ACCUMULATION OF SELENIUM IN BENTHIC BIVALVES AND FINE-GRAINED SEDIMENTS OF SAN FRANCISCO BAY, THE SACRAMENTO-SAN JOAQUIN DELTA, AND SELECTED TRIBUTARIES, 1984 - 1986

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Metric (SI) units are used in this report. For readers who prefer inch-pound units, the conversion factors for the terms used in this report are listed below:

Multipy	By	To obtain
cm (centimeter)	0.394	inches
m (meter)	3.281	foot
km (kilometer)	0.6214	mile

By weight:

micrograms per gram (ug/g) is equivalent to parts per million (ppm)
1 microgram (ug) = 10^{-6} gram (g)
nanograms per gram (ng/g) is equivalent ot parts per billion (ppb)
1 nanogram (ng) = 10^{-9} gram (g)

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By C. Johns and S. N. Luoma

ABSTRACT

Fine-grained, oxidized, surface sediments and two benthic bivalves (*Corbicula sp.*, a suspension-feeding freshwater clam, and *Macoma balthica*, a deposit-feeding brackish water clam) were used to examine spatial distributions of selenium within San Francisco Bay and the Sacramento/San Joaquin River Delta and to compare riverine with local inputs of biologically available selenium to this large, complex, urbanized estuary. Selenium concentrations in *Corbicula* were elevated in the western Delta and northern reach of San Francisco Bay compared to concentrations in *Corbicula* from river systems not enriched in selenium. Biologically available selenium did not appear to enter the southern Delta or northern reach of the Bay from the San Joaquin River, a possible source, in levels that could measurably influence bioaccumulation by *Corbicula*. Selenium concentrations in *Macoma balthica* also were elevated in southern South San Francisco Bay and near the western edge of Suisun Bay.

INTRODUCTION

The impacts of anthropogenic mobilization of selenium have stimulated research in the aquatic chemistry, geochemical cycling and biological interactions of this element (Lakin, 1972; Rudd, et al., 1980; Stadtman, 1980; Doran, 1982; Turner and Rudd, 1983; Lemly, 1985; Zehr and Oremland, 1987; Cutter, 1987a). Although considerable interest has focused on selenium chemistry in marine and estuarine waters (Measures and Burton, 1978; Measures, et al., 1983; Cutter and Bruland, 1984; Takayanagi and Wong, 1984; Takayanagi and Cossa, 1985; van der Sloot, et al., 1985) less is known about processes that influence selenium concentrations in invertebrate biota and sediments from natural waters (Copeland, 1970; Fowler and Benayoun, 1976a; Adams and Johnson, 1977; Rodgers, et al., 1979; Lemly, 1985; Pelletier, 1986; Saiki, 1986).

San Francisco Bay is an especially interesting environment in which to compare selenium distributions to possible sources of input. As with any aquatic ecosystem, a natural background of selenium exists in the Bay, originating from weathering of rocks and soils. However, the natural weathering process has been accelerated in the semi-arid drainage basin of the San Joaquin River by irrigation and artificial drainage of saline, selenium rich soils. Selenium occurs in high concentrations in drainage waters from agricultural fields in the West San Joaquin Valley (Presser and Barnes, 1985; Saiki, 1986); and some of that drainage enters the San Joaquin River which flows toward San Francisco Bay. Elevated selenium concentrations were recently found in aquatic birds from the marshes of Suisun and San Pablo Bays and the southern portion of South Bay (Figure 1; Ohlendorf, et al., 1986, 1987). The San Joaquin River was proposed as a source of selenium enrichment in these birds, and further, as a factor contributing to the population decline of striped bass and dungeness crab in the Bay (Greenberg and Kopec, 1986; Ohlendorf, et al., 1987).

Sources other than the San Joaquin River also could contribute selenium to the Bay, however. San Francisco Bay is a large, urbanized estuary (Conomos, et al., 1979) and is influenced strongly by local activities (Nichols, et al., 1986; Luoma and Cloern, 1982). Outfalls from 49 major industrial discharges and public treatment works are located around the Bay (Belliveau, et al., 1983). These include municipal dischargers, oil refineries, fossil fuel combustion facilities, electronics, and chemical plants whose raw materials, processes and effluents commonly contain selenium (Shamberger, 1981; Lemly, 1985; McKeown and Marinas, 1986). Recent analyses show high concentrations of selenite in several specific effluents and suggest that these could contribute significantly to the selenium load observed in Bay water (Cutter, 1987b). Mitigation of the causes of selenium enrichment in waterfowl will require determining the relative contribution of such local sources to biologically available selenium in the estuary compared to contributions of agricultural inputs from the San Joaquin River.

Purpose and Scope

In this paper we examine spatial distributions of selenium in fine-grained, oxidized sediments and two species of benthic invertebrates in San Francisco Bay and compare our results to distributions of selenium in suspension and solution measured previously by others (Cutter, 1987b). The goal of this paper is to use these measurements to compare riverine with local inputs of biologically available selenium to an estuarine system, and to assess some of the geochemical, hydrologic, and biologic processes that affect reflection of such inputs in sediment and macroinvertebrate tissues.

Acknowledgments

Corbicula and sediments from Suisun Bay and the Delta were provided through the diligent efforts of Doug Ball and his assistants with the U.S. Bureau of Reclamation. Christopher Johannson initiated work on selenium analysis of the bivalves. Selenium analyses of sediment were provided by Art Horowitz of the U.S. Geological Survey, National Water Quality Laboratory, Atlanta, Georgia. We appreciate the thoughtful and constructive reviews of the manuscript by Dan Cain, Marc Sylvester, and Fred Nichols.

DATA COLLECTION AND LABORATORY PROCEDURES

Sampling Design

Selenium concentrations were measured in fine-grained oxidized surface sediments (<100 um) and in two species of benthic bivalves, the freshwater clam *Corbicula sp.* and the brackish water clam *Macoma balthica*. One specific objective of sampling was to determine if selenium was more enriched in clams and sediments from the lower San Joaquin River, upstream of the urbanization surrounding San Francisco Bay (termed South Delta - Figure 1), compared to clams and sediments from areas of the Delta and the Bay (termed West Delta and Suisun Bay) surrounded by urbanization and subjected to industrial discharges of selenium. To accomplish this, concentrations measured from late 1984 through 1986 at stations C1 - C6 were compared to concentrations measured at the same dates at station C7 (Figure 1; Table 1).

A second objective was to determine if selenium in clams and sediments from the South Delta station (C7) was enriched compared to selenium in clams and sediments from rivers unlikely to receive selenium-enriched agricultural runoff. This was accomplished by sampling the Sacramento (C9) and Tuolumne (C10) Rivers once each, simultaneously with collections at C7 (Figure 1; Table 1). Samples also were collected once at a second location in the South Delta (C11) to assure that C7 concentra-

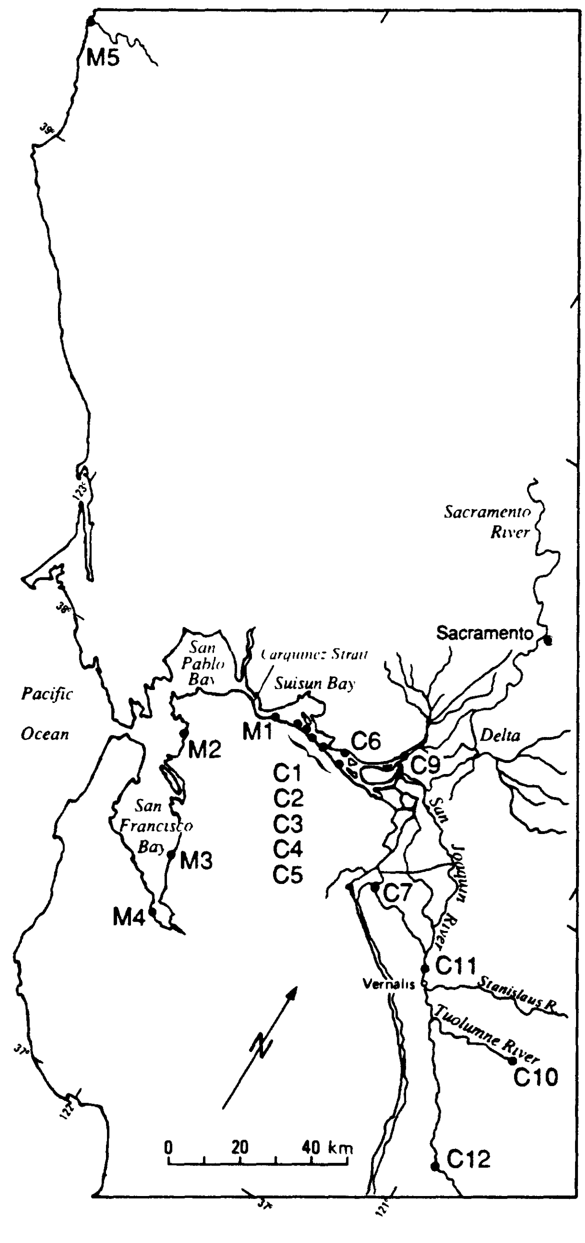

Figure 1. Locations of Sampling Stations

Table 1. Summary of Samples

Station	9/84	12/84	1/85	3/85	5/85	6/85	7/85	9/85	11/85	2/86	3/86	4/86	5/86	6/86	8/86	9/86
C1	X		X	X	X	X	X	X	X	X			X	X	X	X
C2	X		X	X	X	X	X	X	X	X			X	X		X
C3	X	X	X	X	X	X	X	X	X	X			X	X	X	X
C4	X	X	X	X	X	X	X	X	X	X			X	X	X	
C5	X	X	X	X	X	X	X	X	X	X			X	X	X	X
C6	X	X	X	X	X	X	X	X	X	X			X	X	X	X
C7	X	X	X	X	X	X	X	X	X	X			X	X	X	X
C9									X							
C10																X
C11																O
C12																X
M1								O								
M2													O			
M3								O								
M4								X		X	X	X	X			
M5													X			

X = Collection of Bivalves and Sediment
O = Collection of Bivalves only

tions were representative of more than one location in this complex region (Figure 1). Finally a fourth station was sampled in the middle reach of the San Joaquin River to compare the above stations with one from an area of known selenium enrichment (C12). The measurement of selenium in clams and sediments through 1985 and 1986 at C7 also allowed assessment of seasonal changes that might influence the one-time comparisons among river stations (Table 1).

A third objective was to determine if clams and sediments were enriched with selenium in brackish sections of San Francisco Bay. Samples were collected once at one location in each of North, Central, and South San Francisco Bay (Figure 1; Table 1), and the results were compared to one collection from a small coastal estuary on the Northern California coast (Big River). Samples also were collected at several times at a fifth station in South Bay, where selenium enrichment in birds was previously reported (Ohlendorf, et al., 1986, 1987; Figure 1, Table 1). Although not adequate to fully characterize spatial or seasonal distributions of selenium in the brackish portion of this large, complex estuary, this small sampling effort was designed only to assess the possibility of a major, bay-wide enrichment with biologically available selenium.

Sample collection, preparation, and analysis

Corbicula were sampled subtidally, using a long-handled rake with a screen basket. Individuals from each station were depurated in tanks of deionized, distilled water for three days. *Macoma* were collected intertidally. The clams were depurated for 48 hours in oceanwater diluted to the salinity of water collected from the mantle cavity. After depuration, the shell lengths of 15 to 25 clams representing the full range of shell sizes within the sample were measured to the nearest 0.1 cm. The sample was then divided into 5 to 8 pools of several individuals each, based on shell length. Whole bodies were dissected from the shells, homogenized, and then lyophilized.

Lyophilized tissue was analyzed for total selenium by a dry-ash procedure after May (1982). Approximately 0.12 grams of freeze-dried tissue was weighed into a clean 50 ml erlenmeyer flask. The tissue was wetted with absolute methanol. Then 5 ml of ashing aid composed of 40% magnesium nitrate in deionized water (w/v) was added along with 0.5 ml of a chemically inert defoaming agent. Samples were dried in a draft oven at 80^{o}C then ashed in a muffle furnace by bringing the temperature slowly up to 450^{o}C over a period of approximately 8 hours. Ashing continued overnight at 450^{o}C. Cooled, ashed samples were reconstituted in 25 ml of 4M HCl, topped with a refluxing bulb, and brought to boiling temperature for 45 minutes on a hot plate. Heating the sample solution was necessary to ensure complete conversion of selenate to selenite (Presser and Barnes, 1984, 1985). Solutions were allowed to cool and then transferred to clean polyethylene bottles for storage until analysis (usually within 1 week).

Samples were analyzed for selenium by hydride generation atomic absorption spectroscopy. Reagent blanks and standard reference materials were carried through the procedure at regular intervals. Recoveries of total selenium in reference biological tissues are reported in Table 2.

Sediment samples at all stations were collected from the oxidized surface layer, wet-seived through a 100 um mesh screen with either deionized water (Corbicula stations) or oceanwater diluted to ambient salinity (Macoma stations) and dried at 80°C. Total selenium in the sediment was determined by hydride generation after total digestion of the sediment in HF and $HClO_4$. Recoveries of selenium from sediment, rock, and particulate standard reference materials are reported in Table 2.

SELENIUM ACCUMULATION IN BENTHIC BIVALVES AND FINE SEDIMENTS

Selenium Concentrations in Corbicula

Mean selenium concentrations in *Corbicula* at Station C7 on the lower San Joaquin River, ranged from 2.8 to 3.7 ug Se/g tissue between September 1984 and September, 1986. Although mean concentrations were highest in the early part of each year, the differences among collections at C7 were not statistically significant ($P>0.50$, Figure 2). Mean selenium concentrations in *Corbicula* differed among stations C7 - C12 on the three river systems ($P<0.001$; Figure 3). This was because mean selenium in *Corbicula* in the mid-San Joaquin River at Station C12 (4.0 ug/g) was significantly greater than at Stations C7, C9, and C11 ($P<0.01$) or Station C10 ($P<0.05$; Figure 3). Stations C7 and C11, on the two lower forks of the San Joaquin River, were not significantly different from one another (in September 1986) and did not differ significantly from either Station C9, on the Sacramento River, or from Station C10 on the Tuolumne River ($P>0.05$; Figure 3). Mean selenium concentrations in *Corbicula* tissues at stations C9-C11 ranged from 2.8ug/g to 3.1 ug/g.

Selenium concentrations from all collections at station C1-C7 were used to calculate a grand mean for each station (Figure 3). These mean selenium concentrations showed some significant differences among stations ($P<0.001$). All stations in urbanized Suisun Bay and the western Delta had signficantly higher selenium in *Corbicula* than occurred in the lower San Joaquin at the southern Delta station C7 ($P<0.05$; Figure 3). The highest grand mean selenium concentrations were at Station C1, 5.2 ug/g, followed by 4.9 ug/g at C2. These were signficantly greater than mean selenium concentrations at C3, C4, C5, and C6 (Figure 3; $P<0.05$). In general, selenium showed a trend of increasing mean selenium concentrations from the Delta into San Francisco Bay (Figure 3). Concentrations at most stations were similar to those observed in the middle San Joaquin (C12).

Table 2. Recoveries of Total Selenium from Standard Reference Materials [a].

Type of Material	Certified Value	Recovered Value
Oyster Tissue (NBS SRM 1566)	2.1 + 0.5	2.1 (n=15;stdev=0.27)[b]
Albacore Tuna (NBS RM 50)	3.6 + 0.4[c]	3.7 (n=8;stdev=0.22)
Estuarine Sediment (NBS SRM 1646)	0.6[d]	0.4 (n=6;stdev=0.0)
River Sediment (NBS SRM 1645)	1.5[d]	1.1 (n=6;stdev=0.08)
Urban Particulate (NBS SRM 1648)	27 + 2	23.5 (n=2;stdev=1.4)
USGS Standards		
MAG-1 (Marine Mud)	1.1	0.8 (n=3;stdev=0.1)
W-2 (Rock)	0.1	0.1 (n=3;stdev=0.0)
SGR (Green River Shale)	3.5	3.6 (n=3;stdev=0.1)

a Concentrations in micrograms selenium per gram
b "n" is number of separate samples processed; stdev is standard deviation of the mean.
c Not certified. Value given as the probable mean.
d Only reported values (not certified) are obtainable.

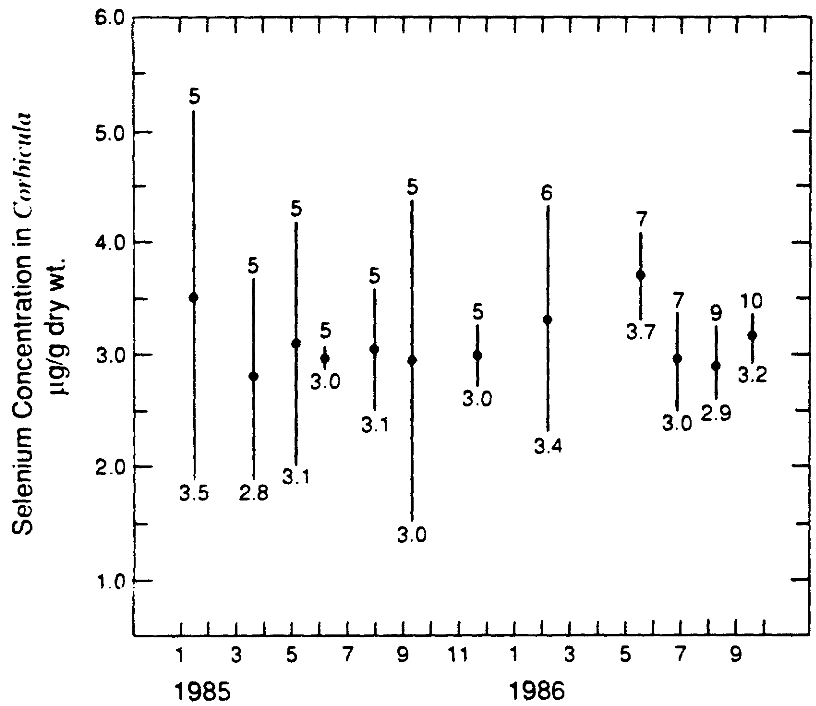

Figure 2. Mean selenium concentrations in Corbicula from Station C7, January, 1985 through September, 1986. Vertical bars represent 95 percent confidence intervals for the means. The number of size pools analyzed is listed above each bar. The mean selenium concentration is listed below each bar and expressed as micrograms per gram dry weight.

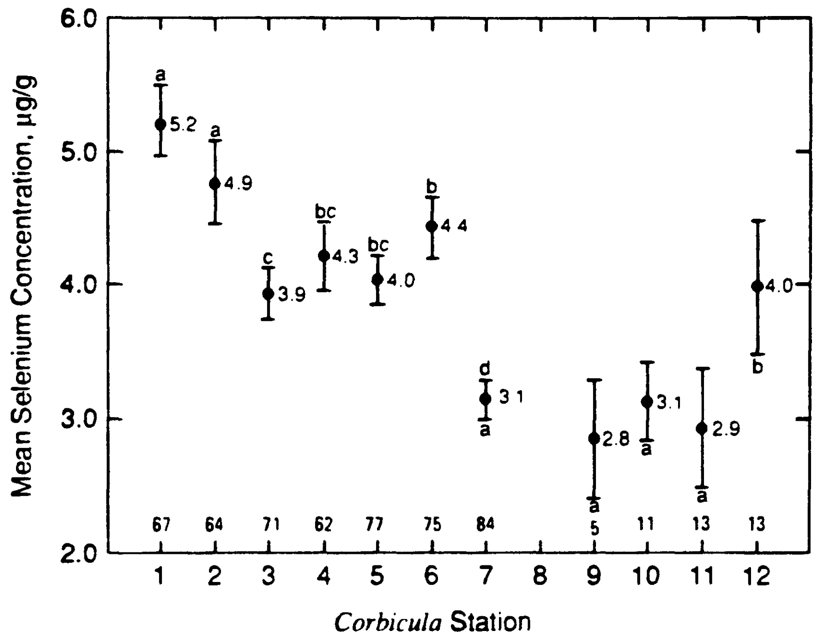

Figure 3. Mean selenium concentrations in Corbicula sp. from northern San Francisco Bay and the Sacramento, San Joaquin, and Tuolumne Rivers (as micrograms per gram, dry weight). Vertical bars represent 95 percent confidence intervals for the means. The number of size pools analyzed for each mean is given above the station number. Results of two analysis of variance tests (P<0.001 for both) and subsequent tests for differences among means (T-K Method, Sokal and Rohlf, 1981) are indicated by sets of letters above and below the bars. Bars (means) labelled by the same letter are not significantly different (P<0.05 unless otherwise noted in text).

Selenium concentrations rarely correlated with Corbicula shell length within either individual collections or all collections at any station. However, mean shell lengths of Corbicula were greater at Station C7, C11, and C12 than elsewhere ($P<0.05$; Figure 4). These differences did not appear to account for differences in mean selenium concentrations among stations. Station C7 and C10 differed in mean size of animals, but not in selenium concentrations. Station C1 and C9 differed in selenium concentration, but not in size (Figures 3,4).

Selenium Concentrations in Macoma

Mean selenium concentrations in Macoma balthica from five collections at Station M4 ranged from 3.1 ug/g in May, 1986 to 6.7 ug/g in February, 1986, with a grand mean of 5.15 ug/g among all size pools from five collections. Mean selenium concentration in Macoma differed among the five stations sampled ($P<0.001$). Selenium was signifcantly higher at Station M4 than at Stations M2, M3, and M5 ($P<0.01$) but M4 was not different from Station M1 ($P<0.05$;Figure5).

The mean shell length of Macoma differed among stations ($P<0.005$). Macoma from Station M4 were larger than those from Station M5 ($P<0.05$). Animals from M1 displayed a greater mean shell length than those from M2 and M5 ($P<0.05$,$P<0.01$) and were slightly, but not signficantly, larger than animals from M4. Regression of selenium concentration on shell length for all size pools from Station M4 accounted for 55.6% of the variablility in selenium concentrations in Macoma at this station ($P<0.001$), suggesting that size effects might account for some of the temporal variablity at this station. None of the other stations evidenced significant regressions of selenium concentration by shell length ($P>0.10$). Nevertheless, selenium concentrations were plotted against shell lengths for all size pools from all stations to assess any size biases among stations. Concentrations at all specific shell lengths followed the same order of difference among stations as the grand means (M4>M1>M3,M5>M2). Differences were most clear for larger, older animals (Figures 5,6).

Selenium Concentrations in Fine-Grained Sediments

Total selenium concentrations in all samples of fine sediments were typically less than 1.0 ug/g (Table 3). Among the stations in the southern Delta (C7), the Sacramento (C9), Tuolumne (C10), and Big Rivers (M5), 82% of the samples collected contained 0.2 ug/g selenium while the remainder contained 0.1 ug/g. At stations C1-4 and C6, a slight elevation of selenium in fine sediments was indicated; 25 percent of the sediment samples contained concentrations greater than 0.2 ug/g and none less than 0.2 ug/g. Selenium concentrations at Station C5 were unusual among the western Delta stations, with values ranging up to 1.0 ug/g. Only 15 percent of the samples at C5 contained as little as

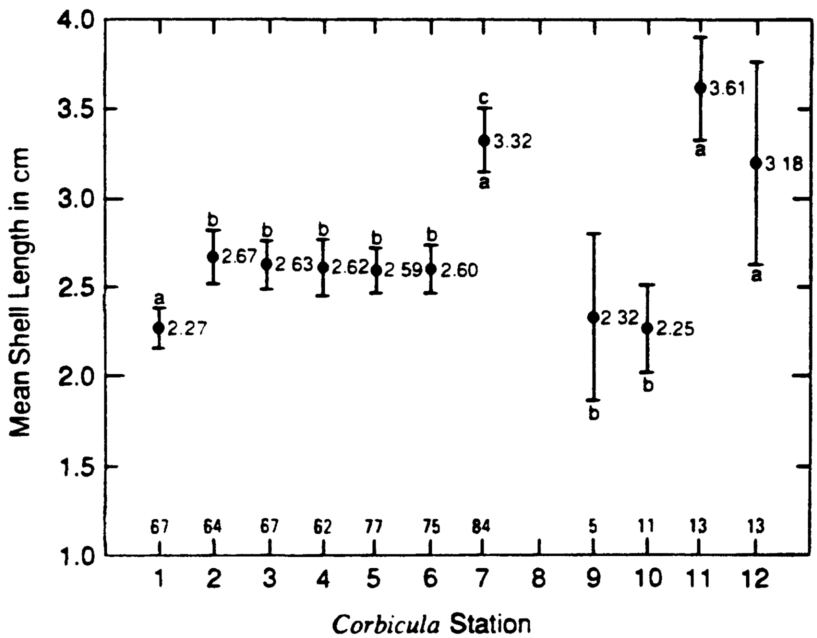

Figure 4. Mean shell lengths for <u>Corbicula sp.</u> from northern San Francisco Bay, and the Sacramento, San Joaquin, and Tuolumne Rivers. Vertical bars delimit 95 percent confidence intervals for the means. The number of size pools used for each mean is given above each station number. Results of two analysis of variance tests and subsequent tests for differences among means (T-K Method, Sokal and Rohlf, 1981) are indicated by letters above and below the vertical bars. For ANOVA of C1-C7, $P<0.05$; for ANOVA with C7-C12, $P<0.001$. Bars (means) labelled by the same letter are not significantly different, $P<0.05$.

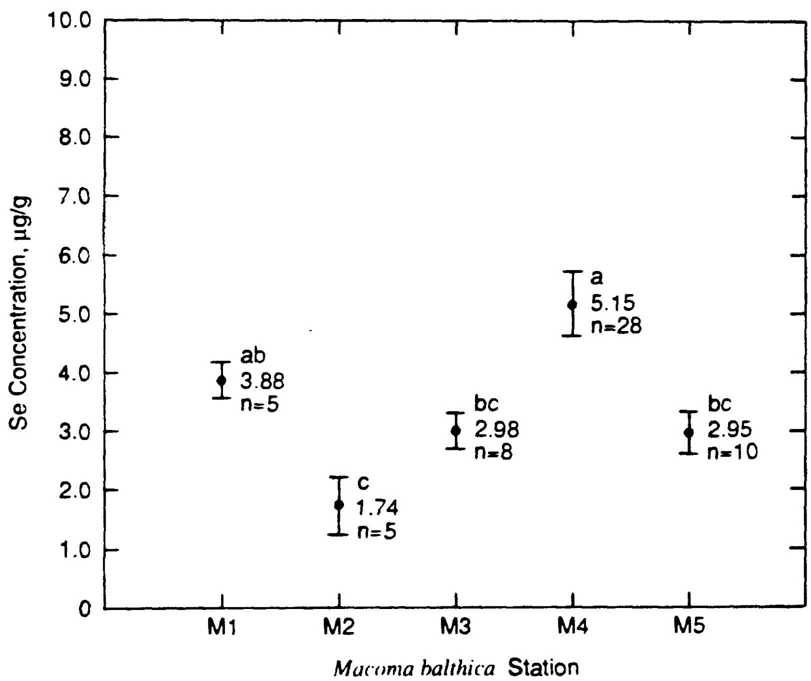

Figure 5. Mean selenium concentrations for Macoma balthica stations in San Francisco Bay and Big River. Vertical bars delimit 95 percent confidence intervals for the means. Bars (means) labelled with the same letter are not significantly different at $P<0.05$ (T-K Method, Sokal and Rohlf, 1981).

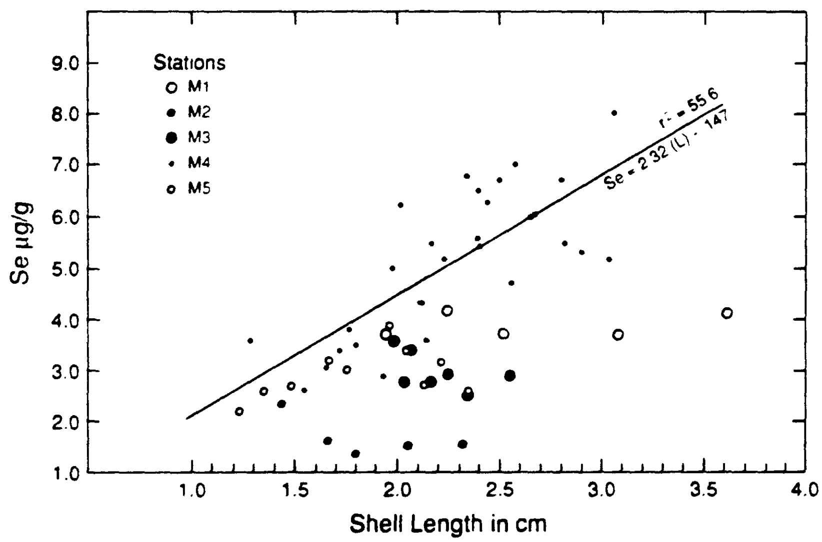

Figure 6. Selenium concentration in _Macoma balthica_ as a function of shell length, all size pools from all stations. The regression of selenium concentration on shell length is based on M4 data for September, 1985 through May, 1986.

Table 3. Selenium Concentrations in Fine Sediments from *Corbicula sp* and *Macoma balthica* Stations (ug/g dry wt.)

Station	9/84	12/84	1/85	3/85	5/85	6/85	7/85	9/85	11/85	2/86	3/86	4/86	5/86	6/86	8/86	9/86
C1				0.2		0.2			0.2	0.2			0.3	0.35		0.3
C2										0.2						
C3	0.2			0.2		0.2			0.2	0.3				0.2		0.4
C4	0.2			0.2		0.2			0.3	0.2				0.2		
C5	0.5	0.2	0.3	0.5	1.0		0.6	0.3	0.35	0.5			0.2	1.0	0.9	0.6
C6	0.2	0.2	0.2	0.2	0.5	0.2			0.2	0.2			0.2	0.2	0.2	0.2
C7	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2			0.2	0.2	0.2	0.2
C9									0.2							
C10																0.1
C12																0.5
M3													0.15			
M4								0.2		0.4	0.55	0.3	0.3			
M5												0.1				

0.2 ug/g selenium and 61 percent exceeded 0.4 ug/g. At Station C12 in the middle San Joaquin River, fine sediment contained 0.5 ug/g selenium , similar to concentrations found at C5. At Station M4 selenium in sediment varied from 0.2 to 0.7 ug/g with 46 percent of the samples exceeding 0.2 ug/g. The lowest selenium concentrations observed, 0.1 ug/g, were from the Tuolumne River (C10), Big River (M5) in northern California, and one sample from the lower San Joaquin river (C7).

SPATIAL DISTRIBUTION OF SELENIUM IN BIVALVES

Definition of Background Concentrations

Few published reports define concentrations of selenium in bivalves from unenriched environments, particularly for *Macoma balthica* and *Corbicula*. The data that are available show that *Macoma balthica* and a similar species, *Scrobicularia plana*, from the Tees estuary in Great Britian, averaged 3.0 and 2.2 ug/g, respectively (Bryan, et al., 1985). *Corbicula* from an unenriched station upstream from a coal-fired power plant on the New River, Virginia, contained 2.95 ug/g Se (converted from 0.59 ug/g wet wt. by assuming 80% moisture content; Rodgers, et al., 1979). In the present study, *Corbicula* and *Macoma* from sites presumed to be outside of selenium-enriched areas contained concentrations of selenium similar to those in the above studies (2.8 to 3.1 ug/g in the Sacramento, Tuolumne and Big Rivers). Such values should represent background concentrations for these bivalves in central California. The Tuolumne River drains soils derived from granitic and metamorphosed sedimentary and igneous rocks on the western side of the Sierra Nevada. These types of rocks generally contain low selenium concentrations (Deveral and Millard, 1986). Total dissolved selenium concentrations in the Tuolumne River downstream from Station C10 were <1 ug/L from September 1984 through January, 1986 (Gilliom, 1986; Gilliom, unpublished data). Low dissolved selenium concentrations also were measured in the Sacramento River near Station C9. Total dissolved selenium ranged from 0.040 to 0.104 ug/L between 1984 and 1986, well within the range of concentrations observed from unenriched rivers and estuaries elsewhere in the world (Cutter, 1987a,b; Measures and Burton, 1978; Takayangi and Cossa, 1985).

It is well established that elevated concentrations of dissolved selenium occur in the middle reaches of the San Joaquin River (Gilliom, 1986; Gilliom and Clifton, 1986; Cutter, 1987b). The bioavailability of this selenium is documented by the significantly elevated concentrations in *Corbicula* at C12; and by more extensive measurements of selenium enrichment in animals and plants from this region by others (Leland, et al., 1987; Saiki, 1986). However, biologically available selenium did not appear to occur in the lower San Joaquin in concentrations sufficient to measurably affect bioaccumulation in *Corbicula*. If significant concentrations of biologically available selenium were entering the Delta and San Francisco Bay from the San Joaquin River, mean selenium concentrations in Corbicula should have been elevated at the lower San Joaquin stations (C7, C11). Instead, differences among mean selenium concentrations in Corbicula from stations on the Tuolumne, Sacramento, and lower San Joaquin (southern Delta) were negligible.

It is possible that some unknown geochemical process caused a reduction in the bioavailablility of selenium at C7 and C11. However, concentrations of selenium in sediments at both C7 and C11 also were low (0.2 ug/g or less). These low concentrations in both bivalves and sediments are consistent with changes in the hydrologic system that dilute and divert selenium as the San Joaquin enters at Delta. The Stanislaus River, a major tributary, enters the San Joaquin near the most downstream station where dissolved selenium was measured and above C11. Because it originates in the selenium-poor eastern side of the watershed, the Stanislaus could substantially dilute dissolved selenium concentrations. More important, however, may be the extensive diversion of San Joaquin water as it enters the Delta. Historically, both the San Joaquin and Sacramento Rivers were major sources of freshwater to San Francisco Bay, with the Sacramento providing approximately 80% of the combined freshwater input when measured upstream from the Delta (Conomos, 1979). The present contribution of the San Joaquin River to San Francisco Bay is much reduced, although difficult to estimate precisely. Estimates of water exports from the lower San Joaquin and water uses within the Delta exceed the measured flow of the river during much of the year (U.S. Bureau of Reclamation data). During such times Sacramento River water is drawn to the pumps in the southern Delta, and, as a result, water quality in the Delta is dominated by the Sacramento (Arthur and Ball, 1979; Ball and Arthur, 1979; CDWR 1984, 1985, 1986). Both selenium concentrations and selenium speciation in solution in the western Delta were characteristic of the Sacramento rather than the San Joaquin River in January, 1985, June, 1985 and September, 1986 (Cutter, 1987b). Selenium concentrations measured in Corbicula in September 1986, also are consistent with the suggestion that, during much of the year, San Joaquin River water enriched by agricultural inputs of selenium is diverted or greatly diluted as a result of water management practices before it reaches San Francisco Bay. Human influences on hydrology, in this case, appear to be more important than geochemistry or biology in controlling the fate of selenium.

Cutter (1987b) observed detectable inputs of selenium from the San Joaquin River to San Francisco Bay in April, 1986, after a period of unusually high river flow, when it was likely that a substantial quantity of San Joaquin water did enter the estuary. Selenium concentrations also were slightly elevated in Corbicula in May, 1986 at C7; although the increase was not statistically significant. The minimal response of Corbicula to this documented selenium input may reflect 1) the minor elevation in total selenium that occurred (concentrations in were two-fold higher than in the Sacramento River, Cutter 1987b); 2) loss of selenium from animal tissues after high flows and any accompanying selenium inputs receded (however, tissue loss rates of selenium in invertebrates are slow, with half-lives of six months or more - Fowler and Benayoun, 1976a; Okazaki and Panietz, 1981); or 3) the predominance of selenate in San Joaquin water (selenite is the more biologically available form of selenium to bivalves - Pelletier, 1986; Fowler and Benayoun, 1976a). The highest mean concentrations of selenium observed in _Corbicula_ at Station C7 in 1985 also occurred during high flow, although again the increase was not statistically significant. As Cutter (1987b) suggested, selenium dynamics in this system warrant further study, especially during high river flows. To test hypotheses proposed above, the critical area to sample selenium in the water column, including analysis of suspended particulate, would be sites in the Delta downstream from both the Stanislaus River and the water diversions but upstream of the urban area.

Selenium in Bivalves from the Northern Reach of San Francisco Bay

Elevated selenium concentrations in _Corbicula_ in the western Delta and Suisun Bay indicate regional enrichment relative to the lower San Joaquin, Sacramento, and Tuolumne Rivers (Figure 3). Past studies in the northwest portion of the Carquinez Strait also found elevated selenium concentrations (5 to 11.4 ug/g) in native and transplanted _Mytilus edulis_ (Anderlini, et al., 1975; Risebrough, et al., 1977).

Selenium concentrations in _Corbicula_ in the northern reach of the Bay and Delta also are consistent with the distribution of dissolved selenium concentrations and concentrations on suspended particulate. Cutter (1987b) observed a broad maximum in total dissolved selenium and selenite through western Suisun Bay and the Carquinez Strait most of the year (Figure 1); these coincide with the highest concentrations of selenium in _Corbicula_ tissues (Figure 3), suggesting that biologically available forms of selenium are enriched in this part of the Bay.

Outfalls from several major industrial dischargers are situated along the Carquinez Strait and western Suisun Bay shoreline (Belliveau, et al., 1983). Some of these effluents contain very high concentrations of selenite, sufficient to account for internal selenium inputs to the Bay estimated from a conservative mixing model of dissolved selenium concentrations during low flow periods (Cutter, 1987b). Selenite inputs in this region of the estuary could contribute to increased selenite absorption from water by both _Corbicula_ and phytoplankton. Phytoplankton absorb dissolved selenite, in preference to selenate, and, using the sulfate reductive assimilatory pathway, incorporate selenium into seleno-amino acids and proteins (Wrench, 1978; Shamberger, 1981; Wrench and Measures, 1982; Bottino, et al., 1984). Selenium uptake in filter-feeding invertebrates is thought to occur primarily through ingestion of food; phytoplankton comprise a major portion of the diet of _Corbicula_ (Foe and Knight, 1985). Thus, distributions and concentrations of selenium in *Corbicula* in the Bay could be influenced by distributions of phytoplankton as well as directly by selenium inputs.

Selenium concentrations are reported to range between 0.1 and 2 ug/g in non-seleniferous soils (Adriano, 1986) and to average 0.1 ug/g (Norrish, 1975). Sedimentary selenium in lakes subject to atmospheric deposition from the Sudbury, Ontario smelting region ranged from 3 to 13 ug/g (Nriagu and Wong, 1983). Selenium concentrations in fine sediments (Table 3) were occasionally elevated in the western Delta and Suisun Bay compared to the lower San Joaquin station C7, and more strongly enriched at C5 in the western Delta. Most values were within the range reported for non-seleniferous soils. The sedimentary enrichment in the urbanized area was not as clear as enrichment of selenium in solution and *Corbicula*. Furthermore, the sedimentary enrichment at C5 was not accompanied by enrichment in *Corbicula* beyond that observed at other Suisun Bay-western Delta stations (Figure 3). The role of sediments in adsorption, desorption or conversion of selenium species with possible concomittant influence on biological availability remains poorly understood.

Selenium in Bivalves from Central and Southern San Francisco Bay

The regional selenium enrichment of Suisun Bay, apparent from selenium distributions in solution, sediment, and *Corbicula*, was also evident in *Macoma* from Carquinez Strait. Selenium concentrations in *Macoma* at M1 near the Carquinez Strait were intermediate between those at M4 and background concentrations found at M5 (Figure 5). In 1975 Anderlini, et al., (1975) found that selenium in *Macoma balthica* from the Carquinez Strait contained from 4.5 to 6.7 ug/g with most values between 5.2 and 5.6 ug/g. Anderlini, et al. (1975) also observed native *Mytilus edulis* with 5.0 to 7.3 ug/g selenium in the Carquinez Strait; Risebrough, et al.(1977) found 7.5 to 11.4 ug/g selenium in *Mytilus edulis* in east San Pablo Bay and the Carquinez Strait in 1976. Background concentrations of selenium in *M. edulis* range from 1.2 to 3.7 ug/g with most values from 2.0 to 2.6 ug/g (Anderlini, et al. 1975; Bjerregaard, 1985; Bryan, et al., 1985; Mikac, et al., 1985; Vos and Hovens, 1986; Wu, et al., 1982). If we assume values from M5 represent background concentrations for *Macoma*, then data from three different species indicate a regional enrichment of selenium in the northern reach of the estuary. Furthermore, previous work suggests this enrichment has persisted since at least 1975 (Anderlini, et al., 1975; Girvin, et al., 1975; Risebrough, et al., 1977).

Selenium enrichment in *Macoma* and in sediments also was evident at M4 in south San Francisco Bay near where elevated selenium concentrations were earlier found in aquatic waterfowl (Ohlendorf, et al., 1987). It is not clear whether this enrichment represents a localized input or regional enrichment in extreme South Bay. Cutter (1987b) found that dissolved selenium in south San Francisco Bay was dominated by Se(-II+0), with highest concentrations in the southernmost tip of the bay, and decreasing, consistent with a conservative mixing model, toward the Golden Gate. In contrast to the observations in North Bay, selenium enrichment in sediments in the brackish estuary are similar to enrichment patterns in Macoma. However, limited sampling in Cutter's (1987b) study and ours, along with differences in station locations (most importantly, channel versus intertidal sampling) make clear spatial resolution difficult. Selenium concentrations in Mytilus edulis from stations in south San Francisco Bay in previous studies, ranged from 3.4 to 9.9 ug/g (Girvin, et al., 1975; Risebrough, et al., 1977) and showed no simple spatial trend, although higher tissue concentrations were found in southern South San Francisco Bay. Concentrations of other trace elements in both sediment and bivalves exhibit substantial spatial heterogeneity in San Francisco Bay due to localized impacts from numerous discharge sources (Luoma and Cloern, 1982; Thomson, et al., 1984).

CONTRIBUTION OF BIOLOGICAL PROCESSES TO TISSUE CONCENTRATIONS

Differences in size or growth rates along with interactions among elements must all be considered when interpreting selenium concentrations in bivalve tissues. Neither size nor growth appear to bias the Corbicula data. However, selenium concentrations were influenced by size in Macoma from station M4 (Figure 6) and may have been affected by differential growth rates among populations. Growth rates of Macoma balthica within San Francisco Bay vary seasonally and interannually, within and among populations, dues to differences in availablility of food sources (Nichols and Thompson, 1982; Thompson and Nichols, 1987; Cain, et al., 1987). Persistent differential growth rates between Macoma populations at M1 and M4 contributed 16% of the variablility in tissue copper content at these stations (Cain, et al., 1987). Macoma at M1 showed a similar range of shell lengths as Macoma at M4, but selenium concentrations in the larger size pools were lower at M1 than at M4. However, growth rates are faster at M1 than M4 (Cain, et al., 1987) and animals of the same size will not be the same age at these stations. Differences in tissue selenium concentrations could, therefore, be affected by different lengths of exposure. Similarly, Macoma at M2 were clearly much younger animals than at M5. Most animals at M5 had weathered shells with several growth rings, reflecting ages, probably, of several years in the largest animals. M2 is a site where Macoma usually are not found (Luoma, unpublished data) and most animals collected for this study appeared to be less than one year of age. These animals may have recolonized the site after high freshwater flows the previous February and March had lowered the salinity at this station to unusually low levels. Thus, the very low selenium concentrations at M2 could have resulted, at least in part, from a short period of exposure as well as low environmental concentrations.

Selenium concentrations in bivalve tissues should parallel bioavailable environmental selenium concentrations making such organisms suitable geochemical indicators (Phillips, 1980). In laboratory uptake studies, bioaccumulation of selenium in Mytilus galloprovincialis strongly depended on ambient selenium concentrations , especially selenite, in sea water; and higher levels of accumulation occurred when phytoplankton were present in the seawater as well as selenite (Fowler and Benayoun, 1976a). Another species, Mytilus edulis, also accumulated selenium when selenite was present in seawater (Pelletier, 1986).

Interactions of selenium with other elements have been suggested, but controversy remains as to whether these interactions would modify selenium uptake. In particular, interactions of mercury and selenium have been found in terrestrial and marine mammals and appeared to be related to mercury detoxification in the liver (Koeman, et al., 1973, 1975; Martin, et al., 1976; Kari and Kauranen, 1978). In contrast, fish appeared to accumulate mercury and selenium in muscle tissue. However, while some studies have found significant linear relationships between the two elements in fish tissues (Ganther, et al., 1972; Koeman, et al., 1975; Mackay, et al., 1975; Leonzio, et al., 1982), others did not (Freidman, et al., 1980; Speyer, 1980).

The literature on mercury-selenium interactions in molluscs also is contradictory. Some studies indicate significant linear relationships of mercury and selenium in tissues of molluscs sampled in the vicinity of mercury sources (eg., Mikac, et al., 1985). Pelletier (1986) found that high concentrations of environmental mercury increased rates of selenium uptake in Mytilus edulis in the laboratory. However, Fowler and Benayoun (1976a) observed a trend toward reduction of selenium accumulation when dissolved mercury was present, although final tissue selenium concentrations did not differ significantly. They concluded that selenium uptake was not directly linked to the presence of mercury, but that their results did not preclude a causal interaction. Furthermore, Pelletier (1985) concluded that clear evidence for a 'natural joint bioaccumulation' of the two trace elements in molluscs did not exist.

Evidence for a selenium-mercury interaction in bivalve tissues, using historical data from San Francisco Bay, also is inconclusive. No significant linear relationships between selenium and mercury were evident in either Mytilus edulis transplants or Macoma balthica from the Carquinez Strait ($r=0.185$, $p>0.05$; $r=0.152$, $p>0.05$; data from Anderlini, et al., 1975) although tissue mercury concentrations were low. However, in Mya arenaria and Tapes japonica sampled from North, Central, and South San Francisco Bay stations, mean selenium concentrations in the tissues were strongly correlated with tissue mercury levels ($r=0.958$, $p<0.01$; $r=0.961$, $p<0.01$; data from Girvin, et al., 1975). Mytilus edulis, sampled from the same regions, did not show a clear linear relationship between the two elements ($r=0.454$, $p>0.05$; data from Girvin, et al.,1975). Although the two elements were sometimes correlated, selenium and mercury concentrations in the tissues each also reflected concentrations in the sediments (Anderlini, et al., 1975; Girvin, et al., 1975).

Biological processes may affect some of the observed selenium concentrations in Macoma and Corbicula, but they do not appear to be a dominant influence. The lowest concentrations of selenium in both species in this study occurred in environments where environmental exposures were expected to be low, and/or where sedimentary and solute concentrations also were low. The general enrichment of selenium in Macoma or Corbicula in Suisun Bay/Carquinez Strait and at station M4 also was consistent with measured selenium enrichment in water and sediments, and with historic analyses of these and other species. Thus, in general, tissue concentrations of selenium in Macoma and Corbicula appeared to be useful, sensitive indicators of biologically available selenium in the environment.

CONCLUSIONS

1) Background concentrations of selenium in whole soft tissues of both Corbicula and Macoma average 3.0 ppm.

2) Selenium does not appear to be entering either the southern Delta or the northern reach of San Francisco Bay from the San Joaquin River in levels sufficient to measureably influence bioaccumulation by Corbicula. This is partly because management practices prevent San Joaquin River water from entering the Bay during much of the year in quantities sufficient to affect water quality.

3) Selenium concentrations in Corbicula from the western Delta and Suisun Bay are elevated and indicate regional enrichment of selenium relative to the southern Delta, and other river systems not enriched in selenium.

4) Selenium concentrations are also elevated in the estuarine bivalve, Macoma balthica, at some stations, probably reflecting regional selenium enrichment in the northern reach of the Bay and possibly patchiness of sources or bioavailable selenium in south San Francisco Bay.

5) Benthic bivalves appear to be more sensitive indicators of environmental selenium than fine sediments, for both suspension-feeding and deposit-feeding bivalves.

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APPENDIX A

Note:

This appendix includes tables of all selenium and arsenic concentrations measured in *Corbicula sp.* and *Macoma balthica* samples from all stations and collection times between September 1984 and May 1987. The additional selenium analyses of *Macoma balthica* and arsenic concentrations in both bivalves will be discussed in a future manuscript.

Lyophilized clam tissues were analyzed for arsenic using the same procedure as for selenium. However, potassium iodide was added to an aliquot of sample to reduce all As(V) to As(III) prior to analysis by hydride generation. Recoveries from NBS reference materials averaged 107% for SRM 1572 Citrus Leaves (n=6), 97% for SRM 1566 Oyster Tissue (n=13), and 94% for RM 50 Albacore Tuna (n=21).

List of Tables

Table 1.

Station: C1, Roe Island

Species Sampled: Corbicula sp.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	2.49	4.0	8.0
	2	2.16	3.7	7.6
	2	2.02	3.6	9.2
	2	1.88	3.8	5.9
January 16, 1985	4	1.80	1.8	11.0
	4	1.85	5.0	10.1
	4	1.77	6.2	9.3
March 19, 1985	2	2.58	6.6	9.6
	2	2.345	2.7	10.9
	3	1.90	5.1	7.3
	4	1.71	6.2	9.4
	4	1.58	6.4	6.7
May 10, 1985	1	3.44	5.3	10.3
	1	3.17	4.2	10.2
	2	2.81	5.3	10.7
	2	2.26	4.5	8.0
	3	1.74	7.1	10.0
June 7, 1985	3	2.07	5.2	8.6
	3	1.85	4.8	8.3
	3	1.71	5.6	8.8
	3	1.55	7.0	9.2
	3	1.47	5.8	7.9
July 31, 1985	2	2.62	5.1	10.8
	2	2.36	4.5	8.4
	3	2.24	4.9	7.8
	5	2.07	5.6	10.5
	5	1.80	5.7	9.2

Table 1 Continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	2.65	5.7	9.3
	3	2.44	5.3	10.8
	3	2.20	5.6	8.3
	4	1.95	5.9	10.7
	4	1.73	5.1	6.7
November 20, 1985	3	2.52	3.1	9.0
	4	2.34	4.9	11.5
	6	2.12	4.6	9.6
	6	1.84	5.0	9.9
	7	1.62	6.6	12.4
February 4, 1986	5	2.74	5.5	10.9
	5	2.46	4.4	11.0
	5	2.29	4.3	9.5
	6	2.04	5.6	10.7
	5	1.84	7.0	10.8
May 15, 1986	3	2.82	3.4	9.7
	3	2.65	4.5	10.0
	4	2.49	5.0	8.9
	4	2.38	4.7	9.7
	6	2.13	5.0	9.7
	5	1.82	5.2	11.4
June 24, 1986	1	2.90	5.6	11.9
	2	2.72	6.1	12.3
	4	2.53	5.3	9.8
	3	2.24	6.0	10.0
	4	1.96	5.2	11.4
September 15, 1986	2	3.15	6.0	12.9
	2	3.06	7.2	13.0
	2	2.905	5.4	10.6
	2	2.845	5.5	11.8
	2	2.735	5.2	9.5
	2	2.62	5.7	11.3
	2	2.50	5.6	9.7
	3	2.397	5.0	10.3
	2	1.895	5.7	9.7
	3	1.61	6.2	10.7

Table 2.

Station: C2, Middle Ground

Species Sampled: <u>Corbicula sp.</u>

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	4.02	5.4	13.5
	2	3.24	4.6	10.0
	2	2.98	3.9	8.4
	2	2.28	3.3	8.3
	2	1.76	3.4	6.7
January 16, 1985	2	3.73	7.5	19.5
	2	2.90	3.6	9.4
	2	2.71	3.8	7.2
	3	2.18	3.6	7.8
	4	1.81	3.7	6.4
March 19, 1985	2	3.08	4.3	9.7
	2	2.78	4.2	7.4
	2	2.42	4.3	9.3
	3	2.03	3.4	6.9
May 10, 1985	1	3.66	5.3	15.6
	2	3.13	4.7	10.2
	2	2.53	3.0	9.4
	3	2.14	4.4	8.8
	3	1.86	4.5	8.8
June 7, 1985	1	3.78	7.0	14.3
	2	2.96	4.9	11.1
	2	2.63	3.2	7.6
	2	2.38	4.4	9.0
	3	1.95	4.6	8.1
July 31, 1985	2	3.55	4.6	13.8
	2	3.02	3.6	8.8
	3	2.40	4.1	8.4
	3	2.13	4.9	9.4
	4	1.98	5.7	9.2

Table 2, continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	3.72	8.4	15.0
	2	3.12	5.4	8.9
	2	2.84	4.9	7.7
	3	2.40	6.8	10.4
	4	2.10	6.2	7.6
November 20, 1985	1	3.78	8.4	20.4
	1	3.23	5.2	13.6
	4	2.96	3.5	12.0
	5	2.47	2.8	10.8
	6	2.32	2.5	8.5
February 4, 1986	1	3.66	5.4	13.5
	3	3.16	2.6	9.9
	5	2.53	5.0	10.7
	5	2.20	4.3	10.2
	6	1.83	5.7	10.8
May 15, 1986	1	2.99	5.9	12.5
	2	2.85	4.6	9.8
	4	2.58	5.6	10.2
	5	2.43	4.6	8.5
	5	1.90	5.9	9.3
August 4, 1986	1	3.36	4.8	11.5
	2	3.15	4.7	12.2
	4	2.79	5.0	10.8
	5	2.28	5.0	8.9
	4	1.93	5.3	9.6
	6	1.59	5.4	9.7
September 15, 1986	1	3.21	6.6	10.3
	2	3.065	6.1	11.5
	1	2.92	6.4	11.1
	3	2.78	5.0	10.8
	3	2.54	6.0	10.1
	3	2.38	5.2	9.3
	3	2.10	5.8	9.9
	4	1.945	6.0	8.9
	3	1.62	5.7	7.8

Table 3.

Station: C3, Harris Harbor

Species Sampled: <u>Corbicula sp.</u>

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	3.46	2.5	7.9
	2	2.96	2.9	9.5
	2	2.38	0.8	7.7
	2	2.02	2.5	7.9
	2	1.80	3.0	5.8
December 6, 1984	2	3.67	*	9.0
	2	3.105	4.4	8.3
	2	2.48	4.3	7.5
	2	2.43	3.1	7.5
	3	1.90	3.7	6.5
January 16, 1985	2	3.60	4.4	*
	2	2.95	2.5	9.2
	2	2.53	5.4	8.8
	2	2.35	3.4	10.1
	4	1.84	4.1	9.1
March 19, 1985	2	3.27	2.9	9.5
	2	2.79	3.5	9.9
	2	2.46	4.7	8.2
	3	2.13	4.7	6.4
	3	1.91	5.4	7.0
May 10, 1985	2	2.50	6.0	8.3
	2	2.36	4.3	8.4
	2	2.27	4.6	8.9
	2	1.95	5.2	9.5
	3	1.57	4.6	4.7
June 7, 1985	2	2.96	3.4	8.7
	2	2.56	3.6	6.6
	2	2.36	3.4	8.1
	2	2.24	3.7	7.0
	2	1.89	3.4	7.3
July 31, 1985	2	2.85	3.3	9.0
	2	2.655	3.8	8.4
	2	2.53	2.4	8.2
	3	2.13	3.9	10.0
	4	1.74	3.6	9.1

Table 3, continued.

Date of Collection	# of Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	4.40	4.8	13.4
	2	2.87	3.9	8.9
	4	2.42	4.1	9.2
	4	2.18	2.9	8.0
	5	1.88	3.9	7.7
November 20, 1985	2	3.87	4.1	9.5
	4	3.42	3.9	11.0
	4	3.06	2.4	10.4
	4	2.65	3.4	11.4
	6	2.34	3.9	9.0
February 4, 1986	2	3.91	3.9	9.2
	3	3.47	3.3	9.5
	4	3.05	4.4	10.5
	5	2.71	2.9	9.0
	7	1.95	3.3	8.2
May 15, 1986	1	3.72	3.6	9.5
	3	3.10	4.6	8.2
	4	2.60	4.4	10.1
	4	2.26	3.6	7.5
	6	1.92	5.0	6.8
June 24, 1985	2	3.16	3.2	8.2
	2	3.02	3.4	8.7
	4	2.85	3.2	8.5
	4	2.56	3.7	8.5
	4	2.15	4.4	8.8
August 4, 1986	2	3.16	4.3	10.1
	3	2.96	3.4	9.2
	3	2.75	4.0	8.1
	4	2.54	4.0	8.8
	5	2.11	4.2	9.2
September 15, 1986	1	3.06	4.5	9.1
	2	2.90	4.4	8.7
	2	2.75	4.1	*
	2	2.67	5.9	10.8
	3	2.53	5.7	11.4
	3	2.35	4.7	9.2
	4	2.05	4.8	8.8
	3	1.81	4.0	8.9

Table 4.

Station: C4, Mallard Slough

Species Sampled: *Corbicula sp.*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	3.11	3.1	9.0
	2	2.45	2.3	5.7
	2	2.42	2.3	6.5
	2	2.22	2.5	8.3
	2	1.52	3.2	7.1
December 6, 1984	2	3.36	4.0	8.9
	2	2.74	4.2	8.2
	2	2.23	4.6	5.7
	3	1.66	4.4	6.4
	4	1.54	4.3	5.3
January 16, 1985	2	3.32	3.8	25.8
	2	2.98	4.1	10.9
	2	2.85	3.4	10.4
	2	2.60	5.7	10.2
	3	2.00	4.9	5.2
March 19, 1985	2	3.37	6.0	9.8
	2	3.11	3.8	9.4
	3	2.23	5.4	7.1
	3	1.83	5.6	6.4
	4	1.58	6.7	7.2
May 10, 1985	2	3.05	5.0	14.3
	2	2.26	4.5	13.2
	2	2.19	3.3	6.1
	2	1.83	3.8	6.2
	3	1.57	5.8	5.6
June 7, 1985	2	3.10	3.6	10.3
	2	2.76	4.0	6.6
	2	2.45	3.4	7.7
	3	1.98	3.7	7.4
	2	1.52	3.0	5.9
July 31, 1985	2	2.75	3.8	9.2
	2	2.28	4.2	7.9

Table 4 continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	2.75	4.3	7.9
	3	2.47	4.7	9.9
	3	2.26	5.5	8.6
	2	2.17	4.2	7.9
	3	2.04	6.3	9.6
November 20, 1985	1	4.04	4.8	10.4
	4	3.20	4.1	11.1
	4	2.90	6.2	13.0
	5	2.57	5.0	13.8
	5	2.22	3.2	12.1
February 4, 1986	1	3.85	5.2	12.3
	4	3.42	4.2	11.6
	4	3.04	4.5	9.6
	5	2.62	4.7	9.4
	2	1.92	4.1	9.3
May 15, 1986	1	3.30	3.1	*
	2	2.87	4.5	11.6
	4	2.74	4.8	11.2
	5	2.51	4.1	10.5
	6	2.18	5.1	9.1
	5	1.98	6.4	10.3
June 24, 1986	1	3.70	3.3	9.8
	2	3.54	4.0	11.8
	2	3.35	2.8	12.7
	2	3.04	3.8	11.3
	3	2.72	4.6	9.9
	4	2.32	4.1	9.2
August 4, 1986	2	3.62	3.4	10.8
	2	3.20	4.5	11.2
	3	2.86	4.3	10.5
	4	2.46	5.2	11.4
	4	2.29	4.8	10.7

Table 5.

Station: C5, New York Slough

Species Collected: Corbicula sp.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	3.42	4.3	15.0
	2	3.01	3.8	12.2
	2	2.42	3.1	8.3
	2	2.30	2.4	8.5
	2	1.72	3.8	5.5
December 6, 1984	2	3.29	2.7	9.5
	2	2.73	4.9	9.9
	2	2.27	3.3	8.0
	2	2.08	3.1	5.2
	2	1.85	5.3	6.7
January 16, 1985	2	2.95	3.6	8.5
	2	2.86	5.2	9.1
	2	2.54	5.8	9.6
	3	2.13	2.7	4.6
	5	1.59	5.7	3.8
March 19, 1985	1	3.74	4.9	9.1
	2	3.20	4.2	8.2
	2	2.57	3.9	6.6
	3	2.04	3.1	6.1
	4	1.91	3.5	5.9
June 7, 1985	2	3.17	4.0	8.6
	2	2.84	3.6	8.0
	2	2.16	3.3	6.1
	2	1.98	3.4	6.7
	3	1.61	4.5	5.8
July 31, 1985	2	2.93	3.7	7.6
	4	2.48	4.0	7.5
	4	2.30	4.22	5.6
	4	2.10	5.4	9.4
	4	1.79	5.4	8.8

Table 5 continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	3.44	5.7	13.0
	4	2.46	4.1	7.3
	4	2.32	4.6	6.5
	4	2.14	2.8	7.0
	4	1.90	3.8	6.5
November 20, 1985	2	3.64	4.7	12.5
	3	3.29	3.7	11.4
	4	2.87	3.9	10.6
	6	2.38	3.5	7.2
	6	1.97	4.9	8.6
February 4, 1986	1	3.29	4.3	9.9
	4	3.09	4.4	9.4
	4	2.70	4.0	8.5
	5	2.44	4.1	8.4
	6	1.89	5.0	7.7
May 15, 1986	1	3.70	4.7	10.6
	3	3.28	4.3	11.0
	4	3.04	3.9	10.8
	5	2.57	2.9	9.0
	5	2.28	4.3	8.0
	1	3.41	4.3	13.0
June 24, 1986	1	3.20	4.6	18.4
	3	3.07	3.2	10.2
	4	2.72	3.0	9.2
	4	2.45	3.3	7.0
	5	2.17	3.5	9.5
	5	1.87	3.8	9.2
August 4, 1986	1	3.95	3.8	9.4
	2	3.36	4.2	14.6
	2	3.16	3.2	13.4
	4	2.65	3.2	11.5
	4	2.42	3.3	8.3
	4	2.14	3.9	10.2

Table 5 continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 15, 1986	1	3.31	5.1	11.3
	1	3.19	4.4	10.6
	2	3.02	3.9	10.4
	2	2.87	4.6	13.0
	3	2.65	4.0	10.0
	3	2.51	4.4	9.8
	3	2.27	4.0	8.8
	4	1.95	4.4	8.9
	3	1.52	6.1	8.0

Table 6.

Station: C6, Chain Island

Species Sampled: Corbicula sp.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	2.21	3.8	15.3
	2	1.84	2.6	6.3
	2	1.79	3.2	6.4
	2	1.60	2.4	6.2
	2	1.54	4.0	8.0
December 6, 1984	2	3.18	6.4	16.8
	2	2.96	3.9	8.9
	2	2.29	3.3	6.4
	3	1.95	2.8	4.9
January 16, 1985	2	3.16	5.8	15.8
	2	3.03	6.1	12.3
	2	2.65	5.1	10.6
	3	2.15	5.4	9.4
	4	1.75	6.2	7.3
March 19, 1985	2	3.14	4.3	13.0
	2	3.01	4.3	11.7
	2	2.54	5.9	15.1
	3	2.00	4.6	7.4
	4	1.69	5.1	7.2
May 10, 1985	1	3.09	2.8	7.8
	2	2.945	3.8	9.1
	2	2.36	3.9	9.2
	2	2.00	3.0	5.8
	2	1.77	4.5	8.0
June 7, 1985	1	3.78	5.0	17.0
	2	3.56	6.0	18.1
	2	2.91	3.8	10.2
	2	2.26	3.1	8.0
	3	1.86	2.7	4.5
July 31, 1985	1	3.62	6.9	21.7
	2	3.06	3.1	9.8
	2	2.80	4.8	11.5
	3	2.32	3.7	9.8
	4	1.68	5.7	7.3

Table 6 Continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	3.59	5.3	17.5
	1	3.44	6.0	20.1
	3	2.96	5.2	11.0
	3	2.51	5.8	11.8
	4	2.25	5.6	9.7
November 20, 1985	4	3.14	3.3	14.7
	4	2.90	4.6	9.8
	5	2.53	4.7	11.5
	5	2.27	4.5	9.7
	5	1.95	4.4	12.3
February 4, 1986	1	3.71	6.2	19.0
	3	3.33	6.0	16.1
	4	2.97	4.5	10.5
	5	2.39	4.2	9.4
	6	1.97	4.2	9.7
May 15, 1986	1	3.11	4.6	11.4
	3	3.00	4.5	10.5
	3	2.69	4.3	8.8
	4	2.49	4.1	8.8
	4	2.26	4.4	9.0
	4	1.99	4.8	8.0
June 24, 1986	1	3.26	3.9	12.3
	2	3.08	4.0	11.2
	3	2.86	3.4	10.5
	3	2.74	4.4	9.6
	4	2.24	3.3	10.8
	5	1.91	3.6	8.5
August 4, 1986	1	3.32	4.0	9.8
	3	2.95	3.8	11.0
	3	2.74	3.3	10.0
	3	2.46	4.2	10.2
	3	2.17	4.0	8.8
	4	1.94	4.1	8.1
September 15, 1986	1	3.29	4.5	12.6
	3	3.02	5.1	12.4
	2	2.92	4.7	11.7
	3	2.76	4.6	10.3
	3	2.56	5.0	11.1
	4	2.42	4.7	10.5
	3	2.33	3.9	8.6
	4	2.09	4.8	11.1

Table 7.

Station: C7, Delta Mendota Canal intake

Species Sampled: *Corbicula sp.*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 25, 1984	2	3.84	2.8	7.2
	2	3.41	2.5	7.2
	2	2.98	2.5	6.5
	2	1.74	3.7	5.2
December 6, 1984	2	3.63	4.0	11.4
	2	3.32	3.4	6.2
	2	2.96	3.2	4.6
	2	2.71	3.8	5.4
January 16, 1985	2	3.14	1.3	4.6
	2	2.84	4.0	5.8
	2	2.67	3.6	6.5
	2	2.09	4.6	4.9
	3	1.79	4.2	5.4
March 19, 1985	1	4.47	2.8	9.8
	2	3.79	1.6	6.9
	2	3.48	3.2	6.2
	2	2.86	3.5	6.2
	2	2.33	3.0	7.6
May 10, 1985	1	3.91	4.3	10.5
	1	3.40	2.6	6.8
	2	2.99	2.5	6.0
	2	2.31	2.4	6.4
	2	1.71	3.9	5.8
June 7, 1985	1	3.89	3.0	8.8
	1	3.63	2.9	6.5
	2	3.07	3.1	5.6
	2	2.60	3.0	5.4
	2	2.10	2.9	5.1
July 31, 1985	1	4.16	2.3	8.1
	1	3.91	3.0	6.0
	2	3.28	3.1	6.6
	2	2.84	3.5	9.8
	3	2.24	3.4	6.2

Table 7 continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 11, 1985	1	4.23	2.3	6.6
	2	3.73	5.0	8.2
	2	3.30	2.3	3.6
	2	2.95	2.4	5.6
	3	2.42	2.8	4.3
November 20, 1985	1	5.04	3.3	17.6
	2	4.36	2.6	8.0
	4	3.52	3.1	9.3
	4	2.96	3.0	8.2
	5	2.58	3.0	8.9
February 4, 1986	1	5.31	3.6	6.9
	1	4.98	2.3	8.7
	1	4.35	2.4	9.6
	1	3.96	3.7	11.0
	3	3.35	3.2	8.1
	3	2.51	4.9	6.0
May 15, 1986	1	4.53	4.4	8.2
	1	4.00	3.7	7.6
	3	3.20	3.4	6.0
	3	3.07	3.2	6.4
	3	2.67	3.5	5.1
	3	2.52	3.5	6.1
	6	1.99	4.3	5.8
June 24, 1986	1	4.11	2.5	4.6
	1	3.96	3.1	7.3
	1	3.70	2.8	7.0
	2	3.45	2.4	5.5
	4	3.03	3.3	5.8
	4	2.27	3.0	5.0
	4	1.81	3.8	5.2

Table 7 continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
August 4, 1986	1	4.61	2.2	7.2
	1	4.52	2.7	7.7
	1	4.18	2.4	7.8
	1	3.90	3.4	7.8
	2	3.63	2.9	6.1
	2	3.43	3.2	6.5
	2	3.25	2.8	6.0
	2	2.90	3.2	6.2
	3	2.40	3.6	5.9
September 15, 1986	1	4.56	3.0	8.6
	1	4.49	2.8	8.5
	1	4.18	2.8	7.8
	1	4.06	3.0	7.4
	1	3.82	2.9	6.6
	1	3.70	2.9	7.1
	1	3.65	3.7	6.6
	1	3.39	2.4	6.6
	1	3.29	3.6	6.6
	2	2.975	3.7	5.6
	1	2.72	3.3	4.6
	2	2.56	2.7	6.1

Table 8.

Station: C8, Grizzly Bay

Species Sampled: <u>Corbicula sp.</u>

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt.)	Arsenic Concentration (ug/g dry wt.)
May 15, 1986	2	2.78	5.2	7.8
	4	2.53	6.0	8.4
	5	2.36	5.1	9.6
	4	2.04	5.0	9.9
	5	1.78	6.2	9.7
June 24, 1986	1	2.76	4.4	8.4
	3	2.64	3.9	10.2
	3	2.51	4.5	11.6
	5	2.42	4.8	11.0
	4	2.14	6.0	8.9
	4	1.99	5.2	9.6
August 4, 1986	1	2.81	4.8	10.8
	2	2.74	5.8	10.5
	3	2.56	5.2	11.9
	3	2.24	5.3	9.8
	3	2.06	5.6	10.7
September 15, 1986	1	2.84	5.4	11.0
	1	2.75	5.0	10.5
	2	2.62	5.0	10.8
	2	2.56	5.5	9.9
	3	2.43	5.2	10.6
	3	2.29	5.7	10.9
	3	2.03	5.4	9.8

Table 9

Station: C9, Rio Vista bridge, Rio Vista, CA

Species Sampled: *Corbicula sp.*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
November 21, 1985	4	2.79	2.3	9.9
	3	2.61	3.1	8.4
	7	2.22	2.8	9.2
	7	2.12	2.8	7.7
	7	1.87	3.2	8.1

Station: C10, Tuolumne River above Modesto, CA

Species Sampled: *Corbicula sp.*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 9, 1986	2	2.71	2.7	9.6
	2	2.59	3.0	8.7
	2	2.54	2.7	8.2
	2	2.615	2.6	11.4
	2	2.48	2.9	9.5
	2	2.13	3.0	8.6
	2	2.03	3.2	8.5
	2	2.31	3.1	10.0
	2	1.90	3.4	7.9
	2	1.80	3.9	6.7
	2	1.70	3.8	7.3

Table 10.

Station: C11, lower San Joaquin River at Mossdale

Species Sampled: Corbicula sp.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 15, 1986	1	4.44	5.1	9.1
	1	3.99	2.6	7.2
	1	3.98	3.0	8.7
	1	3.85	3.0	7.6
	1	3.81	2.4	6.4
	1	3.72	2.2	6.6
	1	3.61	2.4	6.5
	1	3.60	2.7	6.7
	1	3.56	2.9	7.1
	1	3.41	2.9	7.0
	1	3.39	2.7	7.0
	1	3.15	3.4	6.9
	1	2.44	2.6	7.0

Station: C12, Freemont Ford on the San Joaquin River

Species Sampled: Corbicula sp.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 9, 1986	1	4.36	3.4	10.9
	1	4.26	2.8	11.2
	1	4.12	3.3	9.5
	1	3.97	3.7	9.3
	1	3.84	3.9	9.9
	1	3.60	5.3	8.2
	1	3.01	3.9	6.0
	1	3.10	2.8	7.6
	2	2.865	4.1	7.8
	1	2.79	3.7	6.8
	1	2.20	4.8	6.4
	2	1.815	4.9	6.2
	6	1.505	5.1	6.2

Table 11.

Station: M4, Palo Alto Harbor

Species Sampled: Macoma balthica

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 17, 1985	5	2.83	5.5	10.3
	8	2.56	4.7	11.9
	8	2.41	5.4	14.1
	7	2.18	5.5	11.9
	10	1.78	3.8	10.4
February 19, 1986	3	3.07	8.0	12.5
	6	2.66	6.0	12.2
	5	2.51	6.7	11.2
	6	2.40	6.5	9.8
	3	2.03	6.2	11.7
March 24, 1986	2	2.815	6.7	8.4
	2	2.585	7.0	11.3
	3	2.45	6.3	8.6
	4	2.40	5.6	10.6
	7	2.35	6.8	8.6
	5	2.24	5.2	8.6
April 29, 1986	1	3.04	5.2	7.3
	1	2.88	5.3	7.2
	2	2.67	6.0	7.7
	3	2.13	4.3	7.9
	2	1.98	4.9	9.8
	2	1.79	3.5	7.0
	8	1.28	3.6	6.7
May 28, 1986	2	2.15	3.6	7.6
	2	1.94	2.9	5.0
	4	1.73	3.4	6.2
	7	1.64	3.1	5.2
	4	1.55	2.6	5.1
June 25, 1986	1	2.60	4.8	5.2
	3	2.39	8.5	11.7
	2	1.92	2.9	6.1
	7	1.70	3.2	6.5
	11	1.53	3.3	5.4

Table 11 Continued.

Date of Collection	# of Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
July 23, 1986	1	3.20	6.6	10.9
	1	2.86	5.3	10.0
	2	2.74	4.3	7.7
	1	2.52	4.8	9.1
	9	1.85	3.7	10.2
	7	1.75	4.4	7.8
	9	1.54	5.1	8.4
August 20, 1986	1	2.80	4.5	7.4
	2	2.61	4.5	6.8
	2	2.36	3.9	6.4
	6	1.84	4.0	7.1
	8	1.65	4.0	7.5
September 17, 1986	1	2.99	4.0	8.2
	2	2.51	3.9	7.6
	2	2.25	4.5	6.6
	3	2.08	3.8	7.3
	3	1.95	4.6	7.3
	4	1.85	4.0	7.6
	5	1.63	4.7	9.4
October 15, 1986	2	2.655	3.4	8.3
	2	2.41	5.0	7.6
	2	2.195	5.4	10.3
	2	2.04	3.5	9.0
	2	1.915	3.5	8.1
	2	1.85	4.0	9.4
	5	1.63	4.6	7.3
	5	1.49	5.4	9.0
November 26, 1986	1	3.08	3.1	12.8
	2	2.69	4.2	9.9
	2	2.36	2.7	7.2
	2	2.24	2.9	8.3
	2	2.00	2.8	8.0
	3	1.85	2.9	7.7
	3	1.61	2.5	10.2

Table 11 Continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
December 10, 1986	1	2.90	5.2	12.2
	2	2.69	4.8	10.3
	2	2.475	5.0	9.9
	2	2.315	5.5	9.9
	2	2.115	4.6	10.3
	4	1.735	4.3	9.1
	6	1.435	4.0	10.3
January 26, 1987	1	2.83	5.8	9.3
	2	2.47	5.0	9.9
	4	1.92	5.9	8.9
	3	1.78	5.2	8.4
	4	1.43	5.5	9.7
February 23, 1987	1	2.90	6.1	8.3
	2	2.74	6.0	10.5
	1	2.61	7.0	9.9
	3	2.517	6.6	9.0
	1	2.30	5.4	9.3
	3	2.103	5.5	9.4
	5	1.768	5.4	8.4
	2	1.585	6.2	9.7
March 24, 1987	3	2.74	7.6	9.3
	4	2.52	6.4	10.6
	3	2.35	6.6	8.0
	3	2.17	6.0	8.2
	4	1.82	5.8	6.6
	4	1.66	5.8	9.3
	7	1.48	5.0	9.6
April 21, 1987	1	3.22	5.9	10.7
	1	2.82	6.1	9.0
	2	2.63	6.1	13.9
	3	2.39	6.7	10.2
	3	2.18	5.7	11.4
	3	1.94	4.2	7.7
	4	1.78	4.6	8.5
	4	1.64	4.6	8.4

Table 11 Continued.

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
May 19, 1987	1	2.87	5.56	10.1
	1	2.77	4.8	13.4
	3	2.598	6.4	13.5
	3	2.43	4.6	9.8
	4	1.87	3.8	9.9
	5	1.79	3.7	10.4
	6	1.52	4.6	7.8

Table 12.

Station: M1, Martinez Harbor

Species Sampled: *Macoma balthica*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 16, 1985	4	3.63	4.1	14.5
	5	3.08	3.7	10.3
	11	2.52	3.7	10.5
	19	2.26	4.2	13.0
	33	1.94	3.7	9.8
May 20, 1987	1	3.10	3.8	10.2
	3	2.93	3.7	9.3
	2	2.74	3.8	11.3
	2	2.65	3.9	11.2
	2	2.54	4.2	8.2
	3	2.00	3.6	6.9
	5	1.66	3.2	6.9

Station: M2, Berkeley, north of the marina

Species Sampled: *Macoma balthica*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
April 1, 1986	3	2.33	1.6	7.6
	3	2.06	1.6	7.3
	4	1.80	1.4	7.3
	4	1.65	1.7	8.7
	8	1.44	2.4	7.1

Table 12 Continued.

Station: M3, Hayward, near San Mateo Bridge

Species Sampled: *Macoma balthica*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
September 16, 1985	5	2.56	2.9	13.3
	9	2.25	2.9	15.0
	9	2.08	3.4	12.0
	14	1.99	3.6	12.3
	19	1.74	3.0	10.0
May 20, 1987	2	2.65	3.4	16.6
	2	2.49	3.4	12.3
	3	2.36	4.5	13.1
	4	2.15	3.5	11.1
	4	2.075	3.6	10.0
	5	1.95	3.8	11.7
	4	1.88	3.6	9.6
	4	1.73	3.4	9.8

Table 13.

Station: M5, mouth of Big River at Mendocino, California.

Species Sampled: *Macoma balthica*

Date of Collection	# in Size Pool	Average Shell Length	Selenium Concentration (ug/g dry wt)	Arsenic Concentration (ug/g dry wt)
May 14, 1986	3	2.35	2.7	7.9
	4	2.24	3.2	14.1
	15	2.14	2.7	13.3
	6	2.05	3.4	17.0
	9	1.97	3.9	12.5
	7	1.76	3.0	8.9
	4	1.67	3.2	10.2
	9	1.49	2.7	7.6
	11	1.36	2.6	6.5
	20	1.24	2.2	6.1