Table 3-11. Central Bay taxa for which months since mining was a significant variable

Taxa	Partial Correlation with Months Since Mining
Megamoera subtener	0.5408
Nephtys ?californiensis	0.4361[1]
Total Amphipoda	0.5050

Note [1]: Months since mining was the least important significant variable for this

Table 3-12. The numbers and percentages of organisms from Central Bay sites judged to be sensitive or tolerant of degraded benthic habitat by Weisberg *et al.* (2008)

	Number of Organisms per Meter^2																									Overall
Lease-Site	709N-01	709N-02	709N-03	709E-01	709S-01	709S-02	709S-03	7779N-01	7779N-02	7779E-01	7779E-02	7779W-01	7779W-02	7779W-03	7779W-04	7780N-01	7780S-01	7780S-02	2036-01	2036-02	CBCN-01	CBCN-02	CBCN-03	CBCS-04	CBCS-05	Average
# Sensitive Organisms	54	126	54	18	108	1227	36	36	54	0	36	253	3411	18	3249	0	18	505	181	2274	0	36	0	36	18	470
# Tolerant Organisms	54	162	36	0	0	235	253	0	0	0	0	542	1318	90	505	54	0	0	1155	0	18	0	0	0	18	178
% Sensitive Organisms	10.7%	26.9%	15.8%	2.9%	4.3%	40%	1.1%	2.2%	5.3%	0%%	2.6%	7.2%	61.2%	9.1%	58.1%	0%%	0.5%	54.9%	4.%	92.6%	0%	6.9%	0%	7.4%	0.1%	23.8
% Tolerant Organisms	10.7%	34.6%	10.5%	0%	0%	7.6%	7.5%	0%	0%	0%	0%	15.5%	23.6%	45.4%	9.0%	17.6%	0%	0%	25.6%	0%	1.5%	0%	0%	0%	0.1%	9%

= Cluster 1 = Cluster 3 = Cluster 5
= Cluster 2 = Cluster 4

Table 3-13. ANOVA results for differences in physical factors among Central Bay clusters

Factor	(r^2)	(p)	Tukey Results[1]
# Sensitive organisms	0.9368	<0.0001	5>4=3=1=2
# Tolerant organisms	0.4372	0.0171	5>1=3, 5=2=4, 2=1=3=4

Note[1]: Highest mean value is on the left and lowest is on the right

Table 3-14. ANOVA results for differences in organism abundances between leased and control sites in the Central Bay

Factor	(r^2)	(p)	Tukey Results[1]
# Sensitive organisms	0.0544	0.2620	Leased=Control
# Tolerant organisms	0.0607	0.2352	Leased=Control

Note[1]: Highest mean value is on the left and lowest is on the right

Table 3-15. ANOVA results for differences in organism abundances among Central Bay sample sites that were mined, possibly mined, and not mined in the previous 36 months

Factor	(r^2)	(p)	Tukey Results[1]
# Sensitive organisms	0.0295	0.7191	Yes=No=Possible
# Tolerant organisms	0.0822	0.3893	Yes=No=Possible

Note[1]: Highest mean value is on the left and lowest is on the right

Table 3-16. Stepwise linear regressions results for highly significant ($p < 0.005$) effects of depth, sediment grain size, total organic carbon and months since mining on organism abundances at Central Bay sites

Taxa	(r^2)	(P)	Regression Model[1]
# Sensitive organisms	0.5083	<0.0001	y = 90.7 + 54.5mgravel
# Tolerant organisms	0.6820	<0.0001	y = 28.2mgravel – 26.0depth

Note[1]: months = (months since last mining), depth = (site water depth), TOC = (total organic carbon), mgravel = (medium gravel), fgravel = (fine gravel), vcsand = (very coarse sand), csand = (coarse sand), msand = (medium sand), fsand = (fine sand), vfsand = (very fine sand)

3.1.4 Data Interpretation

3.1.4.1 Impact to and Recovery of Central Bay Benthic Communities following Mining

While substantial variation in the composition of benthic assemblages exists among Central Bay sites in leased and control areas, as indicated by Table 3-1 and Figure 3-1, very little of the variation between sites can be attributed to sand mining activities. Clustering of sites based upon abundant and common taxa revealed distinct biological communities, but with a mix of leased and control sites in most clusters. While ANOVA discriminated significant differences among clusters in taxa densities and sediment grain size, none of these biological or grain size differences among clusters were associated with either lease status (samples collected within mining leases versus those collected in control areas) or mining status (sites that had been mined, possibly mined and not mined, in the previous 36 months). The statistical analysis did suggest, however, two possible effects of mining activities. First, significantly reduced percentages of medium sand occurred at sites that had been identified as having been mined in the previous 36 months. Nevertheless, none of the common or abundant taxa with a highly significant regression model exhibited a positive correlation with medium sand, suggesting that this particular grain size does not appear to be a controlling factor for benthic taxa. Second, only two taxa (*i.e.*, the polychaete *Nephtys ?californiensis* and the amphipod *Megamoera subtener*) and total amphipods had densities that significantly correlated with the number of months since mining. Although *N. ?californiensis* was present in samples from only five sites, *Megamoera subtener* was one of the most abundant taxa observed in the Central Bay study area. In all three cases, correlations were positive, indicating increasing densities with increasing time since mining was not the most important variable controlling spatial patterns in any of these cases.

There were no abundance patterns of organisms that are sensitive to or tolerant of degraded benthic habitats that were consistent with mining effects. Neither sensitive nor tolerant organisms varied between leased and control sites or between mined, possibly mined and never mined sites. Moreover, both sensitive and tolerant taxa were positively correlated with medium gravel, which probably indicates more stable benthic habitats at locations with higher gravel sediment content.

Despite a general absence of statistical results showing mining effects, examination of data from individual sites suggests that any damage to benthic communities would be spatially limited, of short duration or obscured by other physical processes. For example, Site 2036-02 was mined within four months of the sampling effort for the current study and had the 7th highest number of taxa and the 9th highest density of organisms of any of the Central Bay sites sampled (Table 3-1). Moreover, the sample from this site was dominated by *Nutricola* spp., a bivalve that would not be expected to recolonize quickly. These results could suggest that the sample was not collected within the specific area of the seafloor that was mined or it could represent unmined seafloor sediments that were located immediately adjacent to the mining trackline that slumped into the excavated trench, transporting resident infauna along with the slumping sand.

Overall species richness and organism densities also did not suggest discernable effects of sand mining. Sample sites that were located along previous sand mining tracks had all been mined within 19 months of our sampling effort (see Tables 3-1 and 3-2) and had a mean organism density of 2,806/m^2, whereas all other sites (*i.e.*, those that possibly had been and those that had not been mined within the previous 36 months) had a mean organism density of 1,654/m^2. These same site groups had a mean number of taxa per sample of 26 and 12, respectively.

3.1.4.2 Comparison with Other Studies

Benthic communities in the area of Central Bay where sand mining occurs have not been well studied. For the past several decades, much of the focus on benthic sampling in San Francisco Bay has been in conjunction with contaminant studies (SFEI 2009). As a consequence, areas of the Bay that posed little risk of chemical contamination of sediments have received little attention. Nevertheless, several studies of benthic communities in San Francisco Bay, or on the effects of aggregate mining on benthic communities, are available for comparison (Newell *et al.* 1998; NOAA 2007; Thompson & Lowe 2004; Thompson *et al.* 2000; Weisberg *et al.* 2008*)*. In a study of aggregate mining in British waters, Newell *et al.* (1998) reported initial recolonization of mined areas by opportunistic species with small body sizes and short life cycles, followed by increases in species richness and abundances of larger, more long-lived equilibrium species. The early colonizers reported by Newell included the polychaete *Capitella capitata* (complex) and the amphipod *Ampelisca abdita* (Table 3-17), both found in our study. Among the forms Newell reported for communities recovering from disturbance are bivalves, which also were well represented in our samples. *C. capitata* (complex), and bivalves both were very abundant in Cluster 5 (Figure 3-2), which was comprised of two sites that have not been mined (Table 3-2), suggesting co-occurrence of early colonizers and equilibrium species. Moreover, as the two sites in Cluster 5 had not been mined, *C. capitata* (complex) abundances in our study are not clearly associated with sand mining disturbance. Densities of *A. abdita* also do not appear to be associated with mining disturbances in our study. Although *A. abdita* did not occur in any of the samples from control sites, and only occurred in three of the 20 mining lease sites, the three sites where it occurred included two sites that had not been mined within the previous 36 months and one site that had been mined within the previous 19 months (Table 3-1 and Table 3-2).

Thompson *et al.* (2000) and NOAA (2007) both reported *A. abdita* from numerous benthic habitats in San Francisco Bay including transition estuarine, margin estuarine, main estuarine and muddy marine, which are not habitat categories typically characterized by physical disturbance (Table 3-17). In their analysis of the use of best professional judgment by benthic taxonomic experts in assessing the condition of benthic infaunal communities, Weisberg *et al*. (2008) reported that nine surveyed California "expert benthic ecologists" considered the presence of *C. capitata* (complex), oligochaetes, *Mediomastus* spp., and *A. brevis* among the tolerant taxa commonly observed in stressed environments. Weisberg *et al.* also

reported that Ophiuroids, Amphipoda, Mollusca, and *A. abdita* were taxa that were considered more sensitive to environmental stress, primarily organic enrichment or elevated contaminants.

The high gravel content of sediments in Cluster 5 (sites 7779W-02 and 7779W-04), as well as at sites 7779W-01 and 2036-01 (Table 3-2), associated with higher numbers of taxa and densities of organisms (Table 3-1), could suggest a more stable benthic environment at those sites. Gravels remain in place under strong currents that would cause smaller particle sizes to be resuspended. These same currents could provide a natural physical disturbance at sites with finer sediments, which could account for the lower numbers of organisms and taxa at those sites. Moreover, the clustering of recently mined sites from within mining leases with sites that had never been mined, both within leases and from control areas, suggests that the factors causing the relatively low number of taxa and organism densities at many sites were apparently widespread over the study area.

In fact, data from Thompson *et al.* (2000) suggest that benthic habitats with relatively low numbers of taxa and low organism densities are present in other areas of Central Bay. The single Central Bay site used to characterize the Marine Sandy habitat in Thompson *et al*. (2000) was near Red Rock, approximately 7 km north of the current study area near the Richmond Bay Bridge. The organism densities, number of taxa, and physical characteristics of the Red Rock site were similar to, but generally lower than, averages for Central Bay sites that had been mined in the 36 months prior to sampling (Table 3-18).

We are aware of data from only one other study for the deeper and coarser sediment seafloor areas of Central Bay that were sampled in the current study. This study was conducted by MEC (1990) for Tidewater Sand and Gravel Company in the Point Knox Shoal area of Central Bay that encompasses CSLC leases 709 N, 7779E and 2036. This study was extremely limited in scope and depth, collecting only five benthic samples and analyzing organisms only to higher taxonomic classifications, such as total polychaetes, isopods and clams. A total of 86 organisms were reported and for three of the five samples, nematodes were the dominant infaunal taxon. They also reported the occurrence of small rocks and shell debris with live epifauna, including hydroids, barnacles (as observed in the current study) and bryozoans.

The general absence of previous benthic sampling efforts in this area of Central Bay could account for the fact that the current study had only five of the 15 most abundant taxa in common with previously reported "representative infauna" for Central Bay and eight taxa that were observed in the current study and not reported in both NOAA (2007) and Thompson *et al.* (2004) (Table 3-17). The seven taxa found in common with Thompson *et al.* (2004) were reported in comparable densities to those observed in the current study (Table 3-18).

Newell *et al*. (1998), in addition to his discussions on benthic recovery rates following aggregate mining and the effects of life history strategies on natural succession, suggest that benthic infaunal communities are not necessarily as correlated with sediment grain size composition and organic carbon concentration as much as they are to the physical conditions that cause differences in these sediment characteristics. In this hypothesis, sediment disturbance is a key ecological factor that results in sediment grain size differences. He argues that in higher energy environments, such as those caused by high currents or wave action, bottom sediments are regularly disturbed and the finer sediment fractions washed away or moved back and forth on the seafloor. As a result, Newell *et al.* (1998) assert that only those benthic organisms that are able to cope with an unstable habitat are able to colonize these locations. These taxa are typically suspension filter feeders like bivalves and tubeworms and larger opportunistic scavengers like some polychaetes and amphipods. Other taxa that are able to cope with a physically disturbed environment are early colonizers (r-species) that frequently reproduce with large broods, such as the polychaete *C. capitata* (complex).

Table 3-17. Characteristics of the most abundant Central Bay taxa in this study, as described in three other studies

Taxon	Group	Newell *et al.* (1998)[1]	Thompson *et al.* (2000)[2]	NOAA (2007)[3]
Nematoda	Nematoda	NR[4]	M-s, M-md, E-mn, E-mr	NR[4]
Heteropodarke heteromorhpha	Polychaeta	NR[4]	M-s	E-dw
Photis spp.	Amphipoda	NR[4]	M-md	NR[4]
Nutricola spp.	Bivalvia	NR[4]	NR[4]	NR[4]
Capitella capitata (complex)	Polychaeta	Early colonizer	NR[4]	NR[4]
Glycinde spp.	Polychaeta	NR[4]	NR[4]	E-h, E-ss
Gnathopleustes pugettensis	Amphipoda	NR[4]	NR[4]	NR[4]
Oligochaeta	Oligochaeta	NR[4]	FB-m, FB-s, E-t, E-mn, E-mr, M-s, M-md	O-c, O-ce, M-sc, M-ss, P-c, P-sc, E-sc, E-h, E-ss
Armandia brevis	Polychaeta	NR[4]	NR[4]	NR[4]
Glycera spp.	Polychaeta	NR[4]	M-s	P-c
Megamoera subtener	Amphipoda	NR[4]	NR[4]	NR[4]
Mediomastus spp.	Polychaeta	NR[4]	E-t, E-mn, M-s, M-md	E-dw, E-sc, E-h, E-ss
Ampelisca abdita	Amphipoda	Early colonizer	E-t, E-mn, E-mr, M-md	M-ce, M-sc, P-c, P-sc, P-ss, E-dw, E-sc, E-h, E-ss
Mactridae	Bivalvia	NR[4]	NR[4]	NR[4]
Leptosynapta spp.	Holothuria	NR[4]	NR[4]	NR[4]

Note [1]: The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed

Note [2]: Results of the Benthic Pilot Study 1994-1997 Part 1–Macrobenthic Assemblages of the San Francisco Bay-Delta, and their Responses to Abiotic Factors; E - Estuarine, FB - Fresh-brackish, M - Marine; mr - margin, mn - main, md - muddy, s - sandy, t - transition

Note [3]: Report on the Subtidal Habitats and Associated Biological Taxa in San Francisco Bay; O - Oligohaline (0.5 - 5.0 ppt), M - Mesohaline (5.0 - 18.0 ppt), P - Polyhaline (18.0 - 30.0 ppt), E - Euhaline (30.0 - 35.0 ppt; c - channel, ce - channel edge, sc - slough channels, ss - shallow subtidal, dw - deep water, h - harbors

Note [4]: Not reported

Table 3-18. Comparisons of densities for the most abundant taxa found in the current study with results from Thompson *et al.* (2000)

Taxa	Group	Mean Number per Sample ($0.05m^2$)	
		Average for Mined Sites in Current Study	Thompson *et al*, for Marine Sandy habitat (RMP Site BC60 – Red Rock, 1994–1997)
Nematoda	Nematoda	1,343	8
Heteropordarke heteromorpha	Polychaeta	95	18
Photis spp.	Amphipoda	13	0
Nutricola spp.	Bivalvia	281	NR[1]
Capitella capitata (complex)	Polychaeta	28	NR[1]
Glycinde spp.	Polychaete	142	NR[1]
Gnathopleustes pugettensis	Amphipoda	5	NR[1]
Oligochaeta	Oligochaeta	111	1
Armandia brevis	Polychaetea	85	NR[1]
Glycera spp.	Polychaete	21	3
Megamoera subtener	Amphipoda	15	NR[1]
Mediomastus spp.	Polychaete	93	1
Ampelisca abdita	Amphipoda	75	0
Mactridae	Polychaeta	15	NR[1]
Leptosynapta spp.	Holothuria	3	NR[1]
Total Number of Taxa	-	15	7
Total Organism Densities	-	155	35
Depth	-	24	11
% Gravel	-	20	6
% Sand	-	77	84
% Silt		3.5	2.8
% TOC	-	0.3	0.4

Note[1]: Not reported

In contrast with Newell *et al.* (1998), we have reported high specificity of numerous taxa for narrow ranges of sediment grain size, and other studies also have documented the importance of sediment characteristics for controlling the distribution of benthic infauna in the absence of variation in physical factors, such as currents or waves (Osenberg *et al*. 1992; Pinedo *et al*. 2000; Spies *et al*. 1988). For example, in an experiment in the Santa Barbara Channel, Spies *et al.* (1988) found differences in recruitment patterns of meiofauna, depending upon the amount and type of organic enrichment within a small area, that would not have exhibited differences in currents or waves. Moreover, Pinedo *et al.* (2000) found that the densities of an infaunal polychaete varied according to the availability of sediment particles of the size it required to construct its tube across an area that likely did not have large variation in currents.

Benthic habitat instability, as described by Newell *et al*. (1998) results in several community and ecological conditions. Benthic infaunal communities in unstable environments, such as those that occur in the shallow nearshore sandy coastal environments where wave action constantly keeps surface sediments in motion, tend to be low in number of species and individual abundances. Newell *et al.* (1998) further suggests that, because of the ongoing instability in these coarser sediment areas of the

seafloor where aggregate mining generally occurs, the resident infaunal communities are never able to progress beyond an early or moderate ecological stage of development.

The area of Central Bay where sand mining occurs is characterized by high currents (NOAA 2007), which was substantiated by surface currents in excess of 2 knots observed during field sampling for the current study (Table 2-4). The high percentage of coarser sediments in many of the collected samples throughout the area where sand mining occurs indicates that sufficient energy is present to prevent the finer fractions from being deposited. Moreover, high-resolution, multi-beam side scan sonar mapping of Central Bay in 1997 and again in 2009 (USGS 2009), shows the presence of sand waves throughout the area where sand mining occurs (Figure 3-3). Many of the samples collected in this study came from areas with large sand waves (Figure 3-4).While this study did not directly measure currents, there is evidence that the sand mining leases in Central Bay are exposed to strong currents, which could provide a natural, ongoing disturbance that masks the effects of sand mining.

3.2 Delta

3.2.1 Characterization of Delta Benthic Habitats and Biological Communities

From the 15 samples collected from the Middle Ground Shoal and Suisun Marsh mining leases and three control areas, 16 taxa were identified, a substantially lower number than observed in Central Bay. Benthic communities in the Delta were numerically dominated by bivalvia, followed by polychaeta and amphipoda (Table 3-19), which averaged 369, 37 and 25 animals/m^2, respectively. Total organism densities averaged 472/m^2.

There were relatively smaller differences among sites in the numbers of taxa and numbers of organisms in the Delta than in Central Bay (Table 3-1 and Table 3-19). Site 7781E-02 had greater than 800 organisms/m^2 and 7 taxa. Site DCMG-03, located in the control area closest to Middle Ground Shoal (Figure 2-2), also had greater than 800 organisms/m^2, but had only 4 taxa. In contrast, site 7781W-01 had only 54 organisms/m^2 and 2 taxa and site DCMG-05 had only 325 organisms/m^2 and 3 taxa.

There were large differences among Delta sample sites in sediment grain size composition (Table 3-20), especially in the proportions of coarse, medium and fine sands. Site 7781W-01 had nearly 70% coarse sand, approximately 20% medium sand and <1% fine sand, whereas Site 7781E-05 had <1% coarse sand, <2% medium sand and nearly 90% fine sand. This latter sample was the only sample collected in the San Joaquin River, at the southern extent of the mining lease (Figure 2-2). Sites 7781W-02, 7781E-02, 7781E-03, 7781E-04, MS-01, DCSM-01, DCSM-02, DCMG-04 and DCMG-05 all had 50–70% medium sand.

Statistical multivariate clustering of sites based upon organism abundances revealed three groupings, which did not correspond to mining lease or control sites (Table 3-19 and Figure 3-5). Clusters 1 and 3 had at least two control sites combined with lease sites.

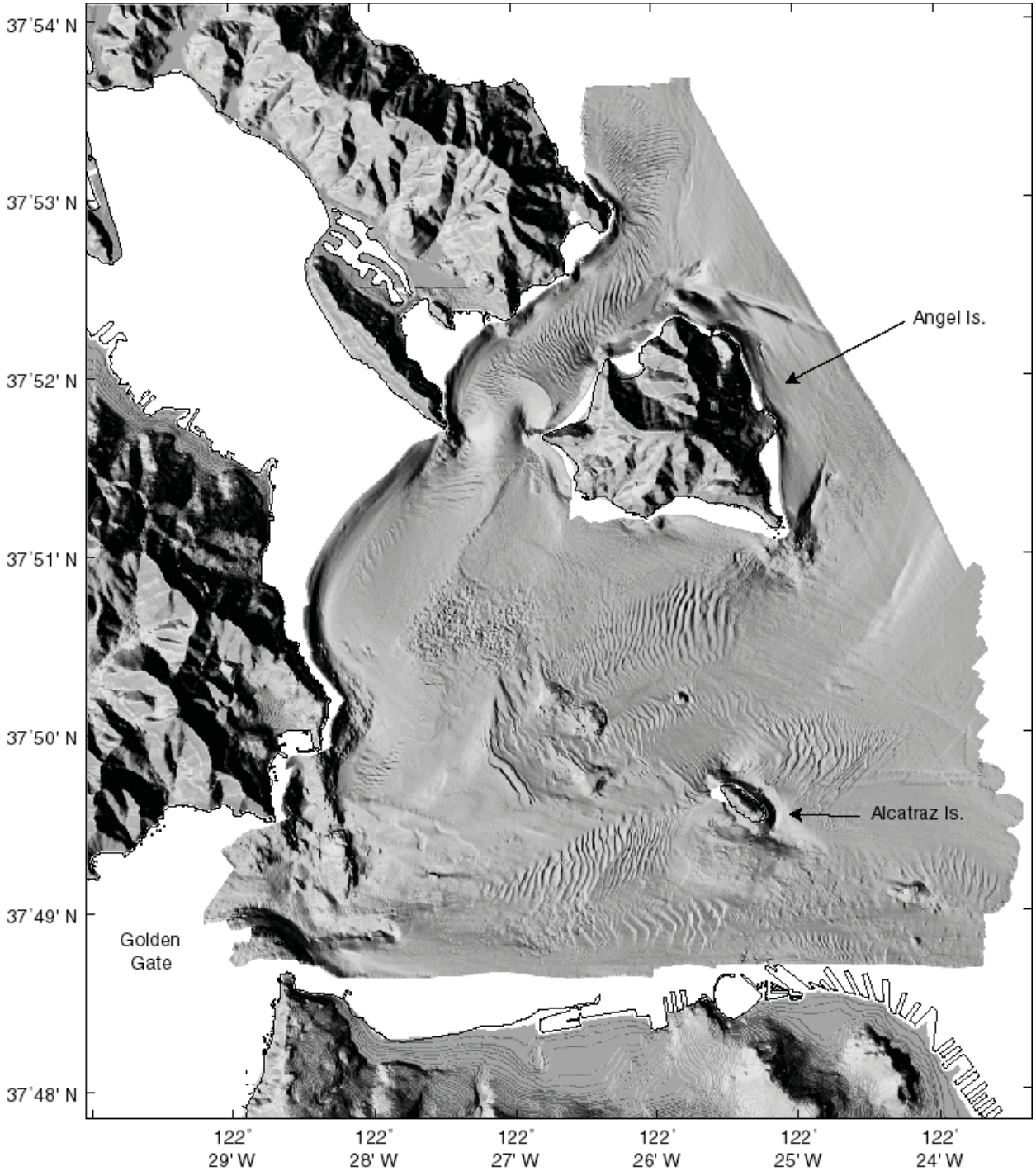

Figure 3-3. Seafloor map of Central San Francisco Bay, illustrating standing sand waves (USGS 2009)

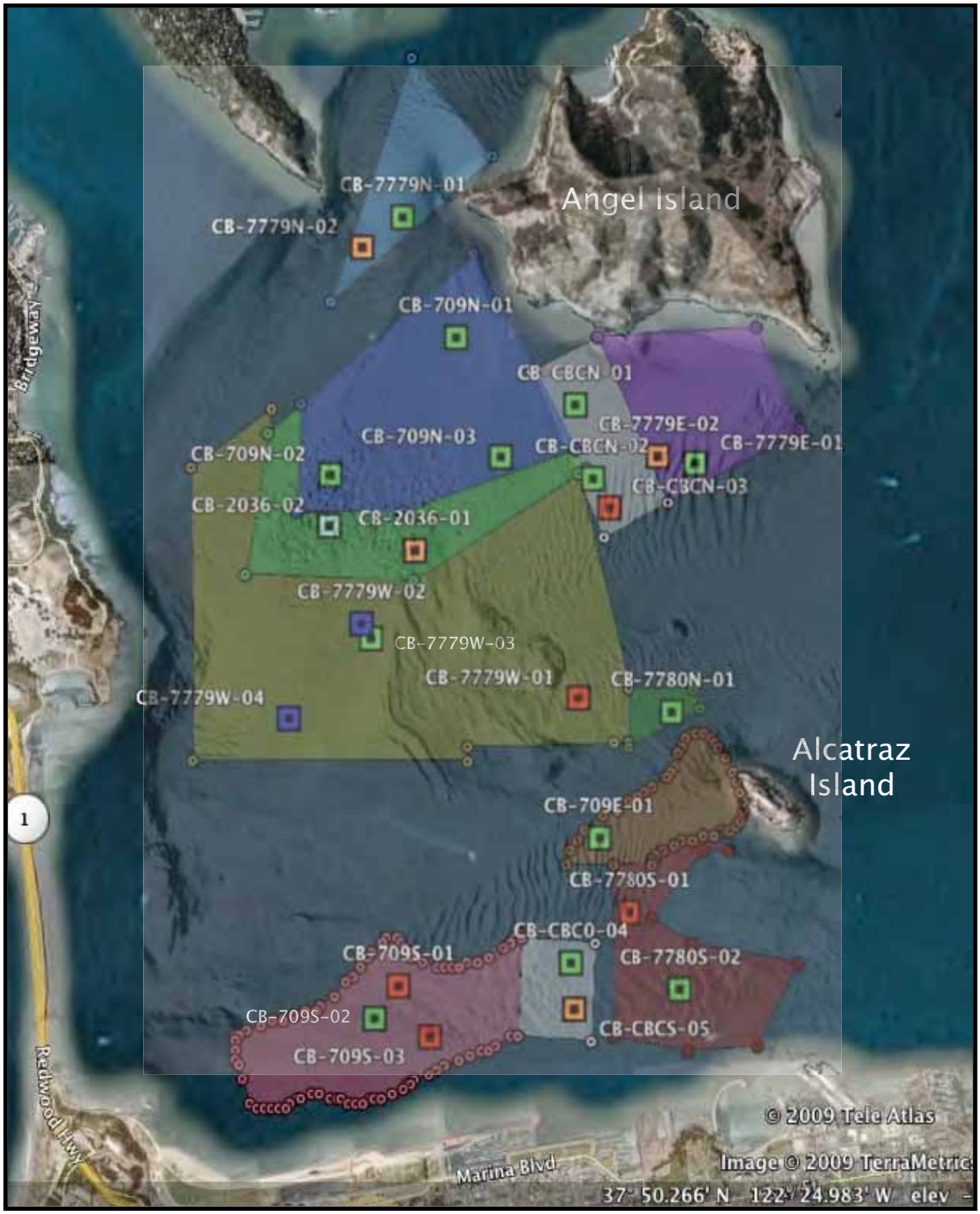

Figure 3-4. Overlay of survey station locations (squares) relative to standing sand waves and other seafloor microhabitats in Central Bay. Colors of square site symbols correspond to clusters in Figure 3-1.

Table 3-19. Organism densities and numbers of taxa collected in benthic samples from the Delta

		Number of Organisms per Meter²															Overall	>0.50% of Total Abundances or
	Lease-Site	D-7781W-01	D-7781W-02	D-7781E-01	D-7781E-02	D-7781E-03	D-7781E-04	D-7781E-05	D-MS-01	D-MS-02	D-MS-03	D-DCSM-01	D-DCSM-02	D-DCMG-03	D-DCMG-04	D-DCMG-05	Average	>10% of All Samples
Nemertea	Nemertea Unidentified	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	1	
Annelida	Polychaeta	0	90	18	126	36	99	32	36	10	18	18	10	36	7	18	37	
	Dorvillea longicornis	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	1	
	Glycinde picta	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	1	
	Marenzalaria viridis	0	90	18	90	36	9	32	36	10	18	18	10	36	7	18	29	X
	Mediomastus spp.	0	0	0	18	0	54	0	0	0	0	0	0	0	0	0	5	X
	Sphaerosyllis californiensis	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	1	
Arthropoda	Cirripedia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
	Balanus sp. A	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
	Isopoda	0	18	0	18	0	0	0	18	0	0	0	0	0	0	0	4	
	Synidotea laevidorsalis	0	18	0	18	0	0	0	18	0	0	0	0	0	0	0	4	X
	Amphipoda	18	36	18	54	36	0	54	54	18	18	0	18	0	36	18	25	
	Americorophium spinicorne	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	1	
	Americorophium stimpsoni	0	18	0	0	0	0	36	0	0	0	0	0	0	0	0	4	X
	Gammarus daiberi	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	1	
	Grandiphoxus grandis	18	18	0	36	36	0	0	36	0	0	0	0	0	0	18	11	X
	Phoxicephalidae unidentified*	0	0	0	0	0	0	0	18	18	18	0	0	0	36	0	6	X
	Tritella spp.	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	1	
Mollusca	Bivalvia	36	433	487	523	271	343	271	325	433	180	469	144	776	578	271	369	
	Corbicula fluminea	0	0	0	0	0	0	217	0	0	0	72	0	0	0	0	19	X
	Corbula spp.	36	433	487	523	271	343	54	325	433	180	397	144	776	578	271	350	X
	Number of Taxa per grab**	2	6	3	7	4	7	6	5	5	5	5	4	4	5	3	5	
	Total Number of Organisms/m²	54	667	541	847	379	559	389	469	471	234	505	164	848	628	325	472	

* Very tiny specimens
** Not adjusted for "spp." entries or "+" entries.

= Cluster 1
= Cluster 2
= Cluster 3
=4–5 taxa and 400–599 organisms/m²
=>5 taxa and >599 organisms/m²

Table 3-20. Depths and sediment characteristics of samples collected in the Delta

	Site														
Physical Factor	D-7781W-01	D-7781W-02	D-7781E-01	D-7781E-02	D-7781E-03	D-7781E-04	D-7781E-05	D-MS-01	D-MS-02	D-MS-03	D-DCSM-01	D-DCSM-02	D-DCMG-03	D-DCMG-04	D-DCMG-05
sample depth, MLLW, corrected (m)	15.4	15.8	11.6	10.3	16.4	18.8	5.0	12.3	11.0	11.4	9.3	8.5	12.0	10.8	13.4
TOC (%)	0.28	0.27	0.18	0.16	0.15	0.15	0.29	0.26	0.58	0.21	0.35	0.35	0.34	0.15	2.71
Gravel, Medium (%)	0.37	0.80	1.13	0.68	0.00	0.00	0.00	0.61	0.26	2.13	0.00	0.00	0.41	0.56	0.00
Gravel, Fine (%)	1.16	1.49	1.33	1.31	0.01	0.17	0.16	0.45	0.16	1.21	0.02	0.01	0.17	0.19	0.88
Sand, Very Coarse (%)	7.00	1.27	6.37	1.87	0.14	0.80	0.34	3.00	0.36	2.38	0.88	0.88	0.31	0.30	0.88
Sand, Coarse (%)	69.21	9.51	24.28	11.96	3.50	5.85	0.35	23.21	2.16	4.31	13.91	31.50	1.94	1.71	7.57
Sand, Medium (%)	20.59	62.03	46.85	64.10	67.06	55.93	1.70	53.77	35.97	32.04	64.39	61.06	33.59	53.98	61.36
Sand, Fine (%)	0.11	23.86	17.78	19.30	28.32	36.18	89.61	17.26	58.50	36.74	14.56	6.22	56.76	30.88	27.15
Sand, Very Fine (%)	0.05	0.26	0.26	0.33	0.37	0.35	3.79	0.94	0.68	1.09	1.38	0.12	0.85	0.95	0.21
Silt (%)	0.84	0.35	1.26	0.16	0.35	0.41	2.44	0.35	0.93	10.80	2.87	0.06	3.03	5.49	1.16
Clay (%)	0.68	0.43	0.74	0.29	0.27	0.32	1.60	0.42	0.99	9.31	1.98	0.15	2.94	5.94	0.80
Mining Status	No	No	No	Possible	Yes	Yes	No	Possible	Possible	Possible	No	No	No	No	No
Estimated months since last mining	60	60	60	36	13	10	60	36	36	36	60	60	60	60	60

= Cluster 1
= Cluster 2
= Cluster 3

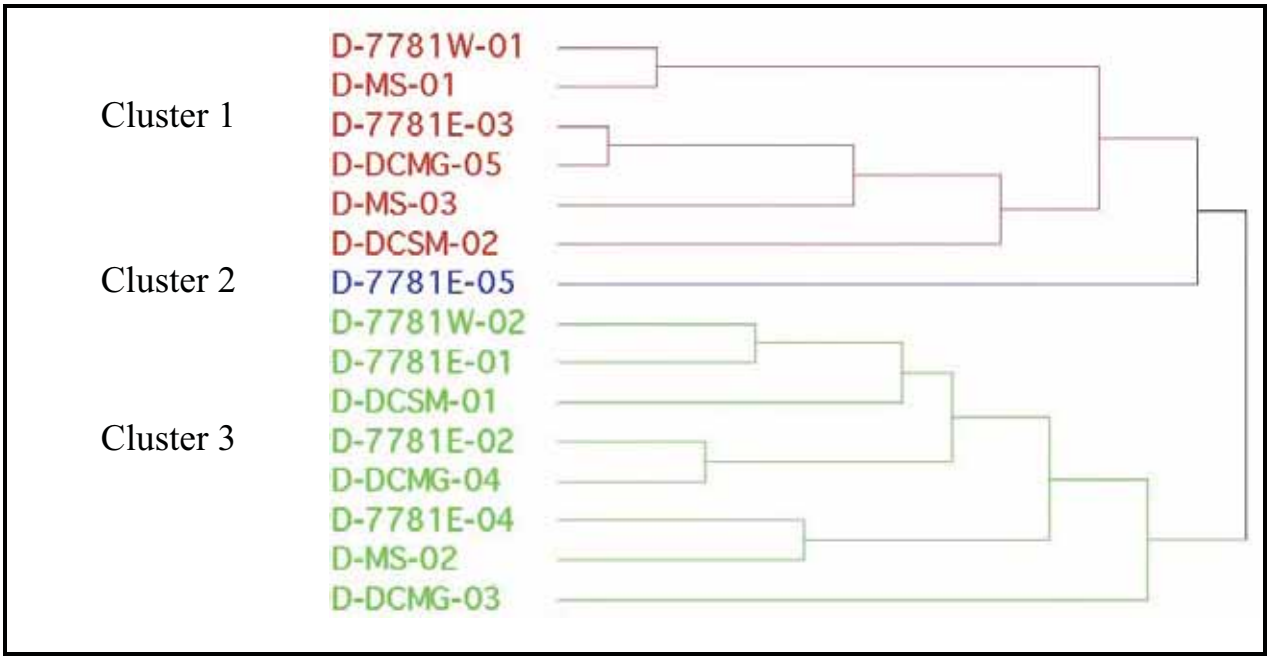

Figure 3-5. Multivariate statistical clusters of Delta sites (Ward's minimum variance method) based upon abundances of common or abundant taxa

Densities of many of the Delta benthic taxa differed among clusters (Figure 3-6). Cluster 1 had medium densities of the bivalve *Corbula* spp. and low densities of the polychaete *Marenzalaria viridis* and the amphipod *Grandiphoxus grandis*. Cluster 2 had high densities of *M. viridis* and the bivalve *Corbicula fluminea*, with low densities of the amphipod *Americorophium stimpsoni* and *Corbula* spp. Cluster 3 had high densities of *Corbula* spp. and medium densities of *Marenzalaria viridis*.

ANOVA confirmed differences among clusters in densities of many of the most common and abundant Delta taxa (Table 3-21). *M. viridis*, *A. stimpsoni* and *C. fluminea* had significantly higher densities in Cluster 2 than in either of the other clusters, whereas *Corbula* spp. had significantly higher densities in Cluster 3. The total number of organisms was greater in clusters 2 and 3 than in Cluster 1.

Some of the organism differences among clusters could have been due to differences in depth or grain size (Table 3-22). ANOVA and Tukey's tests revealed that Cluster 2 had greater percentages of fine and very fine sands and lower percentages of medium sand than either of the other clusters. Finally, there were no differences among clusters in the estimated months since mining.

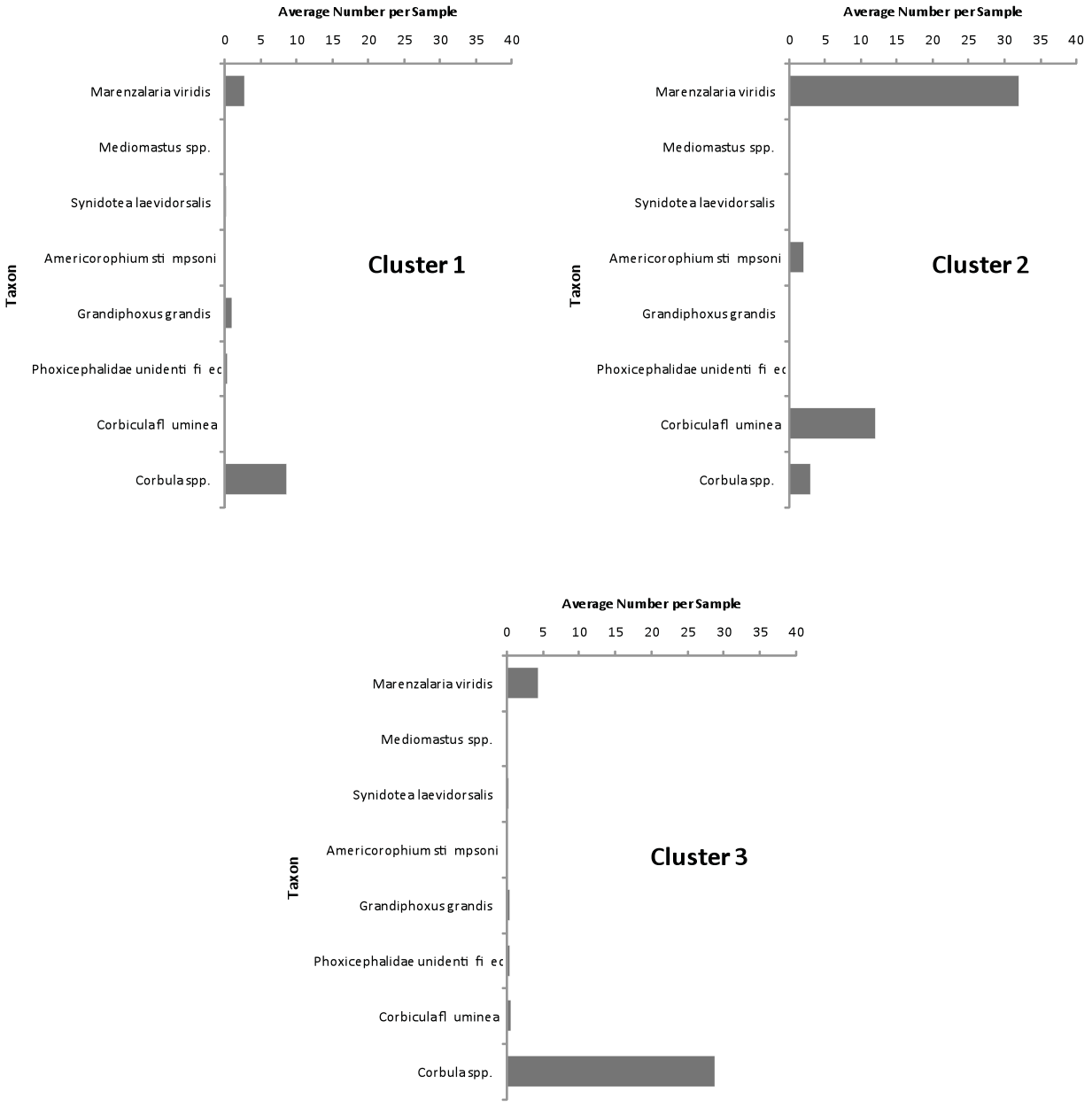

Figure 3-6. Densities of the most common and abundant benthic taxa in three clusters identified for Delta sites

Table 3-21. ANOVA results for differences in organism abundances among clusters of Delta sites

Taxa[1]	Group	(r^2)	(p)	Tukey Results[2]
Corbula spp.	Bivalvia	0.7210	0.0005	3>1=2
Marenzalaria viridis	Polychaeta	0.8303	<0.0001	2>3=1
Corbicula fluminea	Bivalvia	0.9021	<0.0001	2>3=1
Grandiphoxus grandis	Amphipoda	0.1797	0.3047	1=3=2
Phoxicephalidae unidentified	Amphipoda	0.0234	0.8674	3=1=2
Mediomastus spp.	Polychaeta	0.1045	0.5158	3=2=1
Synidotea laevidorsalis	Isopoda	0.0278	0.8455	3=1=2
Americorophium stimpsoni	Amphipoda	0.8011	<0.0001	2>3=1
Total Polychaeta	Polychaeta	0.7742	0.0001	2>3=1
Total Amphipoda	Amphipoda	0.2067	0.2492	2=1=3
Total Bivalvia	Bivalvia	0.7082	0.0006	3>1, 3=2, 2=1
Total Number of Organisms	-	0.8225	<0.0001	2=3>1
Total Number of Taxa	-	0.2972	0.1205	2=3=1

Note [1]: Taxa listed in order of overall average densities
Note [2]: Highest mean density is on the left and lowest is on the right

Table 3-22. ANOVA results for differences in physical factors among Delta clusters

Factor	(r^2)	(p)	Tukey Results[1]
Months since mining	0.0489	0.7403	2=3=1
Depth	0.3288	0.0914	1=3=2
% Total Organic Carbon	0.0930	0.5567	1=2=3
% Medium Gravel	0.0494	0.7377	1=3=2
% Fine Gravel	0.0418	0.7740	1=3=2
% Very Coarse Sand	0.0735	0.6325	1=3=2
% Coarse Sand	0.2004	0.2613	1=3=2
% Medium Sand	0.4510	0.0274	3=1>2
% Fine Sand	0.5826	0.0053	2>3=1
% Very Fine Sand	0.8213	<0.0001	2>3=1
% Silt	0.0076	0.9551	2=1=3
% Clay	0.0025	0.9853	1=3=2

Note [1]: Highest mean value is on the left and lowest is on the right

3.2.2 Effects of Sand Mining on Delta Bottom Sediments and Benthic Communities

As with data for Central Bay, the clustering of leased and control sites suggested sand mining does not appear to be exerting a strong influence on Delta benthic communities. Nevertheless, additional statistical tests were performed to examine this possibility, assess whether sand mining is associated with differences in sediment grain size, and to help determine the factors associated with differences in taxa densities. ANOVA and Tukey's tests were performed to test for differences in organism abundances and sediment characteristics between samples from leased and control sites, as well as among sites with different times since they were last mined (*i.e.*, those known to have been mined in the last 36 months, those that might have been mined within the last 36 months and those that were not mined within the last 36 months).

None of the most common and abundant Delta taxa varied between leased and control sites (Table 3-23), and only one differed among sites that had been, had possibly been, or never had been mined in the previous 36 months (Tables 3-24). Only the polychaete, *Mediomastus* spp. differed among sites that had or had not been mined, with greater densities occurring at sites that had been mined (Table 3-24).

There were no apparent effects of sand mining on physical habitat characteristics at sand mining lease locations. ANOVAs performed to test for differences in months since mining, site depth, grain size and total organic carbon revealed that sites located within mining leases differed from control sites only for months since mining, with samples from control sites having more months since mining than sites on leases (Table 3-25). Moreover, sites known to have been mined in the previous 36 months had significantly fewer months since mining than either sites that had not been mined or sites that possibly were mined and significantly greater depth than did sites that had either not been mined or possibly were mined (Table 3-26).

As was the case for Central Bay, the absence of statistically significant effects on Delta benthic organism densities associated with either being in a lease or assumed recent antecedent mining activity could be due to uncontrolled confounding factors. Stepwise linear regressions were performed to investigate whether any combination of months since mining, sediment grain size, total organic carbon concentration and site water depth could account for significant amounts of variation in Delta organism densities. Linear regressions for Delta benthic data also included longitude as a possible independent variable, which served as a surrogate for any salinity gradient effects that occur in that part of the Delta.

Stepwise linear regressions detected few Delta taxa for which highly significant regression models occurred (Table 3-27). Only the polychaete *Marenzalaria viridis*, the isopod *Synidotea laevidorsalis*, the amphipod *Americorophium stimpsoni* and the bivalve *Corbicula fluminea* exhibited highly significant regressions and none of them respond to any variables except sediment grain size or longitude, the surrogate for the Delta salinity gradient. *M. viridis* and *C. fluminea* both responded negatively to longitude, which suggests lower densities for these taxa at more western sites with higher salinities. Longitude was the most important variable and second-most important variable for *M. viridis* and *C. fluminea*, respectively (Table 3-28). The remainder of the three most important variables for these four taxa ranged from medium gravel to silt, with both positive and negative correlations occurring (Table 3-28).

Table 3-23. ANOVA results for differences in organism abundances between leased and control sites in the Delta

Taxa[1]	Group	(r^2)	(p)	Tukey Results[2]
Corbula spp.	Bivalvia	0.1195	0.2069	Control=Leased
Marenzalaria viridis	Polychaeta	0.0231	0.5891	Leased=Control
Corbicula fluminea	Bivalvia	0.0037	0.8288	Leased=Control
Grandiphoxus grandis	Amphipoda	0.1250	0.1961	Leased=Control
Phoxicephalidae unidentified	Amphipoda	0.0063	0.7794	Control=Leased
Mediomastus spp.	Polychaeta	0.0597	0.3801	Leased=Control
Synidotea laevidorsalis	Isopoda	0.1250	0.1961	Leased=Control
Americorophium stimpsoni	Amphipoda	0.0682	0.3472	Leased=Control
Total Polychaeta	Polychaeta	0.0357	0.5003	Leased=Control
Total Amphipoda	Amphipoda	0.1731	0.1230	Leased=Control
Total Bivalvia	Bivalvia	0.1199	0.2061	Control=Leased
Total Number of Organisms	-	0.0164	0.6495	Control=Leased
Total Number of Taxa	-	0.0737	0.3276	Leased=Control

Note [1]: Taxa listed in order of overall average densities
Note [2]: Highest mean density is on the left and lowest is on the right

Table 3-24. ANOVA results for differences in organism abundances Delta sites that were mined, possibly were mined and were not mined in the previous 36 months

Taxa[1]	Group	(r^2)	(p)	Tukey Results[2]
Corbula spp.	Bivalvia	0.0187	0.8926	No=Yes=Possible
Marenzalaria viridis	Polychaeta	0.0133	0.9229	No=Yes=Possible
Corbicula fluminea	Bivalvia	0.796	0.6079	No=Possible=Yes
Grandiphoxus grandis	Amphipoda	0.1667	0.3349	Yes=Possible=No
Phoxicephalidae unidentified	Amphipoda	0.1927	0.2768	Possible=No=Yes
Mediomastus spp.	Polychaeta	0.4123	0.0412	Yes>No, Yes=Possible, Possible=No
Synidotea laevidorsalis	Isopoda	0.2130	0.2377	Possible=Yes=No
Americorophium stimpsoni	Amphipoda	0.0909	0.5645	No=Possible=Yes
Total Polychaeta	Polychaeta	0.0137	0.9206	Yes=No=Possible
Total Amphipoda	Amphipoda	0.1731	0.1230	Leased=Control
Total Bivalvia	Bivalvia	0.0489	0.7404	No=Yes=Possible
Total Number of Organisms	-	0.0331	0.8171	No=Yes=Possible
Total Number of Taxa	-	0.2031	0.2560	Yes=Possible=No

Note [1]: Taxa listed in order of overall average densities
Note [2]: Highest mean density is on the left and lowest is on the right

Table 3-25. ANOVA results for differences in physical factors between leased and control sites in the Delta

Factor	(r^2)	(p)	Tukey Results[1]
Months since mining	0.2741	0.0452	Control>Leased
Depth	0.0792	0.3094	Leased=Control
% Total Organic Carbon	0.1608	0.1385	Control=Leased
% Medium Gravel	0.1144	0.2175	Leased=Control
% Fine Gravel	0.1759	0.1196	Leased=Control
% Very Coarse Sand	0.1488	0.1555	Leased=Control
% Coarse Sand	0.0125	0.6917	Leased=Control
% Medium Sand	0.0777	0.3144	Control=Leased
% Fine Sand	0.0145	0.6687	Leased=Control
% Very Fine Sand	0.0033	0.8372	Leased=Control
% Silt	0.0158	0.6551	Control=Leased
% Clay	0.0265	0.5619	Control=Leased

Note [1]: Highest mean value is on the left and lowest is on the right

Table 3-26. ANOVA results for differences in physical factors among Delta sites that were mined, possibly were mined and were not mined in the previous 36 months

Factor	(r^2)	(p)	Tukey Results[1]
Months since mining	0.9990	<0.0001	No>Possible>Yes
Depth	0.4086	0.0428	Yes>No=Possible
% Total Organic Carbon	0.0598	0.6907	No=Possible=Yes
% Medium Gravel	0.2847	0.1340	Possible=No=Yes
% Fine Gravel	0.1419	0.3992	Possible=No=Yes
% Very Coarse Sand	0.0621	0.6806	No=Possible=Yes
% Coarse Sand	0.0785	0.6122	No=Possible=Yes
% Medium Sand	0.0886	0.5731	Yes=Possible=No
% Fine Sand	0.0047	0.9722	Possible=Yes=No
% Very Fine Sand	0.0363	0.8012	No=Possible=Yes
% Silt	0.0862	0.5824	Possible=No=Yes
% Clay	0.0895	0.5698	Possible=No=Yes

Note [1]: Highest mean value is on the left and lowest is on the right

Table 3-27. Highly significant (p < 0.005) results from stepwise linear regressions for effects of depth, sediment grain size, total organic carbon and months since mining on organism abundances at Delta sites

Taxa[1]	(r^2)	(p)	Regression Model[2]
Marenzalaria viridis	0.8763	0.0029	y = 7723 – 60.5longitude – 5.39vcsand – 3.27csand – 3.54msand – 3.27fsand – 7.45silt
Synidotea laevidorsalis	0.8088	0.0047	y = 44.1 – 0.536vcsand – 0.441csand – 0.437msand – 0.452fsand – 0.970silt
Americorophium stimpsoni	0.8249	0.0032	y = 0.529fgravel + 0.041csand + 0.039msand + 0.044fsand – 0.566vfsand – 4.34
Corbicula fluminea	0.9537	<0.0001	y =2021 + 2.99vfsand – 16.6longitude

Note [1]: Taxa listed in order of overall average densities
Note [2]: months (months since last mining), depth (site water depth), TOC (total organic carbon), mgravel (medium gravel), fgravel (fine gravel), vcsand (very coarse sand), csand (coarse sand), msand (medium sand), fsand (fine sand), vfsand (very fine sand)

Table 3-28. The first, second and third most influential independent variables for each Delta taxon or group with a highly significant (p <0.005) linear regression, as indicated by their respective partial correlations

Taxa[1]	1st Most Important Variable		2nd Most Important Variable		3rd Most Important Variable	
	Name	Partial Correlation	Name	Partial Correlation	Name	Partial Correlation
Marenzalaria viridis	Longitude	-0.7317	Very coarse sand	-0.6815	Silt	-0.6704
Synidotea laevidorsalis	Silt	-0.8788	Coarse sand	-0.8743	Fine sand	-0.8715
Americorophium stimpsoni	Very fine sand	0.7974	Fine gravel	0.7183	Fine sand	0.6966
Corbicula fluminea	Very fine sand	0.9691	Longitude	-0.8022	NA	-

Note [1]: Taxa listed in order of overall average densities

3.2.3 Data Interpretation

3.2.3.1 Recovery of Delta Benthic Communities following Mining

As with Central Bay benthic communities, substantial variation was evident in the composition of benthic assemblages among Delta sampling sites in mining leases and control areas, as indicated by Table 3-19 and Figure 3-6. Significant differences in organism densities among the three clusters identified among Delta sampling sites always involved Cluster 2, Cluster 3, or both Cluster 2 and Cluster 3, exceeding Cluster 1. The polychaete *Marenzalaria viridis*, the amphipod *Americorophium stimpsoni*, the bivalve *Corbicula fluminea,* and total polychaetes all had significantly higher densities in Cluster 2 than the other two clusters (Table 3-21). This cluster (Figures 3-5 and 3-6) consisted of one sample, which was the eastern-most site on the San Joaquin River. *M. viridis* and *C. fluminea* were also significantly correlated with longitude, which served as a surrogate for the Delta salinity gradient.

In all the other sampled locations represented by Clusters 1 and 2, the invasive Asian clam, *Corbula spp*. was the dominant taxon (Figure 3-6). Most of the individuals collected were larger than the sizing screens used by the sand mining companies to grade and retain extracted sand. It can be assumed that many of the entrained *Corbula* would be discharged in the barge overflow pipe during mining and resettle in recently mined areas. None of this observed variation could be attributed to mining activities, as only densities of the polychaete *M. viridis*. differed significantly between sites that had and had not been mined, with higher densities at mined sites (Table 3-24). Unlike in Central Bay, sediment grain size in the Delta had no apparent correlation with sand mining. Consequently, results for the Delta indicate the predominant factors affecting organism abundances were simply sediment grain size and salinity.

As was found for the Central Bay, comparison of the sites that had recently been mined with sites characterized as possibly mined and never mined indicated that any mining effects on Delta benthic communities are either spatially very limited or of short duration. Sites 7781E-03 and 7781E-04 were mined within 13 and 10 months of sampling, respectively (Table 3-24). Data provided by the lease operator indicated that none of the other sampling sites had been mined within the previous 36 months.

Sites 7781E-03 and 7781E-04 averaged 469 organisms/m^2 and 5.5 taxa per sample, whereas all other sites together averaged 472 organisms/m^2 and 4.6 taxa per sample. Consequently, any potential negative effects of sand mining on Delta benthic communities appear to be either very spatially limited, such that collected samples were collected outside the dredge track, or they become undetectable within two years of mining.

3.2.3.2 Comparison with Other Studies

The taxa and densities of benthic organisms reported by the current study for Delta sites are similar to those reported by two other recent studies (Newell *et al.* 1998; NOAA National Marine Fisheries Service 2007; Thompson & Lowe 2004; Thompson *et al.* 2000). Thompson *et al.* (2000) and NOAA (2007) either separately or together reported the bivalves *Corbula* spp. and *Corbicula fluminea,* the polychaete *Marenzalaria viridis* and *Mediomastus* spp., the amphipods *Grandiphoxus grandis* and *Americorophium stimpsoni* and the isopod *Synidotea laevidorsalis*, from several habitats in the Bay and Delta (Table 3-29). Mean densities for several of these taxa from fresh-brackish sandy habitat reported by Thompson *et al.* (2000) were roughly similar to those reported in the current study (Table 3-30).

Table 3-29. Characteristics of the most abundant Delta taxa in this study, as described in two other studies

Taxa	Group	Thompson *et al.* (2000)[1]	NOAA (2007)[2]
Corbula spp.	Bivalvia	FB-md, FB-s, E-t, M-s, E-mn, E-mr, M-md	O-c, O-ce, M-c, M-ce, M-sc, M-ss, P-c, P-sc, P-ss
Marenzalaria viridis	Polychaeta	FB-md, FB-s, E-mn	O-c, M-c, M-ce, M-sc, M-ss, P-c[2]
Corbicula fluminea	Bivalvia	FB-md, FB-s, E-t	O-c
Grandiphoxus grandis	Amphipoda	E-t, E-mn	NR[3]
Phoxicephalidae unidentified	Amphipoda	NR[3]	NR[3]
Mediomastus spp.	Polychaeta	E-t, E-mn, M-s, M-md	E-dw, E-sc, E-h, E-ss
Synidotea laevidorsalis	Isopoda	NR[3]	M-ce
Americorophium stimpsoni	Amphipoda	NR[3]	O-c, O-ce, M-ss

Note [1]: Results of the Benthic Pilot Study 1994-1997 Part 1–Macrobenthic Assemblages of the San Francisco Bay-Delta, and their Responses to Abiotic Factors; E - Estuarine, FB - Fresh-brackish, M - Marine; mr - margin, mn - main, md - muddy, s - sandy, t - transition

Note [2]: Report on the Subtidal Habitats and Associated Biological Taxa in San Francisco Bay; O - Oligohaline (0.5 - 5.0 ppt), M - Mesohaline (5.0 - 18.0 ppt), P - Polyhaline (18.0 - 30.0 ppt), E - Euhaline (30.0 - 35.0 ppt; c - channel, ce - channel edge, sc - slough channels, ss - shallow subtidal, dw - deep water, h - harbors

Note [3]: Not reported

Table 3-30. Comparisons of densities for the most abundant Delta taxa found in the current study with results from another study

Taxa	Group	Mean Number per Sample ($0.05m^2$)	
		Current Study	Thompson *et al.* (2000) for fresh-brackish sandy habitat
Corbula spp.	Bivalvia	18	1
Marenzalaria viridis	Polychaeta	6	2
Corbicula fluminea	Bivalvia	1	19
Grandiphoxus grandis	Amphipoda	.6	0
Phoxicephalidae unidentified	Amphipoda	.3	NR[1]
Mediomastus spp.	Polychaeta	.3	0
Synidotea laevidorsalis	Isopoda	.2	NR[1]
Americorophium stimpsoni	Amphipoda	.2	NR[1]

Note [1]: Not reported

4 Conclusions

The benthic communities observed in Central Bay and the Delta are generally consistent with those reported in other studies. The Central Bay study area is deeper and contains coarser sediments than typically sampled by other programs and contained numerous taxa that had not been listed as characteristic for Central Bay by previous investigators. In both the Central Bay and Delta, densities of benthic taxa were predominantly correlated with sediment grain size. In the Delta, salinity appears also to be an important variable controlling abundances of some taxa.

Sampling sites in both Central Bay and the Delta that had previously been mined within three years of sampling for the current study exhibited no biological characteristics suggesting effects from sand mining. Some potential effects of aggregate mining that were detected in Central Bay included a reduction in medium sand at sites that had been mined and densities of two taxa (*Nephtys ?californiensis*, and *Megamoera subtener*) and total amphipoda that were positively correlated with the months since mining.

The benthic communities of Central Bay where sand mining occurs does not appear to be highly degraded due to organic enrichment or elevated contaminant levels. This conclusion is based on an assessment of benthic community taxa, relative to their sensitivity or tolerance to environmental stress, using best professional judgment indicators as presented by Weisberg *et al.* 2008.

Strong currents in the mining areas of Central Bay can be assumed not only to affect benthic sediment composition, but associated infaunal organisms as well. The natural disturbance of bottom sediments by strong, tidally induced bottom currents, as indicated by standing sand waves in the Central Bay study area, appears to maintain a dynamic environment that prevents infaunal organisms from establishing a highly developed community, as evident by the low numbers of taxa and low organism densities at many sites. Sample sites that contained high percentages of gravel appeared to support a more developed infaunal community with substantially higher numbers of taxa and total abundances.

Recovery of benthic communities to pre-mining conditions appears to occur within two years. This rapid recovery could be due, in part, to natural environmental conditions that appear to disturb benthic communities throughout this area of Central Bay. Also, rapid recolonization of mined tracks can occur not only by larval recruitment, but also by immigration from surrounding unmined sediments, either through active movement by individual organisms or through transport by slumping sediments. Slumping of unmined sediments into mined areas is one possible explanation for the numerical presence of the bivalve *Nutricola* spp. at a location that was mined within four months before sampling. High abundances of taxa that are not early colonizers could also reflect the difficulty of precisely collecting samples from the small swath of seafloor covered by the mining dredge. Regardless of the cause, high abundances of such taxa indicate that mining disturbances to benthic infauna in Central Bay and the West Delta are probably spatially very small.

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