Title

Long Term Variability of Fresh Water Flow into the San Francisco Estuary using Paleoclimatic Methods

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ABSTRACT

Sediment cores were raised from fringing marshes along the northern reach of the San Francisco Bay. A variety of stratigraphic analyses were utilized to reconstruct sea level and river flow (salinity) over the past 7000 yr. Over thirty A.M.S. dates provide chronostratigraphic control. An overall trend in RSL rise of 0.12-0.14 cm/yr is established for the northern reach of the estuary. River discharge was broadly comparable to modern flows. However, an extended period of higher flow commenced approximately 3800 yr and continued for almost 2 millennia. Superimposed upon these general trends are numerous short-term events. Acute droughts and salinity intrusion occurred during the period of high river flow. No extreme flood events are noted during this period, although evidence for abnormally high discharge occurs at other times.

INTRODUCTION

Estuaries are dynamic systems; influenced by both oceanic and terrestrial waters (Pritchard, 1967; Fairbridge, 1980). It is these controlling factors that make estuaries valuable arenas for paleo-environmental work, as material sequestered in estuarine bottom muds or fringing marsh systems contain potential information regarding episodes of climatic change and relative sea-level, as well as anthropogenic disturbances. In this paper we present evidence for variable river flow during the middle to late Holocene from sedimentary sequences located along the northern reach of the San Francisco estuary.

The San Francisco estuary comprises a series of interconnected bays (Figure 1), making it the largest estuary along the Pacific Coast of the United States (Conomos *et al.*, 1985). It can be divided into a southerly and northerly arm, separated by the Central Bay. Oceanic water enters through the Golden Gate and freshwater via the Sacramento and San Joaquin rivers which meet in the Delta region. Combined these rivers, which are primarily fed from waters originating in the Sierra Nevada, discharge 90% of the freshwater into the Bay (Nichols *et al.*, 1986).

PREVIOUS STUDIES

Relative sea-level rise (RSLR) was established for South San Francisco Bay by Atwater *et al.* (1977). This work has been broadly used to extrapolate sea-level rise throughout the estuary (Josselyn, 1984?). Atwater *et al.* (1977) estimate that beginning approximately 9500 yr sea-level rose at a rate of 2 cm/yr until 8000 yr. The rate of rise subsequently slowed significantly to approximately 2 mm/yr for the following 2000 yr and has averaged 1-2 mm/yr from 6000 yr until present. The authors caution that the sea-level curve developed is unable to depict low level variability and so presents a smooth visually fitted curve. The late Holocene section is poorly constrained (2 dates), and so the assumption that sea-level has risen at a uniform rate since 6000 yr is questionable.

Recent work by Ingram and colleagues (Ingram and Sloan, 1992; Ingram and DePaolo, 1993, and Ingram *et al.*, 1996a and b) have used strontium and oxygen isotope data to determine paleosalinity and infer paleodischarge. Paleodischarge variability should be sensitive to statewide climate changes as the estuary receives water from approximately 40% of the States surface area (Conomos, 1979). Both methods highlight general trends in freshwater flow to the estuary, but there appears to be poor correlation between events, in particular low flows (Ingram and DePaolo, 1993 and Ingram *et al.*, 1996a and b?).

METHODS AND ANALYSES

Site selection and Coring

In order to develop a spatial and temporal picture of RSL changes in the Holocene estuary, we established coring sites along an east-west transect, following the modern salinity gradient (Figure 1). Changes in tidal vegetation serve as an ideal proxy for salinity. Three sites were selected; 1/ China Camp State Park is a pristine tidal salt marsh, located on the western edge of San Pablo Bay; 2/ Peyton Hill is a brackish marsh situated along the middle of the transect close to the Carquinez straits; 3/ Browns Island, a Regional Park, is a pristine brackish to freshwater marsh located close to the confluence of the Sacramento and San Joaquin rivers. Each site was cored in the middle-high marsh zone using a Livingstone corer fitted with a plastic sleeve. Coring continued until it became impossible to raise sediment to the surface. Cores were stored in a cold room after collection.

Analyses

All sediment cores were archived by x-radiography. Each core was cut in half and its lithology and contacts described (Nelson, 1992). A broad spectrum of analyses, examining both biotic and abiotic factors, were undertaken, in order to establish broad scale environmental changes within the estuary. Samples for the various analyses were taken at approximately 20-25 cm intervals, or closer if lithostratigraphy was variable. Detailed procedures and protocols are found in Goman (1996). Unless stated otherwise sample size was approximately 1 cm^3.

Macro-fossils: Seeds from approximately 9 cm^3 of sediment were isolated and identified using herbarium specimens and samples collected in the field, as well as several field guides and keys (Hickman, 1993; Mason,1957; Munz, 1973; Martin and Barkley, 1961; and Montgomery, 1977). Whole seeds and fragments of seeds were counted and summed. A key to the most commonly found seeds was developed (Goman, 1996).

Sediment Composition and Geochemistry: The percentage change in organic material over inorganic material is used to determine fossil marsh type. Samples were processed according to standard Loss-on-Ignition procedures (Dean, 1974). Results had good reproducibility, with the coefficient of variability (CoV) <2%.

Changes in sediment grain size (clay:silt) were determined throughout the cores. Samples were initially sieved to remove large organic material (> 63 μ), the procedure then followed Folk (1980). For the most part reproducibility was good (CoV typically <10%).

Sediment samples were prepared for geochemical analysis by digesting in HNO_3 and HCl. A Perkin-Elmer model 3100 Atomic Absorption Spectrometer fitted with an HGA-600 Graphite Furnace was used to analyze samples for iron and lead. Reproducibility was generally good (CoV <10%).

Chronostratigraphy: Accelerator mass spectrometry (A.M.S.) radiocarbon dates of organic material from the sediment cores provides chronostratigraphic control. Seed material was the preferred medium for A.M.S. estimates, as earlier work (Wells, 1995) had determined that there were few age reversals among seed derived ages. A.M.S. age estimates were determined at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratories. All radiocarbon dates have been calibrated using CALIB 3.0 (Stuiver and Reimer, 1993).

RESULTS

China Camp

The vegetation at China Camp is principally dominated by *Salicornia virginica*, although patches of *Distichlis spicata* and *Jaumea carnosa* are present. *Spartina foliosa* grows at lower elevations of the marsh in a narrow band from the bay edge to about 30 m inland. The core site at China Camp was located in the *Salicornia* dominated high marsh. A total of 620 cm of sediment was collected. Compaction was a problem especially in the top 3 m of sediment.

Lithostratigraphy: The top 2.5 m of sediment comprises muddy peat with many fine to medium size roots running throughout. Laminations are present in discrete sections throughout the core, indicating that bioturbation is minimal. Between 2.5-4.5 m sediments are dark gray muds with no, or trace amounts of root material. However, three distinct muddy peat horizons are present at 265-279 cm, 290-302 cm, and 405-422 cm. Above and below these more organic sections, finely banded sediment is present. These sediment bands, which vary in thickness from <0.5-10 mm, are typically dark brown to black organic rich layers nested within a gray mud. The distance between bands is not uniform and the thickness of the laminated zones varies. The lowermost muddy peat is bracketed by approximately 35 cm of laminations, while the uppermost muddy peat sections have <10 cm of the surrounding laminated zones.

From 4.5 m to the base of the core, sediments are gray muds with little fine organic material, but large macro-fossils (>3 cm long). The fossils are stalks or root stock and appear to be in growth position. They are tentatively identified as *Spartina*. In the basal section of the core, 604-620 cm, fine bands of organic material are present.

Chronology and Rates of Sedimentation: Sediments from China Camp encompass approximately 4700 yr (Table 1). While the long term sedimentation rate is nearly constant, short period changes are indicated by the complex lithostratigraphy found between 250-450 cm; it is assumed that sedimentation rates varied through time in this section of the core (Table 2).

Sedimentology: The sediments from China Camp are the least organic of the three sites examined, with average organic composition 17± 8%. Clay accumulation at the site has been remarkably constant, with average values of 66±13%. Unusually high silt (90%) concentrations were found at 475 cm. X-radiographic analysis for this depth shows a thin highly inorganic lamination (~2 mm thick) surrounded by less dense material encompassing a total thickness of *c.*1.5 cm.

Geochemistry: Lead is present at low levels throughout the core (0.007±0.003 g/kg) except in the top 30 cm, where lead concentration peaks at 0.043 g/kg. Iron values are highest in the mud deposits (31 ±6 g/kg) and lower in the muddy peats (27 ±5 g/kg). Considerable variability is exhibited between 2.5-4.5 m (14 to 32 g/kg) reflecting the complex stratigraphy.

Seeds: Eight types of seed were identified from the China Camp macro-fossil samples. *Salicornia* comprised over 90% of the seeds found and are present throughout the upper 5 m of the core. In the basal 120 cm a few seeds of *Scirpus* are present. Seeds tentatively identified to

Distichlis were identified from the central section of the core and *Triglochin* seeds were found at about 1 m below the surface.

Peyton Hill

The low marsh regions at Peyton Hill have a diverse plant assemblage, with *Scirpus acutus, S. californicus, Typha angustifolia,* and *Phragmites communis* dominating. *S. robustus* grows in the middle marsh zone, while the high marsh is characterized by *Salicornia* and *Distichlis*. Two sediment cores were obtained from the high marsh region at Peyton Hill. The first core (PH93:A) penetrated 715 cm; a duplicate core (PH93:B), encompassing the top 310 cm, was taken 2 m away from core site A.

Lithostratigraphy: The top 26 cm are dominantly muddy peats, with fine roots throughout. A thick band of sandy clay is located between 4 and 11 cm. Below this sediments are very dark brown muddy peats until about 370 cm. Interspersed at variable intervals within this matrix are clay laminations. The contacts between these laminations and the dominant muddy peat matrix have varying degrees of sharpness from abrupt to gradual.

Gray mud deposits persist below the muddy peat deposits until the base of the core. Very fine to fine rootlets run through the muds. Root presence varies from rare to common within different sections of the core. Within the muds several sections of clayey peat are present (474-502 cm, 529-539 cm, 548-560 cm, and 585-606 cm). Within these peats are discrete layers of clay, 2-5 mm thick. These laminations generally have sharp to abrupt contacts with the surrounding clayey peats.

Chronology and Rates of Sedimentation: Calculated rates of sedimentation indicate that the rate of deposition has not been uniform. Of note is the particularly high rate of sedimentation (0.31 cm/yr) between 406 and 450 cm.

Sedimentology: The clayey-peat section has an average organic concentration of 33±13%. In the lower section of the core (below 370 cm) organic content averages 19±7%. Like China Camp, Peyton Hill grain size distribution is constant (67±14% clay). Anomalously high silt content (c. 75%) was found at 416 cm. Textural description indicates that this silt zone extends from 415-442 cm.

Geochemistry: Anthropogenically enriched lead and iron levels are present in the top 20 cm of both cores, with concentrations as high as 0.05 g/kg and 31 g/kg respectively. Lead averages 0.002± 0.001 g/kg for the remainder of the core. There is a general increase in iron concentration from the upper sediments to the base of the core. Average concentrations are 25±7 g/kg. Consistently higher than average concentrations of iron occur between 360-440 cm, peaking at 43 g/kg at 403 cm. This encompasses the silty region.

Seeds: A total of 10 seed types are identified to genus or family level, a further 9 types remain as unknowns. *Scirpus* seeds are identified to species or species grouping where possible. Seed surface morphology was used to differentiate *S. robustus* from other species in the genus. Preservation was generally good, except for the bristle bracts on *Scirpus* seeds, which were typically absent (Goman, 1996).

The seed stratigraphy can be subdivided into two major zones. The top 310 cm of sediment is characterized by seeds of *Salicornia* and *Triglochin*; below 310 cm *Scirpus* and other seeds of the Cyperaceae family are the dominant types. *Scirpus* is generally absent from the top sediments. Seeds of *Potamogeton* are present throughout the core, although there is an absence between 240-405 cm. These seeds were most commonly found within inorganic deposits.

Browns Island

Vegetation is diverse at Browns Island and includes a number of endangered species (Knight, 1980). In low marsh regions and portions of tidal sloughs *Scirpus acutus, Typha angustifolia, T. latifolia* and *Phragmites communis* are found. *S. americanus* dominates the middle portions of the marsh, and gives way to salt loving plants (*Distichlis* and *Triglochin maritima*) towards the central and higher portion of the island. The island was cored at two locations. The first core (BI92) was collected from a *Scirpus americanus* dominated middle marsh region, on the western edge of the central slough that penetrates the island's interior. This core retrieved 779 cm of sediment. The second core site (BI93) lies in the ecotone between middle and high marsh in a mixture of *S. americanus* and *Distichlis spicata*, also present were *Jauma carnosa* and *Triglochin maritima*. BI93 is the longer of the two cores (1061 cm), penetrating into silty-sands.

Lithostratigraphy: The sediment matrix for both cores is dominantly peat. This organic matrix is composed of the remains of roots, rhizomes, and stems in variable states of preservation, although the general trend is towards greater humification with depth. Unlike China Camp and Peyton Hill, the Browns Island cores lack extensive inorganic laminations, although 2 silty laminae are present at 45 and 748 cm in BI92. The lamina at 45 cm is approximately 5 mm wide and contains mica. On the x-radiograph the contacts with the surrounding organic matrix are diffuse. The lamina at 748 cm has an abrupt contact with the underlying peats, while its upper contact grades into the overlying peat by about 740 cm.

The lowest 260 cm of core from BI93 are composed of inorganic material. Below 8 m the sediments are typically clays with organic laminations, *c.* 1 cm wide, occurring at random intervals. Below 940 cm the sediments are silty-sands. The section between 780-809 cm was a vivid orange, that turned brown on exposure to air. Observation of the sediment matrix found a large woody rhizome (6 cm deep) at 8 m, which abruptly rested on clays. Above the rhizome the core structure was crumbly until 780 cm, unlike the typical cohesiveness of the other peat regions. The x-radiographs indicate that for 10 cm above 780 cm the core is more inorganic; a clayey-sand lens caps it at 770 cm.

Chronology and Rates of Sedimentation: BI92 is the most intensively dated core of this study, with 30 radiocarbon dates; BI93 has 7 dates. Rates of sedimentation are generally low for BI92 (<0.1 cm/yr) and comparable to rates recorded at China Camp and Peyton Hill. However, in the central section of the core from 339-687 cm rates increase markedly, as does the rate between 160-272 cm. The rate of sedimentation for the BI93 peat section of the core compares well with rates in BI92. The rates of sedimentation for the silty-sands and clays with organic laminations in BI93 are much higher than the peaty sections, and are comparable to the rate of sedimentation in inorganic muds at Peyton Hill.

Sedimentology: The sediments from the peat sections at Browns Island are the most organic sediments of all the study sites (BI92 55±17%; BI93 65±7%). At BI93 where core composition changes with depth, the average organic composition is 34±25% for the clay with organic laminations, and 4±0.5% for the silty-sands. Clay is the predominant inorganic component of the peats (BI92 72±17; BI93 92±3%). A marked change in grain size distribution occurs in the basal 1.5 m of sediment from BI93. These sediments are dominated by silts (73±5%), with a minor component of sand (5±5%).

Geochemistry: The sediments from BI93 were analyzed every centimeter between 230-375 cm, and thereafter every 10-50 cm. The BI92 core was sampled approximately every 50 cm. The top sediments at BI92 show elevated lead levels as expected, although concentrations are considerably higher than surface sediments elsewhere in the estuary.

The BI93 core sediments between approximately 230 and 400 cm contain high concentrations of lead (1-3 g/kg) as well as extremely low concentrations (<0.0001 g/kg). The basal inorganic sediments from BI93 have lower lead concentrations than the rest of the core, but higher concentrations than cores elsewhere in the estuary. The lead concentrations at depth in the BI92 core are not as high as the BI93 core. However, an increase in the lead curve occurs at 300 cm, a depth similar to the elevated concentrations between 230-400 cm in the BI93 core.

Iron concentration in the peats are higher in the BI92 core (17±10 g/kg) than for BI93 (8±4 g/kg). Elevated iron concentrations were detected in the inorganic sediments from BI93 (29±8 g/kg). This value is comparable to figures obtained from the inorganic sediments at the other sites.

Seeds: A total of 8 seed types are identified from Browns Island to genus or family level; 15 types remain unknown (Goman, 1996). Some of the *Scirpus* seeds were further identified as *S. robustus*, *S. californicus*, and *S. americanus/acutus*. The seeds categorized as Cyperaceae are probably *Carex* or *Cyperus*.

The results from the two cores compare well. BI93 has a greater diversity of seed types. The majority of these seed types are located in the silty sands at the base of the core. Here seeds of *Najas* and *Zannichellia* are numerically important; *Scirpus* is generally absent except for fragments. The central portions of the cores are also noticeable for the absence of *Scirpus*.

Seeds of *Potamogeton* are found in association with foraminifera (*Trochominna inflata*) at BI92 45 cm.

RELATIVE SEA LEVEL AND VARIATIONS IN FLUVIAL DISCHARGE

The Holocene history of the estuary has been divided into five principle zones. Zones 1 through 3 are documented at all the sites, but the oldest zones (4 and 5) are recorded only in the sediments from Browns Island. Therefore, only tentative system wide conclusions can be drawn for the period between 6700-5500 yr. Chronostratigraphic correlation is shown in Figure 2.

According to the data from Browns Island, the early Holocene Sacramento and San Joaquin Rivers controlled sediment deposition until about 6200 yr. The identification of seeds of *Najas* and *Zannichellia* indicate conditions were similar to those experienced today near the city of Sacramento. Subsequently RSLR fluctuated, remaining in the MLLW to MTL range, as marsh formed and drowned repeatedly, although an overall trend towards less inundation occurred by about 5500 yr. Although no sediments were recovered at China Camp and Peyton Hill for the period prior to this, these sites were presumably sub-tidal.

Evidence for earthquake induced subsidence is recorded in the topmost sediments from Zone 4 of both cores. Orange colored peats in the Browns Island 1993 core are capped by a clayey-sand lens, while in the 1992 core a silty-sand layer abruptly covers the underlying peat. Both sections date to approximately 5700 yr. An estimated 30 cm of subsidence occurred (Goman and Wells 1997).

Zone 3 is recorded to at all three sites, at least partially. Conditions in San Pablo Bay (China Camp) and the Carquinez Straits (Peyton Hill) reflect a continually rising RSL, as intertidal mudflat is present at both sites. Vegetative macro-fossil remains at these sites indicate

MLLW to MTL conditions persisted through Zone 3. The mean rate of accretion for this period at all three sites is 0.14 cm/yr.

At Browns Island a peat marsh had fully developed by Zone 3, as the data indicate that inundation and the influence of salt water was on the decline. Rates of sedimentation within this period vary, but are often high. This suggests that there may have been considerable variability in river flow affecting the island. During periods of higher flow, salinity was probably not a limiting factor for growth, and so we might expect greater biomass production and increased accretion (Mahall and Park, 1976a; Cuneo, 1987; Pearcy and Ustin, 1984).

Evidence for higher river flow during Zone 3 is present at Peyton Hill. At least five deposits record high flow events. The deposits are characterized by silty or sandy clays, higher seed diversity, charcoal fragments, and seeds of *Potamogeton*. These deposits range in thickness from 4-16 cm and may reflect individual extreme flood events (Table 3). Given the thickness of the deposits at Peyton Hill, evidence of extreme flooding would be expected on Browns Island for this period, but no silt or clay lamina are found in either of the cores from Browns Island for this period. These silty to sandy deposits at Peyton Hill therefore probably reflect oscillations in the longterm discharge of the Sacramento and San Joaquin Rivers, rather than short term perturbations. Since marsh elevation at Browns Island was higher than that at Peyton Hill, it was affected less by the high flow events. Flow increases at Peyton Hill were cyclical, occurring about every 300 yr and persisting for an average of 50 yr.

Each of these deposits is typically overlain by discrete layers of organic-rich sediment. These layers represent the emergence of incipient marshes at the end of the high flow periods. The marsh surface would have been raised by the deposition of material during the high flow periods, enabling *Scirpus californicus* and *S. acutus* to colonize the mudflat. It is not clear whether these periods simply reflect lower discharge histories relative to the preceding high flows, or extended drought (extremely low flow). If extended drought did occur during marsh development, evidence for salinity intrusion might be expected. While levels of iron are somewhat higher during these phases, no distinct pattern emerges, nor does it with lead. Intensively sampling this section of the core for geochemical analyses may resolve this question.

Although extended periods of drought during this period remain speculative, lower river discharge would result in a decline in RSL. The survival time of these marshes was short (10-170 yr), indicating a resumption to average or higher flow conditions and a concomitant RSLR.

Evidence for a second tectonic event, centered near the Carquinez Straits, occurring about 3600 yr is found throughout the estuary (Goman and Wells, 1997). Maximum subsidence occurred at Peyton Hill (possibly as much as 60 cm), and is marked by the deposition silt, while subsidence occurred to a lesser extent at Browns Island and minimally at China Camp.

The Zone 3/2 boundary does not occur at a clearly defined time but rather reflects a shift in response to changing conditions, probably reflecting site history and the maturity of the marshes at each site. Zone 3 ended about 3500 yr at China Camp, about 3200 yr at Peyton Hill, and about 300 yr earlier at Browns Island. Zone 2 stratigraphy is controlled by longterm variations in freshwater flow (see below). The proximity of Browns Island to the confluence of the Sacramento and San Joaquin Rivers and the relative maturity of the island over the other sites may explain its earlier transition. The later Zone 2 boundary at China Camp indicates that there was a three hundred year lag before the effects of long term changes in fluvial discharge were experienced. It is surprising that the Zone 3/2 boundary at Peyton Hill occurs later than that of China Camp; given its central location near the Carquinez Straits it would be expected to respond to variable discharge after Browns Island but before China Camp. The delayed transition between Zone 3 and 2 at Peyton Hill probably reflects site history and marsh maturity. The subsidence event at Peyton Hill at 3600 yr, may have delayed the marshes response to discharge changes experienced in Zone 2.

In Zone 2 the data from both Browns Island and Peyton Hill indicate a maturation of the marsh with tidal elevations slightly below MHHW. Browns Island experienced higher freshwater discharge over the following 1500 yr, which is reflected in the establishment of stands of salt intolerant plants. High flow was maintained over centuries, rather than decades, as was the case in Zone 3.

Higher flow levels are corroborated by the results from Peyton Hill. Here water conditions must have been much fresher than currently. Considering marsh evolution, the core site at Peyton Hill at this time would be classified as middle marsh. However unlike comparable regions today at Peyton Hill, *S. americanus* and not *S. robustus* dominated the marsh plain, indicating that the marsh was affected by less saline waters. This suggests that the salinity of Bay waters in the region of the Carquinez Straits were comparable to modern summer salinities experienced at Browns Island. Currently, summer salinities at Browns Island range from 0-2 ‰, but are significantly higher at the Carquinez Straits, 8-18 ‰ (Conomos *et al*, 1985). Therefore, during this period summer flows must have been considerably higher than today.

This conclusion is complemented by other studies in the Bay itself and more broadly within the State. Palaeosalinity work by Ingram and DePaolo (1993) determined that average river inflow was higher than modern (pre-diversion) levels prior to 2000 yr. Elsewhere in California, records indicate a peak in precipitation for this period. At Mono Lake a high stand commenced approximately 3800 yr, and ended approximately 1800 yr (Stine, 1990).

During the period of higher discharge in Zone 2 at least three periods of extended drought occurred. At Browns Island abnormally high concentrations of lead were deposited during this period. Lead was presumably deposited during extreme salinity intrusion into the western edge of the Delta. Meanwhile at China Camp the development of incipient *Salicornia* marsh on three separate occasions indicates that declines in the longterm rate of RSL rise occurred. However the overall trend for this Zone is one of higher RSL and the deposition of Bay muds, as a result of increased river discharge. Unlike Zone 3 these Bay muds at China Camp lacked *Spartina* roots suggesting that for much of this zone subtidal conditions existed. Contacts between facies are gradual indicating RSL changes occurred over the longterm rather than abruptly.

The incipient marsh chronology from China Camp and the period of elevated lead levels from Browns Island appear similar. The slight disparity in chronology, especially for episode 'a', may reflect the inherent uncertainties in dating rather than a true temporal difference. An incipient marsh corresponding to episode 'a' also formed at Peyton Hill, approximately 3300 yr.

Ingram and DePaolo (1993) also isolated several episodes of higher salinity relative to pre-diversion levels in Richardson and San Pablo Bays and thus lower river flow (Table 4). Again the chronology shows minor disparities. It is highly likely that the records are recording the same episodes of extreme drought.

The period between 3500 and 200 yr is therefore characterized by much higher flows of freshwater from the Sacramento and San Joaquin Rivers. Superimposed on these longterm conditions were three episodes of extreme drought, which affected conditions throughout the estuary. These drought episodes probably varied in duration from decades to centuries, indicating much greater climate variability than at present.

RSLR has remained stable over the last 2000 yr. The results from all three sites indicate that the marshes began to mature into high marsh systems at about this time. For example, at Peyton Hill *S. robustus* replaced the stands of *S. americanus* that flourished during the higher freshwater flows of the previous zone. *S. robustus* in turn was succeeded by *Salicornia.*

Inundation declined reflecting the position of the marsh plain at all the core sites as being at or above MHHW. The data suggest that river flow was similar to modern pre-diversion levels. Rates of sedimentation throughout the estuary are now down to an average of 0.13 cm/yr.

Contrary to evidence from other studies in the Bay and State (Hughes and Brown, 1992; Graumlich, 1993; Stine, 1994; and Ingram *et al.,* 1996), there is no clear evidence for extreme drought events during this period. Once the marsh plain grows to a height close to or above MHHW it will become insensitive to negative changes in freshwater flow. The surface of the marsh is naturally inundated less frequently and so experiences net evaporation of water, and thus salt is concentrated at the surface. During droughts the salinity of Bay waters may increase, but because of the decline in RSL associated with the lower river flows, inundation period for the high marsh region will also be less frequent. It may therefore be impossible to differentiate between marsh maturation and the effects of acute drought. Further analysis of sediment cores retrieved from the low and middle marsh regions of the study sites today would be more revealing for this time period.

In contrast to negative events, extreme positive flow events should be recorded in the high marsh sediments. Browns Island was affected by at least one high flow event approximately 530 yr, when silty-sand, foraminifera, and seeds of a submerged water plant (*Potamogeton*) were deposited on the island. No comparable silty-mica rich horizon has been identified at Peyton Hill. However, this may be because of the poor recovery of the uppermost meter of sediments.

Thin clay rich lenses are found within the peats at Peyton Hill as are seeds of *Potamogeton*. This suggests occasional seasonal flooding, possibly from nearby Pacheco Creek.

Elevated concentrations of lead are present in the surficial sediments at all the sites. Concentration levels increase between *c.* 20-30 cm depth and thus delimit the onset of intensive settlement and industrialization about the Bay margins. These lead concentrations are comparable to those determined in a temporally intensive study located in the Suisun Bay (Luoma *et al.*, 1990).

CONCLUSIONS

Analysis of fringing marsh sediments from the San Francisco Bay has determined a complex history of river flow to the estuary, with trends in freshwater flow lasting millennia, centuries, or decades. Estuarine conditions are recorded at all the sites between 5500 and 3500 yr, although extent of coverage varies according to site. On at least five occasions river flow was higher than average for several decades resulting in variable RSLR. No droughts were identified for this period.

RSL rose between 2000-3500 yr as a result of extended higher than average water flow from the Sacramento and San Joaquin Rivers. High flow was maintained over centuries. Interbedded within this is evidence for at least three periods of acute drought, which resulted in negative RSL. These droughts were profound, affecting the North Bay as a whole, as testified by the emergence of incipient *Salicornia* marsh at China Camp and the intrusion of saline water at Browns Island. Overall this period experienced a relative rise in sea-level.

Average flow conditions returned by about 2000 yr. The sensitivity of the cores for recording low RSL events (droughts) diminishes with time as the marsh surface nears MHHW elevations. However, extreme discharge events are recorded on the marsh plain. A flood event occurred approximately 530 years ago.

The surface sediments from all sites bear witness to the effects of industrialization within the estuary, as lead concentrations rise to chronic levels beginning approximately 100 years ago.

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Table 1 Radiocarbon Ages for the Northern San Francisco Bay

Site	Depth (cm)[1]	Seed Material Dated	Laboratory Number (CAMS)[2]	Radiocarbon Age[3] (^{14}C yr B.P.)	Calibrated Age Range[4] (1σ)
China Camp	1 (2)	*Salicornia*	20546	>Modern	0 (0)
“	25 (41)	"	20547	200 ± 50	0-293 (147)
“	110 (181)	"	20548	930 ± 130	696-953 (825)
“	199 (250)[5]	"	20549	690 ± 80	557-673 (615)
“	295 (303)	"	20550	2330 ± 60	2322-2355 (2339)
“	447 (450)	*Distichlis* (?)	26039	3260 ± 110	3364-3624 (3494)
“	580 (580)	*Scirpus*	20551	3960 ± 60	4312-4508 (4410)
Peyton Hill	309 (310)	*Salicornia* and *Scirpus*	20552	2580 ± 60	2715-2756 (2736)
“	353 (358)	*Scirpus*	20553	2920 ± 60	2954-3201 (3078)
“	406 (407)	"	20554	3270± 60	3400-3563 (3482)
“	450 (455)	"	20555	3410 ± 60	3575-3699 (3637)
“	590 (592)	"	20556	4220 ± 60	4646-4840 (4743)
“	642 (656)	"	20557	4420 ± 60	4871-5211 (5041)
“	705 (708)	"	20558	4740 ± 60	5328-5582 (5455)
Browns Island 1992	6 (40)	Seeds	4795	>Modern	0 (0)
“	12 (80)	"	4794	430 ± 60	339-517 (428)
“	12 (80)	Stem	4793	>Modern	0 (0)
“	43 (66)	Root	4792	>Modern	0 (0)
“	**43 (66)**	**Seeds**	**4791**	**480 ± 60**	**496-540 (518)**
“	112 (116)	Root	4790	>Modern	0 (0)
“	**160 (180)**	**Seeds**	**4789**	**1430 ± 60**	**1287-1351 (1319)**
“	160 (180)	Root	4788	>Modern	0 (0)
“	203 (204)	Leaf	4787	1210 ± 60	1059-1223 (1141)
“	**272 (277)**	**Leaf**	**4786**	**1740 ± 60**	**1552-1711 (1632)**
“	339 (350)	Leaf	4785	2060 ± 60	1937-2107(2022)
“	**339 (350)**	**Seeds**	**4784**	**2470 ± 100**	**2351-2741 (2546)**
“	**523 (526)**	**Seeds**	**9962**	**3580 ± 210**	**3624-4147 (3886)**
“	528 (532)	Root	4782	2730 ± 60	2763-2867 (2815)
“	**547 (553)**	**Leaf**	**4781**	**3630 ± 60**	**3840-4063 (3952)**
“	**605 (606)**	**"**	**4780**	**3820 ± 60**	**4092-4343 (4218)**
“	634 (636)	"	4779	4470 ± 70	4880-5286 (5083)
“	648 (651)	"	4778	5410 ± 260	5915-6447 (6181)
“	**687 (692)**	**Seeds**	**9961**	**4290 ± 60**	**4829-4870 (4850)**
“	715 (719)	Leaf	4775	5150 ± 80	5762-5983 (5873)
“	723 (728)	"	4774	4930 ± 70	5597-5733 (5665)
“	747 (756)	**Seeds**	4773	**4930 ± 60**	**5599-5728 (5664)**
“	758 (769)	**Bulk Peat**	4771	**5190 ± 60**	5907-5988 (5948)
“	779 (794)	**Leaf**	4772	**5530 ± 100**	6212-6412 (6312)

Browns Island 1993	409 (409)	Seeds	10110	2920 ± 60	2952-3201 (3077)
"	801 (801)	Woody Debris	12190	4970 ± 60	5645-5841 (5743)
"	801 (801)	"	12185	4640 ± 50	5302-5450 (5376)
"	**928 (929)**	**Seeds**	**12187**	**5390 ± 60**	**6103-6281 (6192)**
"	**928 (929)**	**Bulk Peat**	**12189**	**5340 ± 40**	**6035-6187 (6111)**
"	1000 (1000)[5]	Woody Debris	12183	5030 ± 70	5666-5896 (5781)
"	**1060 (1064)**	**Leaves**	**12184**	**5880 ± 90**	**6574-6845 (6710)**

1 Depths in parentheses are decompacted depths used to calculate rates of sedimentation.

2 Center for Accelerator Mass Spectrometry.

3 One sigma error range as reported by CAMS.

4 Calib 3.0 (Stuiver and Reimer, 1993). Numbers in parentheses are the mid-points of calibrated range.

5 Sample identified as contamination.

Table 2 Rates of Sedimentation.

Site	Sediment accumulation rate depth range (cm)	Dominant Sediment Matrix	Sediment accumulation rate (cm/yr) [1]
China Camp	0-25 (0-41)	Muddy-Peat	0.26
"	25-110 (41-181)	"	0.21
"	110-295 (181-303)	Mixed	0.08
"	295-447 (303-450)	"	0.13
"	447-580 (450-580)	Mud	0.14
Peyton Hill	0-309(0-310)[2]	Muddy-Peats	0.11
"	309-353 (310-358)	"	0.14
"	353-406 (358-407)	Muds	0.12
"	406-450 (407-455)	"	0.31
"	450-590 (455-592)	Mixed	0.12
"	590-642 (592-656)	Muds	0.21
"	642-705 (656-708)	"	0.13
Browns Island 1992	0-43 (0-66)[3]	Peat	0.13
"	43-160 (66-180)	"	0.14
"	160-272 (180-277)	"	0.31
"	272-339 (277-350)	"	0.08
"	339-523 (350-526)	"	0.13
"	523-547 (526-553)	"	0.41
"	547-605 (553-606)	"	0.2
"	605-687 (606-692)	"	0.14
"	687-747 (692-756)	"	0.08
"	747-758 (756-769)	"	0.05
"	758-779 (769-794)	"	0.07
Browns Island 1993	0-409 (0-409)[2]	Peat	0.13
"	409-801 (409-801)	Peat	0.15
"	801-928 (801-929)[4]	Clays with organic laminations	0.16
"	928-1060 (929-1064)	Predominantly silty sands	0.24

[1] Decompacted depths and the mid-point of the calibrated ages range are used to calculate rates of sedimentation.

[2] No date was obtained from the top sediments, this rate assumes that at 0 cm age is modern.

[3] Two sediment cores were obtained for the top section of BI92, because of overlap between the cores, dates obtained from the longer of the two cores are used.

[4] The dates at 928 cm have been averaged, and the oldest date from 801 cm was used.

Table 3 Peyton Hill Silty-Sandy Layers

Depth (cm)	Number of years Persisted[1]	Approximate Calibrated Age[2]
502-506	20	4100
539-548	50	4400
606-616	40	4900
627-643	60	5000
655-670	80	5200

[1]Rounded to nearest decade.

[2]Rounded to nearest century.

Table 4 Comparison of Chronology of low flow data

Episode	China Camp (Cal. yr. B.P.)	Browns Island (Cal. yr. B.P.)	Ingram and DePaolo (1993)[1]
c	2090-2210	1910-2050	2100 (RB)
b	2300-2390	2430	2510-2530 (SPB)
a	3180-3330	2590-3020	3450-3700 (RB)

[1] These dates were obtained on estuarine carbonate material. They have been adjusted and calibrated for the oceanic carbon reservoir effect (Ingram and DePaolo, 1993). RB=Richardson Bay; SPB=San Pablo Bay.

Figure Captions

Figure 1 Map of San Francisco Bay showing research sites.

Figure 2 Chronostratigraphic correlation between China Camp (CC93), Peyton Hill (PH93), and Browns Island (BI92 and BI93) cores. Dates are calibrated years B.P. Note the figure presents generalized stratigraphy.

Figure 3 Summary diagram presenting stratigraphic changes in sedimentary, geochemical, and macro-fossil composition for 1993 China Camp core.

Figure 4 Summary diagram presenting stratigraphic changes in sedimentary, geochemical, and macro-fossil composition for 1993 Peyton Hill core.

Figure 5 Summary diagram presenting stratigraphic changes in sedimentary, geochemistry, and macro-fossil composition for the 1992 Browns Island core.

Figure 6 Summary diagram presenting stratigraphic changes in sedimentary, geochemistry, and macro-fossil composition for the 1993 Browns Island core. Note no retrieval of top meter.

Figure 7 Summarized paleoenvironmental history of the Northern San Francisco Bay.

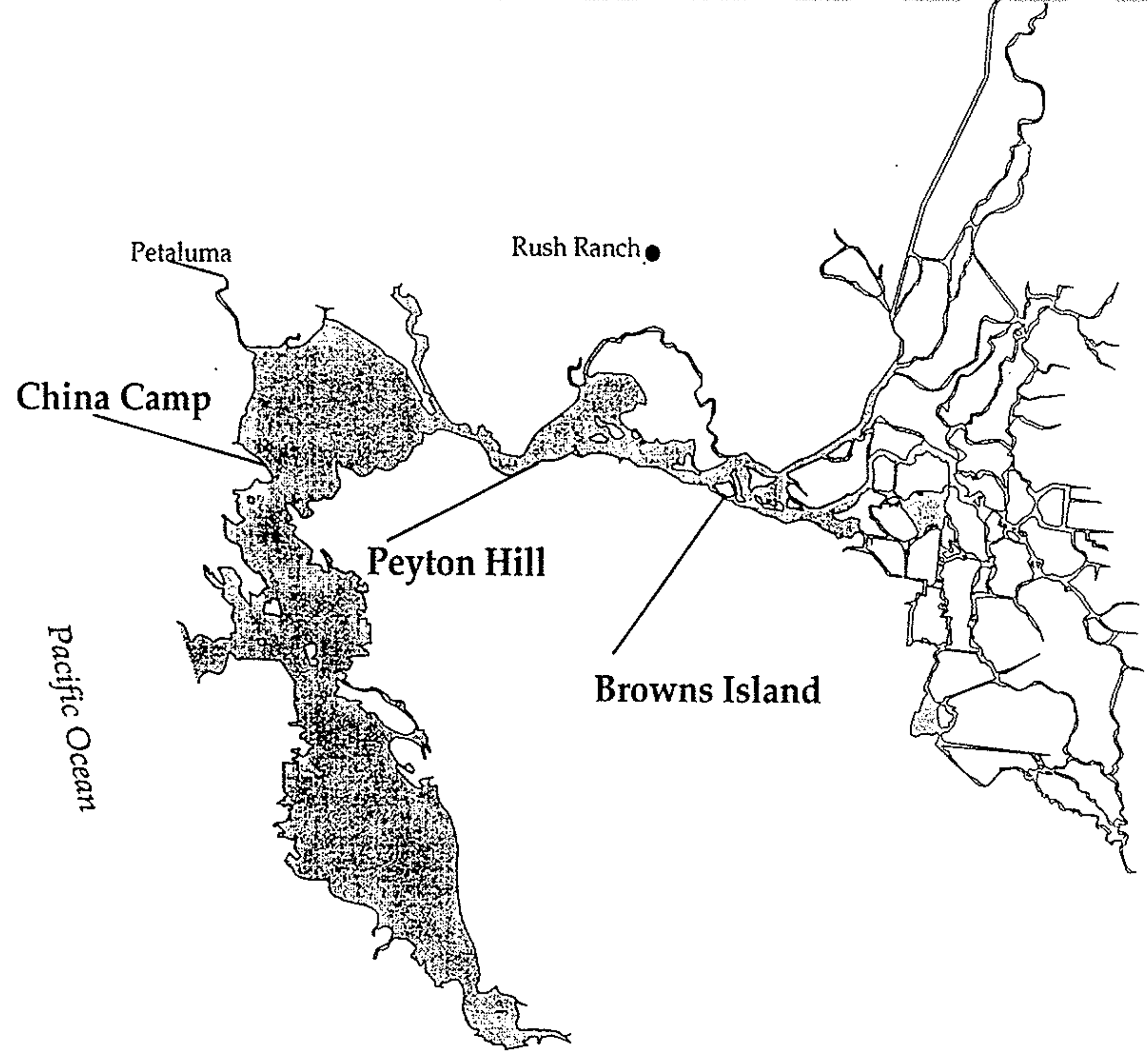


Figure 1 Location of research sites in the San Francisco Bay.

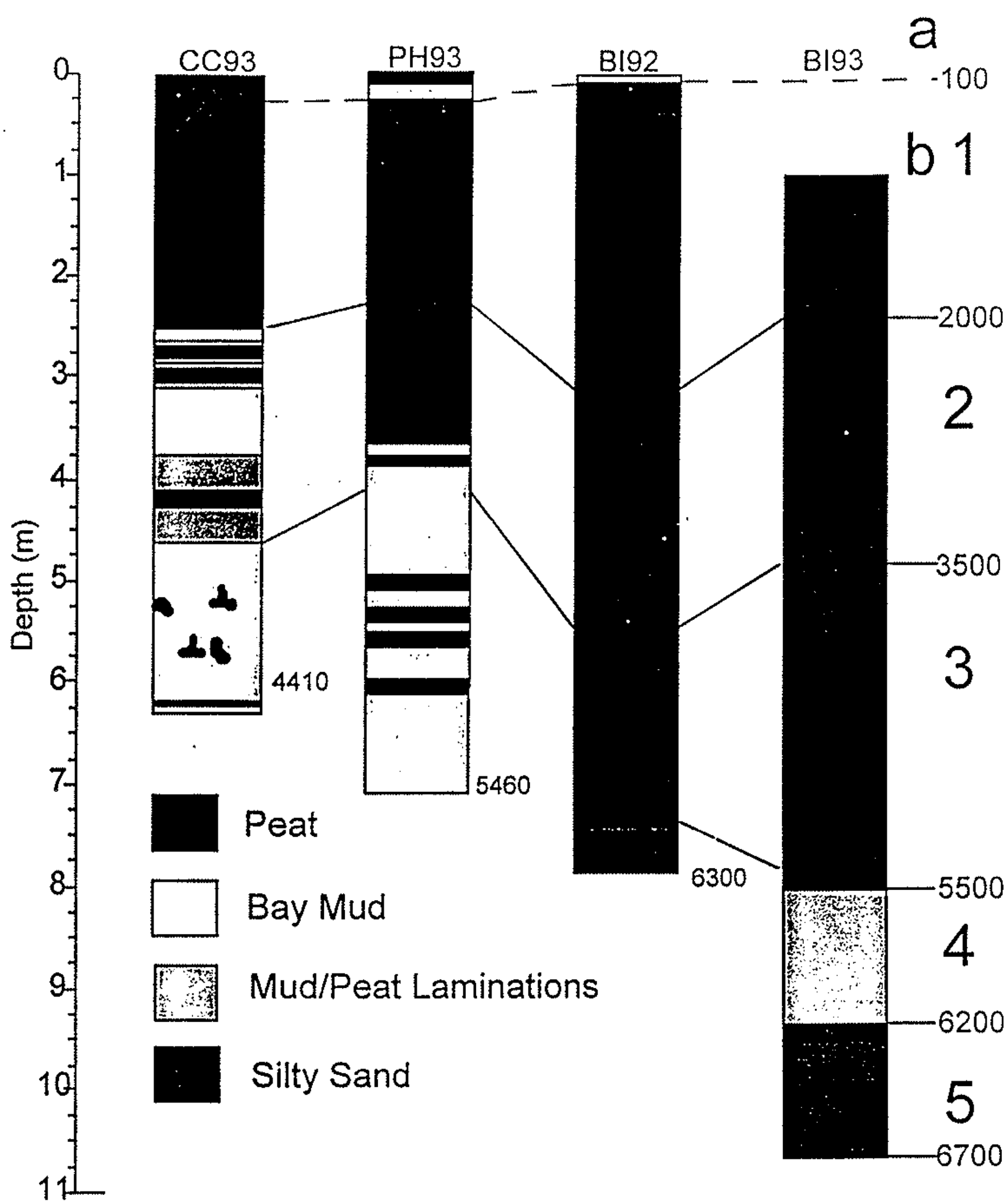
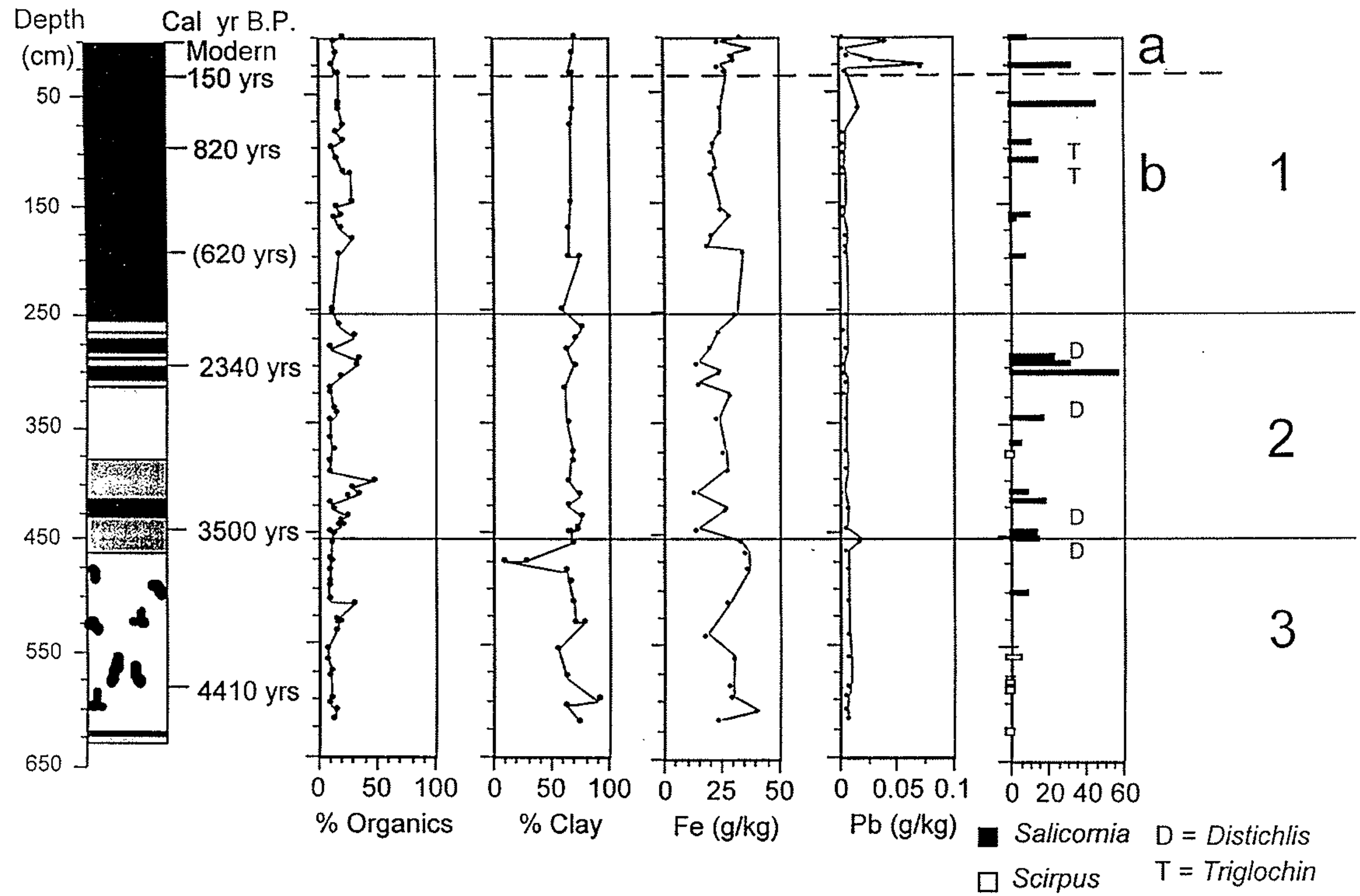


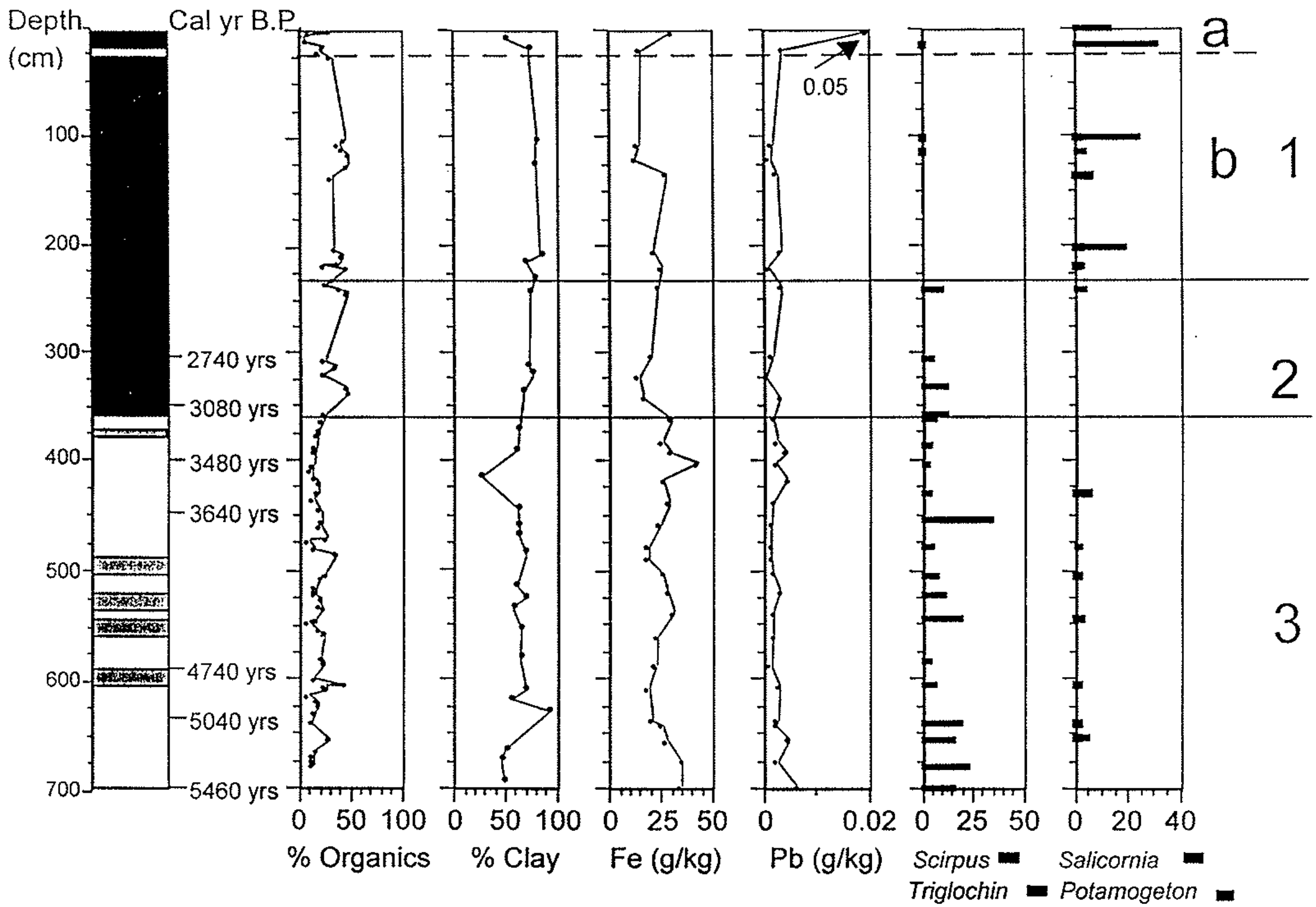
Figure 2 Chronostratigraphic correlation between China Camp (CC93), Peyton Hill (PH93), and Browns Island (BI92 and BI93) cores. Dates are calibrated years B.P. Note the figure presents generalized stratigraphy.

FIG 3:



Depth (cm)
50
150
250
350
450
550
650
Cal yr B.P.
Modern
150 yrs
820 yrs
(620 yrs)
2340 yrs
3500 yrs
4410 yrs
0 50 100
% Organics
0 50 100
% Clay
0 25 50
Fe (g/kg)
0 0.05 0.1
Pb (g/kg)
0 20 40 60
T
T
D
D
D
D
a
b
1
2
3
Salicornia
Scirpus
D = Distichlis
T = Triglochin

FIG 4:



Depth (cm)
Cal yr B.P.
100
200
300
400
500
600
700
2740 yrs
3080 yrs
3480 yrs
3640 yrs
4740 yrs
5040 yrs
5460 yrs
0.05
0 50 100
% Organics
0 50 100
% Clay
0 25 50
Fe (g/kg)
0 0.02
Pb (g/kg)
0 25 50
Scirpus
Triglochin
0 20 40
Salicornia
Potamogeton
a
b 1
2
3

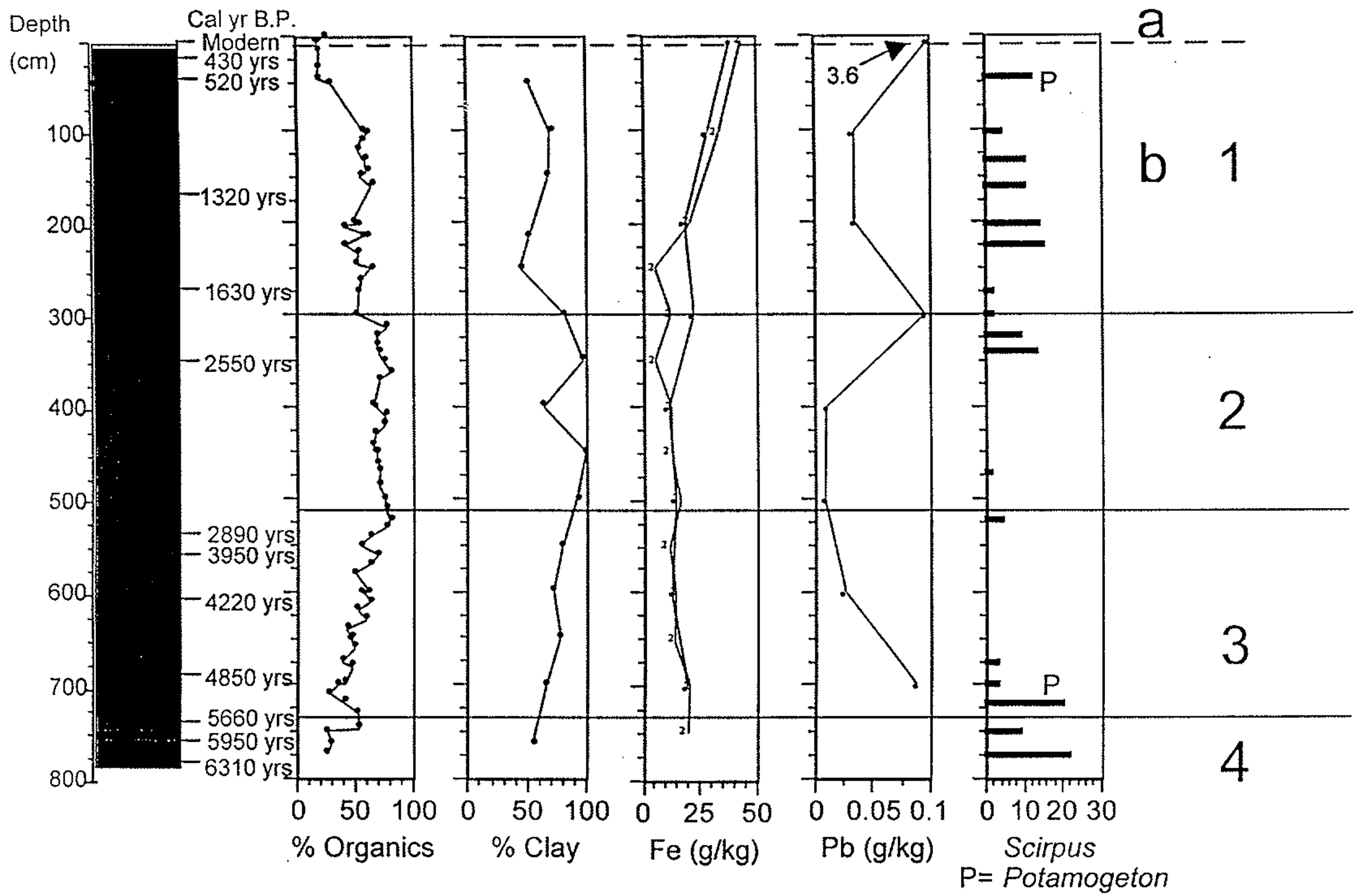


Figure 5 Summary diagram presenting stratigraphic changes in sedimentary, geochemistry, and macro-fossil composition for the 1992 Browns Island core.

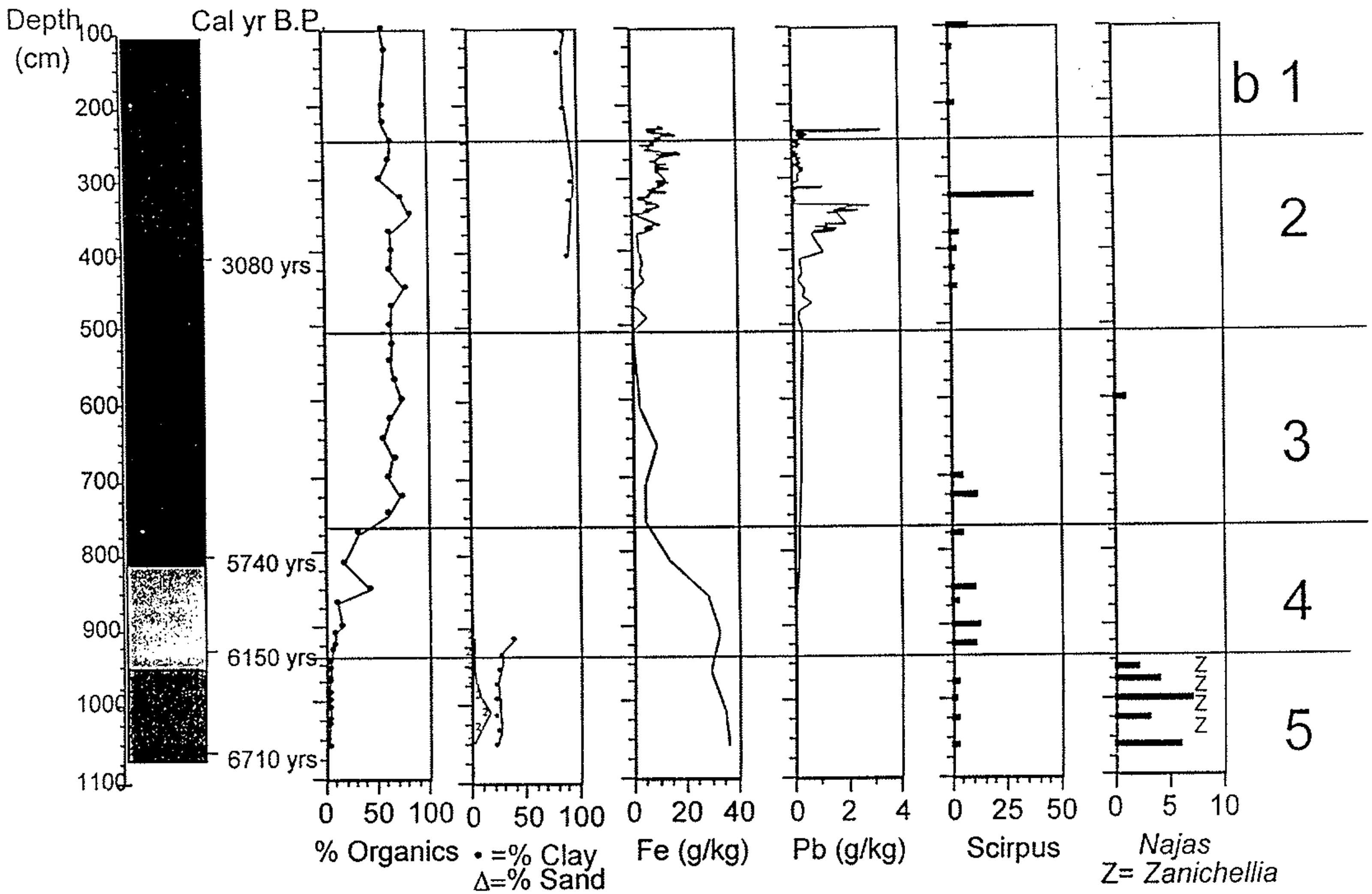


Figure 6 Summary diagram presenting stratigraphic changes in sedimentary, geochemistry, and macro-fossil composition for the 1993 Browns Island core. Note no retrieval of top meter.

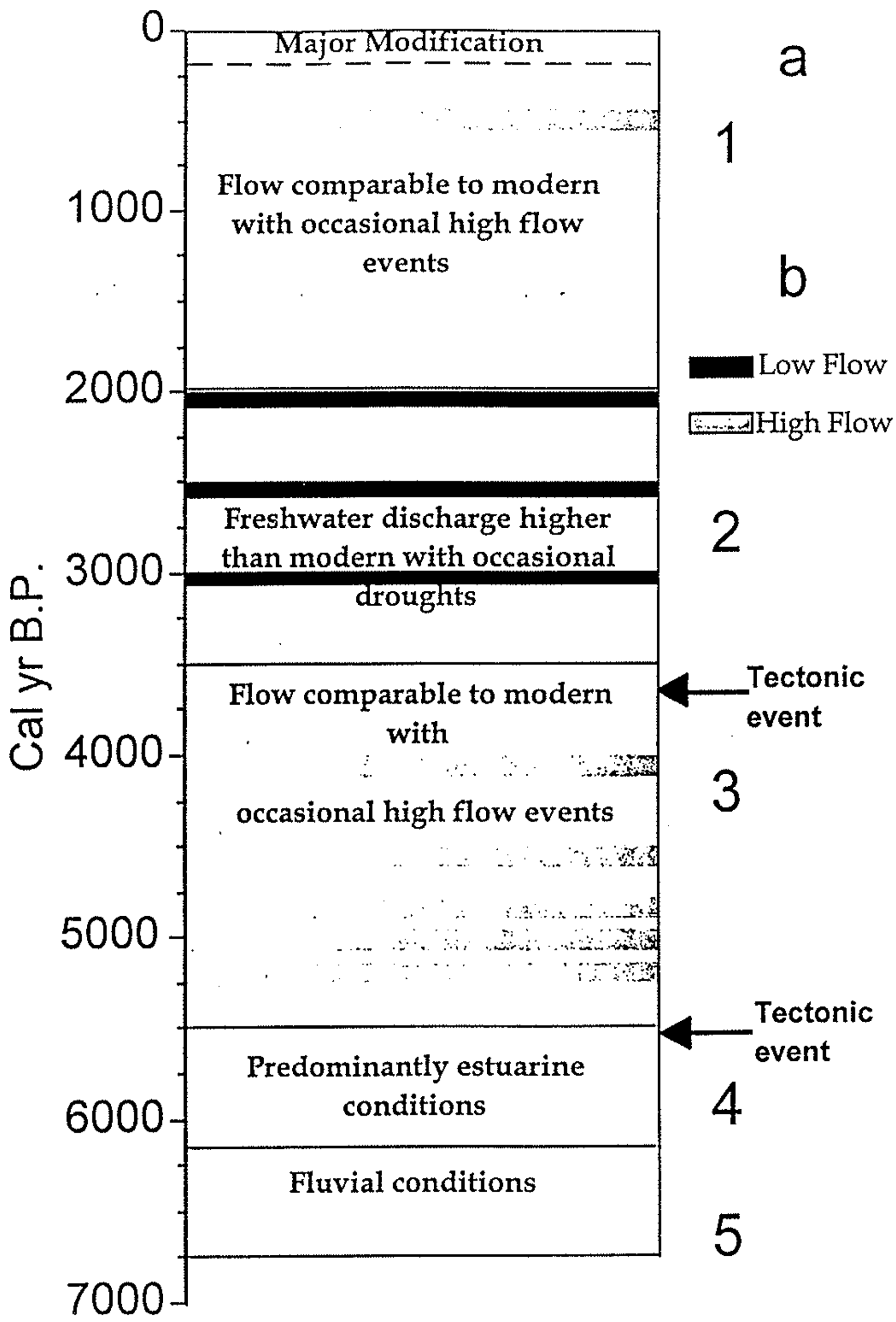


Figure 7 Summarized paleoenvironmental history of the Northern San Francisco Bay.