this submittal.

Sincerely,
Tierra Solutions, Inc.

Paul J. Bluestein, P.E.
Facility Coordinator
On behalf of Occidental Chemical Corporation
(as successor to Diamond Shamrock Chemicals Company)

Enclosure

cc: Janine MacGregor – NJDEP
Amelia Wagner, Attorney – Newark Bay Study Area
Robert Romagnoli – ARCADIS
Paul Brzozowski – Alternate Facility Coordinator NBSA RI/FS, Tierra Solutions, Inc.

Estimation of the Biologically Active Zone
Newark Bay, New Jersey

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Revision 2
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1. INTRODUCTION

Bioturbation is the mixing of sediment and porewater that results primarily from feeding and movement of infauna and, to a lesser extent, from epifauna and megafauna. Except for areas of high sedimentation or areas devoid of infauna (such as anoxic basins), it is bioturbation that mixes sediment and erases evidence of physical stratigraphy in surficial sediment (Fager 1964, Johnson 1974). Bioturbation by infauna mixes sediment vertically and horizontally at various rates depending on a combination of factors that include sediment grain size, organic content/quality, community structure, and season (Rhoads 1974, Rhoads and Boyer 1982, Dauwe et al. 1998, François et al. 2002). Given that most persistent pollutants that enter estuaries and coastal bays are particle reactive and bind to sediment particles (Olsen et al. 1982), the level of bioturbation plays a key role in distributing pollutants within the biologically mixed layer or biologically active zone (BAZ), (e.g., Stull et al. 1996, Sherwood et al. 2002, McMurtry et al. 1985).

The BAZ is defined to extend from the sediment surface down into the sediment to the maximum depth of the subsurface biogenic structure and includes both the biodiffusive and bioadvective components of bioturbation (Guinasso and Schink 1975). The primary biogenic structures used to define the BAZ are burrows and feeding voids. Infauna act as either biodiffusors essentially randomly mixing sediment by free burrowing, in particular small-bodied surface dwelling species, or bioadvectors form more permanently occupied burrows that can penetrate deeper into the sediment. As bioadvectors, infauna can convey sediment either upward or downward. Upward conveyors produce feeding voids (water filled voids within the sediment) while downward conveyors can transport surficial sediment to depth. Burrows, when connected to the sediment surface, can also act as conduits for bioadvection of surficial sediment to the depth of the burrow floor even after abandonment of the burrow (Aller and Aller 1998, Rosenberg 2001, François et al. 2002).

Many of the biogenic activities of infauna that lead to bioturbation of sediment, such as subsurface feeding, surface defecation and burrowing can be observed *in situ* with the use of a sediment profile camera. The sediment profile camera was developed by Rhoads and Cande

(1971) to investigate processes structuring the sediment-water interface and as a means of obtaining *in situ* data on benthic habitat conditions. The technology of remote ecological monitoring of the sea floor (REMOTS, Rhoads and Germano 1982) has allowed for the development of a better understanding of the complexity of sediment dynamics from biological and physical points of view (for examples, see: Nilsson and Rosenberg 2000, Diaz and Cutter 2001, Rosenberg et al. 2001, Solan et al. 2004).

Data from sediment profile images (SPI) can be used to estimate the BAZ by measuring the depth within the sediment to which biogenic structures extend. From SPI images collected on the continental slope off North Carolina in an area of high infaunal activity, Diaz et al. (1994) estimated the biologically mixed layer depth, analogous to the BAZ, to be 6 to 18 cm. These estimates were comparable to mixed layer depths derived from X-ray images of sediment cores (6 to 20 cm, Diaz et al. 1994) and ^{210}Pb isotope profiles (4 to 12 cm, DeMaster et al. 1994). Solan et al. (2004) also used SPI images to estimate the effect of loss of functional biodiversity on the biogenic mixing depth, also similar to the BAZ in this study.

This study is part of a larger remedial investigation/feasibility study (RI/FS) for Newark Bay, NJ being conducted by Tierra Solutions, Inc. pursuant to an administrative order on consent with the U.S. Environmental Protection Agency. The work was conducted as part of the Phase I Sediment Sampling and Source Identification Program under the Newark Bay Study Area Remedial Investigation Work Plan (Tierra 2005). The objective of this survey was to estimate the depth of the BAZ at a series of stations representing the different geomorphic units in Newark Bay being sampled under the RI/FS.

2. METHODS

At each station, a digital Hulcher sediment profile camera system was deployed five times and three grab samples were collected. A total of 14 stations were sampled (Figure 1). The location of each deployment of the camera system and grab was marked using a Hypack MAX navigation system. In addition, the station and time of each camera deployment and grab sample was recorded by hand in the field log. Stations were divided into three geomorphic units; intertidal (SED002, SED003, SED038, SED058, and SED065), shallow subtidal (SED014, SED022, SED041, SED045, SED056, and SED065), and navigation channel (SED004, SED043, and SED063).

The digital profile camera captured a 5.2-megapixel image using a Minolta Dimage-7i camera. The camera was set to ISO 200, white balance to flash color temperature, contrast to normal, saturation to normal, maximum image size of 2560 X 1920 pixels, and saved using super-fine jpg compression. Images were stored in the camera on a 1-gigabyte IBM microdrive. A surface video camera was also mounted on the profile camera frame to monitor prism penetration and provide information on surface sediment. The video feed from the surface and profile cameras were sent to the surface vessel; this allowed monitoring of the Hulcher camera operation and image capture in real-time. The camera was triggered from the surface about 1-sec after bottom contact and after the prism stopped penetrating the sediment. Depending on sediment compaction, 75 to 125 pounds of lead were added to the camera frame to achieve target penetration at all stations. More detail on sediment profile camera operation can be found in Rhoads and Cande (1971). As the SPI were being collected, they were stored on electronic media in the camera, downloaded onto a laptop computer, and transferred to CD-ROM for more permanent storage.

A 0.1 m2 van Veen grab was used to collect sediment for supplemental examination of biogenic activity. At each station three grabs were collected and processed in the field. From each grab a 2.5 cm diameter x 10 cm long core was taken from near the center of the grab and used to estimate the apparent color redox potential discontinuity (aRPD) layer depth, and to determine sediment grain size. The grab contents were then placed on a wash table, dissected, and visually examined for biogenic structures. The sediment was then divided and part washed through a 2 mm and part through a 4 mm sieve to determine if large deep burrowing fauna were present. Notes on each grab's fauna, grain size, and biogenic structures were recorded in a field notebook. All relevant field notes regarding the physical and biological observations made as part of this investigation for the identification and characterization of the BAZ are included in the tables and Appendix A of this report.

2.1. Image Analysis

All SPI were evaluated visually with data of all features recorded in a pre-formatted spreadsheet file. The least disturbed image, usually the last in the series, was digitally processed to enhance contrast and color for determination of the aRPD layer depth with Adobe PhotoShop®. Data from each image were sequentially saved to a spreadsheet file for later analysis. Details of how these data were obtained can be found in Diaz and Schaffner (1988) and Rhoads and Germano (1986). A description of each parameter measured and evaluated follows.

Prism Penetration - This parameter provided a geotechnical estimate of sediment compaction with the profile camera prism acting as a dead weight penetrometer. The further the prism entered into the sediment, the softer the sediment and likely the higher the water content. Penetration was measured as the distance the sediment moved up the 23 cm length of the faceplate. At the stations with the softest sediment, the weight of the profile camera was set at 50 to 75 lbs to avoid over penetration of the prism. For all other stations the weight was set at 125 lbs. The difference between 50 and 125 lbs in soft sediment could result in a difference of 10 to 15 cm of penetration.

Surface Relief - Surface relief or boundary roughness was measured as the difference between the maximum and minimum distance the prism penetrated. This parameter also estimated small-scale bed roughness, on the order of the prism faceplate width (15.5 cm), which is an important parameter for predicting sediment transport and in determining processes that dominate surface sediment (Rhoads et al. 1978). The origin of bed roughness can be determined from visual analysis of the images. In physically dominated habitats, features such as bed forms and sediment granularity, cause bed roughness. In biologically dominated habitats, bed roughness is a result of biogenic activity such as tube structures, defecation mounds, or feeding pits.

Apparent Color Redox Potential Discontinuity (aRPD) Layer - This parameter is an important estimator of benthic habitat conditions, which relates directly to the quality of the habitat (Rhoads and Germano 1986, Diaz and Schaffner 1988, Nilsson and Rosenberg 2000). The aRPD provides an estimate of the depth to which sediment appears to be oxidized. The term "apparent" is used in describing this parameter because no actual measurement is made of the redox potential. It is assumed that given the complexities of iron and sulfate reduction-oxidation chemistry, the reddish-brown sediment color tones (Lyle 1983, Haese et al. 1998, Rosenberg et al. 2001) indicate sediment is in an oxidative geochemical state, or at least are not intensely reducing. This is in accordance with the classical concept of aRPD layer depth, which associates it with sediment color (Fenchel 1969, Vismann 1991).

Estimation of the aRPD was done in a Red-Green-Blue (RGB) Color space. Prior to estimating the aRPD, each image is histogram equalized and trimmed up to 5% using the image program Adobe PhotoShop® to enhance contrast and the brown-reddish color associated with oxidized sediment. The area of the user-defined aRPD layer was counted and converted to linear measurement by dividing by the width of the image used in the analysis.

Sediment Grain Size - Grain size is an important parameter for determining the nature of the physical forces acting on the bottom and is one of the major factors in determining benthic community composition (Rhoads 1974, Snelgrove and Butman 1994). The sediment type descriptors used for image analysis follow the Wentworth classification as described in Folk (1974) and represent the major modal class for each image. Maximum and minimum grain sizes were also estimated. Grain size was determined by comparison of collected images with a set of standard images for which mean grain size had been determined in the laboratory. For sediment larger than gravel, individual grains were measured. Table 1 is provided as a means of comparing Phi scale sizes corresponding to sediment grain size descriptors derived from SPI.

Surface Features and Bed Roughness - These parameters include a wide variety of physical (such as bed forms) and biological features (such as biogenic mounds, shell, or tubes). The presence of certain surface features is indicative of the overall nature of the processes acting on surface sediment. For example, bed forms are always associated with physically dominated habitats, whereas the presence of worm tubes or feeding pits would be indicative of a more biologically accommodating habitat (Rhoads and Germano 1986, Diaz and Schaffner 1988). Surface features were visually evaluated from each image and compiled by type and frequency of occurrence.

Subsurface Features - Subsurface features include a wide variety of structures (such as infaunal organisms, burrows, water filled voids, gas voids, or sediment layering) that reveal the importance of physical and biological processes influencing the bottom. For example, layered sediment or homogeneous sediment is generally dominated by physical processes while sediment with burrows, infaunal feeding voids, and/or visible infaunal organisms is generally dominated by biological processes (Rhoads and Germano 1986, Diaz and Schaffner 1988, Nilsson and Rosenberg 2000). Active burrows can be identified in the images by the oxidation state of their walls. Typically the walls of a burrow, and also the lumen of feeding voids, become oxidized with time as the fauna actively or passively pump oxygenated water (Aller 1982). This oxidation results in browner colored sediment as minerals (primarily those of iron and manganese) change oxidation state. After the fauna abandon burrows and voids the sediment lining these structures typically become reduced within hours or days and change in color toward grayish tones (Diaz and Cutter 2001). Subsurface features were visually evaluated from each image and compiled by type and frequency of occurrence.

Successional Stage - Sediment profile data have also been used to estimate the successional stage of the fauna (Rhoads and Germano 1986). Characteristics associated with pioneering or colonizing (Stage I) assemblages (in the sense of Odum, 1969), such as dense aggregations of small polychaete tubes at the surface and shallow aRPD layers, are easily seen in SPI. Advanced or equilibrium (Stage III) assemblages also have characteristics that are easily seen in SPI, such as deep aRPD layers and subsurface feeding voids. Stage II is intermediate to Stages I and III, and has characteristics of both (Rosenberg 2001). A set of SPI parameters was evaluated to estimate successional stage with the generalized associations described in Table 2.

Organism Sediment Index - Rhoads and Germano (1986) developed the multi-parameter organism-sediment index (OSI), from data provided by SPI, to characterize benthic habitat quality in soft-bottom estuarine and coastal embayments. The OSI defines quality of benthic habitats by evaluating the depth of the aRPD, successional stage of macrofaunal organisms, the presence of gas bubbles in the sediment (an indication of high rates of methanogenesis that are associated with high carbon inputs to the sediment), and visual signs of the presence of low dissolved oxygen conditions (sulfide covered tubes, anaerobic sediment at the interface, bacterial mats) at the sediment-water interface. The parameter ranges and scores that are used in the calculation of the OSI are listed in Table 3 (taken from Rhoads and Germano 1986). Stage I on III refers to the presence of pioneering Stage I species present on or near the sediment surface and equilibrium Stage III species present below the sediment surface. Similarly Stage II on III is the presence of intermediate successional stage species at the surface with equilibrium species at depth in the sediment. The OSI ranges from -10 for poorest quality habitats to +11 for highest quality habitats. For example, replicate 3 from subtidal station SED041 had an OSI of 6, calculated as follows: aRPD layer depth of 1.9 cm was scored as 3, estimated successional stage was I-III and scored as 5, gas voids were present and scored as –2, dissolved oxygen did not appear to be low and thus did not contribute to the scoring. The three parts were summed to get the OSI (3 + 5 – 2 = 6).

The OSI has been used to map disturbance gradients (Valente et al. 1992) and to follow ecosystem recovery after disturbance abatement (Rhoads and Germano 1986, Day et al. 1988, Revelas et al. 1987). The formulation of the OSI and contribution of each component are scaled to reflect the increasing importance of bioturbation, sediment mixing mediated by organisms, and other biogenic activity, such as structure building, in defining good benthic habitat quality. For estuarine and coastal bay benthic habitats in the northeastern United States, OSI values >6 indicate good habitat conditions and are generally associated with bottoms that are not heavily influenced by stress, either physical or anthropogenic (Rhoads and Germano 1986).

Biologically Active Zone (BAZ) - The biologically active zone (BAZ) was divided into two zones. An upper zone that extended from the sediment surface to the average depth of active burrow structures and a lower zone that extended from the average depth of active burrows to the maximum depth of active feeding voids. The BAZ was inferred from the depth to which various biogenic structures occurred in the SPI.

Active burrows were defined as being surrounded by brownish sediment and active voids were defined as containing what appeared to be brownish sediment. When feeding voids become inactive and the sediment returns to a reduced state, they are considered to be anaerobic voids and relic features of biogenic activity. Thus the depth of anaerobic voids would represent the maximum depth to which organisms would influence sediment mixing.

The upper, lower, and total BAZ depths were quantified in each replicate sample from each station as possible from the SPI data (see Appendix A). In most instances, the total BAZ represents the sum of the upper and lower BAZ. For replicate SPI images where the average depth of active burrows was deeper than active feeding voids, the lower BAZ layer was considered to be undefined. In these cases, the total BAZ was not calculated. At some stations/replicates, the total BAZ could be seen in the SPI images, but it was not possible to identify the break between the upper and lower BAZ. In these cases, only the total BAZ was estimated. For instance, at station SED002 replicate 1, the total BAZ could be estimated from the maximum oxic void depth but not the thickness of upper and lower layers because there were no burrows obvious in the image. For this replicate, only the total BAZ was reported.

The replicate BAZ estimates were averaged by zone to produce the estimate for each station. The station BAZ estimates were than averaged to produce estimates for the three geomorphic units sampled (intertidal, subtidal, and channel). For the intertidal BAZ estimates, station SED004 was not included because the lower BAZ zone could not be estimated for any of the five SPI replicates.

2.2. Data Reduction and Statistics

To summarize the data reduction performed on the SPI data, quantitative parameters were averaged from the replicate images (prism penetration, surface relief, maximum aRPD depth, average aRPD depth, and OSI). For present/absent parameters (bed forms, shell hash, biogenic pits/mounds, fluff layer, detritus, tubes >1mm, macroalgae, mud snails), if one replicate had a present value (+), then the station summary was given the value of present. For example, if only one replicate had shell hash, then the summary for that station would be shell hash present. For categorical parameters (grain size, bed roughness, successional stage, amphipod tubes, and worm tubes), the median value of the five replicate images was assigned to a station.

Analysis of variance or t-Test was used to test for differences between category levels of the qualitative parameters and between stations and geomorphic units for the quantitative parameters. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with Bartlett's test (Zar 1999). Data were $\log_{10}(x + 1)$ transformed when necessary or Welch Analysis of Variance (ANOVA), which allows for unequal variances, was used to test for differences. Odds were tested with the Fisher Exact test (Agresti 1990).

3. RESULTS AND DISCUSSION

3.1. Overview

On 4, 5, and 6 October 2005, SPI and supplemental grab sample data were collected at 14 stations within Newark Bay (Figure 1). Location and depth at time of sampling for each station and replicates are listed in Table 4. The locations of SPI replicates 1 and 2 at station SED043 were not recorded. A summary of the SPI data is presented in Table 5. Detailed data for each of the SPI replicates are provided in Appendix A. Notes on the grab samples can be found in Table 6. SPI image files are presented in CD-ROM Appendix B. Mosaics of the SPI by geomorphic unit are shown in Figures 2, 3, 4, and 5. The location of burrows, oxic voids, anaerobic voids, gas voids, and worms is marked on these figure with a B, V, A, G, and W, respectively, followed by a number which corresponds to the order of these features in Appendix A. For example, B3 in image SED022 replicate 5 is the third burrow estimated to be 4.1 cm long. The width of all images is 15.5 cm and tick-marks on the sides of the images are 5.0 cm intervals from the bottom of the prism faceplate. Throughout the text, example stations are given in parentheses.

3.2. Physical Processes and Surface Sediment

For the intertidal unit, physical processes dominated sediment surfaces at four of the five stations (Table 5). Bed forms were observed at the sandy intertidal stations SED030 and SED038. At intertidal station SED058, the sediment surfaces appeared to be dominated by a combination of physical and biological processes with small pits and mounds that appeared to be from faunal feeding activity. Biogenic pits and mounds are common features in marine soft-sediment (Zajac 2004). Sediment surfaces at all the channel and subtidal stations appeared to be a combination of physical and biological processes, except subtidal station SED060 that was primarily physically dominated. Surface relief, primarily in the form of small feeding pits and mounds at muddy stations and bed forms at sandy stations, was not significantly different between geomorphic units (intertidal, subtidal, or channel, ANOVA, df = 2, $F = 0.16$, $p = 0.852$). Data from grab samples indicated that the intertidal stations had coarser sediment and more detritus than subtidal and channel stations (Table 6). Overall, the processes structuring the surface sediment in the grabs appeared to be similar to the SPI with most of the grabs showing signs of both physical and biological processes. Grabs for the intertidal stations also appeared to be mostly physically dominated and had fewer biogenic structures on the sediment surface (Table 6).

While there was some variation in sediment grain size between geomorphic units, there was no significant difference in prism penetration (ANOVA, df = 2, F = 1.48, p = 0.270). The range in penetration was greatest for the intertidal stations (6.7 to 18.7 cm) followed by subtidal (12.7 to 19.2 cm) and channel stations (11.9 to 17.0 cm). The sandy intertidal stations (SED003 and SED038) did have the lowest penetration of all stations, but this was offset by deep penetration at the muddy intertidal stations (SED002 and SED058, Figure 2). The majority of stations were composed of fine mixed sediment (fine-sand-silt-clay) (Table 5, Figures 3, 4, and 5). Two of the intertidal stations were also composed of fine-sand-silt-clay. Pure clayey sediment appeared to be present at two stations in the form of reddish clay balls (SED041 and SED043).

3.3. Apparent Color Redox Potential Discontinuity (aRPD) Layer Depth

The aRPD layer depth is a measure of the depth to which sediment geochemical processes are primarily oxidative. The thickness of the aRPD layer has long been associated with the level of bioturbation and overall benthic habitat quality, in particular with regards to organic enrichment gradients (Pearson and Rosenberg 1978) with habitat quality positively correlated with aRPD layer depth (Rhoads and Germano 1986, Nilsson and Rosenberg 2000). Below the aRPD layer, geochemical processes are primarily anaerobic or reducing (Fenchel and Riedl 1970). In sandy porous sediment, deep aRPD layers are primarily a function of porewater circulation driven by current or wave action that pumps oxygenated water in the sediment, such as the medium-sand intertidal station SED003 where the aRPD layer depth was 2.5 cm and biogenic activity appeared to be minimal. At the other sandy intertidal station (SED038), the aRPD layer was deeper at 5.5 cm and there was more biogenic activity in the fine-medium-sand sediment (Table 5).

In finer sediment (i.e., that with a significant silt and clay component), physical diffusion limits oxygen penetration to <1 cm (Jørgensen and Revsbech, 1985). There were no examples of diffusion-limited aRPD layers at any of the Newark Bay stations (Table 5). The shallowest aRPD layer depth was found at the silty-clay subtidal station SED041 where the average aRPD was 1.9 cm (SD = 0.3 cm). At SED041, infaunal and burrow structures projected small cylinders of oxidized sediment to a maximum of 6.6 cm in replicate image 2 and oxic feeding voids to 11.0 cm in replicate image 3 (Appendix A). The halo of oxidized sediment around these types of biogenic structures greatly increases the total volume of oxidized sediment and surface area of the aRPD layer (Aller and Aller, 1998). Burrows convoluted the plane of the aRPD layer and projected oxidized sediment below the average aRPD layer depth at all 14 stations (Table 5). Average aRPD layer depths were not significantly different between the three geomorphic units sampled (ANOVA, df = 2, F = 1.51, p = 0.263). Similarly, the aRPD layer depths estimated from the grab samples were not significantly different between intertidal, subtidal, or channel stations (Welsh ANOVA, df = 2, F = 4.20, p = 0.592). When the aRPD between the SPI images and sediment cores from the grab samples were compared, the two estimates were significantly correlated (Pearson-r, N =13, r = 0.80, p = 0.001, Figure 6). Station SED002 was not included because the aRPD could not be estimated from any of the three grab samples. The SPI estimated aRPD layers (mean = 3.1 cm) were also significantly deeper than the grab estimated aRPD layers (mean = 2.6 cm) (Paired t-test, df = 12, t = 2.53, p = 0.026). Overall, the SPI estimated aRPD layer depth tended to be deeper than the grab estimate (Figure 6).

Additional field observations of surface sediment characteristics made while collecting sediment cores at or near the BAZ sampling locations during Newark Bay RI Phase I chemistry/radiological sampling program (conducted in the fall of 2005) are provided in Table 7. These observations, particularly those in the top 0.5 ft (i.e., approximately 15 cm) of the cores, confirm the general conclusions regarding coloration, grain size, and biological activity in the BAZ of Newark Bay sediment. Organic matter and shell fragments observed in the surface sediment are consistent with the findings of oxidized/aerobic conditions and biological activity. Apparent color changes below about 0.5 ft confirm a change from oxidized to reduced conditions; this is consistent with the definition of the aRPD and BAZ per the SPI and grab sample data.

The most important factors regulating aRPDs appear to be grain size and porewater flow at stations SED002 and SED038, both functions of physical processes, and sediment mixing or bioturbation by infauna at the other 12 stations, both functions of biological processes. These and other factors such as organic content, season and water quality are all known to regulate the aRPD layer depth (Rhoads and Boyer, 1982; Jones and Jago, 1993; Diaz and Rosenberg, 1995; Aller and Aller, 1998).

3.4. Successional Stage and Biogenic Activity

The successional stage estimated for stations SED002 and SED003, both intertidal, was Stage I, indicating that benthic communities were composed mainly of pioneering species, such as small tube-building spionid polychaetes associated with the early stages of community development. The other 12 stations had evidence of Stage I fauna but were dominated by what appeared to be more well developed Stage III equilibrium species (Table 5). These Stage I-III stations were characterized by head-down deposit feeding polychaetes, such as *Pectinaria gouldii* and maldanids, which formed subsurface feeding voids (Tables 5 and 6). *Pectinaria gouldii* (ice-cream cone worm) was the most abundant large polychaete found in the grab samples and occurred at 9 of the 14 stations and was most abundant at the deeper channel stations (SED004, SED043, and SED063). Maldanids were observed at one subtidal station (SED014). What appeared to be active feeding voids were observed at all stations except SED003, which was intertidal and had medium-sand sediment that would not typically support the formation of feeding voids. Shallow (<5 cm) oxic voids were likely created by the polychaete *Pectinaria gouldii* that constructs a sand-grained tube and subsurface deposit feeds. Individuals up to 5 cm long were observed in the grab samples from these three stations.

Evidence of intermediate successional Stage II species, such as ampeliscid amphipods were observed in the grab samples at intertidal station SED058, subtidal station SED060, and two channel stations (SED043 and SED063). *Ampelisca* spp. can occur at high densities forming an armoring mat on the sediment surface that greatly increases sediment stability (Rhoads and Young 1970, Hunt 2005). At station SED058 the abundance of ampeliscid tubes approached tube mat densities in both the grab and SPI images (Tables 5 and 6). Other species in the grab samples that are considered to be representative of Stage II or III fauna were the deep burrowing bivalves *Macoma balthica* and *Mya arenaria* and the burrowing isopod *Cyathura polita*. Both bivalves are long-lived, large organisms that form vertical burrows in the sediment. *Macoma balthica* occurred at 8 of the 14 stations and was the most abundant bivalve observed in the grab samples. *Mya arenaria* occurred at 4 stations in low densities. Neither of these two bivalves occurred at the channel stations. The only bivalve observed at a channel station was one individual of *Mulinia lateralis*, a short-lived opportunistic species characteristic of Stage I fauna that prefers sediment with high organic content (Boesch 1973, Grassle et al. 1992). *Cyathura polita*, which constructed burrows that extended into the sediment about 3 to 4 cm, was most abundant at the intertidal station SED065 and subtidal station SED045. It also occurred at intertidal station SED038 but was not abundant there.

Surface biogenic structures associated with successional Stage II and III fauna observed in the SPI images were large tubes (>1 mm in diameter) at subtidal station SED022 and channel station SED043, and small feeding mounds or pits that occurred at all subtidal and channel stations plus two intertidal stations (SED058 and SED065). Large tubes (about 4 to 5 mm in diameter) belonging to the polychaete *Diopatra cuprea* were also observed in grabs from subtidal station SED060 and channel stations SED043 and SED063. *Diopatra cuprea* builds a long, nearly vertical parchment tube in sediment, which is reinforced with bits of shell, sediment or debris at the top (Myers 1972). Subsurface biogenic structures associated with infaunal organisms, mostly polychaetes, included active burrows present at all stations and water filled oxic voids at all stations except intertidal SED003 (Table 5). Infaunal individuals were observed in images from all stations except the medium-sand, intertidal station SED003. Most of the organisms appeared to be free burrowers not associated with oxidized burrows and likely acted as biodiffusors. As many as 5 individuals per image were observed in some replicates at channel station SED004, and subtidal stations SED022 and SED060. On average, organisms tended to be found in the upper BAZ in the subtidal and channel geomorphic units. The odds of an organism being found in the upper vs. lower BAZ was 1.4 to 1 for subtidal stations and 1.3 to 1 for channel stations. In the intertidal geomorphic unit, organisms were more likely to be found below the upper BAZ with the odds of an organism being in the lower BAZ being 1.2 to 1 (Fisher exact test, $p = 0.020$).

The average station OSI ranged from 4.6 to 9.4 indicating some difference in benthic habitat conditions over the 14 Newark Bay stations. Lower OSI values (<6), indicative of stressful conditions for infaunal communities (Rhoads and Germano 1986), occurred at intertidal stations SED002 and SED003 (Table 5). Stress in this analysis is defined in the sense of Menge and

Sutherland (1987) as a factor that prevents an organism form operating at its optimal level due to either physical forces (e.g. strong currents or sediment instability) or through inducing physiological responses in the organism (e.g., salinity or hypoxia). The OSI cannot identify the cause of the stressful condition but Diaz et al. (2003) found it to be significantly correlated to benthic habitat quality (i.e., salinity, sediment type, low dissolved oxygen, and contamination) and the benthic index of biotic integrity (B-IBI) of Weisberg et al. (1997) in Chesapeake Bay. In Narragansett Bay, Valente et al. (1992) found the OSI related to organic content of the sediment. Higher OSI values (7 and greater) were associated with evidence of equilibrium Stage III fauna and occurred at the other 12 stations. Overall, OSI values were not significantly different for the three geomorphic units sampled (Welsh ANOVA, df = 2, F = 6.19, p = 0.521).

3.5. Estimation of the Biologically Active Zone

The estimated depths of the BAZ by location and geomorphic unit are provided in Table 8. The BAZ was inferred from the depth to which various biogenic structures occurred in the SPI. This inference assumes that organism activity modifies sediment geochemical processes changing the oxidation/reduction state of key compounds (primarily salts and sulfides of iron and manganese) that give fine-grained sediment characteristic colors (Lyle 1983, Haese 1998). Based on this assumption, the BAZ was divided into two zones that would reflect the rate of organism-mediated sediment mixing or bioturbation. This is similar to the two-compartment sediment mixing models that incorporate bioturbation (see François et al. 2002).

The upper BAZ was defined to extend from the sediment surface to the average depth of active burrow structures observed in the images and would correspond most closely with the thickness of the biodiffusion zone (François et al. 2002), the zone of mixing and resuspension (Swift et al. 1996), and the biogenic mixing depth (BMD) of Solan et al. (2004). Solan et al. (2004) also used SPI to estimate the level of bioturbation and determined the BMD from the vertical color change in the images, delimited at the lower boundary of the aRPD layer depth, corresponding to the interface between the oxidized (high reflectance, lighter colored) and reduced (low reflectance, darker colored) sediment. The lower BAZ extended from the average depth of active burrows to the maximum depth of active feeding voids corresponding most closely to the thickness of the tube bottom zone of François et al. (2002) and the zone of transition of Swift et al. (1996).

Figure 7 shows the relationship between SPI defined BAZ and the mixing compartments defined by Swift et al. (1996) and François et al. (2002).

The upper BAZ would have the highest sediment turnover rate and be analogous to a biodiffusive layer where the sediment particle diffusion process throughout the layer is mediated by organism re-working (François et al. 2002). The sediment mixing in the biodiffusion layer is directly related to the density of organisms and biogenic structures (tubes and burrows, primarily) and approximates a random process. The lower BAZ lies below the upper BAZ and is analogous to a biotransport layer where sediment particles are subjected to non-random and non-local transport by organisms and their biogenic structures (François et al. 2002). Sediment in the biotransport layer is advected either up or down depending on an organism's functional group, which makes the turnover rates more a function of organism size, which is directly related to the size of burrow it can construct and volume of sediment it can move (Lee and Swartz 1980, Aller 1982, Lopez and Levington 1987, Rosenberg 2001).

The thickness of the upper BAZ, again analogous to a biodiffusive layer, was not significantly different between the three geomorphic units sampled (Welsh ANOVA, df = 2, F = 5.25, p = 0.420). The intertidal estimates of 4.5 cm to 11.0 cm for the upper BAZ were about as variable as the subtidal and channel estimates. The coefficient of variation (CV) within a station for the upper BAZ was 9%, 18%, and 12% for intertidal, subtidal, and channel geomorphic units, respectively. Subtidal and channel geomorphic units ranged from about 3 cm to 5 cm (Table 8 and Figure 8). The thickness of the lower BAZ was also not significantly different between geomorphic units (ANOVA, df = 2, F = 0.34, p = 0.722) with larger ranges for all subtidal and channel geomorphic units than intertidal (Figure 8). The within-station coefficients of variation for the lower BAZ were 8%, 14%, and 12% for intertidal, subtidal, and channel geomorphic units, respectively. There was no significant difference by geomorphic unit of the total thickness of the BAZ (ANOVA, df = 2, F = 0.14, p = 0.873), with the variation within geomorphic units lowest for the intertidal (2% CV) followed by subtidal (12%) and channel (16%) areas (Figure 8 and Table 8). Grain size of the sediment did not appear to affect the relative depth of the BAZ in Newark Bay, as the grain size was fairly uniform throughout most of the stations sampled with the exception of two of the intertidal stations (as previously discussed). The BAZ CV was lowest for the intertidal stations/geomorphic unit despite the grain size differences within the sample replicates.

The BAZ depths that were determined for Newark Bay in this investigation are comparable to those found in many aquatic systems. In a 2005 technical memorandum prepared by BBL (now ARCADIS) for Tierra Solutions, Inc. entitled *Literature Review on the Biologically Active Zone (BAZ) in Sediments* (BBL 2005), summaries of existing site-specific studies that measured or estimated the BAZ in sediment are provided. A copy of this technical memorandum is included as Appendix C to this report. Out of 31 studies identified and summarized, 22 determined a depth or depth range for the BAZ. The most common values reported were between 10 and 20 cm, with a range of 3 to 50 cm. While BAZ depths are clearly site-specific, it is apparent that the 15 cm average depth of the Newark Bay BAZ is within the typical range reported for other sites.

4. SUMMARY

The fauna and biogenic structures observed in both the SPI images and grab samples would be sufficient to bioturbate sediment to the estimated total BAZ depths of 13.7 to 16.4 cm. The deepest vertically burrowing species observed in the grab samples were large individuals of the clam *Macoma balthica* and *Mya arenaria* that extend their burrows to 7 cm into muddy sand with gravel (Mermillod-Blondin et al. 2003) and to as much as 30 cm in muds (Hines and Comtois 1985) that are similar to the sampled Newark Bay subtidal and channel sediment. The species with the potential to create the deepest convoluted burrow galleries were *Glycera* spp. and *Nereis* spp. Both these taxa were found as deep as 40 cm below the sediment surface in Chesapeake Bay (Nilsen et al. 1980). Other large-bodied species found in the grabs were the burrowing isopod *Cyathura polita* (maximum depth 15 cm (Hines and Comtois 1985)) and large-bodied tube building polychaetes *Diopatra cuprea* (observed depth of 10-12 cm, this study), maldanids (maximum depth 30 cm (Nilsen et al. 1980)), *Pectinaria gouldii* (maximum depth 7 cm (Nilsen et al. 1980)), and the amphipod *Ampelisca* spp. (maximum depth 5 cm (Nilsen et al. 1980))[1]. The burrowers and *Ampelisca* spp. would contribute to biodiffusive sediment mixing. Maldanids, *Diopatra cuprea*, and *Pectinaria gouldii* would contribute to bioadvective sediment mixing. The majority of these species, plus *Macoma balthica* and *Mya arenaria*, were considered to be pollution sensitive for the purpose of calculating the B-IBI (Weisberg et al. 1997). Species found in the grabs that Weisberg et al. (1997) considered to be pollution tolerant were *Leitoscoloplous* spp. (polychaete), Capitellids (polychaete), and *Mulinia lateralis* (bivalve).

The total thickness of the BAZ inferred from the depth to which various biogenic structures occurred in the SPI was similar across the geomorphic units sampled (no significant difference between intertidal, subtidal, and channel). The depth of the total BAZ was 13.7 cm for subtidal, 14.5 cm for intertidal, and 13.1 cm for channel stations (Table 8 and Figure 8). These BAZ thicknesses correspond well with mixed layer depths estimated in other studies (see Appendix C; Diaz et al. 1994, Swift et al. 1996, François et al. 2002).

The BAZ was divided into an upper layer with a higher sediment turnover rate relative to the lower layer. In the upper BAZ biodiffusive processes dominated and the sediment mixing was mediated by organism re-working (François et al. 2002). The sediment mixing in the biodiffusive layer is directly related to the density of organisms and biogenic structures (tubes and burrows, primarily) and approximates a random process. The lower BAZ, below the upper BAZ, had a lower sediment turnover rate, relative to the upper layer, and was dominated by biotransport with sediment particles subjected to non-random and non-local transport by organisms and their biogenic structures (François et al. 2002). Evidence of both these processes can be seen in the SPI (for examples, see Figures 9, 10, and 11).

Advanced successional stage estimates, close to a Stage III equilibrium situation, indicate the presence of a well-developed, deeper dwelling fauna at all stations except intertidal SED002 and SED003. The latter two stations were in a Stage I pioneering successional stage. The more advanced successional stage stations would also have a stronger potential for deeper bioturbation than early successional stages (Rosenberg 2001). While not significant, there was a tendency for the OSI in the intertidal geomorphic unit to be lower than in the subtidal and channel units. Only intertidal stations SED002 and SED003 had OSI values <6, indicative of stressful conditions for infaunal communities (Rhoads and Germano 1986); stress being defined per Menge and Sutherland (1987) as a factor that prevents an organism from operating at its optimal level due to either physical forces (e.g., strong currents or sediment instability) or through inducing physiological responses in the organism (e.g., salinity or low dissolved oxygen). The OSI cannot identify the cause of the stressful condition but Diaz et al. (2003) found that in Chesapeake Bay the OSI was significantly correlated with benthic habitat quality parameters of salinity, sediment type, low dissolved oxygen, and pollution. In Narragansett Bay, Valente et al. (1992) found the OSI related to organic content of the sediment.

While there is variability in the BAZ throughout Newark Bay, the average depth of just under 15 cm is relatively consistent throughout the geomorphic units and provides a useful guideline for depth-specific sampling (for the RI/FS and related risk assessment) in the surface layer of

[1] It should be noted that American eel (*Anguilla rostra*) is a migratory fish species that occurs seasonally in Newark Bay and sometimes burrows into sediments, thus potentially affecting the BAZ. There was no evidence of eel

sediment where benthic organisms are exposed to sediment-associated contaminants. While there is the potential for the BAZ to change over time, this possibility cannot be anticipated or quantified. However, most of the stations sampled in this investigation were composed of benthic assemblages in a Stage III (i.e., relatively well-developed) successional stage which suggests stability in the sediment structure. Therefore, the evidence suggests that short-term changes in the BAZ have not likely occurred in recent times, and are not likely to occur in the immediate future.

activity in the Bay sediments based on the SPI images from this investigation.

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Tables

Table 1. Comparison of Phi scale to sediment profile image (SPI) sediment grain size descriptors.

Phi Class & Scale	Upper Limit Size (mm)	Grains per cm of image	SPI Grain Size Descriptor	Sediment Grain Size Subclass
-6 to -8	256.0	<<1	CB	Cobble
-2 to -6	64.0	<1	PB	Pebble
-1 to -2	4.0	2.5	GR	Gravel
1 to -1	2.0	5	CS	Coarse-sand
2 to 1	0.5	20	MS	Medium-sand
4 to 2	0.25	40	FS	Fine-sand
4 to 3	0.12	80	VFS	Very-fine-sand
5 to 4	0.06	160	FSSI	Fine-sandy-silt
5.5 to 4.5	0.06	160	FSSICL	Fine-sandy-silt-clay
6 to 5	0.0039	>320	SIFS	Silty-fine-sand
7 to 5	<0.0039	>320	SI	Silt
8 to 6	<0.0039	>320	SICL	Silty-clay
>8 to 7	<0.0039	>320	CLSI	Clayey-silt
>8	<0.0005	>2560	CL	Clay

Table 2. Relationship of sediment profile image (SPI) parameters with infaunal successional stage.

	Successional Stage		
Parameter	I	II	III
Average aRPD Depth (cm)	<1	1-3	>2
Maximum aRPD Depth (cm)	<2	>2	>4
Small Tubes	+++	++	+
Large Tubes	-	++	+++
Burrows	-	++	+++
Feeding Voids	-	+	+++
Small Infauna	+++	++	+
Large Infauna	-	+	++
Epifauna	+	++	++

"-" = not associated with,
"+" = associated with,
"++" = moderately associated with, and
"+++" = strongly associated with.
aRPD – Apparent Color Redox Potential Discontinuity.

Note: These are broad relative indicators of association between successional stage and benthic physical/biological parameters in estuarine systems as typically applied in SPI investigations (see Rhoads and Germano 1986).

Table 3. Parameter ranges and scores for calculation of organism sediment index (OSI).

Depth of the apparent color redox potential discontinuity (aRPD):		Estimated successional stage:	
0 cm	0	Azoic	-4
>0 – 0.75	1	I	1
0.76 – 1.50	2	I-II	2
1.51 – 2.25	3	II	3
2.26 – 3.00	4	II-III	4
3.01 – 3.75	5	III	5
>3.75	6	I on III	5
		II on III	5

Other:	
Methane or gas voids present	-2
No/Low dissolved oxygen	-4

Table 4a. Location and water depth at time of sampling for sediment profile image (SPI) stations, October 2005.

Date	Time	Station	Replicate	Geomorphic Unit	Depth (ft)	Easting	Northing
4-Oct	10:31	SED002	1	Intertidal	5.1	579835	659460
4-Oct	10:36	SED002	2	Intertidal	4.7	579860	659450
4-Oct	10:39	SED002	3	Intertidal	5.3	579849	659446
4-Oct		SED002	4	Intertidal		Data not recorded	
4-Oct		SED002	5	Intertidal		Data not recorded	
4-Oct	8:35	SED003	1	Intertidal	2.5	583029	659258
4-Oct	8:39	SED003	2	Intertidal	2.5	583025	659257
4-Oct	8:43	SED003	3	Intertidal	4.0	583067	659308
4-Oct	8:50	SED003	4	Intertidal	4.2	583095	659353
4-Oct	8:52	SED003	5	Intertidal	4.6	583083	659336
4-Oct	8:53	SED003	6	Intertidal	4.9	583088	659383
4-Oct	13:21	SED004	1	Channel	32.0	586392	658515
4-Oct	13:25	SED004	2	Channel	31.3	586396	658517
4-Oct	13:28	SED004	3	Channel	31.4	586385	658511
4-Oct	13:32	SED004	4	Channel	31.1	586415	658521
4-Oct	13:39	SED004	5	Channel	31.6	586398	658523
4-Oct	11:16	SED014	1	Subtidal	7.8	585948	661926
4-Oct	11:18	SED014	2	Subtidal	7.8	585938	661930
4-Oct	11:20	SED014	3	Subtidal	7.8	585953	661921
4-Oct	11:23	SED014	4	Subtidal	7.8	585949	661910
4-Oct	11:25	SED014	5	Subtidal	7.8	585936	661913
4-Oct	14:11	SED022	1	Subtidal	6.9	591836	664158
4-Oct	14:14	SED022	2	Subtidal	7.1	591841	664153
4-Oct	14:16	SED022	3	Subtidal	7.2	591847	664158
4-Oct	14:19	SED022	4	Subtidal	7.3	591829	664162
4-Oct	14:21	SED022	5	Subtidal	7.2	591837	664166
6-Oct	8:08	SED038	1	Intertidal	5.5	597907	671977
6-Oct	8:10	SED038	2	Intertidal	5.5	597906	671971
6-Oct	8:12	SED038	3	Intertidal	5.5	597900	671966
6-Oct	8:14	SED038	4	Intertidal	5.5	597899	671986
6-Oct	8:17	SED038	5	Intertidal	5.5	597898	671973
5-Oct	11:37	SED041	1	Subtidal	7.5	592308	673530
5-Oct	11:39	SED041	2	Subtidal	7.5	592306	673521
5-Oct	11:40	SED041	3	Subtidal	7.5	592315	673535
5-Oct	11:42	SED041	4	Subtidal	7.5	592316	673528
5-Oct	11:44	SED041	5	Subtidal	7.5	592302	673534
5-Oct	11:47	SED041	6	Subtidal	7.5	592303	673520
4-Oct	16:29	SED043	1	Channel	43.6	594657	673864
4-Oct	16:34	SED043	2	Channel	43.2	594666	673859
4-Oct	16:36	SED043	3	Channel	44.2	594651	673876
4-Oct	16:40	SED043	4	Channel	43.8	594653	673859
4-Oct	16:42	SED043	5	Channel	43.8	594653	673873
5-Oct	16:06	SED045	1	Subtidal	9.1	596603	674889
5-Oct	16:09	SED045	2	Subtidal	9.0	596605	674883
5-Oct	16:14	SED045	3	Subtidal	9.0	596604	674875
5-Oct	16:18	SED045	4	Subtidal	9.1	596609	674880
5-Oct	16:22	SED045	5	Subtidal	9.0	596611	674881

Table 4a. Continued.

Date	Time	Station	Replicate	Geomorphic Unit	Depth (ft)	Easting	Northing
5-Oct	14:14	SED056	1	Subtidal	5.0	596719	679503
5-Oct	14:17	SED056	2	Subtidal	5.1	596718	679498
5-Oct	14:19	SED056	3	Subtidal	5.1	596730	679501
5-Oct	14:22	SED056	4	Subtidal	5.0	596728	679495
5-Oct	14:24	SED056	5	Subtidal	5.1	596722	679504
6-Oct	9:57	SED058	1	Intertidal	7.8	601722	681208
6-Oct	10:00	SED058	2	Intertidal	7.8	601718	681200
6-Oct	10:03	SED058	3	Intertidal	7.8	601727	681210
6-Oct	10:07	SED058	4	Intertidal	7.9	601713	681197
6-Oct	10:10	SED058	5	Intertidal	7.8	601709	681209
5-Oct	13:46	SED060	1	Subtidal	9.3	599082	681177
5-Oct	13:50	SED060	2	Subtidal	8.8	599090	681183
5-Oct	13:52	SED060	3	Subtidal	8.8	599080	681184
5-Oct	13:53	SED060	4	Subtidal	8.6	599101	681194
5-Oct	13:55	SED060	5	Subtidal	8.6	599095	681180
5-Oct	11:01	SED063	1	Channel	36.6	598796	684036
5-Oct	11:02	SED063	2	Channel	37.9	598789	684038
5-Oct	11:04	SED063	3	Channel	38.0	598782	684045
5-Oct	11:06	SED063	4	Channel	37.9	598799	684047
5-Oct	11:09	SED063	5	Channel	36.7	598809	684037
5-Oct	9:02	SED065	1	Intertidal	5.4	600451	686971
5-Oct	9:04	SED065	2	Intertidal	5.3	600454	686974
5-Oct	9:14	SED065	3	Intertidal	5.4	600448	686971
5-Oct	9:15	SED065	4	Intertidal	5.4	600442	686968
5-Oct	9:19	SED065	5	Intertidal	5.3	600455	686977

Table 4b. Location and water depth at time of sampling for grab stations, October 2005.

Date	Time	Station	Replicate	Geomorphic Unit	Depth (ft)	Easting	Northing
4-Oct	9:48	SED002	1	Intertidal	5.0	579855	659436
4-Oct	9:58	SED002	2	Intertidal	4.7	579855	659445
4-Oct	10:10	SED002	3	Intertidal	5.1	579847	659456
4-Oct	9:07	SED003	1	Intertidal	3.6	583088	659383
4-Oct	9:15	SED003	2	Intertidal	3.4	583030	659271
4-Oct	9:16	SED003	3	Intertidal	3.9	583051	659300
4-Oct	9:21	SED003	4	Intertidal	3.9	583062	659301
4-Oct	12:29	SED004	1	Channel	32.3	586405	658509
4-Oct	12:37	SED004	2	Channel	32.2	586379	658524
4-Oct	12:51	SED004	3	Channel	31.6	586396	658529
4-Oct	11:35	SED014	1	Subtidal	7.7	585956	661914
4-Oct	11:53	SED014	2	Subtidal	7.6	585957	661893
4-Oct	12:03	SED014	3	Subtidal	6.9	585966	661935
4-Oct	14:30	SED022	1	Subtidal	7.0	591840	664161
4-Oct	14:42	SED022	2	Subtidal	7.0	591837	664166
4-Oct	14:51	SED022	3	Subtidal	6.2	591849	664163
4-Oct	15:05	SED022	4	Subtidal	6.6	591836	664157
4-Oct	15:15	SED022	5	Subtidal	6.6	59136	664172
6-Oct	8:25	SED038	1	Intertidal	5.6	597904	671981
6-Oct	8:32	SED038	2	Intertidal	5.6	597918	671979
6-Oct	8:43	SED038	3	Intertidal	5.7	597917	671969
5-Oct	11:55	SED041	1	Subtidal	7.4	592309	673532
5-Oct	12:09	SED041	2	Subtidal	7.0	592299	673527
5-Oct	12:23	SED041	3	Subtidal	6.5	592309	673535
4-Oct	15:35	SED043	3	Channel	43.1	594673	673861
4-Oct	15:51	SED043	4	Channel	43.5	594651	673863
4-Oct	16:06	SED043	5	Channel	43.1	594665	673865
5-Oct	15:32	SED045	1	Subtidal	9.2	596601	674884
5-Oct	15:42	SED045	2	Subtidal	9.1	596602	674874
5-Oct	15:50	SED045	3	Subtidal	9.1	596612	674890
5-Oct	14:31	SED056	1	Subtidal	5.0	596733	679504
5-Oct	14:48	SED056	2	Subtidal	4.5	596726	679489
5-Oct	15:09	SED056	3	Subtidal	4.5	596718	679492
6-Oct	9:06	SED058	1	Intertidal	7.6	601720	681219
6-Oct	9:22	SED058	2	Intertidal	7.5	601720	681209
6-Oct	9:32	SED058	3	Intertidal	7.6	601725	681198
5-Oct	12:50	SED060	1	Subtidal	10.0	599095	681174
5-Oct	12:59	SED060	2	Subtidal	9.8	599093	681186
5-Oct	13:21	SED060	3	Subtidal	9.6	599076	681179
5-Oct	10:19	SED063	1	Channel	37.6	598808	684045
5-Oct	10:30	SED063	2	Channel	37.5	598800	684036
5-Oct	10:42	SED063	3	Channel	36.9	598800	684027
5-Oct	9:32	SED065	1	Intertidal	5.3	600459	686969
5-Oct	9:45	SED065	2	Intertidal	5.5	600443	686974
5-Oct	9:56	SED065	3	Intertidal	5.5	600454	686967

Table 5. Summary of sediment profile image (SPI) data for Newark Bay stations, October 2005.

Geomorphic Unit	Station	Penetration Avg. (cm)	Surface Relief Avg. (cm)	aRPD Avg. (cm)	OSI Avg.	Burrows Avg. (cm)	Oxic Voids Avg. (cm)	Anaerobic Voids Avg. (cm)	Infauna Avg. (cm)	Gas Voids Avg. (cm)	Upper BAZ Avg. (cm)	Lower BAZ Avg. (cm)	Succession Stage	Bed[1] Roughness
Intertidal	SED002	18.7	1.8	3.2	5.8	11.0	13.4	8.2	11.6	13.5	11.0	Undefined	I	PHY
	SED003	6.7	0.9	2.5	4.6	4.5	NO	NO	NO	NO	4.5	Undefined	I	PHY
	SED038	7.5	1.0	5.5	9.0	5.5	4.4	NO	5.2	2.4	5.5	Undefined	I-III	PHY
	SED058	17.6	0.9	3.9	9.2	4.5	10.5	NO	6.6	9.3	4.5	11.6	I-III	BIO/PHY
	SED065	11.5	0.6	3.2	9.4	5.5	7.1	NO	3.6	5.5	5.5	9.2	I-III	PHY
Subtidal	SED014	19.2	0.7	2.3	8.0	3.2	6.3	NO	2.9	16.1	3.2	7.0	I-III	BIO/PHY
	SED022	14.9	0.8	2.8	8.2	5.1	7.8	13.5	4.5	NO	5.1	7.8	I-III	BIO/PHY
	SED041	12.7	1.3	1.9	7.2	4.0	7.8	NO	4.4	6.3	4.0	8.8	I-III	BIO/PHY
	SED045	18.1	1.8	3.4	9.2	5.1	8.0	14.8	2.7	NO	5.1	8.4	I-III	BIO/PHY
	SED056	16.8	0.9	3.3	8.0	4.4	8.7	13.2	3.9	10.5	4.4	9.5	I-III	BIO/PHY
	SED060	16.6	0.7	3.3	9.0	5.3	11.5	12.1	8.7	7.6	5.3	12.1	I-III	PHY
Channel	SED004	17.0	0.7	3.7	8.6	5.2	8.4	14.6	5.3	8.2	5.2	12.7	I-III	BIO/PHY
	SED043	12.3	1.4	2.1	8.4	3.6	5.2	10.3	2.8	NO	3.6	8.4	I-III	BIO/PHY
	SED063	11.9	0.6	2.3	8.6	3.7	6.1	10.4	2.9	NO	3.7	6.6	I-III	BIO/PHY

Geomorphic Unit	Station	Modal[2] Grain Size	Minimum Grain Size	Maximum Grain Size	Amphipod Tubes (#/image)	Worm Tubes (#/image)	Bed-forms	Shell	Biogenic Pits or Mounds	Fluff of Fines	Detritus	Tubes >1mm	Macro-Algae	Mud Snail
Intertidal	SED002	SICL	CL	SI	0	0	-	+	-	+	+	-	+	+
	SED003	MS	SI	GR	0	0	+	+	-	-	+	-	+	+
	SED038	FSMS	SI	MS	0	6-23	+	+	-	-	-	-	+	+
	SED058	FSSICL	SICL	FS	6-23	6-23	-	-	+	-	-	-	-	+
	SED065	FSSICL	SICL	FS	0	6-23	-	+	+	-	-	-	-	-
Subtidal	SED014	FSSICL	SICL	FS	0	>23	-	-	+	-	-	-	-	-
	SED022	FSSICL	SICL	FS	0	>23	-	-	+	-	-	+	-	-
	SED041	SICL	CL	SI	0	>23	-	+	+	-	-	-	-	-
	SED045	FSSICL	SICL	FS	0	>23	-	+	+	-	-	-	-	-
	SED056	FSSICL	SICL	FS	0	6-23	-	-	+	-	-	-	-	-
	SED060	FSSICL	SICL	FS	0	>23	-	-	+	-	-	-	-	-
Channel	SED004	FSSICL	SICL	FS	0	>23	-	-	+	-	-	-	-	-
	SED043	SICL	CL	SI	0	6-23	-	-	+	+	-	+	-	-
	SED063	FSSICL	SICL	FS	0	>23	-	+	+	-	-	-	-	+

[1]PHY = Physical processes dominate sediment surface, BIO/PHY = Combination of biological and physical processes dominate surface, NO = None observed.
[2]See Table 1 for sediment class abbreviations. aRPD – apparent color redox potential discontinuity. BAZ – biologically active zone.

Table 6. Summary of grab sample data for Newark Bay stations, October 2005.

Geomorphic Unit	Station	Penetration (cm)	aRPD (cm)	Sediment[1]	Smell	Detritus	Plastic	Shell Hash	Biogenic Structures Observed: Burrow	Egg Cases	Small Tubes	Organisms Observed: Nemertean	Fish
Intertidal	SED002	19.3	Not Detected	SICL, Cinder	Oil Sheen, H_2S Slight	+	-	-	-	-	-	-	-
	SED003	9.7	1.3	SICSGR to MSCSSI		+	-	+	-	-	-	-	-
	SED038	10.3	5.5	FSSI/FSMS, SI balls		-	-	+	-	-	-	-	-
	SED058	20	3.5	SICL	H_2S slight	-	-	+	+	-	-	-	-
	SED065	13	3.0	SIFS		-	+	-	+	-	+	-	-
Subtidal	SED014	17	2.3	FSSICL	Strong Petro. Smell at 10 cm organic layer	-	-	+	-	Maldanid?	+	-	-
	SED022	19.3	2.2	FSSICL	H_2S slight	-	-	+	+	-	+	-	-
	SED041	18.3	2.3	SIFS, Reddish CL	H_2S slight	-	-	+	+	Snail?	+	-	-
	SED045	17.7	2.2	FSSI	H_2S slight, Petro. Slight	+	-	+	+	-	+	-	-
	SED056	19	2.0	FSSICL		-	-	+	+	-	+	+	-
	SED060	20	3.0	SICL		-	-	+	+	-	+	-	Sculpin?
Channel	SED004	13	2.3	SICL		-	-	+	-	-	+	-	-
	SED043	19.3	1.8	SICL	H_2S slight	-	-	-	+	-	+	-	-
	SED063	19.3	2.7	FSSICL		-	+	+	+	-	+	-	-

Geomorphic Unit	Station	Organisms Observed: Nereis	Glycera	Spiochae-topterus	Diopatra	Pectinaria	Capitellid	Leito-scoloplos	Large Fragments	Macoma	Mya	Mulinia	Ilyanassa	Ampelisca	Cyathura	Crangon	Mud Crab
Intertidal	SED002	+	-	-	-	-	-	-	-	+	-	-	+	-	-	-	-
	SED003	+	+	-	-	+	-	-	-	+	-	-	+	-	-	-	-
	SED038	-	-	-	-	+	-	-	+	+	+	-	+	-	+	-	-
	SED058	+	-	-	-	-	+	+	-	+	-	-	+	Many	-	-	+
	SED065	-	-	-	-	Relic	-	-	-	+	+	-	+	-	+	-	-
Subtidal	SED014	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	SED022	-	-	+	-	-	-	-	-	+	-	-	-	-	-	-	-
	SED041	-	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-
	SED045	-	-	+	-	Relic	-	-	-	-	+	-	-	-	+	+	-
	SED056	-	-	+	-	-	+	-	-	+	+	-	-	-	-	-	-
	SED060	-	+	-	+	-	+	-	-	-	-	-	-	+	-	-	-
Channel	SED004	-	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-
	SED043	-	+	+	+	+	-	-	-	-	-	-	-	+	-	-	-
	SED063	-	+	-	+	+	-	-	-	-	-	+	-	+	-	-	-

[1]See Table 1 for sediment class abbreviations.
aRPD – apparent color redox potential discontinuity

Table 7. Summary of field descriptions for 2005 Phase I Remedial Investigation (RI) sediment cores collected for chemical/radiological analyses at or near the biologically active zone (BAZ) sampling locations.

BAZ Location	Sediment Chemistry Core Number	Core ID	Field Descriptions
SED 002	Core 002	NB01SED002B	0-0.5 - dark brown to black silt, trace fine sand, trace gravel, trace organics (roots) 0.5-1.5 - dark grey brown to black silt, trace gravel, trace fine, medium, coarse sand, trace organics (roots and bark) 1.5-2.8 - dark grey brown silt, trace clay, little organics (wood pulp)
SED 003	Core 003	NB01SED003D	0-2.1 - dark grey brown silt, trace fine sand, trace organics (roots, shell fragments, twigs) Engineer's note - 3 inch worm found at 1.0 feet
SED 004	Core 004	NB01SED004B	0-0.7 - dark brown to black silt, trace fine sand 0.81-2.8 - dark brown to black silt, trace fine sand, trace organics (leaves, stems, twigs)
SED 014	Core 014	NB01SED014A	0-0.5 - brown to black silt, trace fine sand, trace organics (roots) 0.5-1.5 - black silt, trace fine sand, trace organics (shell fragments and roots) 1.5-2.5 - grey silt, trace fine sand, trace organics (shell fragments)
SED 022	Core 022	NB01SED022A	0-3.5 - dark grey brown silt, trace fine sand
SED 038	Core 038	NB01SED038A	0-4.0 - grey/brown fine sand, little silt, trace organics (shell fragments)
SED 041	Core 041	NB01SED041A	0-0.5 - grey/brown silt, little fine sand, organics (shell fragments) 0.5-3.5 - grey/brown to black silt, trace fine sand, organics (roots, leaves, wood pulp)
SED 043	Core 043	NB01SED043C	0-2.8 - grey/brown to black silt, trace fine sand, trace organics (roots)
SED 045	Core 045	NB01SED045B	0-1.3 - grey/black silt, little fine sand, trace organics (shell fragments) 1.3-3.5 - grey silt, trace fine sand, organics (shell fragments)
SED 056	Core 056	NB01SED056B	0-6.5 - grey/brown to black silt, trace fine sand, organics (shell fragments, roots)
SED 058	Core 058	NB01SED058B	0-0.5 - grey/brown-black silt, trace fine sand, organics (roots, shell fragments) 0.5-0.6 - grey/black silt, trace fine sands, organics (roots) 0.6-0.8 - fine sand 0.8-4.0 - grey/black silt, trace fine sands, organics(roots)
SED 060	Core 060	NB01SED060B	0-0.5 - grey/black silt, trace fine sand, organics (leaves, roots)
SED 063	Core 063	NB01SED063C	0-4.5 - grey/brown to black silt, trace fine sand, organics (roots, shell fragments)
SED 065	Core 065	NB01SED065A	0-0.5 - grey/brown/black silt, trace fine sand, trace organics (shell fragments, roots) 0.5-6.5 - grey/black silt, trace fine sand, organics (clams)

See Figure 1 for sediment chemistry core locations.

Table 8. Mean of biologically active zone (BAZ) thickness for Newark Bay stations, October 2005.

Geomorphic Unit	BAZ[1] Upper Zone Mean (cm)	Range	SD (cm)	N	BAZ Lower Zone Mean (cm)	Range	SD (cm)	N	BAZ Total Mean (cm)	Range	SD (cm)	N
Intertidal												
SED002	11.0	11.0	---	1	VnoB[2]	---	---	--	13.4	---	---	1
SED003	4.5	3.2-5.3	0.9	4	ND[3]	---	---	--	ND	---	---	--
SED038	5.5	5.2-5.9	0.4	3	V<B[4]	---	---	--	ND	---	---	--
SED058	4.5	3.5-6.6	1.2	5	11.6	9.9-13.6	1.9	3	15.7	14.3-17.5	1.6	3
SED065	5.5	2.9-7.5	1.8	5	9.2	8.4-10.2	0.7	4	14.3	11.3-15.7	2.1	4
All Stations:	6.2	4.5-11.0	2.7	5	10.4	9.2-11.6	---	2	14.5	13.4-15.7	1.6	3
Subtidal												
SED014	3.2	1.8-4.7	1.2	4	7.0	3.6-10.9	2.7	4	9.5	6.2-14.4	3.6	5
SED022	5.1	3.9-6.3	1.0	5	7.8	5.4-10.4	2.1	4	13.0	12.5-16.1	2.9	4
SED041	4.0	2.4-6.0	1.4	5	8.8	6.4-11.0	2.1	5	12.8	9.6-17.0	3.2	5
SED045	5.1	2.7-8.2	2.1	5	8.4	4.8-11.2	3.2	4	14.2	8.6-19.4	5.0	4
SED056	4.4	3.3-5.5	0.8	5	9.5	8.2-11.6	1.9	3	14.1	12.4-17.1	2.6	3
SED060	5.3	3.3-10.5	3.0	5	12.1	8.2-17.9	5.2	3	18.6	12.2-28.4	8.6	3
All Stations:	4.5	3.2-5.3	0.8	6	8.9	7.0-12.1	1.8	6	13.7	9.5-18.6	2.9	6
Channel												
SED004	5.2	4.2-6.7	1.1	5	12.7	8.8-17.3	4.3	3	18.5	13.3-24.0	5.4	3
SED043	3.6	2.5-5.7	1.3	5	8.4	4.2-10.6	2.8	4	11.4	6.8-14.6	3.3	4
SED063	3.7	2.0-7.3	2.1	5	6.6	4.6-8.7	1.7	4	9.4	8.6-10.7	0.9	4
All Stations:	4.7	3.6-5.2	0.9	3	9.2	6.6-12.7	3.1	3	13.1	9.4-18.5	4.8	3

[1] Upper BAZ is defined as the sediment surface to the depth of observed active burrow structures. Lower BAZ is defined as the limit of the upper zone to the maximum depth of active feeding voids. Total BAZ is the sum of the upper and lower zones.
[2] VnoB = Oxic voids present but no burrows, depth of oxic voids was considered total BAZ.
[3] ND = No Data, none of the 5 replicates could be used to estimate BAZ.
[4] V<B = Oxic voids were shallower in sediment than burrows, total BAZ could not be estimate.

Figures

Figure 1. Location of biologically active zone (BAZ) sampling stations, Newark Bay, October 2005.

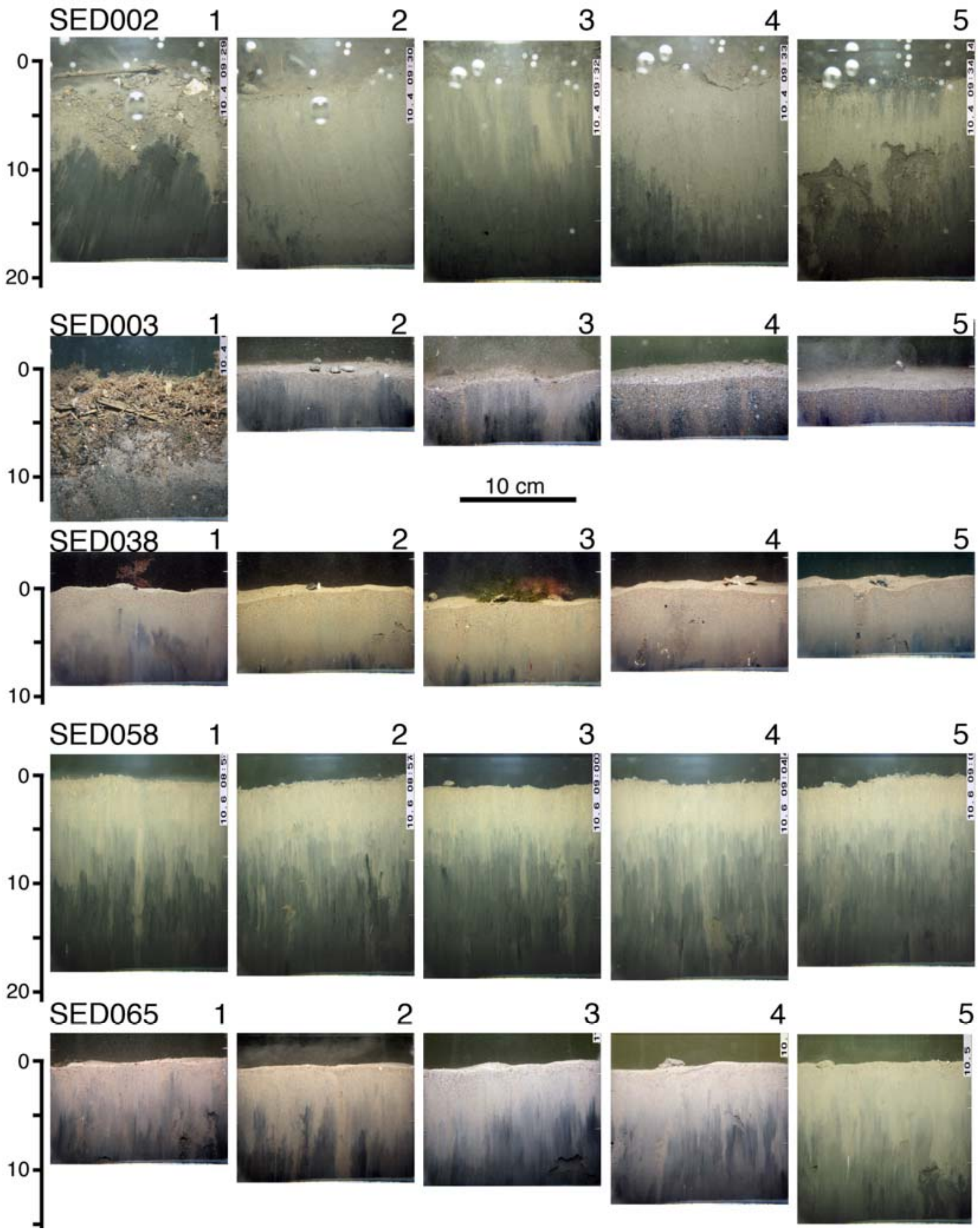

Figure 2. Mosaic of intertidal stations, Newark Bay, October 2005.

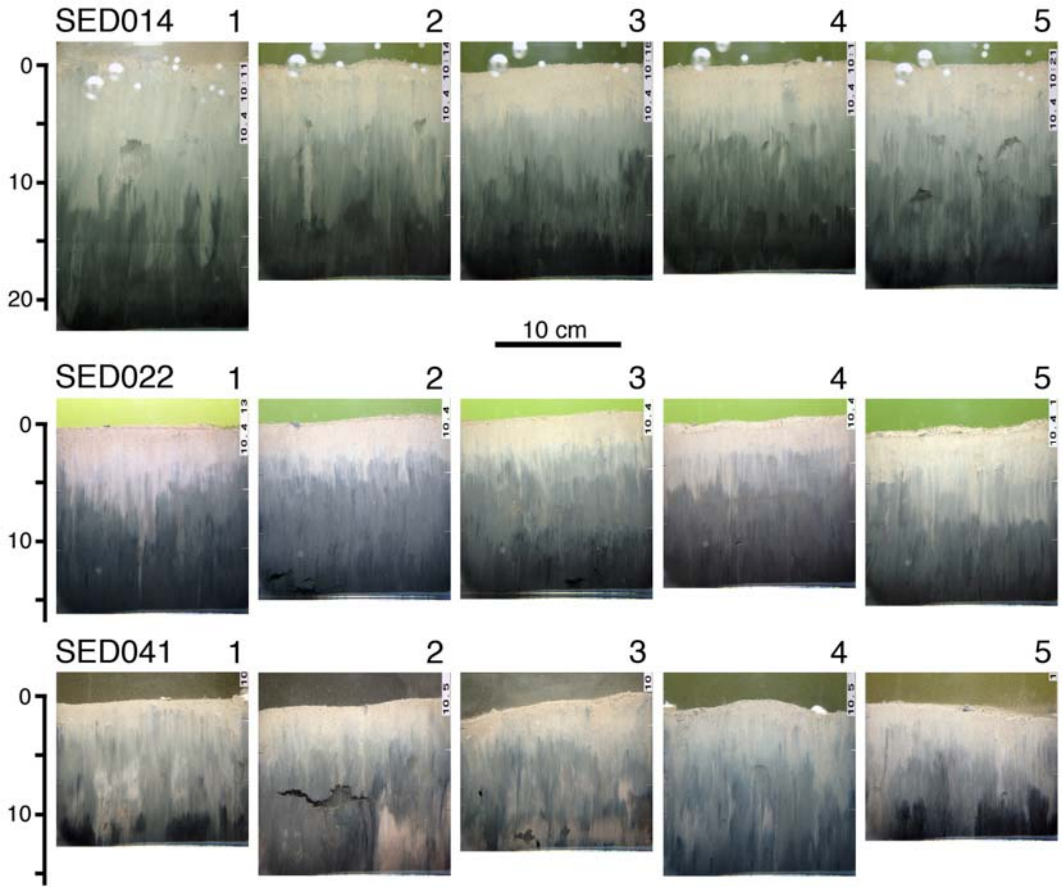

Figure 3. Mosaic of subtidal stations, Newark Bay, October 2005.

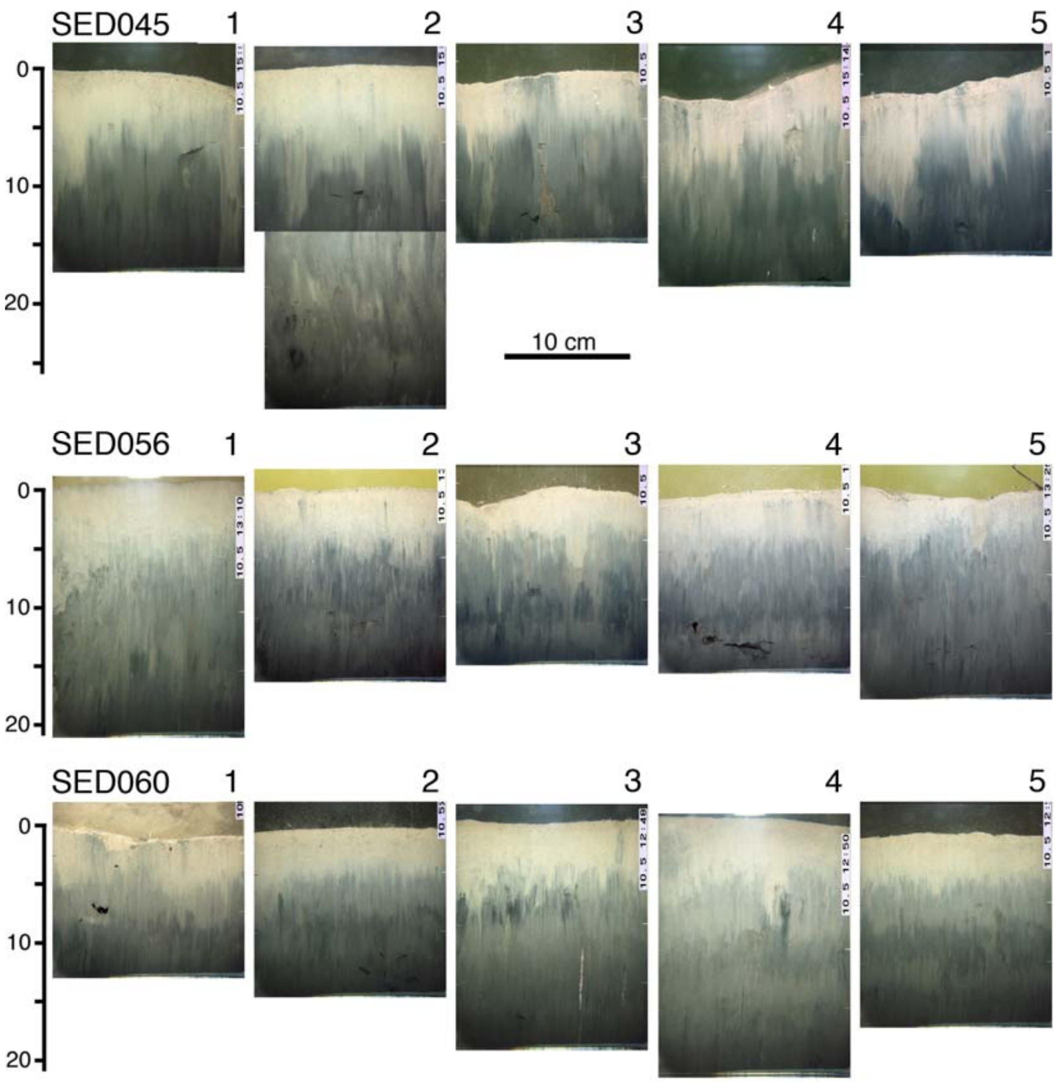

Figure 4. Mosaic of subtidal stations, Newark Bay, October 2005.

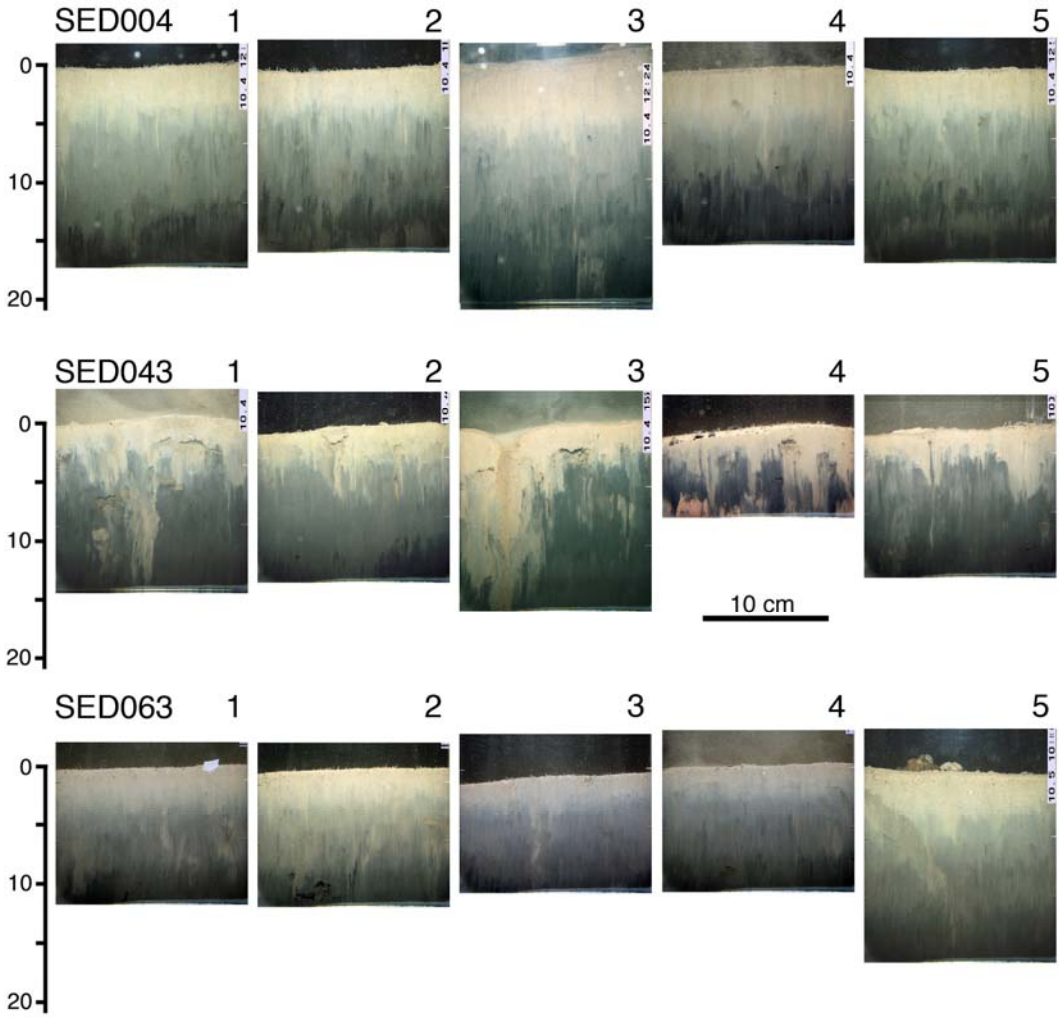

Figure 5. Mosaic of channel stations, Newark Bay, October 2005.

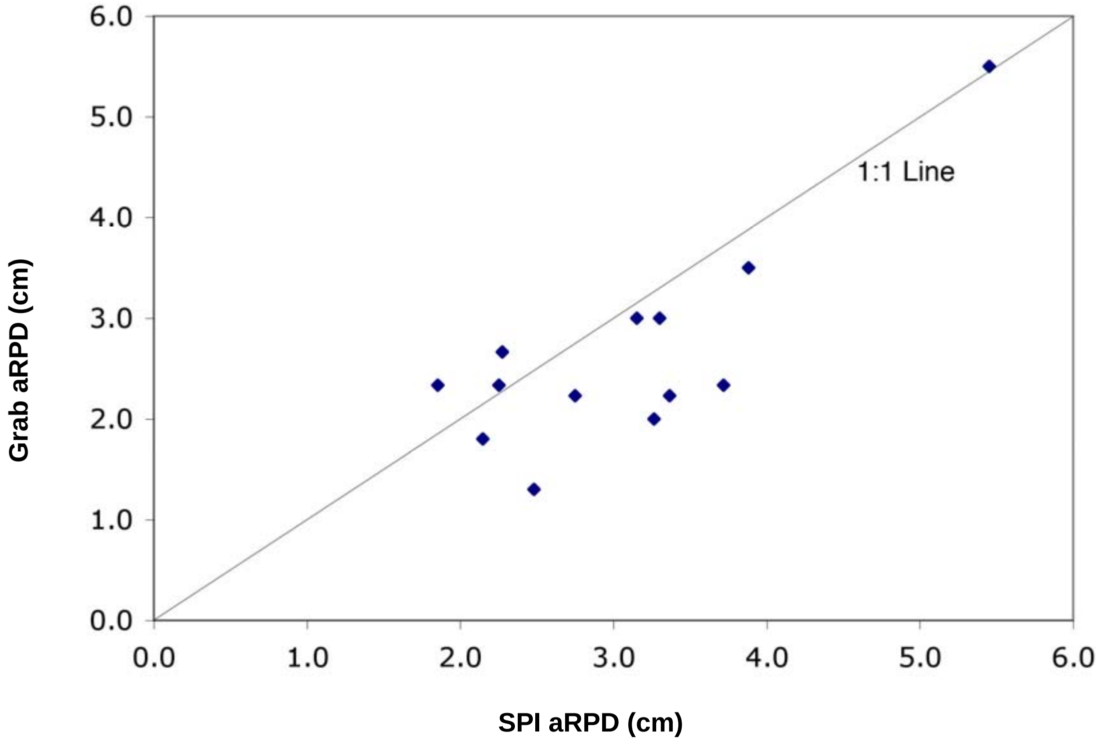

Figure 6. Plot of apparent color redox potential discontinuity (aRPD) depths estimated from grab samples and sediment profile images (SPI). Line is 1:1 ratio.

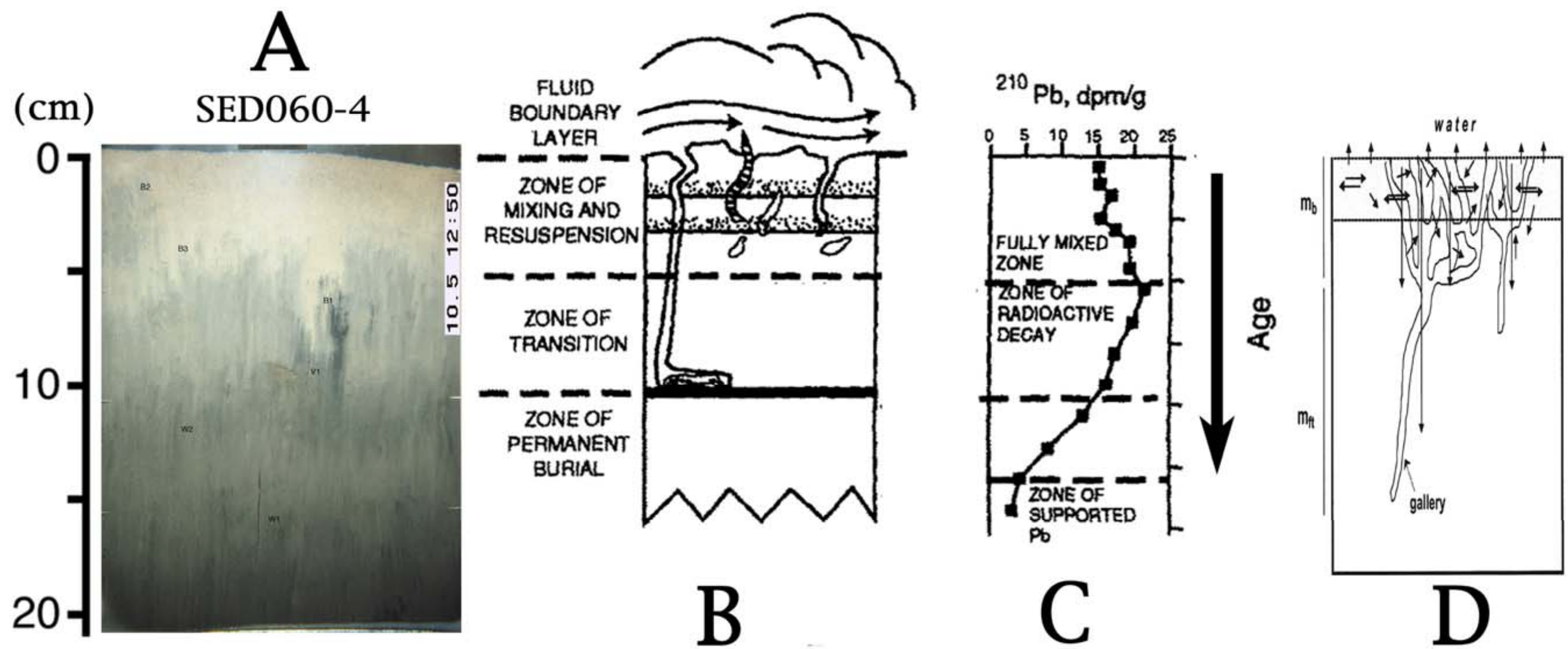

Figure 7. Relationship between sediment profile image (SPI) derived biologically active zone (BAZ) and biologically mixing models. A – SPI image from subtidal station SED060, replicate 4. B – Biogenic mixing zone model of Swift et al. (1996). C – Example of a ^{210}Pb profile that matches the Swift et al. (1996) model. D – Two part mixing model of François et al. (2002), m_b is the biodiffusion zone and m_{ft} is the tube bottom zone. B and C are modified from Swift et al. (1996) and D from François et al. (2002).

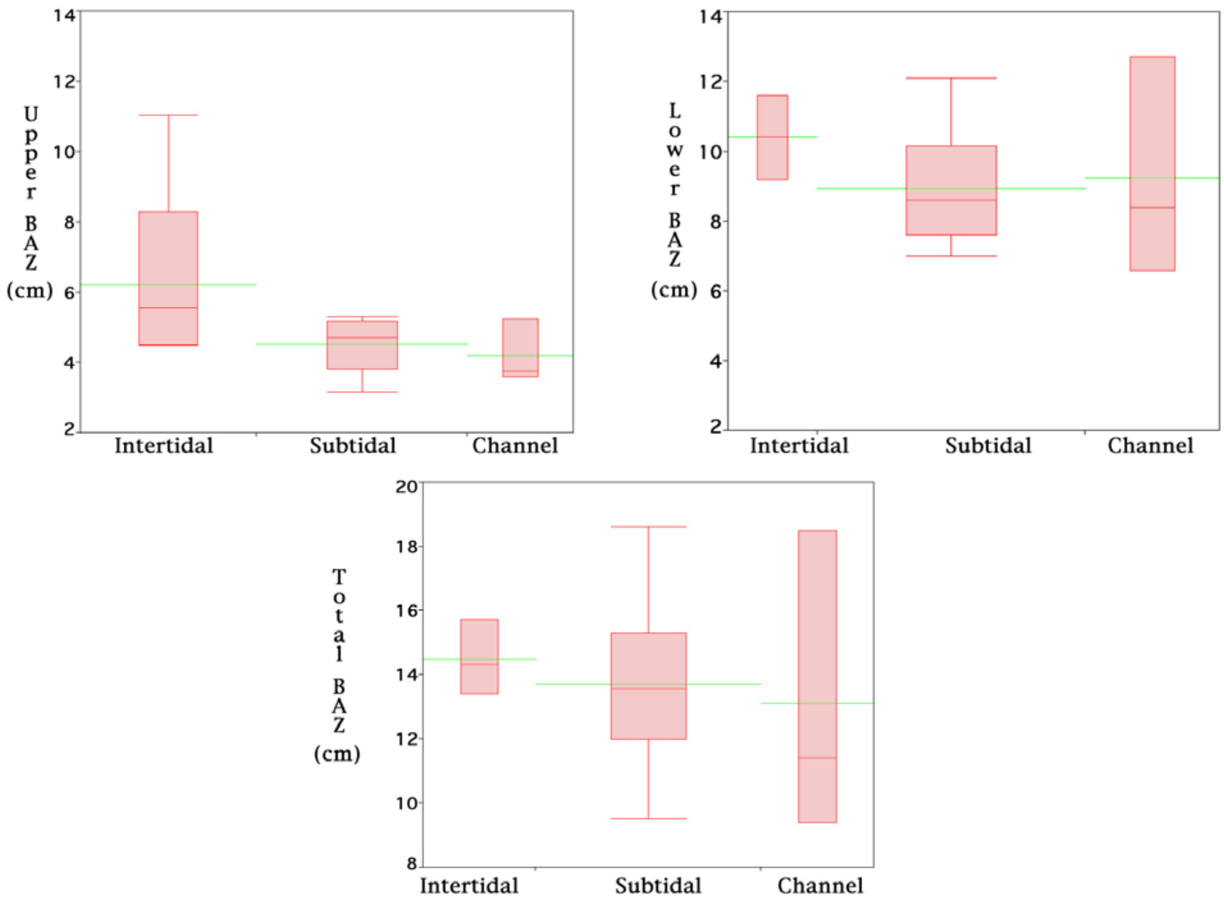

Figure 8. Box plot of the biologically active zone (BAZ) by geomorphic unit sampled, Newark Bay, October 2005. Box is interquartile range, whiskers are ranges, bar in box is median, bar extending from box is mean. Box width is proportional to sample size. See Table 8 for sample sizes for each zone and geomorphic unit.

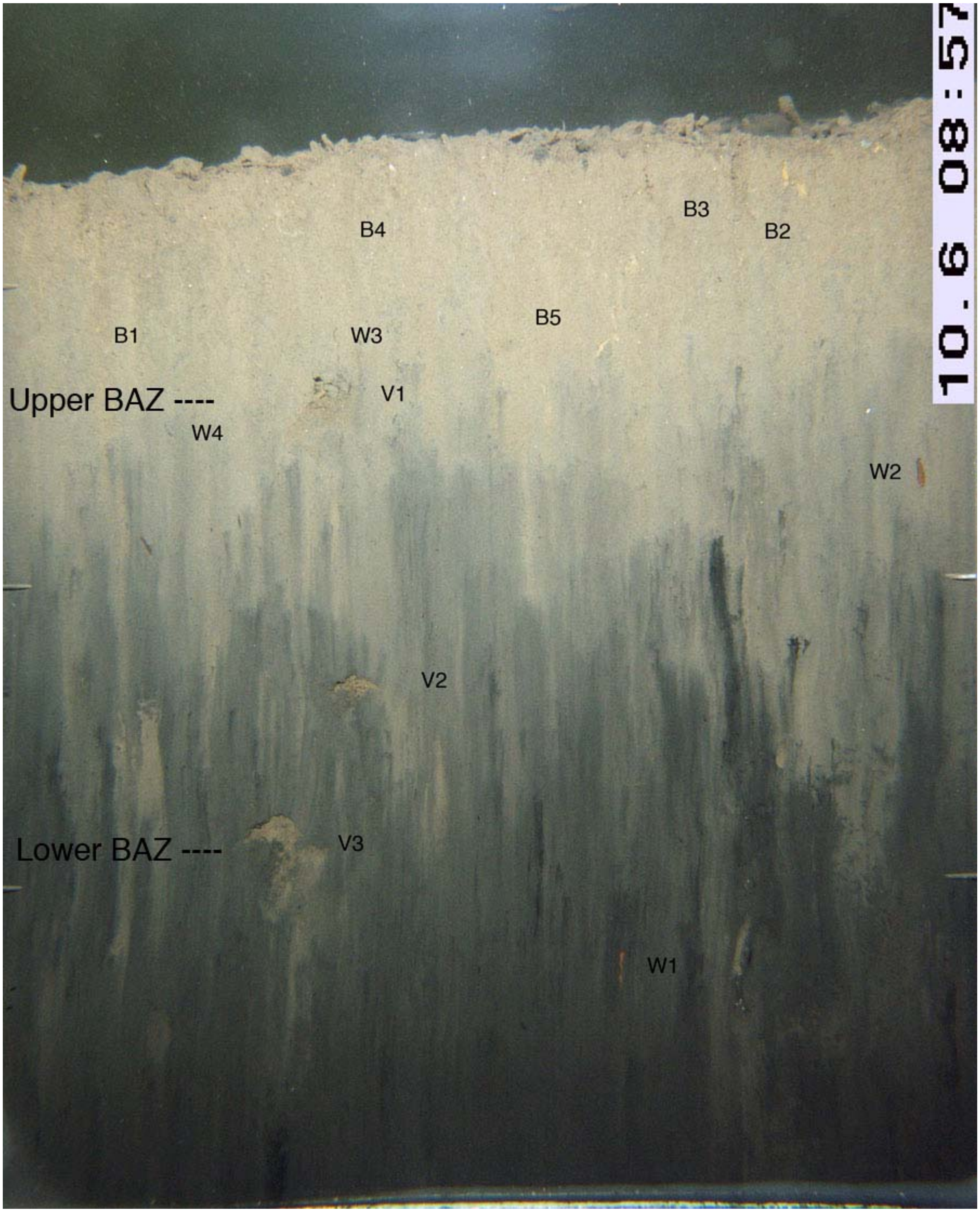

Figure 9. Intertidal station SED058 replicate 2, Newark Bay, October 2005. Burrows are labeled B1, B2, etc., Oxic voids V1, V2, etc., and infaunal worms W1, W2, etc. Tick marks on the side of the image are 5 cm apart.

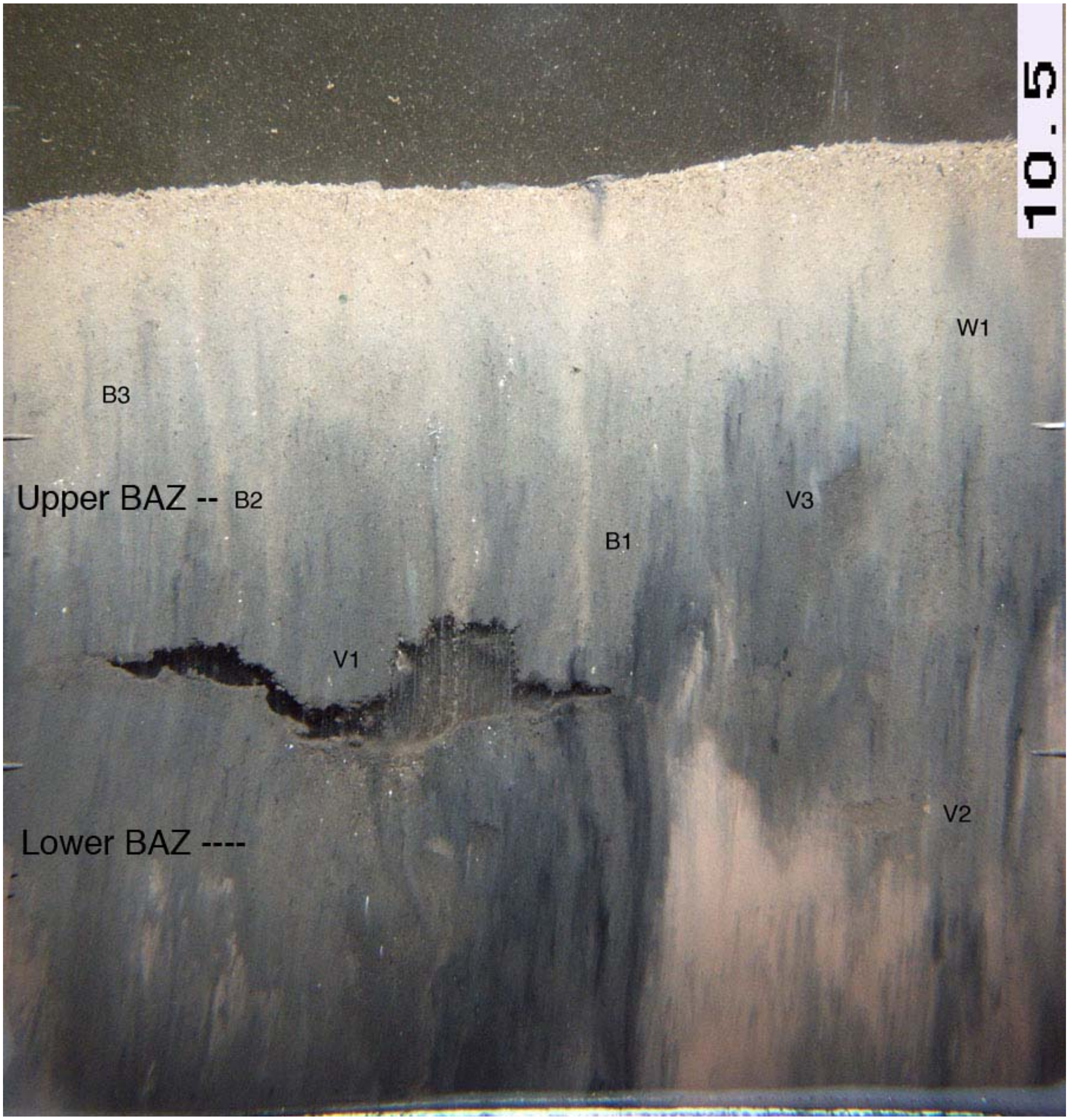

Figure 10. Subtidal station SED041 replicate 2, Newark Bay, October 2005. Burrows are labeled B1, B2, etc., Oxic voids V1, V2, etc., and infaunal worms W1, W2, etc. Tick marks on the side of the image are 5 cm apart.

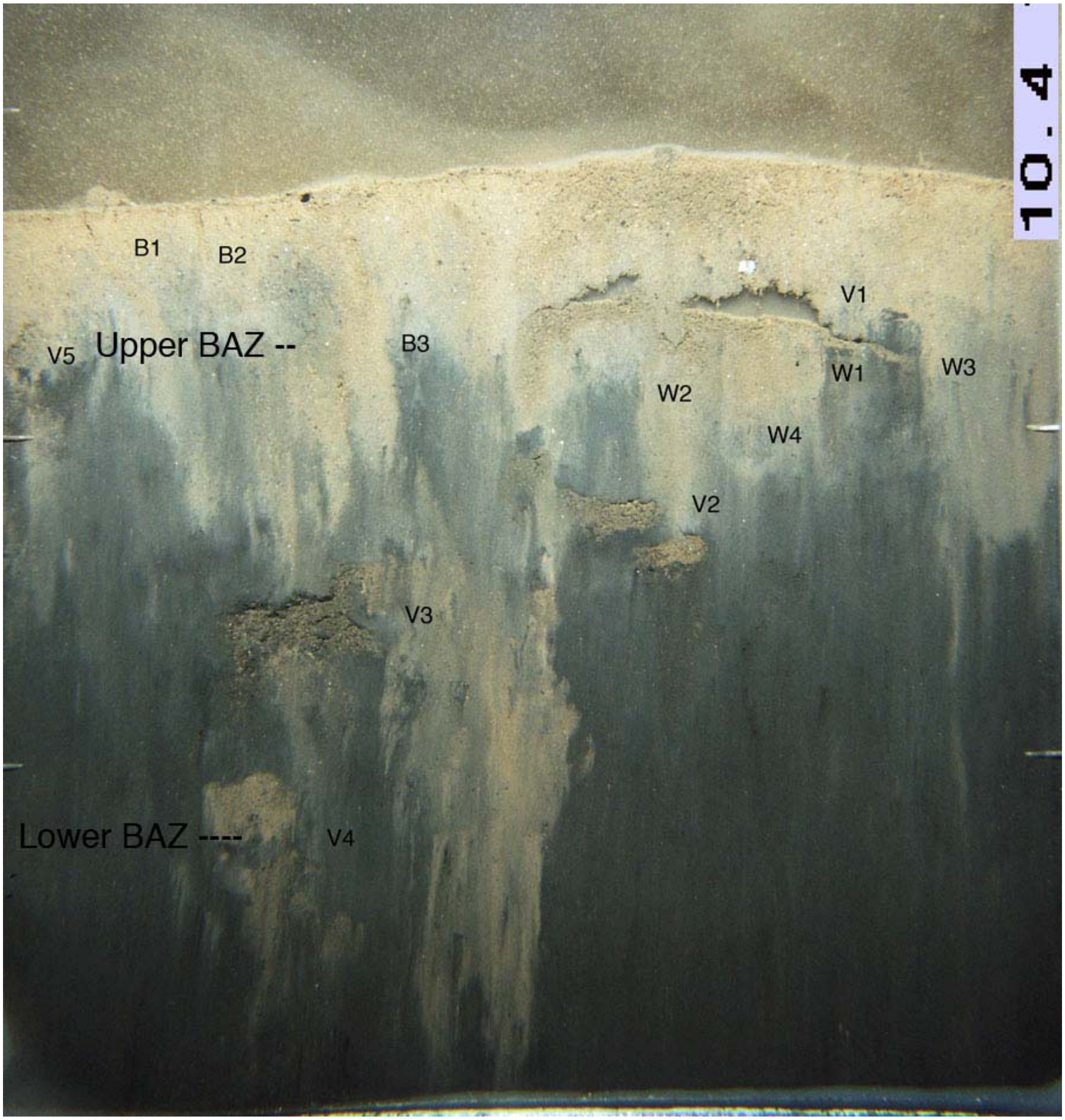

Figure 11. Channel station SED043 replicate 1, Newark Bay, October 2005. Burrows are labeled B1, B2, etc., Oxic voids V1, V2, etc., and infaunal worms W1, W2, etc. Tick marks on the side of the image are 5 cm apart.

Appendices

Appendix A

Data and Results from Biologically Active Zone (BAZ) Investigation, October 2005

Geomorphic Unit Station	Replicate	Prism Penetration cm	Surface Relief cm	aRPD cm	Avg. GrainSize[1]	Modal GrainSize[1]	Maximum Rough.[2]	Amphipod Bed #/image	Worm Tubes #/image	Tubes forms	Bed-Shell	Biogenic Mound	Pits/ Fines	Fluff Detritus	>1mm	Tubes Algae	Macro-Snail	Comment
Intertidal																		
SED002	1	16.8	3.0	3.8	SICL	SI	PHY	0	0	-	+	-	+	+	-	-	+	
	2	17.3	3.1	3.1	SICL	SI	PHY	0	0	-	-	-	+	+	-	-	+	
	3	22.1	0.0		SICL	SI	PHY	0	0	-	-	-	+	+	-	-	-	Over Penetrated
	4	18.8	2.0	3.6	SICL	SI	PHY	0	0	-	-	-	+	+	-	+	-	
	5	18.6	0.6	2.1	SICL	SI	PHY	0	0	-	-	-	+	+	-	-	-	
SED003	1	13.0	0.8	2.6	MS	GR	PHY	0	0	-	+	-	-	+	-	+	-	
	2	5.5	0.5	2.2	MS	CS	PHY	0	1-5	+	+	-	-	-	-	-	+	
	3	6.0	1.7	1.8	MS	GR	PHY	0	0	+	-	-	-	+	-	-	+	
	4	5.5	0.8	2.9	MSCS	GR	PHY	0	0	+	-	-	-	-	-	-	+	
	5	3.5	0.4	2.8	MS	CS	PHY	0	0	+	-	-	-	-	-	-	+	
SED038	1	8.9	0.6	4.3	FSMS	MS	PHY	0	6-23	+	+	-	-	-	-	+	-	
	2	7.1	1.2	6.2	FSMS	MS	PHY	0	0	+	+	-	-	-	-	-	+	
	3	7.4	0.9	6.3	FSMS	MS	PHY	0	1-5	+	+	-	-	-	-	+	+	
	4	7.3	0.8	6.6	FSMS	MS	PHY	0	6-23	+	+	-	-	-	-	-	-	
	5	6.7	1.3	3.9	FSMS	MS	PHY	0	6-23	+	+	-	-	-	-	-	+	
SED058	1	17.6	0.8	4.0	FSSICL	FS	BIO/PHY	6-23	6-23	-	-	+	-	-	-	-	-	
	2	17.7	1.3	4.1	FSSICL	FS	BIO/PHY	>23	6-23	-	-	+	-	-	-	-	-	
	3	17.5	0.5	3.8	FSSICL	FS	BIO/PHY	6-23	6-23	-	-	+	-	-	-	-	+	
	4	18.1	0.8	3.5	FSSICL	FS	BIO/PHY	6-23	6-23	-	-	-	-	-	-	-	-	
	5	16.8	1.3	4.1	FSSICL	FS	BIO/PHY	6-23	6-23	-	-	+	-	-	-	-	-	
SED065	1	9.1	0.8	2.5	FSSICL	FS	PHY	0	6-23	-	+	+	-	-	-	-	-	
	2	10.5	0.4	3.3	FSSICL	FS	PHY	0	1-5	-	+	+	-	-	-	-	-	
	3	10.8	0.5	3.2	FSSICL	FS	BIO/PHY	0	6-23	-	-	+	-	-	-	-	-	
	4	12.5	1.0	3.5	FSSICL	FS	PHY	0	1-5	-	+	+	-	-	-	-	-	
	5	14.5	0.6	3.3	FSSICL	FS	PHY	0	6-23	-	+	+	-	-	-	-	-	
Subtidal																		
SED014	1	22.7	1.0		FSSICL	FS				-	-		-	-				Disturbed Surface
	2	18.3	0.5	1.8	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	3	17.9	0.8	2.7	FSSICL	FS	BIO/PHY	0	>23	-	-	-	-	-	-	-	-	
	4	17.8	0.5	2.3	FSSICL	FS	BIO/PHY	0	6-23	-	-	+	-	-	-	-	-	
	5	19.1	0.6	2.2	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
SED022	1	15.6	0.4	2.9	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	2	15.0	0.7	2.8	FSSICL	FS	BIO/PHY	0	>23	-	-	-	-	-	-	-	-	
	3	14.9	1.0	2.8	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	4	14.1	0.7	2.5	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	5	14.9	1.3	2.7	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	+	-	-	
SED041	1	12.3	0.8	1.7	SICL	SI	PHY	0	>23	-	+	-	-	-	-	-	-	Reddish Clay
	2	14.3	0.9	2.2	SICL	SI	PHY	0	>23	-	+	-	-	-	-	-	-	Reddish Clay
	3	12.0	2.4	1.9	SICL	SI	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	Reddish Clay
	4	14.0	1.2	1.5	SICL	SI	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	Reddish Clay
	5	10.7	1.3	2.0	SICL	SI	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	Reddish Clay
SED045	1	16.0	2.1	3.9	FSSICL	FS	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	
	2	28.9	0.4	4.2	FSSICL	FS	BIO/PHY	0	>23	-	+	-	-	-	-	-	-	
	3	14.0	1.1	2.7	FSSICL	FS	BIO/PHY	0	6-23	-	+	+	-	-	-	-	-	
	4	17.3	3.1	2.8	FSSICL	FS	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	
	5	14.5	2.1	3.2	FSSICL	FS	BIO/PHY	0	6-23	-	+	+	-	-	-	-	-	

Geomorphic Unit Station	Replicate	Prism Penetration cm	Surface Relief cm	aRPD cm	Avg. GrainSize[1]	Modal GrainSize[1]	Maximum Rough.[2]	Amphipod Bed #/image	Worm Tubes #/image	Tubes forms	Bed-Shell	Biogenic Mound	Pits/ Fines	Fluff Detritus	>1mm	Tubes Algae	Macro-Snail	Comment
Subtidal Continued																		
SED056	1	21.2	0.6	3.7	SICL	SI	BIO/PHY	0	1-5	-	-	+	-	-	-	-	-	
	2	16.2	0.3	3.6	FSSICL	FS	BIO/PHY	0	6-23	-	-	+	-	-	-	-	-	
	3	14.2	1.7	3.5	FSSICL	FS	BIO/PHY	0	6-23	-	-	+	-	-	-	-	-	
	4	15.1	0.8	2.8	FSSICL	FS	BIO/PHY	0	6-23	-	-	+	-	-	-	-	-	
	5	17.3	1.2	2.8	FSSICL	FS	BIO/PHY	0	6-23	-	-	+	-	-	-	-	-	
SED060	1	11.9	1.4	2.8	FSSICL	FS	PHY	0	6-23	-	-	+	-	-	-	-	-	
	2	14.3	0.5	3.4	FSSICL	FS	PHY	0	>23	-	-	+	-	-	-	-	-	
	3	19.1	0.4	3.6	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	4	21.3	1.0	3.2	FSSICL	FS	PHY	0	1-5	-	-	-	-	-	-	-	-	
	5	16.2	0.4	3.5	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
Channel																		
SED004	1	17.1	0.6	3.4	FSSICL	FS	BIO/PHY	0	>23	-	-	-	-	-	-	-	-	
	2	15.5	0.8	3.1	FSSICL	FS	BIO/PHY	0	>23	-	-	-	-	-	-	-	-	
	3	21.0	1.4	5.4	FSSICL	FS	PHY	0	0	-	-	-	-	-	-	-	-	
	4	14.8	0.5	3.5	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	5	16.5	0.1	3.1	FSSICL	FS	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
SED043	1	14.3	1.0	2.2	SICL	SI	BIO/PHY	0	1-5	-	-	+	+	-	-	-	-	
	2	13.0	0.9	2.0	SICL	SI	BIO/PHY	0	>23	-	-	+	-	-	-	-	-	
	3	15.0	2.5	3.1	SICL	SI	BIO/PHY	0	1-5	-	-	+	+	-	-	-	-	
	4	6.9	1.6	1.8	SICL	SI	BIO/PHY	1-5	>23	-	-	+	-	-	+	-	-	Reddish Clay
	5	12.4	0.8	1.7	SICL	SI	BIO/PHY	0	6-23	-	-	+	-	-	+	-	-	
SED063	1	11.5	0.6	2.7	FSSICL	FS	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	
	2	11.6	0.4	2.5	FSSICL	FS	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	
	3	9.6	1.0	1.7	FSSICL	FS	BIO/PHY	0	>23	-	+	+	-	-	-	-	-	
	4	10.7	0.6	1.6	FSSICL	FS	BIO/PHY	0	6-23	-	+	+	-	-	-	-	-	
	5	16.1	0.7	2.9	FSSICL	FS	PHY	0	6-23	-	+	-	-	-	-	-	+	

APPENDIX A – Data and Results from Biologically Active Zone (BAZ) Investigation, October 2005

Geomorphic Unit Station	Replicate	Succession Stage	OSI	Length of Burrows 1 cm	Length of Burrows 2 cm	Length of Burrows 3 cm	Length of Burrows 4 cm	Length of Burrows 5 cm	Depth of Oxic void 1 cm	Depth of Oxic void 2 cm	Depth of Oxic void 3 cm	Depth of Oxic void 4 cm	Depth of Oxic void 5 cm	Depth of Anaerobic Voids 1 cm	Depth of Anaerobic Voids 2 cm	Depth of Anaerobic Voids 3 cm	Depth of Infauna 1 cm	Depth of Infauna 2 cm	Depth of Infauna 3 cm	Depth of Infauna 4 cm	Depth of Infauna 5 cm	Depth of Gas Voids 1 cm	Depth of Gas Voids 2 cm	Thickness of Upper BAZ cm	Thickness of Lower BAZ cm	Thickness of Total BAZ cm
Intertidal																										
SED002	1	I-III	11						13.4								11.5							UND	UND	13.4
	2	I	6	11.1	11.0												11.8							11.0	UND	
	3	I																				17.4		UND	UND	
	4	I	4																			15.3		UND	UND	
	5	I	2											7.4	8.9							7.8		UND	UND	
SED003	1	I	5																					UND	UND	
	2	I	4	4.6																				4.6	UND	
	3	I	4	5.3																				5.3	UND	
	4	I	5	4.5	5.0																			4.7	UND	
	5	I	5	3.2	3.3	3.2																		3.2	UND	
SED038	1	I	7														7.2							UND	UND	
	2	I-III	11						4.3	3.4							3.3	6.1						UND	4.3	V<B
	3	I-III	11	5.4					4.6								5.9							5.4	UND	
	4	I	5	5.2																		1.6	3.1	5.2	UND	
	5	I-III	11	5.9	6.1				5.1	4.6							1.9	2.6	5.0					6.0	UND	
SED058	1	I-II	8	4.9	6.3	3.9	13.6	4.4																6.6	UND	
	2	I-III	11	4.8	3.3	4.6	2.7	5.5	4.0	8.9	11.3						13.9	6.1	3.2	4.3				4.2	11.3	15.5
	3	I-III	11	4.3	6.3	3.0	3.8	4.3	9.9								5.5							4.4	9.9	14.3
	4	I-III	8	4.8	3.8	4.2	3.6	3.0	13.6								6.3					9.3		3.9	13.6	17.5
	5	I-II	8	4.3	4.1	2.3	3.8	3.0									7.6							3.5	UND	
SED065	1	I-III	9	3.6	3.0	2.1	2.7		5.3	5.6	7.5	8.4	4.8				2.8							2.9	8.4	11.3
	2	I-III	10	10.1	8.8	3.6			6.7	4.5							1.5							7.5	UND	
	3	I-III	10	7.7	8.6	3.1	3.9	2.6	9.5	5.3														5.2	9.5	14.6
	4	I-III	8	10.8	4.1	4.9			5.1	9.0							4.7	4.0	9.1		8.5	5.5		6.6	9.0	15.6
	5	I-III	10	6.9	6.1	6.3	2.8		9.3	7.5	10.2													5.5	10.2	15.7
Subtidal																										
SED014	1	I-III							7.2								1.3	1.0						UND	UND	7.2
	2	I-III	8	1.8	1.8				5.1	5.6	5.0						4.4	3.1	5.6	2.7				1.8	5.6	7.4
	3	I-III	7	2.4	2.6	2.9			3.6								2.7					16.1		2.6	3.6	6.2
	4	I-III	9	4.8	4.7	4.6			7.0	6.3	6.7	7.6					4.8	2.9	2.7					4.7	7.6	12.4
	5	I-III	8	3.1	3.9				6.8	10.9	8.4						3.2							3.5	10.9	14.4
SED022	1	I-III	9	4.1	3.7				5.4								4.2							3.9	5.4	9.3
	2	I	5	4.3	4.4	4.6								12.9	14.2		4.7	4.4	4.1	3.1	6.6			4.4	UND	
	3	I-III	9	6.3	4.8	3.9			7.5	7.5				14.4			6.1	2.2	5.4	3.7	2.8			5.0	7.5	12.5
	4	I-III	9	5.7					10.4								12.6	3.2	3.4					5.7	10.4	16.1
	5	I-III	9	6.5	8.4	4.1			7.8	7.9				12.7			4.8	1.9	3.5					6.3	7.9	14.3
SED041	1	I-III	8	3.2					6.4								8.6							3.2	6.4	9.6
	2	I-III	8	6.6	4.8	3.6			8.0	10.2	5.3						2.6							5.0	10.2	15.2
	3	I-III	6	6.0					9.9	11.0	10.8						2.3	2.1				6.2	7.8	6.0	11.0	17.0
	4	I-III	6	1.7	3.1				5.8	9.6							2.9					5.6		2.4	9.6	12.0
	5	I-III	8	3.4	3.8				6.5	6.8							4.6	10.0	2.5					3.6	6.8	10.4
SED045	1	I-III	11	4.8					4.7	6.7							2.3	4.1						4.8	6.7	11.6
	2	I-III	11	7.2	4.7	6.3			11.0								2.7	2.4	3.0	0.7				6.1	11.0	17.1
	3	I-III	9	5.9	12.1	6.6			11.2								3.5							8.2	11.2	19.4
	4	I-III	9	3.8	3.6	4.2			4.8	3.7				17.6			2.0	1.8						3.9	4.8	8.6
	5	I	6	2.0	1.9	4.1								11.9										2.7	UND	

APPENDIX A – Data and Results from Biologically Active Zone (BAZ) Investigation, October 2005

Geomorphic Unit Station	Replicate	Succession Stage	OSI	Length of Burrows 1 cm	Length of Burrows 2 cm	Length of Burrows 3 cm	Length of Burrows 4 cm	Length of Burrows 5 cm	Depth of Oxic void 1 cm	Depth of Oxic void 2 cm	Depth of Oxic void 3 cm	Depth of Oxic void 4 cm	Depth of Oxic void 5 cm	Depth of Anaerobic Voids 1 cm	Depth of Anaerobic Voids 2 cm	Depth of Anaerobic Voids 3 cm	Depth of Infauna 1 cm	Depth of Infauna 2 cm	Depth of Infauna 3 cm	Depth of Infauna 4 cm	Depth of Infauna 5 cm	Depth of Gas Voids 1 cm	Depth of Gas Voids 2 cm	Thickness of Upper BAZ cm	Thickness of Lower BAZ cm	Thickness of Total BAZ cm
Subtidal Continued																										
SED056	1	I	4	5.0	4.0												2.3					9.4		4.5	UND	
	2	I-III	10	5.5					11.6	10.4							6.0	5.2						5.5	11.6	17.1
	3	I-III	10	5.1	4.7	3.3	2.8	5.3	8.2	4.7	6.9						3.1	1.9	4.5	5.1				4.2	8.2	12.4
	4	I	7	3.5	2.6	3.8								13.2	13.7		2.0	5.0	3.3	4.1		11.5		3.3	UND	
	5	I-III	9	4.3					8.6					12.8	14.0	12.4	4.1	4.1	5.1					4.3	8.6	12.9
SED060	1	I	7	3.2	3.3	3.3											2.0	2.0	3.1	4.8	4.7	2.8	6.6	3.3	UND	
	2	I	8	5.2	3.5	3.8	2.0							11.9	10.7	13.5	4.2					10.6		3.6	UND	
	3	I-III	10	18.5	14.5	5.0	5.2	9.2	16.3	17.9							18.5	14.5	3.7					10.5	17.9	28.4
	4	I-III	10	7.8	2.0	5.5			10.1								17.5	12.5						5.1	10.1	15.2
	5	I-III	10	4.0					6.2	8.2														4.0	8.2	12.2
Channel																										
SED004	1	I-III	10	6.4	3.8	3.8	11.1	5.9	12.0								8.3	5.2	5.4	3.1	2.8			6.2	12.0	18.2
	2	I	6	4.5	5.5	3.4	3.3	4.2						14.6			3.6							4.2	UND	
	3	I-III	11	6.6	6.8				17.3	6.9							17.7	15.3	5.6	6.5	7.5			6.7	17.3	24.0
	4	I-III	8	2.9	6.9	4.1	4.4	5.1	2.9								2.4	5.4	4.8	10.0		8.5		4.7	UND	
	5	I-III	8	4.4	4.9	3.6	4.6	4.8	4.7	4.2	8.1	8.8					3.0	2.3	0.4			8.0		4.5	8.8	13.3
SED043	1	I-III	8	2.2	1.1	4.2			2.4	5.6	6.6	9.6					2.8	3.4	2.8	4.1				2.5	9.6	12.1
	2	I-III	8	3.6	3.1	5.2	2.8	5.5	1.8	10.6							4.2	2.6						4.0	10.6	14.6
	3	I-III	10	14.9	2.8	2.4	6.0	2.3	3.2	2.4														5.7	UND	
	4	I-III	8	1.4	2.9	2.0	4.0		1.3	4.2	3.2	1.3		10.3			0.7	1.9	2.3					2.6	4.2	6.8
	5	I-III	8	2.3	3.0	4.0			8.1	9.0														3.1	9.0	12.1
SED063	1	I-III	9	3.1	2.5	2.8	2.6	3.1	5.2	6.5				10.6			2.9							2.8	6.5	9.3
	2	I-III	9	3.9	6.7	3.0	3.6	2.7	4.6					10.2			6.4	5.3	2.3					4.0	4.6	8.6
	3	I-III	8	4.2	2.3	2.3	1.7	2.4	4.8	5.7	3.4	6.6					2.4	3.8	2.4	1.6				2.6	6.6	9.1
	4	I-III	8	1.9	2.4	1.9	1.6	2.0	8.7								1.5							2.0	8.7	10.7
	5	I-III	9	14.1	5.5	2.5			6.2															7.3	UND	

[1]See Table 1 in main report for sediment class abbreviations.
[2]PHY = Physical processes dominate sediment surface, BIO/PHY = Combination of biological and physical processes dominate surface, UND = Undefined.
BAZ – Biologically active zone.
OSI – Organism-sediment index.
aRPD – Apparent color redox potential discontinuity depth.
UND – Undefined.

Appendix B

Sediment Profile Images, October 2005

Provided on CD ROM

Appendix C

November 2005 BBL (ARCADIS) Technical Memorandum

Biologically Active Zone (BAZ) Literature Review

MEMORANDUM

BLASLAND, BOUCK & LEE, INC.
engineers, scientists, economists

To: Paul Bluestein

Date: November 11, 2005

From: Tim Iannuzzi
Ashley Standbridge

cc: Rick McNutt, Tierra Solutions, Inc.
Cliff Firstenberg, Tierra Solutions, Inc.
Robert Romagnoli, BBL

Re: Draft - Literature Review on Biologically Active Zone (BAZ) in Sediments

The following is a summary of the available studies that have focused on the description and definition of the biologically active zone (BAZ) in sediments. BBL conducted this literature review as part of our efforts to understand the following:

- How the BAZ is typically measured or defined;
- What set of parameters are typically used by researchers to define/determine the BAZ; and,
- What has been the reported depth of the BAZ at various sites where it has been defined.

The relevant findings of our review are provided in Table 1 which is a matrix of the data and information compiled from the available literature on the subject. This memorandum provides perspectives on the available BAZ literature and highlights key findings from the studies that are discussed in Table 1.

Results of Literature Search/Review

The available literature regarding the BAZ in sediments is limited and varies in technical focus. This is surprising given the importance of defining the BAZ in the ecological risk assessment process, and for estimating the bioturbation/mixing zone in sediments for chemical fate and transport studies.

BBL was able to locate (to date) a total of 31 studies that contained investigations that were either primarily or secondarily focused on the definition or description of the BAZ in sediments. A broad range of data and information were included in these studies. Most studies have been conducted since 1990 and include both laboratory and field experiments. The primary focus of the studies can be classified into four general categories:

- Bioturbation investigations;
- Sediment sampling methods/specifications;
- Sediment fate and transport models and assessments; and,
- Capping for contaminated sediment remediation.

The majority of these studies have some component that focuses on bioturbation activities in sediments, as this is important for each of the four categories of studies and, by definition, determines the existence and depth of the BAZ in sediments. A total of five studies used sediment profile imaging (SPI), similar to that recently conducted by Tierra as part of its work in the Newark Bay Study Area, as a tool to help define the BAZ.

Findings Related to the Description/Definition of the BAZ

A total of 22 of the compiled studies determined a depth or depth range for the BAZ. A wide range of BAZ depths were reported. The most common value, which was determined in 12 studies, is 10 centimeters (cm). The range of reported BAZ depths was 3 cm to 50 cm. Most values were between about 10 cm and 20 cm.

Most of the reported values for the BAZ are location-specific. However, in two papers that describe a model for understanding bioturbation in sediments, Boudreau (1994; 1998) proposes a worldwide constant BAZ depth of 9.8 cm +/- 4.5 cm.

The following is a summary of select studies from Table 1 that deal directly with the description and definition of the BAZ in sediments. The studies suggest varying BAZ depths along a wide-range of geographic areas and ecosystem types.

- Fuller et al. (1999) presented a study on the sediment chronology in San Francisco Bay. They looked at two coring sites in Richardson Bay at the mouth of San Francisco Bay. Fuller et al. discovered that both biological and physical processes caused rapid dilution of sediment-bound contaminants in the upper 33cm of the sediment column.

- ARCADIS Geraghty and Miller, Inc. (1999) defined the BAZ as the zone encompassing 95% of the sediment biota which is noted by the authors as being consistent with U.S. Environmental Protection Agency (USEPA) methodology for developing criteria protective of aquatic life. The data from the six sampling stations in San Diego Bay indicated that between 90 and 99 percent of the organisms were found to a depth of 20 cm.

- In a study in Palos Verdes, CA, Swift et al. (1996) examined the significance of the biodiffusion coefficient. In the Palos Verdes area there is a deep layer of DDT contaminated sediment. Their study found that bioturbation could extend below effluent deposits from an outfall to the contaminated layer. They found that the "fully mixed zone" was variable in the system, ranging from 30 cm deep by the outfall to less than 5 cm up-current of the outfall.

- Diaz et al. (1994) documented the general state of sediment mixing and bioturbation off the coast of Cape Hatteras, NC. Using SPI and X-ray imaging they estimated the mixed layer to range from 5-20 cm. At the same location using Pb-tracers, the BAZ depth was estimated to be slightly less, between 3 and 12 cm.

- Diaz (2004) described sedimentary and benthic conditions in the Scotia and Weddell Seas of Antarctica in 2002. He used SPI to examine bioturbation depths. He based active mixing on the presence of active biogenic structures. Depths of observed benthic activity varied at the many sampling stations. Diaz concluded that BAZ depth is dependent upon sediment type. At silty and clayey stations it measured 9.9 cm, while at silty-sand stations it was only 5.6 cm.

- Cunningham et al. (1999) examined the effects of bioturbation in contaminated sediments in the Campus Lake of Baton Rouge, LA. They assessed how the movement (burrowing, respiration and feeding) of oligochaetes affects the fate and transport of PAHs. Bioturbation was found to occur to a depth of 10 cm.

- Matisoff and Wang (1993) examined the affects of particle mixing by freshwater infaunal bioirrigators in the western basin of Lake Erie. They found that burrowing and feeding activities of the organisms resulted in mixing within the upper 10 cm of the sediment.

- Clark et al. (2001) suggest that depth of bioturbation is highly location-specific, reflecting the different behaviors of benthic organisms and their interaction with the environment. This statement was emphasized by their findings in which they note a range of BAZ values from 5 to 30 cm at various study sites along the Palos Verdes shelf in California. The same study reported a mean BAZ depth of 10 cm in the New York Bight.

The results of our literature review suggest that the geographic location, ecosystem/habitat type, types of organisms inhabiting the sediments, and site-specific physiography and sediment conditions, control the depth of the BAZ in sediments. While the range of reported BAZ depths in these studies is substantial, most measured BAZ depths were between about 10 and 20 cm. The average BAZ depth for Newark Bay, as recently determined by Tierra under the Phase I Remedial Investigation, is about 15 cm. This is consistent with values reported in this literature review.

TJI/eaj

TABLE 1.

REVIEW OF AVAILABLE SCIENTIFIC LITERATURE ON THE BIOLOGICALLY ACTIVE ZONE (BAZ) IN SEDIMENTS

No.	Title	Authors	Publication	Study Date	Study Location	Key Objectives	BAZ-Specific Investigations	Results	Estimated BAZ Depth	Notes:
1	The bioturbation-driven chemical release process	Thibodeaux, L.J. and V.J. Bierman	Environmental Science & Technology, July 2003	NS	NA	Explain key technical aspects of the particle deposition/resuspension and bioturbation processes.	Examine the combined activities of infaunal and epifaunal species responsible for active sediment bed turnover, and to what depths.	Turnover found at 10cm or more. Bioturbation alters the surface sediment layers and effectively destroys any thin clean soil layer less than 10cm thick.	10cm	
2	Assessment of the effects of bioturbation in contaminated sediments	Cunningham, P.B., D.D. Reible, J.F. Fleeger, K.T. Valsaraj, and L.J. Thibodeaux	Proceedings of the 1999 Conference on Hazardous Waste Research	NS	Campus Lake, LSU campus, Baton Rouge, LA	Assess how oligochaete bioturbation-feeding, respiration, and burrowing-impacts the fate and transport of PAHs.	Examine the depth of feeding and burrowing of oligochaetes.	Bioturbation had a drastic impact on both the sediment and the pyrene over the course of a seven-month experiment including an increase in the porosity and moisture content in the upper 14mm.	Feeding depth can extend to a depth of 10cm	Laboratory experiment
3	Analytical approximation to characterize the performance of *in situ* aquifer bioremediation	Keijzer, H., M.I.J. van Dijke, and S.E.A.T.M. van der Zee	Advances in Water Resources. 1999. 23:217-228	NS	NA	Explain the influence of the physical and biochemical properties of the soil on the performance of the in situ remediation: use the front shape to show in more detail how various model parameters affect the contaminant removal rate and the BAZ	Show how various model parameters affect the BAZ , which is based on the front shape of the electron acceptor.	BAZ depends on the front shape of the electron acceptor, especially the biodegradation-dominated part of the electron acceptor concentration front. A tailing in the biodegradation-dominant part implies a large BAZ.	NS	Models
4	Oscillatory dynamics of the biologically active zone in *in situ* bioremediation	Murray, R.E. and B.P. Luce	Water Resources Research. 2002. 38(10):21 1 - 21-15	NS	NA	Model the dynamics of the BAZ.	Model development.	Results model the dynamics of the BAZ in terms of growth of the biomass concentration and changes in the width of the reaction zone.	NS	Models
5	Transformation kinetics of trace-level halogenated organic contaminants in a biologically active zone (BAZ) induced by nitrate injection	Bae, W., J.E. Odencrantz, B.E. Rittmann, and A.J. Valocchi	Journal of Contaminant Hydrology. 1990. 6:53-68	NS	NA	Investigate the degradability of several common halogenated solvents by a BAZ of a denitrifying microflora established through injection of NO_3 as the electron acceptor into a porous-medium column which was fed with acetate as the primary substrate.	Examine the degradation kinetics of compounds in the BAZ and the effect of BAZ contact time.	Models correctly described all trends: removal of the halogenated compounds only occurred in the BAZ; greater removal with increased BAZ contact time; and reduced specific removal rates caused by diffusion limitation in the biofilm.	12.5cm	The first conclusion showed that all removals occurred within 12.5cm downstream of the injection, which defined the extent of the BAZ.
6	Environmental impacts of PAH and oil release as a NAPL or as contaminated pore water from the construction of a 90cm in situ isolation cap	Herrenkohl, M.J., J.D. Lunz, R.G. Sheets, and J.S. Wakeman	Environmental Science & Technology. 2001. 35:4927-4932	NS	Wyckoff/Eagle Harbor Superfund Site (Puget Sound)	Discuss the issues of NAPL and consolidation-related advection into a cap.	Include methods with the upper 10cm, considered the BAZ, remaining below the Washington State Sediment Management Standards min. cleanup standards.	"In a 40cm cap, only one 10cm cap sample (located at 30-40cm, above contaminated sediments) showed impact of pore water into overlying cap material."	10cm	The top 10cm was stated as the BAZ, without explanation.
7	Subaqueous cap design: selection of bioturbation profiles, depths, and process rates	Clark, D.G., M.R. Palermo, and T.C. Sturgis	DOER Technical Notes Collection (ERDC TN-DOER-C21). 2001	NS	NA	Address the estimation of bioturbation profiles, depths, and process rates in relation to subaqueous cap design.	Describe bioturbation profiles and depth estimates.	"Intensity and depth to which bioturbation occurs in the sediment column are highly site specific, reflecting the myriad behaviors of diverse assemblages of benthic organisms and their interactions with the physical environment."	10cm/5.0 to 30 cm	1) The sacrificial mixing zone associated with the RPD, extends to a depth of 10 or more cm. 2) BAZ has a mean depth of 10cm in the New York Bight while the fully mixed zone ranged from 5-30cm on the Palos Verdes shelf
8	Predicting dredged-material cap thickness from data on benthic community structure	Shull, D.H. and E.D. Gallagher	MIT Sea Grant Center for Coastal Resources. 1998. 1-18	NS	Boston Harbor	Present models for predicting the sediment-mixing depth within capped sediments at a particular location given knowledge of the benthic community structure of the region or a list of species which could potentially colonize a sediment cap.	NS	"Under the worst-case scenario approach, a 25cm cap would isolate dredged material, while under the ambient community approach, a 19cm thick cap would be sufficient. It is also assumed that a 30cm cap is required to contain contaminants diffusing upward."	NS	Capping

No.	Title	Authors	Publication	Study Date	Study Location	Key Objectives	BAZ-Specific Investigations	Results	Estimated BAZ Depth	Notes:
9	Mean mixed depth of sediments: the wherefore and the why	Boudreau, B.P.	Limnology and Oceanography. 1998. 43(3):524-526	NS	NA	Present a model for understanding bioturbation.	Try to understand the depth of the BAZ as a constant.	"The resource (food)-feedback model of bioturbation not only predicts the existence of a finite-depth bioturbated zone in sediments, but substitution of currently available parameter values into this model indicates that the mean mixing depth should be a worldwide constant of 9.7cm, independent of water depth or sedimentation rate."	9.7cm	Narrow sacrificial zone of marine sediments with a world-wide, environmentally invariant mean of 9.8cm with a standard deviation of 4.5cm.
10	Is burial velocity a master parameter for bioturbation?	Boudreau, B.P.	Geochimica et Cosmochimica. 1994. 59(4):1243-1249	NS	NA	Examine the relationship between D_b (biodiffussion coefficient describing intensity of mixing at depth x), L (mixing depth), and w (burial velocity).	Try to understand the depth of the BAZ.	"The depth of mixing is limited primarily by the physical difficulty and increasing energy costs of working deeper than 10-15cm; the mixed depth appears independent of the burial velocity, meaning that an average can be used in sediment modeling with 'considerable confidence'"	9.8cm +/- 4.5cm	
11	Biological and physical processes structuring deep-sea surface sediments in the Scotia and Weddell Seas, Antarctica	Diaz, R.J.	Deep-Sea Research II. 2004. 51:1515-1532	January-March 2002	Scotia Sea and Weddell Sea, Antarctica	Describe sedimentary and benthic conditions at the ANDEEP station.	Examine bioturbation depths with sediment profile imaging (SPI).	Bioturbation depths varied between sampling stations: 12.4cm at station E1, 9cm at station F4, 17.5cm at station K1, and 12.4cm at station W8.	9.9cm @ silty and clayey stations, 5.6cm @ silty-sand stations	Depth to which sediments appeared actively mixed by biological processes was based upon the presence of active biogenic structures.
12	Depth correlated benthic faunal quantity and infaunal burrow structures on the slopes of a marine depression	Rosenberg, R., H.C. Nilsson, B. Hellman, and S. Agrenius	Estuarine, Coastal and Shelf Science. 2000. 50:843-853	September 1994	Alkor Deep, Kattegat Sea, Sweden	Investigate the benthic faunal composition and their sedimentary habitat on the slopes and deep bottom of the Alkor Deep (deep sea trench) using SPI.	Examine bioturbation depths with sediment profile imaging (SPI).	"The maximum depth where tunnels and voids were seen in the SPIs were 18.8cm and in most cases below 10cm in the sediment; the bottoms of the Alkor Deep are extensively bioturbated, especially below about 80m water depth"	NS	The mean apparent redox potential discontinuity (RPD) was found as deep as between 8.0 and 11.3cm depth, and RPD was significantly positively correlated with water depth.
13	Sediment profile imaging of soft substrates in the western Mediterranean: the extent and importance of faunal reworking	Grehan, A.J., B.F. Keegan, M. Bhaud, and A. Guille	Academic des Sciences. 1992. t.315, Serie III:309-315	September 1991	Baie de Banyuls on southwest Mediterranean coast of France	Study the extensive nature of biological sediment structuring of the sediments in the Bay.	NS	Commonly, there was evidence of bioturbation to depths of 10cm or more. The RPD depression reached 10cm.	NS	Bioturbation depth
14	Characterization of soft-bottom benthic habitats of the Aland Islands, northern Baltic Sea	Bonsdorff, E., R.J. Diaz, R. Rosenberg, A. Norkko, and G. R. Cutter Jr.	Marine Ecology Progress Series. 1996. 142:235-245	June 1993	Aland archipelago, southwest coast of Finland, Baltic Sea	Classify the benthic environments in the Aland archipelago.	Characterize the sediment and zoobenthic habitats in the Aland archipelago using SPI, and describe qualitatively and quantitatively the benthic infauna.	"The chironomid burrows observed down to 15cm in the soft muddy habitats with low oxygen content illustrate the role of burrowers in oxygenating deep layers of the sediment and participating in the remineralization of nutrients from the sediment to the water column."	NS	Burrowing depth
15	Hydrocarbons and fatty acids in two cores of Lake Huron sediments	Meyers, P.A., R.A. Bourbonniere, and N. Takeuchi	Geochimica et Cosmochimica. 1980. 44:1215-1221	NS	Southeastern Lake Huron	Compare geolipid content of two cores of sediment which differ in age by 11,000 years, but have similar locations.	NS	"Rapid decreases in total acids and the percentage of unsaturated components evident in the upper portion of core SLH-74-12 cease at 12cm. Lack of further change in concentration or in chain-length distribution with greater depth in this core shows that little degradation of acids occurs beneath the BAZ of surface sediments."	12cm	
16	Contaminant characterization of sediment and pore-water in the Clinch River and Poplar Creek	Levine, D.A., R.A. Harris, K.R. Campbell, W.W. Hargrove, and C.D. Rash	Second SETAC World Congress (16. annual meeting): Abstract book, 1995	NS	Clinch River and Poplar Creek, TN	Characterize concentrations and spatial distribution of contaminants for use in ecological risk assessment.	Assess with the top sediments representing the BAZ	Sampling of BAZ conducted to 15cm depth.	15cm	Sediment cores were collected at each site and the top 15cm was analyzed to represent the BAZ

No.	Title	Authors	Publication	Study Date	Study Location	Key Objectives	BAZ-Specific Investigations	Results	Estimated BAZ Depth	Notes:
17	Sea-bed mixing and particle residence times in biologically and physically dominated estuarine systems: a comparison of Lower Chesapeake Bay and the York River Subestuary	Dellapenna, T.M., S.A. Kuehl, and L.C. Schaffner	Estuarine, Coastal and Shelf Science. 1998. 46:777-795	January 1994-December 1995	Lower, central Chesapeake Bay and the York River subestuary	Compare sites within both waterways to investigate biological (Lower Bay) and physical (York River) controls on particle residence time and strata formation.	NS	"In the lower bay, sediment profiles show generally variable excess activities near the surface (0-5cm) and more uniform at depth (10-20cm) suggesting a zone of intense mixing. Also shows intensive bioturbation with no preservation of physical stratification below 5cm. In the York River, physical mixing depths ranged from 40 to 120cm"	NS	
18	Initial field investigation (Chapter 5)	Wisconsin Department of Natural Resources	Wisconsin DNR, Bureau of Watershed Management, 2003 http://www.dnr.state.wi.us/org/water/wm/wqs/sediment/assessment/mgp/subdocs/5.html	NS	NA	Present methods for field sampling.	NS	"Sediment cores can be subsampled by segment defined by visible strata or, if these are lacking, by predetermined depth increments. The upper 10 to 15 cm. segment core is typically considered to represent surficial, biologically active conditions."	10-15cm	
19	Final report - models for alteration of sediments by benthic organisms: sediments	Water Environment Research Foundation	1995	NS	Multiple	(Table 3-1) Reported Values of the Particle Biodiffusion Coefficient (D_B) and the Depth of the Mixed Layer (L).	Literature review	Table shows the mixed layer depth for many locations on the east coast.	NS	
20	*In-situ* monitoring of microbial activity and biodegradation during solute transport in porous media	Yolcubal, I.	Doctorate Dissertation, University of Arizona, 2001	NS	NA	Present three studies: 1) to develop a luminescence detection system for rapid, non-destructive, in-situ, and real-time monitoring of biodegradation and microbial activity that can be used in a porous medium under dynamic conditions. 2) to examine the spatial and temporal distribution of a BAZ in response to changes in local substrate and electronic acceptor availability. 3) to investigate the various constraints in a system influenced by three stressors, microbial lag, population growth, and cell transport, and their attendant impacts on solute biodegradation and transport.	Examine the spatial and temporal distribution of a BAZ, as well as the degree of microbial activity within the zone, in response to changes in local substrate and electron acceptor availability (study #2).	"Using two methods, results showed that bioactive zones are influenced by in situ DO and substrate availability. With abundant oxygen, the BAZ encompassed the entire sediment column. The sediment column was 10cm long. The substrate and electron acceptor availability can influence the location and size of the BAZ. This was demonstrated by results where the zone initially encompassed the entire column then shrank until it was only present in the immediate vicinity of the column inlet (~0.2cm from inlet)."	10cm	Laboratory experiment in columns.
21	Sediment chronology in San Francisco Bay, California, defined by Pb, Th, Cs, and Pu	Fuller, C.C., A. van Geen, M. Bakaran, and R. Anima	Marine Chemistry. 1999. 64:7-27	August 1992	Richardson Bay within the mouth of San Francisco Bay	Present the sediment radionuclide profiles at two coring sites in Richardson Bay.	NS	"The rapid and deep sediment reworking of the upper 33cm of the sediment column by biological and/or physical processes causes rapid dilution of sediment-bound contaminants upon deposition."	33cm	"33-cm mixed zone"
22	Biological redistribution of lake sediments by tubificid oligochaetes: *Branchiura sowerbyi* and *Limnodrilus hoffmeisteri/Tubifex tubifex*	Matisoff, G., X. Wang, and P.L. McCall	Journal of Great Lakes Res. 1999. 25(1):205-219	June 1993	Western basin of Lake Erie and Cleveland Harbor	Report the results of *in vitro* particle mixing by *B. sowerbyi* using radiotracer methods and a model of non-local mixing to quantify oligochaetes mixing rates. This is important to modeling mass transport and the fate of pollutants in sediments.	NS	"The higher the population density the higher the feeding rate and particle selectivity, so that more tracer is retained within the feeding zone."	6-9cm	The tracer-labeled particles are more evenly distributed within the top 9cm of the sediment column in the cell with 4,000 individuals….tracer-labeled particles were recycled within the feeding zone (<6cm).

No.	Title	Authors	Publication	Study Date	Study Location	Key Objectives	BAZ-Specific Investigations	Results	Estimated BAZ Depth	Notes:
23	Particle mixing by freshwater infaunal bioirrigators: midges (Chironomidae: Diptera) and mayfly (Ephemeridae: Ephemeroptera)	Matisoff, G., and X. Wang	Journal of Great Lakes Res. 2000. 26(2):174-182	June 1993	Western basin of Lake Erie	Report the results of *in vitro* particle mixing by three freshwater burrows irrigators using radiotracer methods and a model of non-local sediment mixing. These mixing rates are then compared to published estimates obtained from other macrobenthos that are known to mix sediment particles.	NS	"The results indicate that even if individual organism mixing is relatively large, the sparse populations of bivalves, some chironomids and mayflies result in a relatively small amount of mixing compared to the more abundant benthos."	6-10cm	The burrow irrigation and/or feeding activities of the species studied here result in mixing within the upper 6-10cm of sediment.
24	Interim guide for assessing sediment transport at Navy facilities	Blake, A.C., D.B. Chadwick, P.J. White, and C.A. Jones	June, 2004	NS	NA	Present methods for assessing sediment transport including steps to understand the biologically active zone.	NS		NS	
25	Phase III RCRA Facility Investigation (RFI) aquatic investigation	ARCADIS Geraghty & Miller, Inc.	July 30, 1999	1998	San Diego Bay adjacent to the Solar Turbines Inc. Harbor Drive Facility	Determine whether or not soil and/or groundwater at the Solar facility require action to protect human and ecological receptors in the Bay.	Sample biota to identify the BAZ (first task).	"The diversity data from the 6 stations indicate that between 90 to 99 percent of the organisms are found from sediment surface to a depth of 20cm (8 inches); overall an average of 97 percent of the density was found in the first 20cm. Sediment cores then taken to a depth of 20cm (the BAZ)."	20cm	The BAZ was defined as the zone that encompasses 95 percent of the biota, consistent with EPA methodology for developing criteria protective of aquatic life and consistent with protection of the overall biota population.
26	Contaminant dispersal on the Palos Verdes continental margin II. Estimates of the biodiffusion coefficient, D_B, from composition of the benthic infaunal community	Swift, D.J.P., J.K. Stull, A.W. Niedoroda, C.W. Reed, and G.T.F. Wong	The Science of the Total Environment.1996. 179:91-107.	NS	Palos Verdes, CA in the vicinity of the Whites Point outfall	Describe an alternative approach to determining the time- and space-dependent biodiffusion coefficients in the sea bed.	Examine the significance of the biodiffusion coefficient.	"In each profile, there is a surface mixed layer, referred to as 'fully mixed zone' where the concentration of Pb is approximately constant with depth. This mixed layer is thicker, up to about 30cm, in the outfall deposits and thinner, < 5cm upcurrent from the outfall deposit."	5-30cm	Bioturbation extends through the effluent deposits and into the sediment layer contaminated by DDT.
27	Prediction of the fate of p,p'-DDE in sediment on the Palos Verdes shelf, California, USA	Sherwood, C.R., D.E. Drake, P.L. Wiberg, and R.A. Wheatcroft	Continental Shelf Research. 2002. 22:1025-1058	NS	Palos Verdes, CA in the vicinity of the Whites Point outfall	Assess and forecast the evolution of the p,p'-DDE distribution in sediment at three characteristic sites.	Identify the processes responsible for the DDE profiles in the sediment.	"Burial velocity is episodic. The magnitude and depth-dependence of biodiffusion profiles probably changes as benthic infaunal assemblages shift in response to varying sediment quality, ecological succession, and natural population fluctuations."	10-20cm	Spreading and blurring of DDE profiles in the upper 10-20cm is consistent with biodiffusive mixing.
28	*In situ* assessment of modification of sediment properties by burrowing invertebrates	Jones, S.E. and C.F. Jago	Marine Biology. 1993. 115:133-142	1986-1987	Wales (UK)	Examine the modification of sediment properties by benthic invertebrates, a subject less studied than the distribution of benthic invertebrates as controlled by substrate type.	Assess and quantify the effects of bioturbation.	"Several significant correlations of consistent sign were obtained between biological and geophysical parameters at some, if not all, locations. It is therefore reasonable to conclude that organisms can measurably affect bed properties, but not that they necessarily will in all environments."	10-15cm	One invertebrate, *Arenicola marina*, creates large burrows in the upper 100-150mm of the bed, and reworks the surface layers.
29	Vertical distribution of infauna in sediments of a subestuary of central Chesapeake Bay	Hines, A.H., and K.L. Comtois	Estuaries. 1985. 8(3):296-304	Fall 1980-Fall 1982	Rhode River, western shore of the Chesapeake Bay	Describe the vertical distribution of macroinfaunal species in sediments, and how the vertical distribution of some species changes over time.		"The vertical distribution of infauna in both sediment types exhibited a pattern of large numbers of small organisms in the upper 5cm of sediment, while a few large bivalves living at sediment depths to 30 cm comprised most of the biomass of the Rhode River communities."	5-30cm	Some species have different vertical distributions in different geographical areas, "For example, large *Macoma balthica* in Chesapeake Bay and San Francisco Bay were found in the 15-30 cm strata, whereas the same sized clams in sandier substrate in England only burrowed to about 7.5cm." Also, several species that burrowed deeper than 5cm showed significant temporal shifts in their vertical distribution.

No.	Title	Authors	Publication	Study Date	Study Location	Key Objectives	BAZ-Specific Investigations	Results	Estimated BAZ Depth	Notes:
30	The importance of bioturbation to continental slope sediment structure and benthic processes off Cape Hatteras, North Carolina	Diaz, R.J., R. Cutter, and D.C. Rhoads	Deep-Sea Research II. 1994. 41(4-6):719-734	July-August 1993	70 km east-northeast of Cape Hatteras, NC	Document the importance of bioturbation a part of the Atlantic slope receiving high rates of organic and inorganic materials.	Assess the general state of sediment mixing and bioturbation using SPI.	"The actively mixed layer by the benthos evidenced by sediment profile and X-ray images, is estimated to range from 5-20cm. Mixed layer depths estimated from Pb were slightly less, between 3 and 12cm."	3-20cm	"The average depth of the apparent color redox potential discontinuity layer (RPD), a surrogate measure for the mixing depth of infaunal bioturbation was 5.3 +/- 0.3 cm. Imagery showed many active feeding voids extending below 5-10cm, the RPD depth."
31	Record of decision for the Sediment Operable Unit, St. Louis River/Interlake/Duluth Tar Site, Duluth, Minnesota	The Minnesota Pollution Control Agency	August 2004	February 19, 2003	Duluth, MN	Document the basis for the Bioactive Zone thicknesses for the SLRIDT Site.	Appendix 7: Bioactive Zone	This memo details a literature search on the depth of the biologically active zone. Although there is no definitive answer, "sources indicate that such disturbance may occur to depths of at least one-half meter in benthic sediments and one meter in shallow or wetland sediments."	50cm	The British Columbia sediment management criteria assumes a one meter "bioactive zone" for both freshwater and marine sediments.

NOTES:

NS - Not Specified
NA - Not Applicable