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Constraints on the sedimentation history of San Francisco Bay from ^{14}C and ^{10}Be

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Abstract

Industrialization and urbanization around San Francisco Bay as well as mining and agriculture in the watersheds of the Sacramento and San Joaquin rivers have profoundly modified sedimentation patterns throughout the estuary. We provide some constraints on the onset of these erosional disturbances with ^{10}Be data for three sediment cores: two from Richardson Bay, a small embayment near the mouth of San Francisco Bay, and one from San Pablo Bay, mid-way between the river delta and the mouth. Comparison of pre-disturbance sediment accumulation determined from three ^{14}C-dated mollusk shells in one Richardson Bay core with more recent conditions determined from the distribution of ^{210}Pb and ^{234}Th [Fuller, C.C., van Geen, A., Baskaran, M., Anima, R.J., 1999. Sediment chronology in San Francisco Bay, California, defined by ^{210}Pb, ^{234}Th, ^{137}Cs, and $^{239,240}Pu$.] shows that the accumulation rate increased by an order of magnitude at this particular site. All three cores from San Francisco Bay show subsurface maxima in ^{10}Be concentrations ranging in magnitude from 170 to 520×10^6 atoms/g. The transient nature of the increased ^{10}Be input suggests that deforestation and agricultural development caused basin-wide erosion of surface soils enriched in ^{10}Be, probably before the turn of the century. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: estuary; erosional disturbance; sedimentation rate

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1. Introduction

Explosive population growth around San Francisco Bay and activities in the watersheds of the Sacramento and San Joaquin rivers over the past two centuries have modified both the quantity of sediment deposited in the estuary and its chemical composition (Nichols et al., 1986; Peterson et al., 1993). ^{14}C and ^{10}Be data presented in this paper document the changes in sediment accumulation and provide some constraints on the timing and magnitude of the erosional disturbance.

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^{10}Be ($t_{1/2} = 1.5 \times 10^6$ years) is produced in the atmosphere by cosmic ray spallation of oxygen and nitrogen nuclei. Rain and snow deliver the resulting flux of $1.2 \pm 0.3 \times 10^6$ atoms cm^{-2} year^{-1} to the earth surface (Monaghan et al., 1985/1986; Brown et al., 1989). Because beryllium has a strong affinity for particle surfaces, much of this flux is retained in soils. The concentration of ^{10}Be in soils depends on a number of factors including the length of exposure to atmospheric deposition and the nature of the soil (Monaghan et al., 1983; Pavich et al., 1986; Brown et al., 1992; Monaghan et al., 1992). Concentrations of ^{10}Be typically decrease with depth in a soil column because of input at the surface followed by radioactive decay at depth (Pavich et al., 1985). But the ^{10}Be content of surface soils can also vary by orders of magnitude from one location to the other within a geologically variable watershed (Pavich et al., 1986; Monaghan et al., 1992). It is therefore hard to determine a priori the effect of erosional disturbance on the average ^{10}Be content of particles accumulating downstream in an estuary.

Valette-Silver et al. (1986) first demonstrated in Chesapeake Bay, a perturbed estuary on the US east coast, that the ^{10}Be content of sediments is a useful indicator of erosional disturbance. Historical records show that settlement around Chesapeake Bay by Europeans resulted in the conversion of about 50% of the watershed from forest to agriculture between 1650 and 1840. Brush and Davis (1984) showed that an increase in the proportion of ragweed pollen relative to oak pollen in several sediment cores recorded a change in land use. The changes in pollen coincided with an order of magnitude increase in sedimentation rate. Valette-Silver et al. (1986) showed that the change in land use also produced subsurface maxima in ^{10}Be concentrations in the three cores studied by Brush and Davis (1984), presumably due to accelerated erosion of surface soil enriched in ^{10}Be.

Europeans settled in San Francisco Bay and its watershed about a century later than Chesapeake Bay and historical accounts suggest that the effect on erosion was of, at least, comparable magnitude. For example, sediment released by hydraulic gold mining upstream from San Francisco Bay reduced the depth of the Sacramento river and its tributaries by several meters from the 1850s to the turn of the century (Peterson et al., 1993). The Gold Rush was followed by rapid agricultural development of the Central Valley of California. We present here ^{10}Be data for three cores from San Francisco Bay documenting these erosional disturbances. Two cores were collected from Richardson Bay, a small embayment near the mouth of the estuary, and one core was collected from San Pablo Bay in the landward reach of the estuary (van Geen and Luoma, 1999). We also provide some constraints on changes in sedimentation rate due to accelerated erosion in the watershed with five ^{14}C-dated mollusk shell fragments from the two Richardson Bay cores.

2. Methods

Three cores were selected for this study: core SFB082092-3 from Richardson Bay (abbreviated hereon as RB92-3), SFB020990-3 from Richardson Bay (RB90-3), and core SFB020790-8 (SP90-8) (Fig. 1). The full name of each core refers to the month,

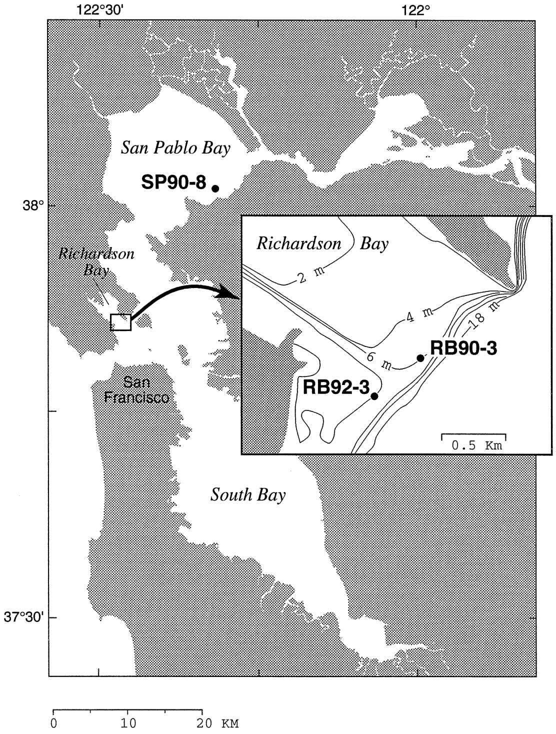

Fig. 1. Map of San Francisco Bay showing location of cores RB92-3, RB90-3, and SP90-8. Bathymetry in meters.

day, and year of collection. Core collection procedures and ^{137}Cs and ^{210}Pb data for cores RB92-3 and SP90-8 are discussed by Fuller et al. (1999). The same methods were followed to obtain the ^{137}Cs and ^{210}Pb profiles for core RB90-3 presented in this paper.

The sand fraction of the sediment in cores RB92-3, RB90-3, and SP90-8 was determined by wet-sieving through a 63-μm nylon-mesh screen. The fine and coarse fractions were dried at 70°C and room temperature, respectively. Grain size trends obtained independently for two of the cores are comparable (Fuller et al., 1999), although some differences indicate considerable centimeter-scale variability.

Mollusk shell fragments from three intervals in core RB92-3 were prepared for radiocarbon dating

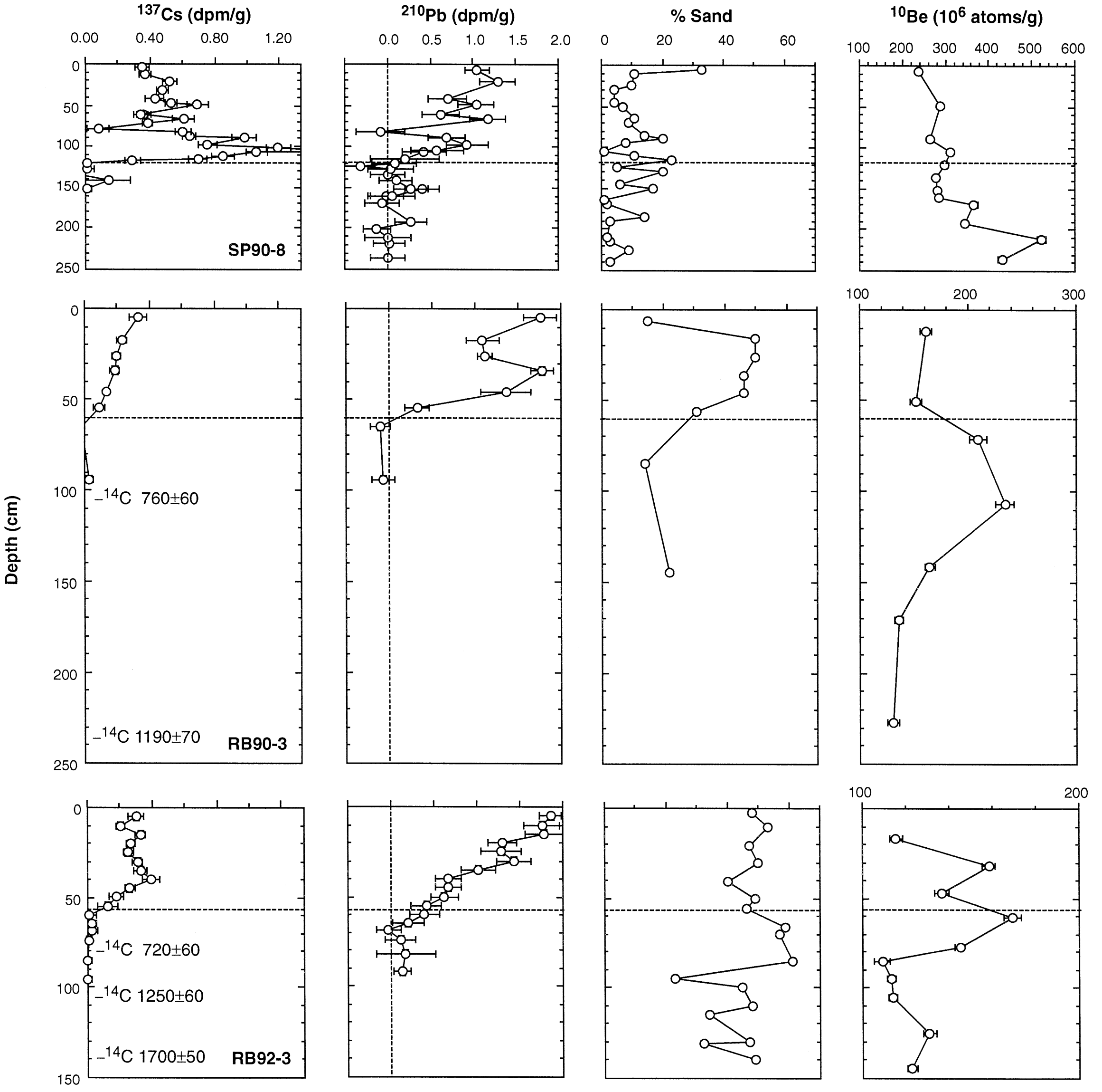

Fig. 2. Profiles of ^{137}Cs, ^{210}Pb, sand content, and ^{10}Be in cores RB92-3, RB90-3, and SP90-8. The provenance and age of radiocarbon-dated mollusk shells are indicated next to the ^{137}Cs profiles. Horizontal dashed lines indicate the transition to sediment containing bomb-produced ^{137}Cs. Note that the ^{10}Be scale changes between cores.

by accelerator mass spectrometry (AMS ^{14}C) at Lawrence Livermore National Laboratories by B.L. Ingram (UC Berkeley) following the methods of Vogel et al. (1987) and Davis et al. (1990). Additional shell fragments from 3.4–4.0 m depth in another core collected within a few tens of meters of the site of core RB92-3 in June 1996 were dated by counting at Beta Analytic, Miami, FL. AMS ^{14}C ages of shell fragments from two horizons in core RB90-3 were previously reported by van Geen et al. (1992). No shell material that could be dated was found in core SP90-8.

^{10}Be concentrations were determined for a total of 29 samples from cores RB92-3, RB90-3, and SP90-8 by total dissolution of ~1 g of sediment in hydrofluoric acid followed by addition of a ^{9}Be carrier. The method of Klein et al. (1982) was followed for target preparation and determination of $^{10}Be/^{9}Be$ ratios by accelerator mass spectrometry at the University of Pennsylvania.

3. Results

^{137}Cs and ^{210}Pb profiles in cores RB92-3 and SP90-8 are discussed in detail by Fuller et al. (1999). The data are shown again in Fig. 2 together with the additional ^{137}Cs and ^{210}Pb determinations for core RB90-3. Unsupported ^{210}Pb activities were calculated by subtracting the measured ^{226}Ra activities which average 1.0 ± 0.1 dpm/g ($n = 20$) in the Richardson Bay cores and range from 0.9 to 1.8 dpm/g in the San Pablo Bay core (Fuller et al., 1999). The vertical scale of profiles in Fig. 2 is adjusted to a constant thickness for the sediment layer containing bomb-produced ^{137}Cs. In both RB92-3 and RB90-3, ^{137}Cs and excess ^{210}Pb activities rise above their respective detection limits around 60 cm depth. In contrast to RB92-3, there is no subsurface maximum in ^{137}Cs in RB90-3. In the San Pablo Bay core, activities of ^{137}Cs and ^{210}Pb increase rapidly above 120 cm depth (Fig. 2). Radiocarbon-dated mollusk shell fragments were all sampled from below the depth of ^{137}Cs penetration in the Richardson Bay cores and, therefore, were not affected by bomb fallout that started in the early 1950s. Conventional radiocarbon ages of the shell fragments range from 720 to 3460 years (Table 1). Radiocarbon ages and depths of provenance for these shells are also shown in Fig. 2. A large and poorly constrained reservoir correction must be subtracted from these ages to take into account, among other factors, the apparent ^{14}C age of California coastal water which ranges from 600 to 1000 years (Robinson, 1981; Stuiver and Brazunias, 1993). Because of this large uncertainty, the possible range for reservoir-corrected ^{14}C ages of the shallowest shell samples in both Richardson Bay cores (720 ± 60 and 760 ± 60

Table 1
Dating of mollusc shell fragments from Richardson Bay

Core RB90-3			Core RB92-3		
Depth (cm)	^{14}C years	Calendar year	Depth (cm)	^{14}C years	Calendar year
106	760 ± 60	–	80	720 ± 60	–
237	1190 ± 70	1420 AD (1300–1510)	107	1250 ± 60	1370 AD (1270–1460)
			140	1700 ± 50	960 AD (800–1060)
			Near site of core RB92-3		
			340–400	3460 ± 130	1060 BC (1370–800)

Mollusk shell fragments from cores RB90-3 and RB92-3 were dated by accelerator mass spectrometry at Lawrence Livermore National Laboratory. Additional shell fragments were collected within a few tens of meter from the site of core RB92-3 in June 1996. A local reservoir age of correction $\Delta R = 235 \pm 85$ ^{14}C was calculated from the shallowest samples in the two Richardson Bay cores by applying the model of Stuiver and Brazunias (1993). The date of the shallowest samples was estimated independently to be 1860 ± 90 AD (see Section 4). The total correction is therefore 637 relative to a mixed layer model age of 402 years (Stuiver and Brazunias, 1993). To convert radiocarbon ages to calendar dates, radiocarbon ages were reduced by the local ΔR values and corresponding calendar ages were determined from the calibration curves of Stuiver and Brazunias (1993). Calendar age ranges were determined by propagating the listed 1-sigma uncertainties of individual determinations augmented by the ±85 year uncertainty in the local reservoir correction through the same procedure.

Table 2
^{10}Be in San Francisco Bay sediments

RB90-3		RB92-3		SP90-8	
Depth (cm)	^{10}Be (10^6 atoms/g)	Depth (cm)	^{10}Be (10^6 atoms/g)	Depth (cm)	^{10}Be (10^6 atoms/g)
12	161 ± 5	16	116 ± 3	8	237 ± 6
51	152 ± 5	32	158 ± 3	49	288 ± 6
71	210 ± 8	47	137 ± 3	89	263 ± 6
107	234 ± 9	60	169 ± 4	104	312 ± 7
142	164 ± 5	77	145 ± 2	122	297 ± 6
171	136 ± 4	85	109 ± 4	136	277 ± 6
227	131 ± 5	95	114 ± 2	152	280 ± 6
		105	114 ± 2	162	283 ± 6
		126	131 ± 3	170	366 ± 8
		144	123 ± 2	192	344 ± 7
				212	524 ± 10
				236	431 ± 8

^{14}C years in RB92-3 and RB90-3, respectively) spans the past several centuries and includes contemporary deposition. Radiocarbon ages over 1200 years for deeper intervals in both Richardson Bay cores indicate that these shells were formed several centuries before any major disturbance of the watershed. This is consistent with the absence of unsupported ^{210}Pb (half-life of 22.3 years) in the same sediment horizons (see Fig. 2 and Fuller et al., 1999).

Profiles of sand content and ^{10}Be concentrations (Table 2) in Richardson Bay and San Pablo Bay are also shown in Fig. 2. In the two deepest horizons of each Richardson Bay core which were clearly deposited before disturbance of the watershed, ^{10}Be concentrations range from 123 to 136 × 10^6 atoms/g (Fig. 3). ^{10}Be concentrations increase below the depth of ^{137}Cs penetration in the same two cores. Surface ^{10}Be concentrations in the two Richardson Bay cores are only slightly higher than in deeper intervals deposited before development of the watershed. The location of the maximum in ^{10}Be concentrations close to the bottom of SP90-8 is consistent with the higher sedimentation rate at this location than in Richardson Bay (Fuller et al., 1999). The magnitude of the maximum in ^{10}Be is higher in the San Pablo Bay core (520 × 10^6 atoms/g at 212 cm) than in the Richardson Bay cores (230 × 10^6 atoms/g at 107 cm for RB90-3, 170 × 10^6 atoms/g at 60 cm for RB92-3). Although grain size can be a factor determining ^{10}Be concentrations in soils, comparison with variations in the sand content within each core indicates that grain size variation did not determine the major features of the downcore ^{10}Be profiles. However, the difference in magnitude of the ^{10}Be maximum among cores does parallel differences in sand content: 2–3%, 14–22%, and 46–59% sand for SP90-8, RB90-2, and RB92-3, respectively, at the nearest horizons above and below the ^{10}Be maxima (Fig. 2).

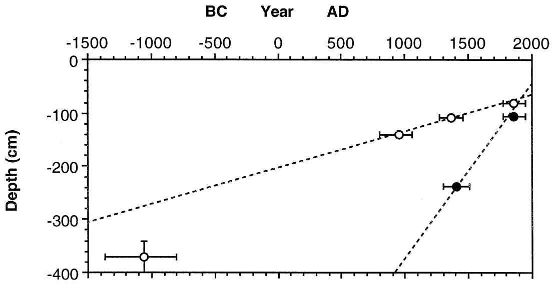

Fig. 3. Calibrated radiocarbon ages of shell fragments as a function of depth in core RB92-3 (open symbols) and RB90-3 (closed symbols). The conversion from conventional radiocarbon ages to calibrated calendar ages is explained in the caption of Table 1. The age of mollusc fragments collected near the site of RB92-3 at 3.4–4.0 m depth is included in the figure, but was not used in the regression.

4. Discussion

Two corrections are required to convert radiocarbon ages of the mollusk shells to calendar ages. The first, the reservoir age of dissolved inorganic carbon at the core site mentioned earlier, carries the largest uncertainty. The second, variations in the level of atmospheric ^{14}C, is well-constrained by tree-ring chronologies for the past 10,000 years (Stuiver and Brazunias, 1993). One source of uncertainty for the first correction is the variability of upwelling along the California coast. The apparent ^{14}C age of inorganic carbon increases by about 1500 years as a function of depth in the upper 1000 m of the northeast Pacific (Ostlund et al., 1987). During spring and summer, water from several hundred meters depth is pumped to the surface near the coast by strong northwesterly winds (van Geen and Husby, 1996). For this reason, the radiocarbon age of mollusk shells collected from the shore of an upwelling system such as the California Current before bomb testing is several hundred years older than in non-upwelling regions (Robinson, 1981). On the basis of shell samples collected from the California coast before the 1950s, Stuiver and Brazunias (1993) report a reservoir correction of $\Delta R = 225 \pm 35$ years relative to the age of their model surface mixed layer of 402 ^{14}C years. The total reservoir correction for nearshore waters in the region is therefore 627 ± 35 ^{14}C years relative to the atmosphere. Stuiver and Brazunias (1993) note that this value is controversial because ΔR values ranging from 300 ± 35 to 500 ± 100 ^{14}C years have also been reported. More recently, Ingram and Southon (1996) determined a reservoir correction of $\Delta R = 290 \pm 35$ for six mollusk shells collected in the 1930s along the northern California coasts that is consistent with the estimate of Stuiver and Brazunias (1993). The significant differences between sites may reflect real geographical variability along the California coast because the effect of coastal upwelling on nearshore water composition is particularly pronounced nearshore and varies with latitude (Robinson, 1981; van Geen and Husby, 1996). Another source of uncertainty for the Richardson Bay reservoir age correction is the ~ 20% (on average, Peterson et al., 1989) contribution of Sacramento and San Joaquin river water containing potentially old inorganic carbon due to input of groundwater (Spiker, 1980; Ingram and Southon, 1996). Release of relatively old inorganic carbon to the water column from benthic respiration within the estuary may also be significant (Spiker, 1980). Some of these factors may explain why Ingram and Southon (1996) obtained a rather wide range in reservoir corrections ($\Delta R = 238$ to 526) for a suite of nine pre-bomb shells collected at various locations within San Francisco Bay. Another reason may be that Ingram and Southon (1996) could not determine whether all the specimens that were analyzed were living at the time of collection.

Because of the large uncertainties, we estimate a local reservoir correction for Richardson Bay from an independent constraint on the deposition interval of the two shallowest mollusk shells in cores RB92-3 and RB90-3 (Table 1). Comparison of shell locations with the penetration depth of bomb-produced ^{137}Cs provides an unequivocal upper bound of 1950 AD. The maximum likelihood date of deposition for the shallowest shell fragment in core RB92-3 is 1909 ± 7 AD calculated for the 80-cm interval by the age model of Fuller et al. (1999), but the model is essentially unconstrained at this depth. A more conservative lower bound is the onset of Spanish settling in the region around 1770 AD (Nichols et al., 1986) because the mollusk shell fragments are located well above (RB90-3) or near (RB92-3) the onset of rising ^{10}Be concentrations attributed to erosional disturbance (Fig. 3). The radiocarbon age of mollusk shells deposited between 1770 and 1950, that is, 1860 ± 90 AD, is 740 ± 40 ^{14}C years estimated from the average age of the two shallowest mollusk shells in the Richardson Bay cores (Table 1). The uncertainty of this value equals the analytical uncertainty of the individual measurements divided by $\sqrt{2}$. Following the procedure of Stuiver and Brazunias (1993) that takes into account variations in atmospheric ^{14}C, a local reservoir age correction for Richardson Bay of $\Delta R = 235 \pm 85$ ^{14}C years is calculated. The large error estimate results from propagating both the uncertainty in the calendar date of deposition and the uncertainty of the mean ^{14}C age of the mollusk shells. This value is consistent with the canonical value $\Delta R = 225 \pm 35$ ^{14}C years of Stuiver and Brazunias (1993) determined from coastal mollusk samples. Within the relatively large uncertainties, the apparent pre-bomb ^{14}C age of the water column in Richardson Bay is indistinguishable from that of California coastal waters. The locally derived ΔR value with its associated uncertainty was used to convert the mollusk shell ^{14}C ages to calendar dates listed in Table 1. Although the absolute value of the reservoir correction is not well-constrained, it probably remained fairly constant over the past several hundred years because the intensity of coastal upwelling did not vary significantly (van Geen and Husby, 1996; van Geen and Luoma, 1999).

The age–depth relation for the three shell samples in core RB92-3 shows that the sedimentation rate at this site averaged about 0.07 cm/year with no evidence of a discontinuity between 960 and 1860 ± 90 AD. The age of shell fragments collected in 1996 very close to RB92-3 at a depth of 3.4–4.0 m indicates that the sedimentation rate was comparable at this site over even longer time scales (Fig. 3). There is no indication of complications observed at other locations in San Francisco Bay that have lead to accumulation of shells widely ranging in radiocarbon age within the same sediment horizon (Ingram and Southon, 1996). The long-term sedimentation rate calculated from radiocarbon in RB92-3 is about an order of magnitude lower than sediment accumulation over the past 50 years determined from ^{137}Cs and ^{210}Pb profiles in the upper part of the core (Fuller et al., 1999). The recent increase in sedimentation rate at this site is consistent with the intercept of the linear depth–age relation at the 1992 date of core collection (Fig. 3). This intercept suggests that 60–70 cm more sediment was deposited at this site due to disturbance of the watershed than calculated by extrapolating the long-term sedimentation rate. The local reservoir correction would have to be in error by ~1000 years, well beyond what is reasonable, to force the intercept of the depth–age relation in core RB92-3 to the level of the present sediment–water interface. The recent increase in sedimentation rate is also consistent with changes in sedimentation independently estimated from shifts in shoreline positions within San Francisco Bay (Peterson et al., 1993).

Interpretation of downcore trends in ^{10}Be is complicated by the fact that concentration in soils within the watershed of the main rivers reaching San Francisco Bay span a particularly wide range. At one end of the spectrum, highly elevated ^{10}Be concentrations have been measured in soils from stable landforms in the Central Valley of California that have been in place for long periods of time. In a 2–3 Myear old terrace along the Merced River, a tributary of the San Joaquin River, Pavich et al. (1986) measured ^{10}Be concentrations of 1200×10^6 atoms/g. At the other end of the spectrum, erosion rather than radioactive decay can limit ^{10}Be inventories in geologically active regions such as California because the length of exposure of individual soil particles to atmospheric deposition is short. In the hills north of Mount Diablo near San Francisco Bay, for example, ^{10}Be concentrations in surface soil are $\leq 30 \times 10^6$ atoms/g (Monaghan et al., 1992) due to rapid soil creep. ^{10}Be concentrations also tend to increase with the clay, Fe, or Al content of the soil and if the pH of runoff is high (Monaghan et al., 1983; Brown et al., 1992). In such a complex setting, a unidirectional change in the mean ^{10}Be content of particles reaching an estuary could be the result of a shift in the relative contribution of particles from different areas. But the simplest explanation for the observed increase in ^{10}Be concentrations followed by a return close to pre-disturbance values in the Richardson Bay cores is a transient input from a ^{10}Be-enriched source. Because ^{10}Be concentrations are generally higher in upper soil layers than at depth, the pattern seen in the Richardson Bay cores is consistent with deforestation and the expansion of agriculture in the watershed of the San Francisco Bay estuary. Erosion of a ^{10}Be-enriched surface soil layer would have resulted in a temporary increase in concentrations in particles deposited downstream in the estuary. The large sedimentation rate increases that accompanied increases in ^{10}Be concentrations in both Chesapeake Bay (Valette-Silver et al., 1986) and San Francisco Bay suggest that these cores recorded large-scale erosional disturbance and not merely local changes in land use. In the case of San Francisco Bay, the large volume of debris produced by hydraulic mining in the watershed probably contributed significantly to the increase in sedimentation as well (van Geen and Luoma, 1999). Diking and filling of much of the salt marshes that once surrounded the estuary (Peterson et al., 1993) resulted in a reduction in particle trapping and may also have contributed to increase the sediment supply.

Comparison of the magnitude of the ^{10}Be maxima in the Richardson Bay cores with the San Pablo Bay core suggests that the impact of erosional disturbance diminished towards the mouth of the estuary (Fig. 2). Elevated ^{10}Be levels deep in the San Pablo

Bay core show that sediment deposited before the onset of erosional disturbance was not reached at this site. This is consistent with bathymetric evidence of sedimentation and erosion compiled by Jaffe et al. (1998). The deeper level of ^{137}Cs penetration in SP90-8 relative to RB90-3 and RB92-3 indicates that the post-1950s sedimentation rate was also higher in San Pablo than in Richardson Bay. Sediment accumulation has probably not been continuous at the site of core SP90-8 since the onset of industrialization of the area, however. Fuller et al. (1999) present evidence of hiatus in core SP90-8 at 120 cm depth, just below the first interval of detectable ^{137}Cs. Of the extensive suite of inorganic and organic sediment constituents analyzed in core SP90-8 (van Geen and Luoma, 1999), ^{10}Be most clearly shows that sediment below this hiatus does not pre-date erosional disturbance of the estuary.

The spatial heterogeneity of sedimentation in an estuary can also explain the difference between ^{10}Be concentration profiles within Richardson Bay. The depth interval of elevated ^{10}Be in core RB90-3 is both broader and deeper than in core RB92-3 (Fig. 2). This is consistent with the higher pre-disturbance sedimentation rate in core RB90-3 than in RB92-3 (0.2 cm/year vs. 0.07 cm/year; Fig. 3) constrained by only two radiocarbon dates. Two longer cores, also from the center section of Richardson Bay, confirm that pre-disturbance sedimentation rates were generally higher near core RB90-3 than at the site of core RB92-3 (van Geen et al., 1992; van Geen, unpubl. data). On the other hand, extrapolation of the depth–age relation to the sediment surface suggests that the amount of additional sediment that accumulated at sites RB90-3 and RB92-3 relative to pre-disturbance conditions is comparable. This is consistent with the similar depths of ^{137}Cs penetrations in RB90-3 (Fig. 2) and RB92-3 (Fuller et al., 1999). Thus, it is possible that sediment was deposited more uniformly within Richardson Bay following the increase in input resulting from erosional disturbance than before.

It is difficult to determine the potential effect of hydraulic gold mining on sedimentation in San Francisco Bay from the ^{10}Be data. Hydraulic mining caused a spectacular increase in bed elevation of the Yuba River and the Sacramento River from 1850 to the turn of the century (Peterson et al., 1993). This material, however, probably contained little ^{10}Be because it had been shielded from atmospheric deposition for a long period. It therefore seems unlikely that the subsurface ^{10}Be maxima in the San Francisco Bay are a direct result of hydraulic mining, although an increase sedimentation may well been (Krone, 1979). While there is an interval of low ^{10}Be values between 85–105 cm depth in core RB92-3 (Fig. 2), this feature cannot be attributed with confidence to hydraulic mining debris.

The discussion concludes with an attempt to date the onset of erosional disturbance. In core RB92-3, the sediment horizon showing the first clear indication of erosional disturbance is located somewhere between 85 and 77 cm depth (Fig. 2). Fuller et al. (1999) showed that a deep bioturbated surface layer in core RB92-3 acts as a strong filter of any change in the composition of settling particles at this site. The result is that a hypothetical spike input is smeared downcore over ~35 cm within a decade and is greatly reduced in magnitude. The mixing/accumulation model of Fuller et al. (1999) calibrated for post-disturbance conditions also shows that the front produced by this spike input is spread over a depth interval of about 10 cm. For dating the onset of the ^{10}Be increase, we have to assume that the same surface mixing conditions prevailed before erosional disturbance of the watershed. Comparison of the shape of the ^{10}Be profile with the output from the model of Fuller et al. (1999) suggests that erosional disturbance could have started as late as in 1920 AD, assuming a sedimentation rate of ~0.8 cm/year. This is an upper limit because the sedimentation rate probably increased to this value from the pre-disturbance rate of 0.07 cm/year in conjunction with the erosional disturbance.

The limited dating information available for core SP90-8 suggests that erosional disturbance may have started considerably earlier. On the basis of detailed bathymetric reconstructions by Jaffe et al. (1998), Fuller et al. (1999) estimated that sediment below 120 cm in core SP90-8 was deposited before 1890. Erosional disturbance probably started well before that date, since ^{10}Be concentrations are elevated throughout the 250–120 cm interval in this core. Elevated Hg levels measured in the same core (Hornberger et al., 1999) suggest that probably both hydraulic mining debris and surface soils enriched in

^{10}Be contributed to increase the sediment supply to San Francisco Bay well before the turn of the century.

5. Conclusions

^{10}Be profiles in three dated sediment cores indicate a major erosional disturbance in the watershed of San Francisco Bay that probably took place before the turn of the century, and certainly before 1920. Comparison of sediment accumulation in Richardson Bay before and after this disturbance determined from ^{14}C and ^{210}Pb, respectively, indicates that the sediment supply to the estuary increased significantly before modern industrial and agricultural activities began. The ^{10}Be profile in the San Pablo Bay core indicates that sediment deposited before the onset of erosional disturbance was not reached at this location. The contributions of hydraulic mining debris and surface soil erosion to the increased supply of sediments to San Francisco Bay cannot be distinguished from the available data.

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