The Task 1: Analysis of Historic Hydrogeomorphic Conditions research program reconstructed the environmental history of the McCormack-Williamson Tract (MWT) in order to provide a strong foundation of understanding and check assumptions currently used in forward-looking wetland restoration planning, analysis, and modeling. The work primarily involved collection of sediment cores and a “forensic” analysis of multiple environmental indicators preserved in the cores, coupled with a shallow seismic reflection surveying of the tract. The effort yielded a wealth of useful information for restoration planning at a very low cost relative to other components of the overall MWT project, and thus serves as a model for the application of historical environmental analysis in other CALFED endeavors.

Beyond the scientific data and analyses reported here, this research program provided significant public/professional outreach and education. Outreach activities included 4 conference presentations, 4 scientific manuscripts (with more yet to come), 1 presentation to stakeholders, multiple meetings to convey results to stakeholders, and the development of multiple web sites providing detailed data and information to the public. Educational activities included the mentoring of a postdoctoral researcher and the training of 14 undergraduate and graduate students. A presentation was even made to the international geoscience community in Strasbourg, France at the expense of the researchers themselves, given their strong belief in the importance of the free exchange of ideas.

The sections of this report each represent a piece of a forensic puzzle. The original intent was to provide a comparison between the conditions reconstructed on the MWT and the adjacent Delta Meadows parkland previously thought to be relatively “pristine”. Specifically we sought to provide: a) an assessment of the stability of the physical structure of the system in the past; b) determination of the amount and direction of energy driving changes in sediment patterns in the system; c) quantification of the relative proportion of vertical accretion due to watershed influx of inorganic sediment versus in situ biomass accumulation; and d) characterization of the spatio-temporal distributions of habitats within and closely adjacent to the MWT. All of this was achieved and more. Notably, data required to facilitate these objectives was also able to yield important insights into the geochemistry and pollution history of the site, which has recent come to light as possibly constraining CALFED’s vision for wetland restoration in the Delta.

Below is a summary of each section included in this final report. The sections provide insight into environmental history of the upper Delta and the restoration significance of that history. The ultimate significance of these findings for restoration is that regardless of careful design of a tidal gradient as has been done in other Delta projects, a restored upper delta will be subjected to an unpredictable flood regime that will result in a spatially complex assemblage of...
geomorphic units that will defy conventional criteria for “success” in restoration. That is not inherently bad in that it is the natural condition of the system. However, the assumption of a well-ordered tidal geomorphic process as exists in other modern tidal freshwater wetlands is not appropriate for MWT. In addition, the presence of extremely high mercury concentrations in both the Delta Meadows and MWT create significant uncertainty in the biogeochemical fate of wetland restoration of MWT, though the opportunity exists for experts to study the biogeochemistry of Delta Meadows and establish how such a wetland functions in face of the existing pollution.

Section 1: The geomorphic dynamics and environmental history of an upper deltaic floodplain tract in the Sacramento-San Joaquin Delta, California,

Contrary to our original expectation and the apparent expectation of the restoration planners we have interacted with MWT has been dominated by spatially complex flood processes characteristic of non-tidal floodplains for most of its history, very similar in nature to the lower Cosumnes floodplain and not at all like the organic peat flats in the lower delta and estuary. The observed sedimentary strata in the cores varied among cores and included basal clay, sand channel, distal floodplain, and an agriculturally-impacted surficial horizon. A comparison of MWT’s history of elevation change against the regional sea level rise curve developed by Brian Atwater two decades ago shows that the surface of MWT has been much higher than the 0.5-0.7 m present day tidal difference between mean sea level and mean higher high water for more than 10,000 years. Energy in the system was directed in a complex pattern reflecting the history of channel migration, channel avulsion, distal floodplain accretion, and a patchwork of non-tidal wetland organic accretion. Watershed-derived inorganic and organic sediment dominated over in situ biomass accumulation. There is no signal of tidal processes for most of MWT’s history. A long-term trend of sediment fining most likely signifies the natural filling of the site’s sediment storage space as typically occurs for floodplains. Pollen preserved in the sediment show that a mosaic of habitats including open floodplains, riparian forests, Scirpus wetlands, and upland woodlands were common during the last 4,000 years, though in the modern era these are more restricted and less productive. Only in the last 2,500 years has MWT come under any definitive tidal influence. Since then the upper deltaic plain has shown a unique geomorphology of poorly drained silt and clay forming a permanent wetland with a very thin veneer of vegetation and organic matter. However, the history of strong flood disturbance present throughout the record of all cores did not abate with the onset of upper deltaic plain conditions.

Section 2: Long-term sediment geochemistry and mercury poisoning risk in an upper deltaic plain proposed for tidal wetland restoration.

The geochemical history of MWT was originally reconstructed to help constrain the timing of recent site geomorphic changes, but ultimately it went well beyond that application, addressing basic science and applied environmental restoration questions regarding processes in the uppermost zone of a delta. Specific goals of this section of the report include identification of depositional processes promoting geochemical retention of specific constituents, assessment of
remobilization of redox sensitive constituents, and determination of the extent of sediment contamination with key trace elements including Hg, As, Pb, Cu, and Zn. All cores showed typical sediment geochemistry behavior in terms of inter-element relations as revealed through regressions and principle components analysis. Organics controlled sulfur abundance, but that did not in turn affect other elemental abundances. Rather than showing similar stratigraphy and geochemical down-core trends, each core had a unique record. When records were segregated by the broad strata types of basal clay, sand channel, distal floodplain, and agriculturally-impacted surficial horizon, each strata type was found to have a significantly different characteristic geochemical signature across the spectrum of elements. The agriculturally impacted surficial layer in all cores showed high Hg, As, P and Pb concentrations. Specifically, total Hg concentrations as high as 438 ppb were recorded in surficial MWT sediment as compared to a long-term background level of 10-30 ppb. As toxic organic formulations typically account for <8% of total Hg, there could be as much as 35 ppb of the toxic form, which far exceeds that recorded in other regions of the Delta and Sacramento Valley. Thus, there appears to be a significant risk of conversion of total Hg into bio-available forms of Hg that are harmful to organisms.

Section 3: Spatio-temporal variability across an upper deltaic plain in the Sacramento-San Joaquin Delta, California, with emphasis on a floodplain, tidal freshwater wetland, and an agricultural boundary

To put the history of MWT into context, given that it is a disturbed site due to the on-going farming, a comparative analysis was performed between the history of MWT and the adjacent protected Delta Meadows (DM) wetland covering the last 4,000 years. Amazingly, wetland peat is present only as a thin veneer at DM too. In fact, AMS radiocarbon dating of the base of the peat shows that the tidal wetland is less than 100 years old. The elevational history of DM also shows that it did not come under tidal influence until the most recent anthropogenic period, suggesting that the wetland itself was a result of human impact, most likely gold mining sedimentation. This finding is very similar to results reported for Atlantic tidal freshwater wetlands of Chesapeake Bay, Delaware, and New Jersey. In terms of habitat history widespread floodplain was dramatically transformed into farmland on MWT and yielded to wetland development at DM. Sedimentary and geomorphic structures from MWT and DM reveal that flooding and inorganic sediment deposition typified the site in the past. In recent times, landscape modeification and utilization has resulted in lost habitat and increased concentrations of geochemical pollutants. Whereas MWT shows the potential for becoming a polluted marsh risking wetland biota, DM is in fact already a highly polluted biohazard. Hg, Pb, As, and P all show extremely high concentrations relative to pre-anthropogenic background levels. The restoration significance of these findings is that there are no long-term, stable tidal freshwater wetlands on the upper deltaic plain of the Sacramento-an Joaquin Delta. Such wetlands are geomorphically ephemeral, but part of an overall habitat patchwork. Also, it is imperative that research be performed right away to determine the significance of the pollution in Delta Meadows so this may serve as a model for what to expect in restoring Delta tracts.
Section 4: Shallow Seismic Reflection Survey Research On An Upper Deltaic Plain In Aid Of Wetland Restoration Planning

Seismographic technology was tested in two phases to ascertain if this technology could be used to extrapolate results from the coring study to the subsurface between where cores were analyzed. In the first phase of the testing, we successfully imaged underground river channels and sedimentary layers, but they turned out to be much too deep to be of relevance for restoration. In the second phase, the physical limits of near-surface data collection were contested using highly customized equipment to image near-surface substrate, yielding excellent raw data. Unfortunately, the amount of seismic data collected using very high sampling resolution exceeded our ability to analyze the data using the low-cost software available to us. Without having the data analyzed, it is not possible to evaluate the depth of the survey or the resolution of sedimentary layers. Consequently, while this project has yielded some very interesting results that will inform wetlands restoration at the McCormack-Williamson Tract, it has revealed a limitation of seismic technology for routine evaluations of potential restoration sites: unreliability of low-cost software and complexity of methods required for analysis and interpretation by skilled geologists. We have concluded at this time that seismology is of much less value than sediment coring in revealing and understanding subsurface structure.
The geomorphic dynamics and environmental history of an upper deltaic floodplain tract in the Sacramento-San Joaquin Delta, California, USA

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Abstract

A multi-proxy approach was used to examine the geomorphic dynamics and environmental history of an upper deltaic floodplain tract in the Sacramento-San Joaquin Delta, California. Three long cores were collected from the McCormack-Williamson Tract (MWT) and these cores were analyzed for bulk density, loss-on-ignition, fine (clay and silt) content, Al concentration, magnetic susceptibility, pollen, and charcoal. Radiocarbon dates obtained for the cores were converted into calendar years and an age-depth model was constructed. Long-term vertical accretion and sedimentation rates were estimated from the age-depth model. Cross-core relations show that coarse sediment generally accumulates more rapidly and has greater magnetic susceptibility compared to fine sediment. Percentage fine and LOI data show a strong linear relationship that indicates flooding is the primary mechanism for the deposition of particular organic matter on the floodplain and that landscape wash load has contributed a highly consistent fraction of persistent organic matter averaging 5.5 % to the site. Down-core grain size profiles show two hydrological domains in the cores, namely millennial fine-coarse fluctuations superimposed on general up-core fining. Coarse sediment is viewed as channel or near-channel overbank deposits, whereas fine deposits are considered to be distal overbank flood deposits. The coarse-fine fluctuations are indicative of changing depositional settings as channels migrate laterally across MWT, whereas the upward fining trend reflects a combination of self-limiting overbank deposition as floodplain elevation increases and decreasing competence as sea level rise reduces flood-pulse energy slopes. MWT has been crosscut and incised numerous times in the past, only to have the channels abandoned and subsequently filled by fine sediment. MWT likely came under tidal influence at about 2,500 cal BP and, at the same time, the channels
around MWT attained their modern configuration. Wetlands have recently developed on MWT, but they are inorganic sediment dominated.

**Keywords:** floodplain, delta, geomorphic dynamics, channel migration, marine transgression, Holocene, California
INTRODUCTION

In comparison to the broad-scale geomorphology of floodplains and intertidal deltas, the fine-scale processes at the interface between the two have received little focus. The floodplain-delta interface is highly important because the processes operating at the interface can influence the formation of oil and gas traps and deposits (Rainwater, 1975; Noble et al., 1991) as well as impact the local environmental geology of lands that are often used for agriculture or urban expansion. The interface is also important because its landscape position can yield an integrated perspective on basin-scale paleoenvironmental conditions (Pasternack et al., 2001).

Current understanding of the long-term geomorphic processes that characterise floodplains stem from the geomorphic analyses of stratigraphic successions of cutbanks, excavated trenches, and sediment cores. Classically, the two dominant processes driving floodplain evolution are lateral accretion (Wolman and Leopold, 1957) and overbank deposition (Bridge, 1984; Nanson, 1986; Walling and He, 1998; Tornqvist and Bridge, 2002). The relative roles of each vary substantially as a function of allogenic controls such as climate (Brakenridge, 1980; Blum and Tornqvist, 2000), climate variability (Knox, 1993; Goodbred and Kuehl, 1998), basin characteristics (Benda and Dunne, 1997), and human activities (Knox, 1995). Additional important processes that affect floodplains include channel avulsion (Bridge, 1984; Goodbred and Kuehl, 1998; Tornqvist and Bridge, 2002) and organic accretion (Mattraw and Elder, 1984; Cotton et al., 1999). These processes and still others result in a large number of floodplain forms, which are well summarised by Brown (1997).

Geomorphic processes acting on deltas have also been described through analyses of sedimentary deposits. The dominant processes controlling deltaic evolution are subaqueous sediment input and sediment redistribution (Galloway, 1975; Coleman, 1976). Constraints on
long-term deltaic evolution stem from the interdependent process of sea-level change and accommodation (Jervey, 1988; Blum and Tornqvist, 2000). Delta morphology has also been linked to the grain size distribution of sediment input (Orton and Reading, 1993). More recent studies have shown that delta plain evolution is strongly influenced by vegetative controls (Pasternack and Brush, 2001; 2002) and by the floodplain processes described above (Goodbred and Kuehl, 1998).

Attempts to delineate the downstream extent of floodplains (Alexander and Marriot, 1999) and upstream extent of deltas (Colman, 1976) suggest no distinctive process or morphology on which to base the delineation. Colman (1976) terms the “upper deltaic plain” as the region above significant tidal or marine influence that is dominated by riverine depositional processes. Because this zone may be ~100 km inland from the subtidal zone, the potential for wind and tidally transported coastal sediment to play a role is often negligible, though winds and tides may be important in the redistribution of riverine channel and overbank flood sediments. Goodbred and Kuehl (1998) reported that the upper delta plain of the Brahmaputra-Ganges system included significant areas of inactive floodplain that were isolated by channel avulsion.

In this study, a detailed investigation was performed to characterise the processes occurring at the interface between a floodplain and a delta using sedimentological and paleoenvironmental reconstruction techniques. Specific objectives to achieve this characterisation of the interface were to 1) develop an age-depth model for a transitional site; 2) document down-core stratigraphic zonation, rates of vertical accretion and sedimentation as well as changes in grain-size; 3) characterise the cross-core relations between grain-size, accretion, sedimentation, and magnetic susceptibility; 4) assess the relative proportion of vertical accretion
due to watershed influx of sediment versus in situ biomass accumulation; and 5) examine the fluvial processes operating at the site as well as the evolution of the tract.

**STUDY AREA**

The Sacramento-San Joaquin Delta is a 299,000 ha inland tidal delta located east of San Francisco Bay in central California with an ~107,000 km$^2$ drainage basin (Fig. 1). According to the classification of Galloway (1975), the delta is dominated by sediment input, with an annual outflow of ~19 billion m$^3$ of water and suspended sediment annual inflow and outflow of ~4.7 and ~3.3 million metric tons, respectively (Conomos and Peterson, 1976). The lower delta plain shows some morphological influence of winds and mixed tides. Monthly mean wind speed ranges from 2-5 m s$^{-1}$ with peak monthly gusts averaging 15-21 m s$^{-1}$ (Conomos and Peterson, 1976). The primary wind direction is westerly. The summer tidal range at the delta front is ~1.4 m and that in upper delta distributary channels is ~1.0 m. The delta has a rejoining distributary channel pattern (sensu Colman, 1976) because of the erratic discharges and high tidal range. Since the mid 19$^{th}$ century, 73 % of the delta’s area has been converted to agriculture necessitating 1,800 km of levees (Logan, 1990).

The McCormack-Williamson Tract (MWT) is uniquely located at the head of the delta downstream from the confluence of the Cosumnes and Mokelumne rivers and adjacent to the Sacramento River (Fig. 1). The Cosumnes River is the only major river flowing out of the Sierra Nevada whose mainstem is undammed. MWT is ~650 ha in area and is bordered by the Mokelumne River to the east, Snodgrass Slough to the west, and artificial dredge channels to the north and northeast. Historic maps show that MWT supported freshwater wetland in the early 20$^{th}$ century (United States Geological Survey, 1911). The wetland was likely tidal, as the
adjacent channels are presently tidal for several miles upstream. Subsequently, the tract was leveed, drained, and converted into agricultural land. After drainage, MWT and other delta islands experienced subsidence as surface organic sediment was oxidised and decomposed (Rojstaczer et al., 1991).

Band (1998) and Florsheim and Mount (2002) indicate that tectonic subsidence around the delta is somewhere between 0.15-0.5 mm/yr. The primary sea level rise curve for the region by Atwater (1980) did not account for tectonic subsidence or local compaction, but acknowledges that compaction of peat deposits in the delta could influence subsidence rates. In modern times farmed peatlands further downstream from MWT have subsided at a rate of 7.5 cm/yr due to surficial decomposition and deflation. Another factor that could cause subsidence in the delta and on the floodplain is underlying sediment compaction caused by aggradation. However, because the long-term rates and amount of subsidence are not precisely known we do not adjust our data to account for subsidence but rather note that subsidence has and is occurring in the delta region.

The general climate in the MWT region is Mediterranean, with cool, wet winters and hot, dry summers. Climate normals for the years 1961-1990 from Lodi, a town located ~15 km southeast of MWT, record an average minimum temperature of 2.3 °C in December and an average maximum temperature of 33 °C in July. Monthly precipitation varies from an average of 1.8 mm in July to 80.8 mm in January. Annual precipitation averages 434 mm. A cool "delta breeze" typically blows inland from the estuary during the summer, cooling nighttime temperatures. Winter precipitation is predominately rain, though in the high Sierra Nevada the main form of precipitation is snow. In the spring, snowmelt is retained in reservoirs for summer use, though historically it created widespread lowland flooding.
The little riparian vegetation that exists at MWT is largely located along the levees. Scientific nomenclature follows that of Hickman (1996). The most common trees include *Quercus lobata* (valley oak), *Populus fremontii* (Fremont cottonwood), *Platanum racemosa* (western sycamore), *Acer negundo* (box elder), *Fraxinus latifolia* (Oregon ash), and *Alnus rhombifolia* (white alder). Atwater (1980) also recorded the presence of *Cornus stolonifera* (creek dogwood). *Vitis californica* (California grape) grows on many trees. Common shrubs include *Rosa californica* (California rose), *Rubus discolor* (himalayaberry), and several species of *Salix*. *Cephalanthus occidentalis* (bottonbush) was noted close to the channels and *Chenopodium ambrosioides* (Mexican tea) occupies open disturbed sites. Nearby wetlands consist predominately of *Scirpus acutus* (common tule).

**METHODS**

To characterize the geomorphic relations and paleoenvironmental conditions on MWT, three long sediment cores (MWT-2, MWT-6, and MWT-8) were collected along the longitudinal axis of the tract (Fig. 1). MWT-2 is located near the southern tip where the elevation is -30 cm relative to the NGVD (1929 National Geodetic Vertical Datum) mean sea level position. MWT-6 is centrally located on MWT and is +30 cm NGVD. MWT-8 is located in the northwest section of MWT and is also +30 cm NGVD.

The cores were collected incrementally using a Geoprobe drilling rig (Fig. 2) with direct push and dual-tube sampling technology that enables the cores to be recovered in 1.22-m plastic liners. Sediment compaction or expansion during coring was measured on a section-by-section basis as the difference between pushed distance and actual core length. Core sections were stored in a refrigerated room at ~4 °C. To split a core section in the laboratory, the core liner
was first cut lengthwise using a circular saw on opposite sides and then a nylon string was passed down the core section between the cuts to yield two halves. Any smeared sediment was carefully scrapped off the exposed sediment surface in a horizontal fashion using a plastic spatula. Subsequently, core lithologies were visually described and plastic u-channels were pushed longitudinally into one half of each core section to retrieve samples for magnetic susceptibility. Next, cores were subsampled in 10-cm intervals and subsamples were placed in labeled plastic bags for cold storage and later analyses. Selected organic samples were sent to Beta Analytic Inc., University Branch, Miami, Florida for accelerator mass spectrometry (AMS) radiocarbon dating (Table 1). The radiocarbon dates were converted to calendar ages using a calibration program developed by Stuiver and Reimer (1993). Non-linear radiocarbon and calendar year age-depth models were developed by fitting a locally weighted function to the reported dates. Vertical accretion (cm yr\(^{-1}\)), sedimentation rates (g cm\(^{-2}\) yr\(^{-1}\)), and charcoal flux were determined using the calendar age-depth model.

In order to obtain a cross-comparison of the cores to interpret geomorphic dynamics, each core’s stratigraphy was determined using both visual and analytical methods, and then a statistical clustering algorithm was applied to the data to objectively zone each core. Analysis of sediment cores involved a multi-proxy approach in which standard physical, chemical, and paleoecological parameters were quantified. Sediment characteristics such as bulk density, loss-on-ignition (LOI), and magnetic susceptibility were measured for all core subsamples. Sediment bulk density (g cm\(^{-3}\)) was determined for the cores by weighing a subsample and measuring its volumetric displacement in a 50 ml graduated cylinder. Percentage organic and inorganic matter was obtained by LOI. Samples were weighed wet, dried overnight at 60 °C, weighed dry, combusted for 6 hours at 600 °C in a muffle furnace, and reweighed. The difference between
sample wet and dry mass is the water content and the difference between sample dry and post-combustion mass is the organic matter content. Magnetic susceptibility was measured for 30 seconds in 1 cm intervals down-core using a Bartington MS2 magnetometer and was adjusted for compaction. U-channels were then stored as archival sediment records at 4 °C.

Percentages of sands versus fines (silt and clay) were determined for each sample using methods adapted from Folk (1974). Organics were removed using 30% H₂O₂ (Black, 1965; Pasternack and Brush, 2002). Next, samples were suspended in 500 ml 0.5% sodium metaphosphate ((NaPO₃)ₓ·Na₂O) to fully disaggregate particles and passed through a 63 µm sieve to separate sands from fines. Sands were collected, rinsed with distilled water, dried, and weighed to determine total mass of sand. The fines suspended in the sodium metaphosphate were retained after wet separation and subsequently transferred into a graduated cylinder to determine total suspended volume. The fines were then transferred into a plastic bottle and vigorously shaken to homogenize the suspension. A 20-ml subsample was pipetted into a weighing dish, dried, and weighed. Subsample mass was calculated as the dry mass minus the mass of 20-ml of 0.5% sodium metaphosphate. The total mass of fines was calculated by multiplying the mass of the dry fines in the 20-ml pipetted subsample by the volume of the sample divided by the subsample volume. Based on the total mass of measured sand and fines, the percentages of each fraction were calculated.

Even though aluminum is not commonly used to directly assess geomorphic dynamics, its abundance and variability in siliciclastic sediment makes it very useful in identifying strata that may not be visually evident. Sediment samples for Al analysis were dried, ground, and passed through a 0.177 mm sieve to obtain the fine fraction. Next, they were treated with hot concentrated nitric acid to destroy organic matter and oxidised sulfide material and then added to
concentrated hydrochloric acid (3 times the volume of the nitric acid) to digest the material. After digestion, sample solutions were analyzed using inductively coupled argon plasma with atomic emission spectroscopy. Because sediment digestion was only "partial" for Al, a reference soil sample (San Joaquin Soil Standard Reference Material 2709) from the National Institute of Standards and Technology was also analyzed for Al using the same procedure. The difference between the measured and known element concentrations for the reference standard was the non-leachable fraction. Because the reference material came from a field near the study site, its texture, composition, and thus leachable fraction should be very similar to those for samples from the sediment cores. For easier up-core comparison, Al concentrations were normalised by a basal average concentration representing an initial state from which up-core changes could be assessed on a simplified scale. Samples from the bottom meter of each core were used to obtain the basal average.

Because observers can easily bias grain size and color information in determining core stratification, cluster-based zoning using quantitative sediment properties was used to promote objective core interpretation. The cores were divided into zones and subzones using a stratigraphically constrained cluster diagram that was based on values of LOI, fine sediment percentage, magnetic susceptibility, and normalized Al concentrations. These variables were selected for cluster analysis because they are continuous throughout the cores and are not modified down-core by compaction. The core zones are used throughout the text to describe, compare, and contrast the cores and core variables.

Additional information on the paleoenvironmental history of the upper delta was obtained from pollen and charcoal analysis. Pollen preparation followed standard procedures (Moore et al., 1991) and the samples were spiked with *Lycopodium* tablets containing 10,679±953 spores.
(Batch Number 938934). The pollen and spores were counted using a Nikon Eclipse E200 microscope at 400x magnification and identified with reference to pollen floras (Moore et al., 1991) and the University of California Museum of Paleontology Pollen Reference Collection. Pollen counts were converted to percentages using a total of all pollen and spores.

Charcoal fragments were retrieved by sieving 1 cm$^3$ of homogenised sediment through a 150 µm sieve (Brown and Hebda, 2002a). The sediment was homogenised to ensure that the charcoal extract was representative of the subsample. The residue that did not pass through the sieve was suspended in water in a gridded petri dish and examined using a dissecting microscope at 40x magnification. Black fragments that were brittle and opaque with sub-metallic lustre and cellular structures were counted as charcoal (Sander and Gee, 1990). Charcoal flux (fragments cm$^{-2}$ yr$^{-1}$) was obtained by multiplying the number of fragments per 1 cm$^3$ of sediment (fragments cm$^{-3}$) by the sedimentation rate (cm yr$^{-1}$).

RESULTS

The majority of the results and interpretations are dependent on a robust age-depth model based on the radiocarbon and calendar chronologies, so that is described first in detail. Once the chronologies are established, then the quantitative stratigraphic histories of each core are presented. Next, cross-core and down-core relationships among sediment variables are reported. Lastly, the age-depth model is reassessed using the established relationships between variables.

Age-depth Models

For the time-scale of interest in this contribution and the nature of the materials collected as part of this investigation, there is no definitive dating approach that would yield an absolutely
accurate representation of chronology. Therefore we employed the widely used radiocarbon
dating method (e.g. Hudson-Edwards et al., 1999; Constantine et al., 2003). Of the 11 AMS
radiocarbon dates obtained for the cores (Table 1), only one from MWT-2 (Beta-160022) shows
date inversion (Fig. 3). This sample derives from a shallow level in MWT-2, but its date is very
old and inconsistent with the other dates in that core and the other cores. The age of the material
is thought to be too old due to long-term storage and eventual reworking of old carbon from
upstream floodplains. The 2 bottom radiocarbon dates from MWT-2 are old and do not yield
valid calibration ages. In consequence, we have elected to present 2 age-depth models, a
conventional radiocarbon model and a calibrated calendar year model (Fig. 3). The radiocarbon
age-depth model for MWT-2 consists of 3 dates whereas the corresponding calendar chronology
is reduced to 1 reliable date. Additional radiocarbon samples were not obtained for MWT-2
because visible organic matter such wood fragments were not observed at any other levels apart
from those already dated. The resulting calendar age-depth model for MWT-2 is a linear model
that likely does not accurately reflect patterns of past sedimentation. Subsequently, an alternate
and preferred calendar chronology, consisting of 3 dates (1 measured and 2 inferred), was
developed for MWT-2 using the radiocarbon age-depth model. The inferred dates were selected
as the points of cross-over between MWT-2 and the other cores in the radiocarbon age-depth
model. The inferred radiocarbon dates were then converted to calendar years (Table 1) and a
new MWT-2 calendar age-depth model developed. All ensuing core calculations, such as
accretion and sedimentation rates, were based on the MWT-6 and MWT-8 calendar age-depth
models as well as the inferred model for MWT-2 respectively.

The most believable and perhaps reliable radiocarbon dates in the age-depth models are
from the organic (peat and wood-in-peat) deposits in MWT-8 at 1040-1050 and 540-550 cm
depth because these ages are derived from *in situ* wetland sediment that was deposited in a stable environment. In MWT-2, the dates at 1065 and 1075 cm depth are also thought to be correct because they suggest extremely slow sedimentation or the existence a hiatus across a sharp lithological boundary that corresponds to late-Wisconsin glaciation in California (Bischoff and Cummins, 2001). The confidence in the remaining dates is intermediate because of possible temporary upstream sediment and carbon storage in hillslope colluvium, floodplains, or terraces that creates a gap between organism death and final deposition in the delta. The basal date in MWT-2 must be viewed with caution since it is near the limit of radiocarbon detection.

**MWT-2 Stratigraphy**

The stratigraphically constrained cluster analysis identified six zones (MWT2-1 to MWT2-6) in the MWT-2 core (Table 2, Fig. 4). Note that the chronology in MWT-2 shifts from radiocarbon years to calendar years because the oldest dates extended beyond the radiocarbon-calendar calibration curve and could not be converted into calendar ages. MWT-2 is 1330 cm long and begins in gray clay from 1330-1135 cm that was deposited between roughly >40,000-29,000 radiocarbon years before present (\(^{14}\text{C}\) ybp). Alternating bands of green silt and clay occur from 1135-1070 cm depth and span the interval from approximately 29,000-24,000 \(^{14}\text{C}\) ybp. The radiocarbon chronology indicates that an interval of extremely slow sedimentation or a hiatus exists at 1070 cm depth and spans approximately 11,000 \(^{14}\text{C}\) years. Silt with visible mica flakes was deposited after about 14,500 calendar years before present (cal BP) from 1070-1026 cm depth. Coarse sand with layers of silt and clay from 1026-800 cm is followed by a layer of beige clay with organic fragments from 800-788 cm depth. These units were deposited between roughly 13,500-8500 cal BP. Olive silt occurs from 788-755 cm depth. Greenish-grey sandy-
clay is recorded from 755-700 cm depth. Alternating layers of grey silt and sand noted between 700-607 cm depth are followed by alternating layers of grey and red-brown sand between 607-482 cm depth. Mottled sand, silt, and clay are observed between 482-427 cm. The mottles are typically dark grey and brown and 1-2 millimeters in size. The units from 755-427 cm depth were deposited between about 8,000-4000 cal BP. Clays containing concretions and organics that were deposited between 4,000-1,900 cal BP (427-220 cm) are interrupted by a thin sand layer at 307-299 cm depth. Sand and silt with organic fragments are present from 220-96 cm. Clays with high organic content occur between 96-0 cm depth.

**MWT-6 Stratigraphy**

Four zones were identified for MWT-6 (MWT6-1 to MWT6-3; Table 2, Fig. 4). Zones MWT6-2 and MWT6-3 are subdivided into two (MWT6-2a and MWT6-2b) and three (MWT6-3a to MWT6-3c) subzones respectively. MWT-6 is 1440 cm long and begins in alternating fine, medium, and coarse red-brown sands with wood fragments from 1440-1170 cm. These sands were deposited before >9,500 cal BP. Alternating bands of sand and silt occur between from 1170-376 cm depth from about 9,500-6,500 cal BP, with less sand between roughly 500-700 cm depth. Clay with organic fragments near the bottom and 1-2 mm dark gray-brown mottles near the top occur from 376-8 cm depth. Organic topsoil is noted from 8-0 cm depth.

**MWT-8 Stratigraphy**

Five zones are identified in MWT-8 (MWT8-1 to MWT8-5; Table 2, Fig. 4). MWT-8 is 1220 cm long and begins in green-blue clay from 1220-1121 cm that was deposited before 16,000 \(^{14}C\) ybp to about 6,500 cal BP. A coarse sand unit between 1121-1105 cm is followed by
a thin layer of gravel from 1105-1100 cm depth. Alternating sand and clay units are visible from 1100-866 cm depth. The units containing sand from 1121-866 cm were deposited between approximately 6,500-5,500 cal BP with the gravel being laid down at about 6,400 cal BP. Clay with wood and other organic fragments occurs between 5,500-4,700 cal BP (866-607 cm depth) with large wood fragments occurring at 662 and 633 cm. Organic-rich clay from 607-550 cm yields to peat between 550-482 cm depth at about 4,500 cal BP. The organic-rich clay recurs at about 4,100 cal BP and comprises the core between 482-399 cm depth. Wood fragments are noted at 435-431 and 399-395 cm depth. Clay with organic fragments from 395-231 cm is replaced by mottled clay from 231-94 cm. Alternating organic and mottled clay units occur between 94-65 cm depth. Clay is again noted between 65-20 cm with imbedded gravel and pebbles at 58-52 cm. The clays between 395-20 cm depth were deposited between 3,500-100 cal BP and the gravels laid down at about 400 cal BP. Organic topsoil occurs from 20-0 cm depth.

**Vertical Accretion and Sedimentation Rate Trends**

The established radiocarbon and calendar chronologies permit calculation of down-core vertical accretion (cm yr\(^{-1}\)) and associated sedimentation (g cm\(^{-2}\) yr\(^{-1}\)) rates and examination of their trends (Fig. 5). The entire MWT-2 core is characterized by relatively slow rates of vertical accretion. The rate increases up-core over a 15,000 year period from a basal low of 0.03 cm yr\(^{-1}\) to a high of 0.12 cm yr\(^{-1}\). In contrast, accretion rates in MWT-6 are initially high (ca. 0.7 cm yr\(^{-1}\)) at about 9,500 cal BP, but decrease sharply through time in 2 stages to ~0.05 cm yr\(^{-1}\). Extremely slow accretion in the bottom of MWT-8 is followed by a marked increase during the mid-Holocene with peak rates of ~0.4 cm yr\(^{-1}\) occurring at 5,500-5,000 cal BP. Slower accretion rates of ~0.1 cm yr\(^{-1}\) recur in the late-Holocene. During the last 3500 years, MWT-2 and MWT-
8 show remarkably similar rates of accretion. However, the age-depth models also reveal that discrepancies exist between the cores in terms of sediment age and depth of deposition. For example, the calendar year model suggests that at 6,500 cal BP the surface elevations of MWT-6, 2, and 8 were roughly 375, 650, and 1100 cm below present surface respectively (Fig. 3). The radiocarbon model similarly records this discrepancy at 5,000 $^{14}$C ybp. The possibility of this steep of a gradient is discussed below in light of the multiple proxies and several explanations are examined.

Temporal trends in sedimentation rates parallel those of vertical accretion to some extent (Fig. 5), given the narrow range of observed bulk densities in each core (Table 2). MWT-2 shows little down-core variability, with sedimentation rates ranging between ~0.05 g cm$^{-2}$ yr$^{-1}$ at the bottom of the core to 0.2 g cm$^{-2}$ yr$^{-1}$ at the top. A high sedimentation rate of 1.5 g cm$^{-2}$ yr$^{-1}$ is initially observed in the bottom of MWT-6 at 9,500 cal BP, after which values decrease noticeably until about 8,000 cal BP. More gradual change is noted between 8,000 cal BP and the present as sedimentation rate decreases from 0.5 to 0.05 g cm$^{-2}$ yr$^{-1}$ respectively. In contrast, sedimentation rate is initially very low in MWT-8, with basal values ranging between 0.01-0.1 g cm$^{-2}$ yr$^{-1}$. In the mid-Holocene, sedimentation rates increase to a maximum of 0.8 g cm$^{-2}$ yr$^{-1}$ at 5,500 cal BP and then decrease to 0.2 g cm$^{-2}$ yr$^{-1}$ by 4,000 cal BP. Between 4,000 cal BP and the present, sedimentation hovers around 0.2 g cm$^{-2}$ yr$^{-1}$.

**Grain-Size Relations with Accretion and Sedimentation**

Vertical accretion and sedimentation rates at MWT are significantly higher and more variable during coarse sediment deposition (Fig. 6). MWT-6 and MWT-8 both show high rates of accretion and sedimentation when fines constitute less than 50% of the total sediment being
deposited. When fines are greater than 50%, both accretion and sedimentation are profoundly slower. No threshold or trend between grain-size and accretion or sedimentation rates is evident in MWT-2. Low rates of sedimentation characterise MWT-2 regardless of fine content. The wetland deposit (MWT8-3 and bottom of MWT8-4) is characterised by a high percentage of fines and by intermediate accretion and sedimentation values that are less than those for coarse inorganic sediment but generally greater than those for fine inorganic sediment.

Comparison of the grain-size data among cores shows that while a variety of sediments were deposited on the MWT floodplain through time, there are recognizable patterns across the tract (Fig. 7). MWT-2 and MWT-8 are characterised by fine-grained sediment below 1100 cm depth that is overlain by coarser grained deposits. Meanwhile, the basal sediments in MWT-6 are generally coarse-grained. Above the coarse-grained units in MWT-2 and MWT-6, there are strong fluctuations in grain-size superimposed on an overall trend of upward fining. MWT-2 records grain-size fluctuations and general upwards fining starting at about 13,000 cal BP. In contrast, MWT-6, while of the similar length, is of shorter duration and records grain-size fluctuations and upward fining starting at a minimum age of about 9,500 cal BP. The fluctuations are marked by three periods of fine-sediment deposition and two periods of coarse-sediment deposition. In MWT-2, the first episode of fine deposition was marked by two intermittent periods of coarsening. The thickness of each fine and coarse layer is greater in MWT-2 than MWT-6. MWT-8 differs from MWT-2 and -6 in that it predominately consists of fine-grained sediment above the lower coarse unit, though perhaps some correlation can be made between the coarser units in MWT-2 and MWT-8 at 6,500-5,500 and 2000-1000 cal BP.

Sources and Rates of Organic Deposition
At MWT, organic content does not diminish as a function of depth in response to duration of potential decomposition (Fig. 4), but instead shows a strong, direct linear relationship to fine sediment content in all cores (Fig. 8). *In situ* organic material stemming from biomass accumulation under either reducing freshwater wetland or agricultural conditions is easily identifiable visually and by relatively high LOI values and the highest fine sediment contents. For example, the *in situ* organic layers in MWT-8 (zones MWT8-3 and bottom of MWT8-4) consist of peat and fine sediment with very high organic matter content compared to fine floodplain sediment. The organic matter in peat consists of visible plant fragments, whereas the organic matter in floodplain sediment is microscopic and may include a balance of terrestrial versus aquatic (algal and microbial) sources (Wolfe et al., 2002).

When the *in situ* organic and peat deposits in MWT8-3 and bottom of MWT8-4 related to wetland development and surficial core intervals impacted by agricultural activity (i.e. zones MWT2-6 and MWT6-4c) are excluded from analysis due to their known and distinct origin, the correlation between organic content and fine content for each core is statistically significant above the 99 % confidence level, with R values ranging from 0.78-0.87. The curve representing all of the combined data has a slope and y-intercept that matches MWT-8 almost perfectly. The MWT-8 and MWT-2 curves have similar slopes, whereas MWT-6 has a slightly greater slope. Based on the sedimentation monitoring research and associated endmember mixing modeling on a tidal freshwater delta reported by Knight and Pasternack (2000), the observed relationship is indicative of mixing between two distinct sedimentary endmembers: landscape wash load that is predominantly fine with higher organic content and channel bed material load that is predominantly sandy with low organic content. Depth intervals with intermediate amounts of
fine sediment and organic content represent linear mixtures of the two sources, as the observed relationships are all linear.

Extrapolation of the regression lines to 100 % fines indicates that the organic content of the fine-sediment endmember, which primarily derives from hillslope sources, is about 5.5 % when all core data is considered but ranging between 4.4-7.9 % for the individual cores. Similarly, extrapolation of the lines to 0 % fines yields an organic content of 0.5 % and a range of 0.1-0.5 % for the coarse-sediment endmember, which derives from channel bed material. In contrast, the wetlands in MWT8-3 and the bottom of MWT8-4 typically contain >95 % fines though this value ranges between 86-99 %. The organic content in these wetlands is between 5-32 %, with the organic rich clay deposits ranging between 5-19 % and the peat ranging between 15-32 %. The sedimentation rate for wash load sediment consisting of >80 % fines and about 5% organic matter ranges between <0.1-0.3 g cm$^{-2}$ yr$^{-1}$ with a very small contribution to that made by the organics (Figs. 6 and 8). Thus, in situ biogenic accumulation of sediment is a negligible component of overall vertical accretion. In contrast, wetlands contain only slightly more fines and yet have noticeably higher sedimentation rates that range between 0.2-0.7 g cm$^{-2}$ yr$^{-1}$, of which 0.05-0.2 g cm$^{-2}$ is directly due to organic accumulation. The wash load fraction having comparable sedimentation rates to that of the wetlands is typically much coarser grained, containing between 20-80 % coarse sediment.

**Paleoenvironmental Indicators**

Magnetic susceptibility also shows a relationship to fine-sediment content, though it is more complex (Fig. 9). In general, coarse sediment has a higher magnetic susceptibility compared to fine sediment. This relationship is related to the transport and deposition of dense
ferromagnetic minerals (i.e. magnetite) with coarser sediment (Berry and Mason, 1983). Indeed, examination of the sediment under a dissecting microscope reveals that black, opaque, magnetic minerals are more common in the medium and coarse sand units compared to the fine sediment.

MWT-6 and MWT-8 illustrate this relationship well with intervals of >50 % fine content having magnetic susceptibility <200 x 10^{-5} SI units and intervals of <50 % fines having magnetic susceptibility between 200-600 x 10^{-5} SI units. MWT-2, on the other hand, shows no general relationship between grain-size and magnetic susceptibility, with coarse sediments having relatively low magnetic susceptibility values and some fine sediments having elevated values (Table 2; Fig. 4). The only other deviation to this pattern is observed in zone MWT6-3b where there are almost no variations in magnetic susceptibility regardless of fine content. Perhaps the low values in the coarse sediment in MWT-2 are related to post-depositional diagenesis of the magnetic minerals. Magnetite can dissolve during diagenesis in contact with reducing or acidic porefluid, resulting in a loss or reduction of the magnetic susceptibility signal (Singer et al., 1996). MWT-2 is located at the southern end of MWT at a lower elevation compared to cores 6 and 8 (Fig. 1). In consequence, MWT-2 experienced greater submergence and related anaerobic conditions, which likely enhanced the reduction and leaching of iron from the system at this site. This process could account for the lower overall magnetic susceptibility observed in MWT-2 coupled with the lack of a relationship between grain size and magnetic susceptibility. The low magnetic susceptibility from the wetlands in MWT8-3 supports this interpretation because the wetland sediment accumulated under similar anaerobic conditions.

Examination of the pollen and spores (herein pollen) in MWT cores shows that most of the grains are small, roughly equivalent in size to silt. Pollen grains are observed in some core zones but not in others (Table 2) and such spotted distribution may be related to the different
types of processes operating on the floodplain (Catto, 1985; Fall, 1987). Some zones are poor in pollen because they are dominated by coarse sediment that was deposited during higher velocity conditions that kept fine sediment and hydraulically equivalent pollen grains in suspension. In addition, the coarse grained deposits would have experienced greater mechanical breakdown of pollen and well as increased post-depositional oxidation of the grains (Havinga, 1967; Brooks and Elsik, 1974; Holloway, 1989; Campbell, 1991). Beuning et al. (1997) similarly noted that the lack of sporopollenin microfossils in subaerially exposed sediments was caused by strong oxidizing conditions. Therefore, we posit that fine-grained units should contain more pollen compared to coarse-grained deposits. Pollen is present in non-agricultural zones MWT2-1, MWT8-3, and MWT8-4. The sediment in MWT2-1 averages 97% silt and clay, suggesting that the pollen in this zone was transported and deposited with fine sediment. Zones MWT8-3 and MWT8-4 are characterised by >95 and >92 % fines respectively, suggesting that the pollen was transported fluvially with the fine component. The remaining zones that contain abundant fines (i.e. >90 %) occur at the top of the cores in the agricultural horizons. MWT6-3c and MWT8-5 record the presence of some pollen, whereas no pollen was noted in MWT2-6. It is hypothesised that the reduced concentration of pollen in the upper-most sediment is related to 3 factors. First, the crops that are grown on MWT include tomatoes, corn, and safflower, all of which are angiosperms and generally poor producers of pollen. Second, the surface soils on MWT are intensely harvested which mechanically degrades the pollen grains. Finally, the soils are well aerated, promoting the chemical (oxidation) degradation of exposed grains. The remaining core zones are void or extremely poor in pollen at the 1-2 cm³ sampling level. These zones contain between 11-86 % fines, suggesting that the pollen was either not deposited with these units but rather transported to some other depositional site with the fines or was post-depositionally
degraded through oxidation. These data suggest that if pollen extraction is desired from a floodplain then sediment with at least >90% fines should be targeted.

The charcoal records show that fire is not and has not been a disturbance factor on the MWT floodplain, even though floodplain vegetation succession studies show that woody plants (i.e. fuel) colonize the site (Tu, 2000). Charcoal fragments are scare on the MWT and occur intermittently down-core (Table 2). The most notable increase in charcoal through time occurs in zone MWT8-3, with flux values reaching a high of 54 fragments cm\(^{-2}\) yr\(^{-1}\). The lithological and pollen data from MWT-8 suggest that Cyperaceae, likely _Scirpus_ (Atwater et al., 1979), wetlands developed in the northwest corner of the tract during zone MWT8-3.

**Age-model Revisited**

Because the calendar chronology for MWT-2 is derived from 1 measured date and 2 inferred dates, it is worthwhile re-assessing the model using the established cross-core relations between grain-size and accretion, sedimentation, and magnetic susceptibility. More confidence can be placed in the sections of the age-model where these relationships are consistent between cores. Slow accretion and sedimentation rates are noted in coarse sediment from MWT-2 compared to more rapid rates in similarly coarse sediment in MWT-6 and MWT-8. Both accretion and sedimentation are time dependent, suggesting that perhaps the section of the age-depth model contemporaneous to coarse sediment deposition in MWT-2 is erroneous. Coarse sediment is mainly observed in zone MWT2-3 (Table 2; Fig. 4), representing the 13,000-4,000 cal BP interval and this interval is subsequently viewed with less confidence. Magnetic susceptibility from coarse sediment in MWT-2 is considerably lower compared to coarse sediment from MWT-6 and MWT-8, much like accretion and sedimentation. However, unlike
accretion and sedimentation, measurements of magnetic susceptibility are not time-dependent, thus implying that the established age-depth model for MWT-2 may in fact be a suitable model because both time-dependent and time-independent variables are behaving similarly and that perhaps the coarse sediment in MWT-2 is itself anomalous compared to the other cores, though the reasons for this are currently unknown. These observations suggest that the MWT-2 age-depth model is a suitable model and that sections dominated by fines can be viewed with more confidence compared to coarse core sections.

DISCUSSION

The three cores from MWT provide new and important insight into geomorphic processes, flow regime history, and evolution of a floodplain-delta interface from the Central Valley in California. There are few paleoenvironmental investigations from this region because suitable organic deposits are rare and inorganic deposits are often difficult to extract. MWT-2 spans the longest duration (>40,000 $^{14}$C ybp) and provides some detail about MWT that cannot be realized from MWT-6 and MWT-8 since they predominately span the Holocene. All 3 cores contain Holocene records and in combination reveal that the MWT was, and continues to be, a highly dynamic site characterised by lateral channel migration, incision, overbank flooding, reducing wetland development, and a mosaic of habitat types. The following discussion initially focuses on developing a facies model for MWT using sediment grain-size characteristics. Next, time-depth discrepancies in the age-model are discussed in light of the established facies model. Finally, the cores are examined temporally and the tract evolution is discussed.
Depositional Facies

Even though the MWT cores were taken along the longitudinal gradient of the upper deltaic plain, they do not show a simple trend in grain size that would be associated with tidal or fluvial hydraulic sorting along that gradient. Instead, a complex variety of lithologies and sedimentation rates exist, suggesting that various localized flow regimes have characterised MWT in the past. The general relationship between inorganic clastic sedimentation and fine content on MWT suggests that coarse sediments are reflective of channel or near-channel deposits since sediment near river deposits typically have greater sedimentation rates compared to those deposited distally on the floodplain. This finding is consistent with our own monitoring of floodplain sedimentation upstream on the lower Cosumnes River floodplain and the extensive literature that has demonstrated a strong correlation between distance from the channel and event-based (e.g. Asselman and Middelkoop, 1995; Steiger et al., 2001) or decadal-scale (e.g. Kleiss, 1996; Allison et al., 1998; Goodbred and Kuehl, 1998; Walling and He, 1998; Walling et al., 1998) sedimentation rates. It is also consistent with the demonstrated relationship between the deposition of sand and channel proximity during flood events (e.g. Jacobson and Oberg, 1997; Ten Brinke et al., 1998; Florsheim and Mount, 2002). In consequence, we interpret the units dominated by fine sediment as overbank flood deposits that were laid down more slowly and distal to the channel. Thick coarse sand units may be either channel deposits or near-channel overbank flood deposits (Walling et al, 1997; Walling and He, 1998; Tornqvist and Bridge, 2002). Our monitoring of sediment deposition on the floodplain in the lower Cosumnes has also found that gravel is only deposited in-channel and not on the floodplain surface.
Tract Elevation

The age-depth model (Fig. 3) suggests that the surface of MWT may have been highly variable in the past. For example, at 6,500 cal BP the model indicates an ~7 m difference in elevation between MWT-6 and MWT-8, which are only 1 km apart (Figs. 1 and 3). Yet, it is hypothesized that the overall surface of the MWT upper deltaic plain was likely subdued through time with only a small elevation gradient in a downstream direction. Perhaps elevational gradients between different depositional facies on MWT such as natural levees or channels could account for the apparent differences in the age-depth model. Indeed, Tonqvist and Bridge (2002) show a rapid decrease of several metres in overbank sediment deposition away from the channel. Alternatively, this pattern could be an artifact of an age-depth model limited by few dates.

Historical maps of the Sacramento River floodplain 22 km upstream of MWT show natural channel levees that are 5 m high adjacent to the channel and 1.5 m high 1 km away (Atwater et al., 1979), yielding a 3.5 m range over the same distance as that between the MWT coring sites, suggesting that a natural levee could possibly account for some but not all of the elevation difference between cores. Natural levees along Snodgrass Slough in a protected state park opposite MWT show that in this region of the upper deltaic plain levees rise only 25-30 cm above the interior plain surface over a 20 m lateral extent (Atwater, 1980), further indicating that natural levee deposits, if indeed present in the cores, can only account for some of the observed differences.

Another mechanism that could account for the observed elevation pattern between cores is related to channel depth. The present-day Sacramento River has a typical channel depth of ~8-11 m, whereas the Mokelumne River adjacent to the eastern side of MWT (Fig. 1) has a channel depth of 3-4.5 m. Around 6,500 cal BP, MWT-6 was characterized by fine sediment and was at
the highest elevation (Figs. 4 and 7), whereas MWT-2 was intermediate in elevation and aggrading sand. MWT-8 was lowest in elevation and aggrading sand and fine gravel. These observations suggest that the lowest elevation at MWT-8 existed because there was a sand and fine-gravel bedded channel there at 6,500 cal BP, and that a smaller channel or inset bar was present at the MWT-2 site. The gravel in MWT-8 is concurrent with the start of increased sedimentation rates in MWT-8 (Fig. 5). However, the lack of bracketing radiocarbon dates coupled with the coarse sampling resolution makes it impossible to determine the exact sedimentation rate of this deposit, though it is thought to have been rapid. In contrast, MWT-6 was apparently located more distal to the paleochannels at this time as evidenced by the presence of silt and clay. It is envisioned that the channels incised into the floodplain, removed underlying fines, and subsequently were followed by channel accretion. These data suggest that MWT was dissected by anastomosing or distributary secondary channels in the past. Thus, the observed 7 m elevational difference between cores could indeed be explained by channel processes and later abandonment.

A third possible explanation for the apparent elevational difference between cores is related to radiometric dating of organic material preserved in fluvial sediments. The observed endmember mixing relationship between particulate organic matter and grain-size on MWT (Fig. 9) suggests that organic matter is eroded, transported, and deposited concomitant with fine mineral sediment during overbank floods. Asselman and Middelkoop (1995) and Walling et al. (1997) note a similar relationship where maximum organic matter coincides to sediment dominated by clay. The near-zero fines intercept in figure 9 suggest that flooding is the primary mechanism responsible for particulate organic matter deposition on the floodplain and that little of the in situ organic matter from floodplain vegetation is preserved unless in a reducing wetland
environment, which was observed only in MWT-8. Thus, while organic matter plays only a small role in local accretion on the upper delta plain, it can be derived from reworked upstream floodplain sources. It is, therefore, conceivable that some of the radiocarbon ages are not contemporaneous with sediment deposition due to carbon storage and reworking. For example, recycling of carbon could account for the presence of the somewhat older sediment near the surface in MWT-6 (Table 2; Fig. 4). The presence of a highly suspicious radiocarbon date of $20,160 \pm 170$ $^{14}$C ybp at 420-430 cm depth in MWT-2 certainly suggests that older carbon has been periodically reworked through the system. Not surprising, these apparently older ages are contained in mineral dominated sediment that certainly could contain older reworked carbon.

Environmental History

Zone MWT2-1 is highly anomalous because it is considerably older than any other core zone. It is also characterised by fine sediment with high magnetic susceptibility (Table 3; Figs. 4 and 9) that is atypical relative to other zones that show fines are typically characterized by low magnetic susceptibility. The origins and reasons for the elevated magnetic susceptibility measurements in the fine sediments found in MWT2-1 are currently not known. The chronology for MWT-2 suggests that these sediments were laid down during the mid-Wisconsin interstadial. Verosub et al. (2001) show that glacial-aged sediment has a higher magnetic susceptibility than interglacial sediment that is often diluted by soil forming (organic) processes. Perhaps zone MWT2-1 has a high magnetic susceptibility because the overall amount of inorganic sediment that was transported during the cool mid-Wisconsin interstadial was greater than the warmer Holocene (Adam and West, 1983). The high percentage of fines coupled with LOI values that are consistent with the established floodplain mixing line (Fig. 8) suggest that floodplains were
prevalent in the location of MWT during the mid-Wisconsin. The pollen from MWT2-1 imply
the landscape was likely open and consisted of widespread savanna with riparian vegetation and
wetlands occurring along riverbanks.

The interval from $23,550 \pm 210$ to $12,420 \pm 90 \text{^14C ybp}$ identified in MWT-2 spans the
late-Wisconsin glaciation (Bischoff and Cummins, 2001). This interval is characterised by either
extremely slow sedimentation rates or by a glacial hiatus such as a paraconformity. At this time,
lowered sea level would have promoted fluvial incision and little or no sediment is expected to
have accumulated at the location of MWT because it would have by-passed the site due to the
lack of a proximal base-level control.

The post-glacial interval, however, is well represented on MWT with all 3 cores spanning
most or all of the Holocene. The variety of core characteristics reveal that several depositional
facies occurred on MWT throughout the Holocene, implying that it was a highly dynamic and
variable site that supported a mosaic of habitats. The relationship of grain-size and
sedimentation rates to channel proximity suggests that the coarse units in MWT6-1 and MWT8-2
(Figs. 4 and 9) are either channel or near-channel overbank deposits because of the higher
sedimentation rates (Fig. 5) compared to other coarse units up-core. The coarse units in MWT2-3
(Fig. 4) also likely reflect channel or near-channel deposits, though the origins of these
deposits are less certain given that the relationship between sedimentation rates and coarse
sediment input is less understood for MWT-2 compared to MWT-6 and MWT-8 (Fig. 6). Thus,
sedimentation and grain-size data from the cores imply that several episodes of post-glacial
channel incision occurred on MWT. Riparian ecosystems and floodplain habitat would have
flanked these channels as they drifted across the tract.
Down-core grain-size profiles (Fig. 7) provide insight into the long-term history and dynamics of MWT and reveal that two dominate hydrological features operated on the tract in past, namely fine-coarse sediment cycles or fluctuations superimposed on general upward fining. The fine-coarse sediment fluctuations are evident in all cores, though they are not as prominent in MWT-8 compared to cores 2 and 6. The fine-coarse fluctuations in MWT-2 show that the fine sediment content during low-energy periods changed from 50% to 75% to 95% at about 7,000, 3,500, and 500 cal BP respectively, whereas the fine sediment content during high-energy periods changed from 20% at 6,000 cal BP depth to 60% at 1,000 cal BP. In MWT-6, the low-energy periods have 75%, 90%, and 95% fine content at 8,000, 6,000, and 3,000 cal BP, while the high-energy periods have 20% and 40% fines at 7,000 and 5,000 cal BP respectively. The fine-coarse fluctuations are less evident in MWT-8 because most of MWT-8 spans only the mid-to late-Holocene and it was likely located more distal to the active channel in a quiescent area that experienced organic sediment accumulation during the late-Holocene. We propose that the fluctuations in grain-size mainly reflect changes in depositional settings from in-channel to near-channel and distal-channel, though overbank flooding must also be considered since floods of different intensity can not only affect the type of sediment being deposited but also the distance from the channel in which it is eventually laid down. Large flood events are capable of depositing coarse sediment further from the channel compared to smaller floods and such pulsed events could be mistaken for facies changes. Evidence that floods of different intensity occurred on MWT in the past is found in several of the coarse-grained units where interbedded sand, silt, and clay are observed (Fig. 4).

As noted previously, coarse sediment is laid down in the channel. On the floodplain, coarse sediment is deposited proximal to the channel during overbank flooding whereas fine
sediment is deposited more distal to the channel. Indeed, on-going monitoring of sediment deposition on the lowermost floodplain of the Cosumnes River 4 km upstream of MWT show that coarse sand similar to what is observed in the cores is carried onto the floodplain surface on an annual basis (Florsheim and Mount, 2002). The down-core fluctuations in grain-size reveal that, through time, channels migrated across MWT and consequently changed the spatio-temporal depositional setting of the tract. A specific example of channel migration and the resulting change in depositional setting can be found in MWT-8 where the switch from largely inorganic sediment deposition to increased organic content at about 5,500 cal BP suggests that a slough migrated away from the core site at this time, enabling wetland formation and organic accumulation.

Examination of temporal grain-size fluctuations suggests that the earliest episode of channel incision and lateral migration occurred in the bottom of MWT2-3. This channel is contemporaneous with the late-glacial interval in the Sierra Nevada between roughly 13,000-10,000 cal BP. The late-glacial climate history of the California is complex and variable and perhaps these sediments reflect (fluvial) remobilization of widespread glacial sediment (Bursik and Gillespie, 1993; Clark and Gillespie, 1997; James et al., 2002) from late-Pleistocene glacial melt-water discharge or in response to a relatively cool wet, and possibly stormy, late-Pleistocene climate as suggested by geomorphic evidence and pollen transfer functions (Adam and West, 1983; Rypins et al, 1989; Reneau et al., 1990). The next episode of channel incision is noted in MWT6-1. A channel migrated in the MWT-6 location before 9,500 cal BP and this channel may have persisted there throughout much of the early-Holocene. Channel deposits are also noted in the mid-Holocene. For example, coarse sediment is observed in the top of MWT2-
3 and in MWT8-2 between 7,000-4,000 and 6,600-5,400 cal BP respectively, suggesting that channels were cross-cutting MWT at this time as well.

The present-day Mokelumne River bounds the MWT to the east (Fig. 1). It is conceivable that the ancestral Mokelumne River flowed over MWT at various times in the past and that the coarse sediments noted in the cores are lateral migration lag deposits left behind and covered by fine floodplain sediment. The presence of gravel and other coarse sediment in the cores reveals that the channel was characterised by a relatively high-energy flow regime. We favour the Mokelumne River over the larger and nearby Sacramento River (presently located with 1 km to the west of MWT) as a possible source for these coarse deposits noted in the cores because they are quite thin and we reason that channel gravel and sand deposits from a large river like the Sacramento would have been relatively thick. Another explanation, however, is that numerous small distributary or anastomosing channels diachronously cross-cut MWT in the past.

The general upward-fining trend evidenced in the down-core grain-size profiles (Fig. 7), on the other hand, may be attributed to a combination of two possible mechanisms, namely self-limiting overbank deposition as floodplain elevation increases (Wolman and Leopold, 1957) or decreasing competence as sea level rise reduced flood-pulse energy slopes. Following each flood event on MWT, sediment accumulation elevated the floodplain surface and thus reduced the energetics and duration of future potential overbank deposition. Lithological evidence from the cores such as interbedded clay, silt, and sand indicates that flooding was an important process that accreted the floodplain surface and thus contributed to the upward fining trend. In addition, several researchers (Atwater et al., 1979; Atwater and Belknap, 1980; Goman and Wells, 2000) have noted that rapid marine transgression averaging about 2 cm yr⁻¹ occurred in the San Francisco Bay and western Sacramento-San Joaquin Delta between roughly 11,400-
7,000 cal BP. This phase of transgression flooded low-lying coastal communities and moved the shorelines inland by as much as 30 m yr\(^{-1}\) (Atwater, 1979). Transgression slowed to about 0.1-0.2 cm yr\(^{-1}\) at about 7,000 cal BP, after which salt marshes managed to keep abreast to the slowly rising sea levels. Continued transgression throughout the Holocene suggests that rising sea levels did indeed decrease flood-pulse energy slopes through time. Thus, it appears that both flooding and flood-pulse energy slopes where both important factors contributing to long-term upward fining trend noted in the cores.

The presence of peat and organic clay deposits containing Cyperaceae pollen in MWT-8 at 5-8 m depth shows unequivocally that freshwater wetlands developed and persisted in the northwest corner of MWT during the mid-Holocene from 5,500-4,000 cal BP. At this time, sea level was also about 5-7 m lower than present (Atwater, 1979), suggesting that mid-Holocene wetlands may have been under tidal influence and diurnally saturated. Examination of MWT core elevations through time and relative to Holocene sea level (Fig. 10) provide shed insight into when MWT first came under tidal influence. Channels adjacent to MWT presently experience a tidal range of ~ 1-1.4 m, so any time that past sea level is within ~70 cm of past MWT elevations a tidal influence could be present. Before 8,000 cal BP there is strong deviation between sea level and core elevation, with sea level being a minimum of about 5 m below the cores, implying that MWT was not under tidal influence at that time. Channel incision occurred at MWT-8 between 7,000-5,500 cal BP and lowered the elevation of MWT-8 to slightly below that of sea level. By 5,500 cal BP the elevation of the wetlands in MWT-8, which is constrained by two very reliable AMS dates, is below that of sea level, suggesting that MWT may have come under tidal influence sometime between 8,000-5,500 cal BP, likely at about 6,500 cal BP (Fig. 10). This interval is certainly contemporaneous to when sea level transgression slowed and
wetlands started to keep pace with sea level rise (Atwater, 1979), tantalizing observations that suggest MWT may indeed have been under tidal influence in the early mid-Holocene. However, an alternate, and more likely, explanation for MWT-8 is that meander cut-off or channel avulsion (Tornqvist and Bridge, 2002), as evidenced by the profound change in grain-size over a relatively short time interval, resulted in oxbow formation with subsequent organic accumulation. In this scenario, MWT-8 may have been below sea level, but not under tidal influence. At 8,000 cal BP both MWT-2 and MWT-6 consisted of fine floodplain sediment and were above sea level. Channels incised both sites at 7,000 and 8,000 cal BP respectively, though the amount of incision did not lower the sites below sea level. In fact, by 6,000 cal BP deposition of fines was recurring at MWT-6, implying that the channel had migrated away from the site and it was slowly accreting. In contrast, the channel persisted at or near MWT-2 until about 4,000 cal BP, at which time the elevation of the site was similar to that of MWT-8 and nearing that of sea level. By about 2,500 cal BP, both MWT-2 and MWT-8 were within the 70 cm sea level differential range. Thus, it seems reasonable to infer that large sections of MWT came under tidal influence at that time. MWT-6, on the other hand, remained above sea level until very recently. These observations confirm that rising tides must have contributed to the long-term fining upward trend observed in the cores, especially during the late-Holocene.

One interesting aspect of the wetland strata is that they contain the most charcoal observed in any of the cores. The general lack of charcoal in the MWT cores suggests that the site did not burn in the past and that flooding was the primary disturbance mechanism. The lack of fire on MWT is likely related to the moist conditions that prevailed in both the riparian zone and the floodplain, though fuel discontinuity was also a factor on the floodplain. The lack of in situ charcoal horizons in the peat coupled with frequent saturation due to tidal influence reveals
that the wetlands did not burn. Instead, the increase in charcoal in MWT8-3 is hypothesised to be related to the interception of charcoal by dense wetland vegetation (Brown and Hebda, 2002b) as it was transported downstream. In this case, the charcoal is likely from upland sites that were perhaps deliberately burned by native people to increase sustenance yield.

After 4,000 cal BP, fines with organics are ubiquitous over MWT (Table 2; Fig. 4). The generally high concentration of fines on MWT after 4,000 cal BP and the lack of coarse deposits suggests that the tract has not recently been cross-cut by major sand-bearing channels and that the present-day configuration of major channels was established about 4,000 years ago. Adam and West (1983) and more recently Anderson (1990) show that late-Holocene climate in California was characterised by increasing precipitation and decreasing temperatures, ushering in a Neoglacial period in the Sierra Nevada (Clark and Gillespie, 1997). The increase in precipitation partially offset the affects of self-limiting overbank deposition and decreased flood-pulse energy slopes. During the last 4,000 years, flooding on MWT led to at least 4.5 m of fine accumulation at MWT-2 and MWT-8 and about 1.5 m at MWT-6. Because MWT-6 is much higher in elevation compared to MWT-2 and MWT-8 during this period (Fig. 10), it received less overall sediment, which could account for the thinner deposit at that site. The mottles noted in the tops of all cores (Fig. 4) are consistent with our interpretation of the late-Holocene since they imply sediment mixing consistent with tidal activity and periodic flooding.

Historic maps show that the entire surface of MWT supported freshwater wetland habitat by 1903 AD (United States Geological Survey, 1911). These wetland deposits are no longer present in the tops of cores due to oxidation and plowing into the agricultural horizon, as evidenced by crop pollen. However, Delta Meadows State Park west of MWT along Snodgrass Slough still has such freshwater wetlands, and they are tidally inundated. Thus, sometime within
the last few millennia the entire fine sediment surface of MWT came under direct tidal action yielding a tidal freshwater wetland. The core sediments show that even though the modern wetland had a higher organic content, delta accretion was still inorganic sediment dominated. Thus, vegetation in this region is opportunistically occurring on the surface and not significantly contributing to delta evolution.

In summary, it is possible to extract the unique elements of an upper deltaic plain that distinguish it from a floodplain and the rest of the delta based on the results of this study. In this case, the delta is forming over a floodplain as sea level rises, whereas in other situations open-water receiving basins form deltas that eventually aggrade into floodplains. Similar to floodplains, an upper deltaic plain has cyclic coarse-fine geomorphic units created by alternating lateral migration and overbank deposition. However, unlike a floodplain, the surface of an upper deltaic plain consists of poorly drained silt and clay forming a permanent wetland with a very thin veneer of vegetation and organic matter. By contrast, lower deltaic zones have a significantly higher proportion of vertical accretion due to peat formation, as evidenced on other tracts downstream of MWT in the Sacramento-San Joaquin Delta (Atwater, 1980).

**CONCLUSION**

The multi-proxy records from MWT provide insight into the dynamics of an upper deltaic plain in the Sacramento-San Joaquin Delta, California. These records show that 1) coarse-grained sediment accretes vertically more rapidly, has greater sedimentation rates, and higher magnetic susceptibility values compared to fine-grained sediment and this pattern is related to proximity to channel and flood regime; 2) particulate organic matter that washes off hillslopes during winter storms and spring snowmelt is deposited on the floodplain with fine
inorganic sediment during overbank flooding; 3) the persistent fraction of organic matter that survives transport, deposition, and possible diagenesis is 5.5 % of the total sediment mass; 4) two hydrological domains are evident in the MWT cores, coarse-fine fluctuations superimposed on general upward fining; 5) the fine-coarse grain size fluctuations are reflective of spatio-temporal changes in depositional settings as well as variations in flood intensity; 6) the upward fining trend is related to self-limiting overbank deposition and reduced flood-pulse energy slopes associated with post-glacial marine regression; 7) throughout its history, the MWT (and by inference other tracts in the delta) were cross-cut by numerous channels and subjected to frequent flooding; 8) MWT first came under tidal influence at about 2,500 cal BP, 9) floodplain sediment containing >90 % fines should be targeted for pollen extraction; and 10) fire is not a common type of disturbance on the upper deltaic plain though wetland interception of charcoal can lead to charcoal accumulation. In summary, our findings reveal that upper delta plains do indeed have a distant geomorphology from floodplains and lower deltaic regions.

ACKNOWLEDGEMENTS

The authors kindly thank The Seaver Institute, University of California, and CALFED (Ecosystem Restoration Program Co-op Agreement no. 114200J095) for providing funding for this research. Jeff Mount and Ken Verosub were especially helpful, providing thoughtful comments and insight into the delta region. In addition, J. Mount kindly contributed considerable financial resource for analytical equipment used in this investigation and K. Verosub graciously permitted access to his magnetics laboratory and use of his equipment. We would also like to thank Roger Byrne, Robert Zierenberg, Mike Singer, Gary Weissmann, and Jim Clark for their thoughts and comments. We thank The Nature Conservancy for access to
their land, help in field logistics, and partnership in research, outreach, and education. We are grateful to Ellen Mantalica, Kaylene Keller, Derek Sappington, Mike Bezemek, Laurel Aroner, Wendy Trowbridge, Jim MacIntyre, Jose Constantine, and the numerous other volunteers for their assistance. Finally, we sincerely thank two anonymous reviewers who provided thorough and constructive comments that improved the manuscript.
REFERENCES


*Geomorphology* **44**: 67-94.


Table 1. AMS radiocarbon dates from cores MWT-2, MWT-6, and MWT-8 with 1 standard deviation statistics. The radiocarbon dates were converted into median calendar ages using a calibration program (Stuiver and Reimer, 1993). The median calendar ages were then rounded to the nearest 500-year interval to reflect the precision of the age-depth model.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Site</th>
<th>Material</th>
<th>Depth (cm)</th>
<th>Conventional $^{14}$C date (ybp)</th>
<th>Median Calendar Age (cal BP)</th>
<th>Rounded Age (cal BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta-160022</td>
<td>MWT-2</td>
<td>Organic sediment</td>
<td>420-430</td>
<td>20160±170</td>
<td>23860</td>
<td>24000</td>
</tr>
<tr>
<td>Beta-160023</td>
<td>MWT-2</td>
<td>Organic sediment</td>
<td>1060-1070</td>
<td>12420 ± 90</td>
<td>14670</td>
<td>14500</td>
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<tr>
<td>Beta-160024</td>
<td>MWT-2</td>
<td>Organic sediment</td>
<td>1070-1080</td>
<td>23550 ± 210</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Beta-151650</td>
<td>MWT-2</td>
<td>Organic sediment</td>
<td>1260-1270</td>
<td>40100 ± 1010</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Beta-160025</td>
<td>MWT-6</td>
<td>Organic sediment</td>
<td>370-380</td>
<td>5730 ± 50</td>
<td>6530</td>
<td>6500</td>
</tr>
<tr>
<td>Beta-160026</td>
<td>MWT-6</td>
<td>Organic sediment</td>
<td>690-700</td>
<td>7700 ± 60</td>
<td>8480</td>
<td>8500</td>
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<tr>
<td>Beta-151651</td>
<td>MWT-6</td>
<td>Organic sediment</td>
<td>1290-1300</td>
<td>8630 ± 40</td>
<td>9560</td>
<td>9500</td>
</tr>
<tr>
<td>Beta-160027</td>
<td>MWT-8</td>
<td>Organic sediment</td>
<td>80-90</td>
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<td>665</td>
<td>500</td>
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<tr>
<td>Beta-160028</td>
<td>MWT-8</td>
<td>Peat in peat</td>
<td>540-550</td>
<td>4290 ± 50</td>
<td>4860</td>
<td>5000</td>
</tr>
<tr>
<td>Beta-151652</td>
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<td>Wood in peat</td>
<td>1040-1050</td>
<td>4970 ± 50</td>
<td>5700</td>
<td>5500</td>
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<td>MWT-8</td>
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<td>1210-1220</td>
<td>15890 ± 100</td>
<td>18970</td>
<td>19000</td>
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<tr>
<td>Inferred-1</td>
<td>MWT-2</td>
<td>N/A</td>
<td>367</td>
<td>3100</td>
<td>3340</td>
<td>3500</td>
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<tr>
<td>Inferred-2</td>
<td>MWT-2</td>
<td>N/A</td>
<td>795</td>
<td>7845</td>
<td>8610</td>
<td>8500</td>
</tr>
</tbody>
</table>
Table 2. Core characteristics where LOI = loss on ignition and MS = magnetic susceptibility.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Depth (cm)</th>
<th>Age (Cal BP)</th>
<th>Al (%)</th>
<th>Bulk Density (g/cm³)</th>
<th>LOI</th>
<th>% Fines (x10^-5 SI units)</th>
<th>Pollen</th>
<th>Charcoal (fragments/cm²/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWT2-6</td>
<td>0-100</td>
<td>0-800</td>
<td>3.1</td>
<td>1.7</td>
<td>5.9</td>
<td>94</td>
<td>Absent</td>
<td>0.3</td>
</tr>
<tr>
<td>MWT2-5</td>
<td>100-230</td>
<td>800-2000</td>
<td>2.0</td>
<td>2.2</td>
<td>1.8</td>
<td>59</td>
<td>Absent</td>
<td>0</td>
</tr>
<tr>
<td>MWT2-4</td>
<td>230-430</td>
<td>2000-4000</td>
<td>2.4</td>
<td>2</td>
<td>3.4</td>
<td>77</td>
<td>Absent</td>
<td>0</td>
</tr>
<tr>
<td>MWT2-3</td>
<td>430-1010</td>
<td>4000-13000</td>
<td>1.5</td>
<td>2.1</td>
<td>1.8</td>
<td>34</td>
<td>Absent</td>
<td>0</td>
</tr>
<tr>
<td>MWT2-2</td>
<td>1010-1140</td>
<td>&gt;13000</td>
<td>2.3</td>
<td>2.0</td>
<td>3.6</td>
<td>74</td>
<td>Absent</td>
<td>0</td>
</tr>
<tr>
<td>MWT2-1</td>
<td>1140-1325</td>
<td>&gt;13000</td>
<td>2.4</td>
<td>1.7</td>
<td>4.8</td>
<td>97</td>
<td>Absent</td>
<td>0</td>
</tr>
</tbody>
</table>

MWT6-3c  | 0-140      | 0-3800       | 2.7    | 1.9                  | 8.3 | 94                       | Absent | 0                           |

MWT6-3b  | 140-260    | 3800-5500    | 2.1    | 1.9                  | 4.6 | 63                       | Absent | 0.1                         |

MWT6-3a  | 260-340    | 5500-6200    | 2.8    | 1.8                  | 7.7 | 86                       | Absent | 1.3                         |

MWT6-2h  | 340-520    | 6200-7500    | 1.8    | 2.0                  | 2.7 | 25-69                    | Absent | 0-16                        |

MWT6-2a  | 520-700    | 7500-8500    | 2.8    | 1.9                  | 4.8 | 58-85                    | Absent | 0-12                        |

MWT6-1   | 700-1435   | >8500        | 1.7    | 2.2                  | 2.0 | 11-56                    | Absent | 0-13                        |

MWT8-5   | 0-90       | 0-700        | 3.2    | 1.8                  | 6.4 | 90                       | Absent | 63                         |

MWT8-4   | 90-480     | 700-4100     | 2.7    | 1.7                  | 5.5 | 92                       | Absent | 24                         |

MWT8-3   | 480-850    | 4100-5400    | 3.0    | 1.4                  | 6.1-32.1 | 95                  | Absent | 0.6                         |

MWT8-2   | 850-1125   | 5400-6600    | 1.9    | 2.2                  | 2.0 | 35                       | Absent | 0-54                        |

MWT8-1   | 1125-1220  | >6600        | 1.7    | 2.0                  | 3.9 | 60                       | Absent | 0.4                         |

The values presented are zone averages unless a range is specified.
Figure 1. A) Regional location map showing the location of the study site (star). B) Map of the Sacramento-San Joaquin Delta. The McCormack-Williamson tract is located within box. C) Core locations on the McCormack-Williamson tract.
Figure 2. The Geoprobe coring rig used to collect the sediment cores. Note the duel tubes in the ground (arrow). The outer tube ensures that the coring hole does not collapse and that each coring drive is vertically aligned with the previous drive. The smaller inner tube is attached to the core head.
Figure 3. Radiocarbon ($^{14}$C ybp) and calendar (cal BP) year age-depth models. The star represents the discarded date inversion. The vertical dotted line represents the 5,700 $^{14}$C ybp and 6,500 cal BP mark that is discussed in the text.
Figure 4. Stratigraphically constrained cluster diagrams for A) MWT-2, B) MWT-6, and C) MWT-8. The diagrams have been normalised using the average values from the bottom 1 m. Therefore, a value of 1 reflects average basal conditions, >1 reflects enrichment, and <1 reflects depletion. Differences between the visual lithology and the cluster analysis confirm the utility of the objective approach. The 2 basal dates in MWT-2 are in radiocarbon years whereas all remaining ages are in calendar years. LOI=loss on ignition and MS=magnetic susceptibility.
Figure 5. Trends in vertical accretion and sedimentation through time.
Figure 6. Cross-core relations between fines, vertical accretion, and sedimentation rates.
Figure 7. Percentage fines variation with depth and calendar age. The two hydrological domains in the cores are the coarse-fine fluctuations superimposed on general upward fining. The core names are shown at the bottom of each panel.
Figure 8. Linear relationship between fine sediment (silt and clay) and particulate organic matter (LOI). The top panel contrasts floodplain samples from all cores with wetland and agricultural samples. The bottom shows the relationship for each individual core. Agricultural and wetland samples are not included in the bottom panel.
Figure 9. Scatter diagram of fines versus magnetic susceptibility. The cluster of samples around 200 SI units and >95% fines are from MWT2-1.
Figure 10. Elevation comparison between a sea level curve from San Francisco Bay (Atwater, 1979) and the cores from MWT. Channels juxtaposed to present-day MWT have a 1-1.4 m tidal range. Therefore, core depths that are 1 m or more above sea level represent intervals when the tract was not under tidal influence whereas convergence between the cores and sea-level to within or less than ~1 m imply tidal influence.
Long-term sediment geochemistry and mercury poisoning risk in an upper deltaic plain proposed for tidal wetland restoration.

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Abstract

The geochemical history of an upper deltaic plain proposed for tidal wetland restoration was reconstructed to address basic science and applied environmental restoration questions regarding processes in the uppermost zone of a delta. Specific goals included identification of depositional processes promoting geochemical retention of specific constituents, assessment of remobilization of redox sensitive constituents, and determination of the extent of sediment contamination with key trace elements including Hg, As, Pb, Cu, and Zn. Three 10-15 m long sediment cores already analyzed for their stratigraphic and geomorphic records were subsampled on a 20-cm interval for geochemical analysis involving aqua regia leaching followed by ICP-AES for characterization of 34 elements. All cores showed typical sediment geochemistry behavior in terms of inter-element relations as revealed through regressions and principle components analysis. Organics controlled S-abundance, but that did not in turn affect other elemental abundances. Rather than showing similar stratigraphy and geochemical down-core trends, each core had a unique record. When records were segregated by the broad strata types of basal clay, sand channel, distal floodplain, and agriculturally-impacted surficial horizon, each strata type was found to have a significantly different characteristic geochemical signature across the spectrum of elements. The agriculturally impacted surficial layer in all cores showed high Hg, As, and Pb concentrations. The significance of these findings for restoration is that a restored upper delta condition will result in a spatially complex assemblage of geomorphic units that will defy conventional criteria for “success” in restoration. Also, there appears to be a risk of conversion of total Hg into bio-available forms of Hg that are harmful to organisms.

KEYWORDS: metal accumulation, wetland restoration, delta sedimentation, trace metals
Upper deltaic plains present a unique and challenging environment for assessment of geomorphic, stratigraphic, and geochemical processes. Because of their landscape position in the tidal freshwater zone, they are subjected to a complex array of physical and chemical coastal or estuarine (i.e. receiving basin) as well as watershed (i.e. contributing basin) processes acting over a wide range of human-relevant timescales (Pasternack, 1998). With regard to hydrological and associated processes that occur on hourly to weekly timescales, such systems are commonly dominated by receiving basin dynamics related to tides and/or winds (Pasternack and Hinnov, 2003). These processes are often visible to environmental managers and thus are highly emphasized in planning. On the other hand, contributing basin dynamics, such as land use change, infrequent floods, geomorphic adjustments, and sediment yield, operate on decadal to centennial timescales (Pasternack et al., 2001). These dynamics control the longevity and sustainability of environmental management activities, but their influence can only be discerned through thorough analysis of longer-term records, such as sediment cores, historic maps, or rare long-term datasets.

In general, deltas are often characterized as having a two-fold history comprising a constructional phase followed by a destructional phase (Elliot, 1986). Such phases can be enhanced or switched from one to the other by human activities (Pasternack et al., 2001), confounding prediction of future conditions. Colman (1976) termed the “upper deltaic plain” as the region above significant tidal or marine influence that is dominated by riverine depositional processes. Given this position at the head of a delta, upper deltaic plains may additionally experience a complex combination of non-tidally influenced floodplain processes as well tidally
influenced delta processes. Goodbred and Kuehl (1998) reported that the upper delta plain of the Brahmaputra-Ganges system included significant areas of inactive floodplain that were isolated by channel avulsion.

In terms of geochemistry, deltas may act as sinks or sources for rock-derived constituents and human-generated pollutants, depending on hydrogeomorphic processes at work. Accumulation and retention can occur by both sediment deposition and solute transport. The former encompasses input and burial of metals already incorporated into or onto fine inorganic and organic particles (Warren, 1981; Olsen et al., 1982; Olsenholler, 1991). Along urbanized coasts, direct urban runoff and tidally redistributed urban pollution can significantly contribute to metal accumulation in deltaic soils (Velinski et al., 1994; Knight and Pasternack, 2000). Solute transport mechanisms, on the other hand, involve adsorption of metals onto soil and decomposing plant litter (Millward and Moore, 1982; Simpson et al., 1983a; Simpson et al., 1983b, Orson et al., 1992), downward migration of free metals into sedimentary strata (Simpson et al., 1983b; Dubinski et al., 1986), and plant uptake (Sculthorpe, 1967; Banus et al., 1975; Dowdy and Larson, 1975). Conversely, erosion and export can occur by wind-wave attack (Pasternack, 1998), overbank flooding and scouring of the delta plain as occurs on floodplains (Florsheim and Mount, 2003), and by channel incision. Solute-based losses can occur over longer periods of time via diagenesis and re-mobilization of easily dissolved constituents (Hudson-Edwards et al., 1998).

In this study, the long-term complex and coupled geomorphic and geochemical dynamics that may be occurring in an upper deltaic plain were uncovered and investigated through interdisciplinary analysis of long (10-15 m) sediment cores. Specific questions that were asked included a) what are depositional processes promoting geochemical retention of specific
constituents?, b) Is there any evidence that of large-scale remobilization of redox sensitive chemical constituents over centuries to millennia?, and c) to what extent does the upper deltaic plain play a role in trapping and retaining rock-derived and human-generated elemental pollutants, specifically Hg, As, Pb, Cu, and Zn?

STUDY AREA

The Sacramento-San Joaquin Delta is a 299,000 ha inland tidal delta located east of San Francisco Bay in central California with an ~107,000 km$^2$ drainage basin (Fig. 1). According to the classification of Galloway (1975), the delta is dominated by sediment input, with an annual outflow of ~19 billion m$^3$ of water and suspended sediment annual inflow and outflow of ~4.7 and ~3.3 million metric tons, respectively (Conomos and Peterson, 1976). The lower delta plain shows some morphological influence of winds and mixed tides. Monthly mean wind speed ranges from 2-5 m s$^{-1}$ with peak monthly gusts averaging 15-21 m s$^{-1}$ (Conomos and Peterson, 1976). The primary wind direction is west to east. The summer tidal range at the delta front is ~1.4 m and that in upper delta distributary channels is ~1.0 m. The delta has a rejoining distributary channel pattern (sensu Colman, 1976) because of the erratic discharges and high tidal range. Since the mid 19th century, 73 % of the delta’s area has been converted to agriculture necessitating 1,800 km of levees (Logan, 1990).

The Sacramento-San Joaquin Delta has been subjected to an extremely high influx of Hg as a result of Hg mining in the Coastal Range northwest of the delta supplying Hg directly through streams such as Cache Creek and through its translocation and use in gold mining in the Sierra Nevada northeast, east, and southeast of the delta. Many studies have been performed to
characterize Hg in organisms (e.g. Choi et al., 1998; Cain et al., 2000), water (e.g. Choe et al., 2003), and sediment (e.g. Domagalski, 1998, 2001). For reference in this study, total Hg concentrations in Sacramento basin river bed material is 50-400 ppb whereas in Sacramento Valley sloughs it is 30-90 ppb (Domagalski, 2001). Of these totals, anywhere from 0-8% tends to be reactive in reducing conditions and thus change into a toxic form (Domagalski, 2001).

The McCormack-Williamson Tract (MWT) is uniquely located at the head of the delta downstream from the confluence of the Cosumnes and Mokelumne rivers and adjacent to the Sacramento River (Fig. 1). The Cosumnes River is the only major river flowing out of the Sierra Nevada whose mainstem is undammed. MWT is ~650 ha in area and is bordered by the Mokelumne River to the east, Snodgrass Slough to the west, and artificial dredge channels to the north and northeast. Historic maps show that MWT supported freshwater wetland in the early 20th century (United States Geological Survey, 1911). The wetland was likely tidal, as the adjacent channels are presently tidal for several miles upstream. Subsequently, the tract was leveed, drained, and converted into agricultural land. After drainage, MWT and other delta islands experienced subsidence as surface organic sediment was oxidized and decomposed (Rojstaczer et al., 1991). The little riparian vegetation that exists at MWT is largely located along the levees.

The general climate in the MWT region is Mediterranean, with cool, wet winters and hot, dry summers. Climate normals for the years 1961-1990 from Lodi, a town located ~15 km southeast of MWT, record an average minimum temperature of 2.3 °C in December and an average maximum temperature of 33 °C in July. Monthly precipitation varies from an average of 1.8 mm in July to 80.8 mm in January. Annual precipitation averages 434 mm. A cool "delta breeze" typically blows inland from the estuary during the summer, cooling nighttime
temperatures. Winter precipitation is predominately rain, though in the high Sierra Nevada the main form of precipitation is snow. In the spring, snowmelt is retained in reservoirs for summer use, though historically it created widespread lowland flooding.

METHODS

Core Retrieval and Processing

To characterize the paleo geochemical conditions on MWT, three long sediment cores (MWT-2, MWT-6, and MWT-8) were collected along the longitudinal axis of the tract (Fig. 1). MWT-2 is located near the southern tip where the elevation is -30 cm relative to the NGVD (1929 National Geodetic Vertical Datum) mean sea level position. MWT-6 is centrally located on MWT and is +30 cm NGVD. MWT-8 is located in the northwest section of MWT and is also +30 cm NGVD.

The cores were collected incrementally using a Geoprobe drilling rig with direct push and dual-tube sampling technology that enables the cores to be recovered in 1.22-m plastic liners. Sediment compaction or expansion during coring was measured on a section-by-section basis as the difference between pushed distance and actual core length. Core sections were stored in a refrigerated room at ~4 °C. Core liners were first cut lengthwise using a circular saw on opposite sides and then a nylon string was passed down through the core sediment to yield two halves. Any smeared sediment was carefully scrapped off the exposed sediment surface in a horizontal fashion using a plastic spatula. Subsequently, core lithologies were visually described and cores were subsampled in 10-cm intervals. Subsamples were placed in labeled plastic bags for cold storage and later analyses.
Quantitative stratigraphic analyses at 10-cm resolution and AMS radiocarbon dating of the sediment cores were performed and are detailed elsewhere (Brown and Pasternack, in prep). Sediment characteristics such as bulk density, grain size distributions, loss-on-ignition (LOI), and magnetic susceptibility were measured for all core subsamples. Non-linear radiocarbon and calendar year age-depth models were developed by fitting a locally weighted function to the reported dates. Vertical accretion (cm yr\(^{-1}\)), sedimentation rates (g cm\(^{-2}\) yr\(^{-1}\)), and chemical loadings (mg cm\(^{-2}\) yr\(^{-1}\)) were determined using the calendar age-depth model.

Chemical Analysis

Determination of the total elemental concentrations of every other sample (i.e. 20-cm resolution) was carried out by Chemex Labs, Inc of Sparks, Nevada. The procedure involved drying the samples and sieving them through a #80 mesh to obtain the fraction smaller than 0.177 mm in diameter, treating them with hot concentrated nitric acid to destroy organic matter and oxidize sulfide material, and adding concentrated hydrochloric acid (3 times the volume of the nitric acid) to generate the aqua regia (3 HCl + HNO3 = 2 H2O + NOCl + Cl2) which was used to digest the material. After digestion sample solutions were analyzed by inductively-coupled argon plasma and atomic emission spectroscopy to obtain the concentrations of 34 elements (Ag, Al, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, Hg, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Sr, Ti, Tl, U, V, W, Zn). Because of the importance of Hg in this study, an additional analysis of Hg was done by cold volatilization atomic adsorption spectroscopy (detection limit 10 ppb).

Because sediment digestion was "total" for most base metals but only "partial" for most major and minor elements, a reference soil sample (San Joaquin Soil Standard Reference
Material 2709) from the National Institute of Standards and Technology was also analyzed using the same procedure. The difference between the measured and known element concentrations for the reference standard was the non-leachable fraction. Because the reference material came from a field close to the study site, its texture, composition, and thus leachable fraction should be very similar to those for samples from the sediment cores. Other than Al, elements showing very poor leaching (< 50%) were excluded from further analysis. Since leaching was only done on fine material, Al should be locked in the mineral structure and hence stable throughout the leaching process. However, samples inevitably experience differential leaching. To account for this artifact, binary correlations between Al and all other elements were computed. Concentrations of all elements showing a strong relation with Al were normalized by the concentration of Al to remove the effect of leaching. This is viewed as superior to simple correction using the leaching percentages from the NIST reference, because the overall composition may vary substantially from sample to sample and the Al correction accounts for this variation whereas the NIST leaching percentages do not.

Chemical analyses were performed on dried samples that still contained organic material. Because organic content strongly relates to fine sediment content and the latter also relates to degree of leaching, it might have been difficult to distinguish whether changes in concentration down-core are due to binding to organic matter or differential leaching, in general. However, based on the quantitative stratigraphic study (Brown and Pasternack, in prep), the organic content of core strata fell into two categories— an organic wash load fraction composing 0-7% of the total sediment and an organic, peat-like fraction composing 10-30% of the total sediment. Because significant amounts of binding would be limited to the much higher content of peat-like strata, organic binding was assessed by observing any significant increase in elemental
concentration in peat layers relative to non-peat layers. Elements showing no peak in concentration in peat strata were assumed to stem from the inorganic fraction, so their concentrations were adjusted to an organic-free basis.

Data Analysis

Chemical compositions were analyzed to assess inter-elemental sediment geochemistry, down-core strata-averaged trends in concentrations, and cross-core geochemical patterns. Standard approaches were used investigate inter-elemental sediment geochemistry. A binary correlation matrix was computed for each core to check for high correlations among elements indicative of binding onto organic content, carbonates, Mn-oxides, and Fe-oxides. Principal components analysis (PCA) was also used to segregate variables into groups according to their related chemical functionality for two datasets: a) raw concentrations for all elements and b) a mix of raw concentrations and Al-normalized concentration where the latter was deemed necessary. The results of PCA include percent of variation explained, communalities, loadings, and rotated loadings (using the 'varimax normalized approach').

Down-core trends were examined to assess the relation between geomorphic units and geochemistry. To do this, the objectively defined strata zonation of Brown and Pasternack (in prep) based on a cluster analysis of LOI, fine sediment percentage, magnetic susceptibility, and relative Al abundance was used to divide the core into distinct units. The average concentration or al-normalized concentration of well-leached constituents was calculated. Finally, these values were sorted in order of abundance and plotted, with a line for each strata.

Cross-core comparisons to assess the spatial pattern of the observed geochemistry were done using two methods. First, cross-core strata-averaged abundances were computed for each
strata type to test the hypothesis that spatial patterns in chemistry more strongly reflect strata type than absolute depth. Second, as a basis for comparison to the strata-averaged cross-core patterns, elemental abundances were considered as a function of depth/time by plotting selected elements for all three cores as a function of time/depth on a single plot to assess temporal cross-correlations independent of stratigraphy.

Plots were assessed for peaks indicative of key events or long-term trends related to climate variation, human activities, or landform changes. Selective elements were plotted as a function of time for all three cores on a single plot to assess cross-core patterns. Concentrations associated with distinct geomorphic units were calculated and compared across units.

RESULTS

Based on the NIST reference sediment from a nearby field, many elements showed excellent recoveries (Table 1). The only important elements that were very poorly leached were Na and K. Ag was the only element significantly overestimated, likely because it was near the detection limit, so it was excluded from further analysis. Sr, Ba and Cr did not leach well, but were further investigated to some extent using caution. Recoveries of Cu and Zn were notably better than previous studies (e.g. Velinski et al., 1999; Knight and Pasternack, 2000).

Inter-element Sediment Geochemistry

Aluminum was found to behave as a master variable controlling the first-order variations in several elements due to the differential leaching, as expected. Al concentrations closely tracked fine sediment content for all cores (Figs. 2). Even though samples were sieved to
exclude coarse sediment prior to chemical digestion, this trend suggests that some of the differences in metal extraction could be due to grain size variations at the sub-177 μm level. When elements were plotted against aluminum, Fe, Ca, Mg, Cu, and Zn showed a strong direct linear response to Al for all cores (Fig. 3-5). Table 2 shows the R²-values for all elements, with any value above 0.26 statistically significant above the 95% confidence level. Key elements that were not influenced by Al were Mn, S, P, Hg, Pb, and As. Ni and Co showed a mixed response and were investigated with and without normalization.

Al-normalized elements were compared against each other using a correlation matrix and binary regressions. No consistent evidence for Fe-oxide or carbonate binding of Mg, Cu, or Zn was evident (Table 3; Fig. 6). MWT-6 showed a strong role for Fe-oxide binding (Fig. 6c,d), but MWT-2 and MWT-8 did not. One interesting result was that the Zn/Cu ratios for the cores were 1.55, 2, and 1.65 for MWT-2, MWT-6, and MWT-8, respectively. These ratios are much lower than that commonly observed in wetlands (~4). The difference appears to be due to higher than normal Cu and slightly lower Zn. These ratios occur throughout all core depths.

MWT-8 was the only core containing peat-like layers with plant fragments and organic content >10%. When the concentration or Al-normalized concentration of each element present in peat-like strata was averaged and compared against the inorganics-dominated strata average, only S showed a significant difference. The average S concentration in peat-like layers was 0.23 % whereas that in inorganic-dominated strata was 0.04 %. This high presence of S suggests a reducing redox state that might affect the remobilization of elements. However, no other elements show significant deviations in the peat-like strata relative to the inorganic-dominated layers.
Principal components analysis (PCA) of the well-leached elemental concentrations for all cores confirmed the dominant role of Al concentration in controlling down-core geochemical variability. For MWT-2 and MWT-6, half of the elements are predominantly explained by a single component, which relates to Al, confirming the need for normalization (Table 4). Other components do not account for much more than a single variable. When PCA was performed on the Al-normalized data to eliminate this effect, the cores show some role for Fe and Mn binding, but nothing consistent between cores (Table 5).

Down-core Strata-Averaged Trends

Table 6 summarizes the distinct sequence of strata for each core, as described by Brown and Pasternack (in prep). When abundances of chemical constituents were averaged for each strata, down-core differences were found to be strongly related with the type of strata rather than absolute depth. This strong chemical stratification points to limited remobilization of elements, in addition to the evidence to this effect already described.

For MWT-2, the basal Pleistocene grey clay has a very distinct geochemical signature. Even though its organic content is normal, it has an extremely high concentration of S (3.1 ppt), whereas other strata in MWT-2 have no detectible S. Associated with this S is a suite of higher concentration constituents, including Mn, Mg, Hg, Cu, Zn, and Ni. The origin of this layer is unknown and the radiocarbon date for it is beyond the calibrated domain, but it is possible that future isotopic analysis of S could reveal whether there was a marine component involved. The major sand channel unit in this core is notable for its relatively low abundance of Hg but high abundance of As. Distal floodplain fines show an intermediate abundance of constituents. The
The surficial layer has experienced mixing due to agricultural plowing and it shows the highest abundance of LOI, Al, Hg and Pb as well as the lowest abundance of Fe, Mg, and Ni.

Core MWT-6 has alternating sand channel and distal floodplain strata. Many chemical constituents in this core show little difference among strata, including Al, Fe, Mg, S, Cu, Zn, Ni, and Co. The basal unit is a thick sand channel deposit that has relatively low LOI and Mn. Sand channel units show lower LOI, Al, Mn, and As relative to the distal floodplain strata. Conversely, they show higher Fe and associated magnetic susceptibility. Once again the agriculturally impacted surface layer shows significant enrichment in LOI and Hg as well as low abundance of Fe, Mg, and Ni.

Core MWT-8 is stratigraphically quite distinct from MWT-2 and MWT-6 in that it is predominantly fine sediment and appears to have been tidally influenced for much longer, based on its age-depth model and the regional Atwater sea-level rise curve. The basal clay unit in this core may be Holocene or Pleistocene, but in this case there is no enrichment in S. The basal layer is enriched in Ni, Fe, Mg, and Ca. It has a low abundance of Al, P, and As. The only sand unit in this core shows no particular enrichment, but has a low abundance of LOI and Hg. An organic-rich wetland strata in the middle of the core that dates to 4100-5400 is very high in LOI (up to 32 %) and S (2.1 ppt). The surficial agricultural horizon is very highly enriched in Hg as well as P, Mn, and As.

Cross-core Geochemical Patterns

Cross-core strata-averaged abundances of elements show highly distinct signatures for the four broad classes of strata (Fig. 8). Basal clays are high in S and associated metals that precipitate in a reducing redox condition, including Fe, Mg, Ca, Zn, Cu, Ni. Sand channel units
are relatively low in all chemical constituents except for Fe and As. The agriculturally impacted surface layer in all cores is highly enriched in Hg, As, Co, and somewhat enriched in Pb and Al. It has the lowest abundance in Fe, Mg, and Ca. Distal floodplain units are intermediate in all constituent abundances.

Elemental abundances plotted as a function of time confirm that the cores show very little synchronous geochemical fluctuation (Fig. 9). The only elements whose abundances do change among all cores at least in some periods are Hg, P, and As. In the case of Hg, all cores show a dramatic increase in concentration from below 50 ppb to greater than 200 ppb. MWT-8 peaks at 438 ppb. These peaks coincide with the surficial agriculturally-disturbed layer, which ranges in depth from 30 cm in MWT-2 to 120 cm in MWT-8. *Because of the mixing, the associated age of the sediment is not correct and should not be used to suggest that the increase in Hg pre-dates human activity.* According to the history recorded in the cores, Hg was at least 3 times lower throughout the past relative to its present concentration. In the case of P, all cores show a relative abundance in the agriculturally impacted surficial layer. MWT-6 has very high abundances of P in distal floodplain fine sediments dating to 7000-8000 years ago as well as Ca during that period. Arsenic is generally not detected throughout much of the cores, but there are some notable concentrations in the agricultural horizon and in ancient sand channel units. All cores show an uptick in the agricultural horizon. MWT-2 shows two peaks in sand channel units and MWT-6 shows a peak in one sand channel unit.

Other elements do show temporal fluctuations, and some of these clearly respond to stratigraphic controls, but others are difficult to explain at this time (Fig. 9). For example, MWT-8 shows very high concentrations of S in peat-like layers mid-core. Also, Mg shows a
distinct drop in MWT-2 and MWT-8 in the tops of these cores. On the other hand, Cu and Zn show frequent fluctuations that do not reflect stratigraphy.

DISCUSSION AND CONCLUSION

The three MWT cores analyzed in detail in this study largely show the typical bulk geochemical interrelationships that are well known. The cost of total sediment digestion or incremental digestion could not be afforded, but careful assessment and adjustment for partial leaching effects was highly successful and enabled the comparison of different elements. Aluminum and grain distribution were found to act as master variables controlling the first order dynamics in the cores.

All cores were found to have low organic content and thus show little trapping of constituents in reducing redox strata. The only peat-like deposits found occurred in MWT-8 and they dated to 4000-5000 years old. These layers were highly enriched in S and thus were very likely reducing in their redox. However, no other elements show significant deviations in the peat-like strata relative to the inorganic-dominated layers. This is strong evidence that the sediments have experienced little mobilization and re-deposition of constituents in the last 4000 years. Thus, the geochemistry of core strata are largely intact, so observed signatures can be confidently attributed to their original condition.

Unlike what is commonly seen in wetland cores, the MWT cores show extremely different geomorphic and geochemical conditions at any given time from core to core. In the cores, deposits of the same type are almost never synchronous. Thus, geochemistry should be understood in terms of strata-averaged conditions with a comparison of geochemistry within and between strata types. The MWT cores show much less within strata than between strata
variation in geochemistry. Almost all elements show a preference for one strata type or another, as detailed earlier.

Pleistocene deposits dating to more than 10,000 years ago take the form of either chemically-enriched clays or sand channel units. For the last 10,000 years (i.e. the Holocene), MWT has been an alluvial floodplain. Major channels cut across the floodplain producing two endmember stratigraphic units- sand channel units and distal floodplain fine units. These units are chemically distinct, with the channels relatively low in Hg, Al, S, and LOI and high in Fe, As, and Ni. Each core shows an independent sequence of channels and distal floodplains, with each unit representing ~1000-2000 years. Because of this differential in local geomorphic process, the elevation and thus position relative to sea level of each core is very different.

MWT-8 was at sea level 6000-8000 years ago and S-enriched (~2.3 ppt) wetlands formed at that time. MWT-6 has been well above sea level until very recently. It has alternating sand and fine units with lower abundances of some elements in the sands and lower abundances of other elements in the fines. MWT-2 is intermediate between MWT-6 and MWT-8 in its elevation, but also shows channel-distal floodplain banding and the associate geochemistry.

The one thing that all cores have in common without any doubt is elevated Hg and As in the agriculturally impacted surface layer. Because of plowing, the last 2000 years of sediment record has been totally jumbled up, so the age-depth model cannot be applied in this zone. Corn pollen- a distinct signature of agriculture that was not present before human agriculture in this area- is present throughout this zone, and proves that the observed peaks in the toxic elements Hg and As does not pre-date human intervention in the system. This is not to say that the Hg derives from agriculture, but that it derives at the same time since agriculture has been occurring. The total abundance of Hg of ~200-400 ppb is significantly higher than that reported for
Sacramento Valley sloughs, and is on the high side relative the Sacramento basin river stream bed sediment (Domagalski, 2001). This suggests that under reducing conditions that result from wetland restoration there would be a potential reactively available concentration of up to 32 ppb, which poses a significant bioaccumulation hazard. It would take further research, perhaps incubation of wetland conditions using surficial sediment samples in a lab setting to know for sure.

ACKNOWLEDGEMENTS

The authors kindly thank The Seaver Institute, University of California, and CALFED (Ecosystem Restoration Program Co-op Agreement no. 114200J095) for providing funding for this research. We would like to thank Jeff Mount, Ken Verosub, Robert Zierenberg, Mike Singer, and Gary Weissmann for their discussions, comments, and resources. We thank The Nature Conservancy for access to their land, help in field logistics, and partnership in research, outreach, and education. We are grateful to Ellen Mantalica, Kaylene Keller, Derek Sappington, Mike Bezemek, Laurel Aroner, Wendy Trowbridge, Jim MacIntyre, Jose Constantine, and the numerous other volunteers for their assistance.

REFERENCES


*Geomorphology* **44**: 67-94.


*Sedimentary Geology* **121**: 239-258.


Warren LJ. 1981. Contamination of sediments by lead, zinc, and cadmium; a review. *Environmental Pollution* (Series B) 2:401-436.
Table 1. Differentiation of elements that were poorly leached (<50%).

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<th>Leach (%)</th>
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Table 2. $R^2$-values for correlation of each element against Al. Values >0.26 exceed the 95% confidence level. Shaded values >0.5.

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<th>MWT-6</th>
<th>MWT-8</th>
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<tr>
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<td>0.11</td>
</tr>
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<tr>
<td>Mg</td>
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</tr>
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<td>0.01</td>
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<td>Ni</td>
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Table 3. Correlation matrix ($R^2$) for Al-normalized elements

A) MWT-2

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<tr>
<th></th>
<th>Fe</th>
<th>Ca</th>
<th>Mg</th>
<th>Cu</th>
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<td>X</td>
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B) MWT-6

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<td>X</td>
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</tr>
<tr>
<td>Zn</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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C) MWT-8

<table>
<thead>
<tr>
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<th>Fe</th>
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<th>Mg</th>
<th>Cu</th>
<th>Zn</th>
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<tbody>
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<td>Fe</td>
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<td>Ca</td>
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<td>Mg</td>
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<td>X</td>
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<td>Cu</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Zn</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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Table 4. Principle Components determined using raw concentrations of all well-leached elements. Shading indicates elements that are strongly controlled by the associated component.

### A) MWT-2

<table>
<thead>
<tr>
<th>Variable</th>
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<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.741</td>
<td>0.018</td>
<td>-0.262</td>
<td>0.432</td>
<td>0.016</td>
</tr>
<tr>
<td>Fe</td>
<td>0.884</td>
<td>-0.124</td>
<td>0.181</td>
<td>0.115</td>
<td>0.046</td>
</tr>
<tr>
<td>Ca</td>
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<td>-0.005</td>
<td>0.256</td>
<td>0.077</td>
<td>0.123</td>
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<tr>
<td>Mg</td>
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<td>0.078</td>
<td>-0.054</td>
<td>-0.131</td>
<td>0.009</td>
</tr>
<tr>
<td>Mn</td>
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<td>0.099</td>
<td>0.906</td>
<td>-0.059</td>
<td>0.019</td>
</tr>
<tr>
<td>S</td>
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<td>-0.458</td>
<td>0.112</td>
<td>-0.307</td>
<td>0.265</td>
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<tr>
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<td>0.352</td>
<td>0.588</td>
<td>0.009</td>
</tr>
<tr>
<td>Cu</td>
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<td>0.056</td>
<td>-0.008</td>
<td>0.212</td>
<td>0.046</td>
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<tr>
<td>Zn</td>
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<tr>
<td>Hg</td>
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<td>0.196</td>
<td>-0.097</td>
<td>0.878</td>
<td>0.033</td>
</tr>
<tr>
<td>Pb</td>
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<td>0.010</td>
<td>0.014</td>
<td>-0.037</td>
<td>-0.063</td>
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<tr>
<td>As</td>
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<td>-0.884</td>
<td>-0.196</td>
<td>-0.157</td>
<td>0.014</td>
</tr>
<tr>
<td>Co</td>
<td>0.212</td>
<td>-0.620</td>
<td>0.536</td>
<td>0.138</td>
<td>-0.119</td>
</tr>
<tr>
<td>Ni</td>
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<td>-0.161</td>
<td>0.249</td>
<td>-0.023</td>
<td>0.008</td>
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<tr>
<td>Prp.Totl</td>
<td>0.415</td>
<td>0.108</td>
<td>0.109</td>
<td>0.113</td>
<td>0.074</td>
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### B) MWT-6

<table>
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<th>PC3</th>
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<tbody>
<tr>
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<tr>
<td>Fe</td>
<td>0.841</td>
<td>0.145</td>
<td>0.168</td>
</tr>
<tr>
<td>Ca</td>
<td>0.638</td>
<td>0.397</td>
<td>0.202</td>
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<tr>
<td>Mg</td>
<td>0.867</td>
<td>0.230</td>
<td>0.162</td>
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<td>Mn</td>
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<td>0.460</td>
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<tr>
<td>Cu</td>
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<tr>
<td>Zn</td>
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<tr>
<td>Hg</td>
<td>-0.140</td>
<td>0.351</td>
<td>-0.806</td>
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<tr>
<td>Pb</td>
<td>-0.305</td>
<td>0.545</td>
<td>-0.079</td>
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<tr>
<td>As</td>
<td>0.100</td>
<td>0.417</td>
<td>0.692</td>
</tr>
<tr>
<td>Co</td>
<td>0.780</td>
<td>-0.024</td>
<td>0.029</td>
</tr>
<tr>
<td>Ni</td>
<td>0.913</td>
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<td>0.030</td>
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<tr>
<td>Prp.Totl</td>
<td>0.470</td>
<td>0.138</td>
<td>0.095</td>
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### C) MWT-8

<table>
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<tr>
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<th>PC1</th>
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<th>PC3</th>
<th>PC4</th>
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<tbody>
<tr>
<td>Al</td>
<td>0.508</td>
<td>0.313</td>
<td>0.657</td>
<td>0.239</td>
</tr>
<tr>
<td>Fe</td>
<td>0.129</td>
<td>0.905</td>
<td>-0.019</td>
<td>-0.024</td>
</tr>
<tr>
<td>Ca</td>
<td>0.378</td>
<td>0.143</td>
<td>0.739</td>
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</tr>
<tr>
<td>Mg</td>
<td>0.903</td>
<td>0.140</td>
<td>0.129</td>
<td>-0.120</td>
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<tr>
<td>Mn</td>
<td>0.071</td>
<td>0.666</td>
<td>0.690</td>
<td>0.024</td>
</tr>
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<td>S</td>
<td>0.104</td>
<td>0.318</td>
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<td>-0.725</td>
</tr>
<tr>
<td>P</td>
<td>0.054</td>
<td>0.797</td>
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<td>0.551</td>
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<tr>
<td>Hg</td>
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<td>0.651</td>
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<tr>
<td>Pb</td>
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<td>0.862</td>
<td>0.087</td>
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<td>-0.830</td>
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<tr>
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<td>0.027</td>
<td>0.341</td>
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<td>Ni</td>
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<td>0.037</td>
</tr>
<tr>
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<td>0.238</td>
<td>0.187</td>
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Table 5. Principle Components determined using raw or Al-normalized concentrations as indicated. Shading indicates elements that are strongly controlled by the associated component.

### A) MWT-2

<table>
<thead>
<tr>
<th>Variable</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
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<tbody>
<tr>
<td>Al</td>
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<td>-0.124</td>
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<td>0.035</td>
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<tr>
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<td>-0.241</td>
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<td>0.159</td>
</tr>
<tr>
<td>P</td>
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<td>0.066</td>
<td>0.007</td>
<td>0.104</td>
</tr>
<tr>
<td>Hg</td>
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<td>0.524</td>
<td>-0.450</td>
<td>-0.403</td>
<td>0.039</td>
</tr>
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<td>-0.015</td>
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<td>-0.093</td>
<td>-0.120</td>
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<td>Fe/Al</td>
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<td>0.399</td>
<td>0.035</td>
<td>0.000</td>
</tr>
<tr>
<td>Ca/Al</td>
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<td>-0.124</td>
<td>0.100</td>
</tr>
<tr>
<td>Mg/Al</td>
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</tr>
<tr>
<td>Mn</td>
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<tr>
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<td>0.669</td>
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<td>0.013</td>
</tr>
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<td>Zn/Al</td>
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</tr>
<tr>
<td>Co/Al</td>
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<td>0.603</td>
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<td>Prp.Totl</td>
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<td>0.201</td>
<td>0.195</td>
<td>0.096</td>
<td>0.070</td>
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</table>

### B) MWT-6

<table>
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<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
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<tbody>
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<td>Al</td>
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<td>S</td>
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<td>0.133</td>
<td>0.091</td>
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<td>-0.180</td>
</tr>
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<td>Pb</td>
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<td>-0.204</td>
<td>-0.551</td>
<td>0.581</td>
</tr>
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<td>0.731</td>
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<td>Fe/Al</td>
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</tr>
<tr>
<td>Mn</td>
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<td>0.046</td>
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</tr>
<tr>
<td>Cu/Al</td>
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<td>Zn/Al</td>
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<td>-0.527</td>
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<tr>
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### C) MWT-8

<table>
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<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
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<td>0.152</td>
<td>-0.061</td>
<td>0.257</td>
<td>0.801</td>
</tr>
<tr>
<td>P</td>
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<td>0.047</td>
<td>0.859</td>
<td>0.195</td>
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<td>Mg/Al</td>
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</tr>
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<td>Zn/Al</td>
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<td>0.231</td>
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<td>Co/Al</td>
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<td>-0.101</td>
<td>-0.137</td>
<td>-0.307</td>
</tr>
<tr>
<td>Ni/Al</td>
<td>0.090</td>
<td>0.930</td>
<td>-0.185</td>
<td>0.063</td>
<td>-0.099</td>
</tr>
<tr>
<td>Prp.Totl</td>
<td>0.238</td>
<td>0.192</td>
<td>0.158</td>
<td>0.133</td>
<td>0.088</td>
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</table>
Table 6. Strata present in the MWT cores (based on Brown and Pasternack, in prep).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Depth (cm)</th>
<th>Age (Cal BP)</th>
<th>Vertical accretion rate (cm/yr)</th>
<th>Al (%)</th>
<th>Bulk Density (g/cm³)</th>
<th>LOI</th>
<th>% Fines</th>
<th>Magnetic Susceptibility (x10⁻⁵ SI units)</th>
<th>Charcoal (fragments/cm²/yr)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWT2-6</td>
<td>0-100</td>
<td>0-800</td>
<td>0.12</td>
<td>3.1</td>
<td>1.7</td>
<td>5.9</td>
<td>94</td>
<td>16</td>
<td>0.3</td>
<td>Ag-impacted, tidally-influenced upper deltaic plain</td>
</tr>
<tr>
<td>MWT2-5</td>
<td>100-230</td>
<td>800-2000</td>
<td>0.11</td>
<td>2</td>
<td>2.2</td>
<td>1.8</td>
<td>59</td>
<td>86</td>
<td>0.0</td>
<td>Tidally-influenced transitional floodplain/delta with sand and fines</td>
</tr>
<tr>
<td>MWT2-4</td>
<td>230-430</td>
<td>2000-4000</td>
<td>0.10</td>
<td>2.4</td>
<td>2</td>
<td>3.4</td>
<td>77</td>
<td>53</td>
<td>0.0</td>
<td>Distal floodplain with fines</td>
</tr>
<tr>
<td>MWT2-3</td>
<td>430-1010</td>
<td>4000-13000</td>
<td>0.07</td>
<td>1.5</td>
<td>2.1</td>
<td>1.8</td>
<td>34</td>
<td>54</td>
<td>0.0</td>
<td>Sand channel unit with intermittent fines</td>
</tr>
<tr>
<td>MWT2-2</td>
<td>1010-1140</td>
<td>&gt;13000</td>
<td>0.03</td>
<td>2.3</td>
<td>2</td>
<td>3.6</td>
<td>74</td>
<td>63</td>
<td>0.0</td>
<td>Pleistocene bands of green clay and silt</td>
</tr>
<tr>
<td>MWT2-1</td>
<td>1140-1325</td>
<td>&gt;13000</td>
<td>n/a</td>
<td>2.4</td>
<td>1.7</td>
<td>4.8</td>
<td>97</td>
<td>178</td>
<td>0.0</td>
<td>Pleistocene grey clay</td>
</tr>
<tr>
<td>MWT6-3c</td>
<td>0-140</td>
<td>0-3800</td>
<td>0.04</td>
<td>2.7</td>
<td>1.9</td>
<td>8.3</td>
<td>94</td>
<td>15</td>
<td>0.0</td>
<td>Distal floodplain with fines; only tidally-influenced in most recent period</td>
</tr>
<tr>
<td>MWT6-3b</td>
<td>140-260</td>
<td>3800-5500</td>
<td>0.07</td>
<td>2.1</td>
<td>1.9</td>
<td>4.6</td>
<td>63</td>
<td>15</td>
<td>0.1</td>
<td>Sand channel/bank unit</td>
</tr>
<tr>
<td>MWT6-3a</td>
<td>260-340</td>
<td>5500-6200</td>
<td>0.11</td>
<td>2.8</td>
<td>1.8</td>
<td>7.7</td>
<td>86</td>
<td>20</td>
<td>1.3</td>
<td>Distal floodplain with fines</td>
</tr>
<tr>
<td>MWT6-2b</td>
<td>340-520</td>
<td>6200-7500</td>
<td>0.14</td>
<td>1.8</td>
<td>2</td>
<td>2.7</td>
<td>25-69</td>
<td>152</td>
<td>0-16</td>
<td>Sand channel unit</td>
</tr>
<tr>
<td>MWT6-2a</td>
<td>520-700</td>
<td>7500-8500</td>
<td>0.21</td>
<td>2.8</td>
<td>1.9</td>
<td>4.8</td>
<td>58-85</td>
<td>152</td>
<td>0-1.2</td>
<td>Distal floodplain with fines</td>
</tr>
<tr>
<td>MWT6-1</td>
<td>700-1435</td>
<td>&gt;8500</td>
<td>0.53</td>
<td>1.7</td>
<td>2.2</td>
<td>2</td>
<td>11-56</td>
<td>190-580</td>
<td>0-13</td>
<td>Sand channel unit</td>
</tr>
<tr>
<td>MWT8-5</td>
<td>0-90</td>
<td>0-700</td>
<td>0.12</td>
<td>3.2</td>
<td>1.8</td>
<td>6.4</td>
<td>90</td>
<td>63</td>
<td>1.0</td>
<td>Ag-impacted, tidally-influenced upper deltaic plain</td>
</tr>
<tr>
<td>MWT8-4</td>
<td>90-480</td>
<td>700-4100</td>
<td>0.12</td>
<td>2.7</td>
<td>1.7</td>
<td>5.5</td>
<td>92</td>
<td>24</td>
<td>0.6</td>
<td>Tidally-influenced upper deltaic plain</td>
</tr>
<tr>
<td>MWT8-3</td>
<td>480-850</td>
<td>4100-5400</td>
<td>0.30</td>
<td>3</td>
<td>1.4</td>
<td>6.1-32.1</td>
<td>95</td>
<td>10</td>
<td>0-54</td>
<td>Tidally-influenced upper deltaic plain with peat-like wetland units</td>
</tr>
<tr>
<td>MWT8-2</td>
<td>850-1125</td>
<td>5400-6600</td>
<td>0.27</td>
<td>1.9</td>
<td>2.2</td>
<td>2</td>
<td>35</td>
<td>270</td>
<td>0-0.4</td>
<td>Sand channel unit with some gravel</td>
</tr>
<tr>
<td>MWT8-1</td>
<td>1125-1220</td>
<td>&gt;6600</td>
<td>0.05</td>
<td>1.7</td>
<td>2</td>
<td>3.9</td>
<td>60</td>
<td>110</td>
<td>0.0</td>
<td>Green-blue clay</td>
</tr>
</tbody>
</table>
Figure 1. A) Regional location map showing the location of the study site (star). B) Map of the Sacramento-San Joaquin Delta. The McCormack-Williamson tract is located within box. C) Core locations on the McCormack-Williamson tract.
Figure 2. Relations between Al concentration and fine sediment content for MWT-2 (a,b), MWT-6 (c,d), MWT-8 (e,f)
Figure 3. MWT-2 relations between Al and other elements indicating differential leaching
Figure 4. MWT-6 relations between Al and other elements indicating differential leaching
Figure 5. MWT-8 relations between Al and other elements indicating differential leaching
Figure 6. Assessment of Fe-oxide control on element abundances after normalizing by Al.
Figure 7. Strata-averaged abundance of elements in descending order for each core. Reds denote sand channel units, blues denote fine floodplain and delta units, greens denote ag-impacted units, others denote old clay units.
Figure 8. Strata-averaged abundance of elements in descending order across all cores.
Figure 9. Cross-core comparison of single element fluctuations through time.
Spatio-temporal variability across an upper deltaic plain in the Sacramento-San Joaquin Delta, California: with emphasis on a floodplain, tidal freshwater wetland, and an agricultural boundary

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ABSTRACT

Tens of millions of dollars have been spent on land acquisition and planning for wetland restoration on the upper deltaic plain of the Sacramento-San Joaquin Delta (SSJD). This study sought to assess the historical spatio-temporal variability of habitat conditions during the last 4,000 years (i.e. the late-Holocene interval) to help guide restoration by checking assumptions used in planning, design, and analysis. From a basic science perspective, it also sought to improve the understanding of habitat heterogeneity on an upper deltaic plain subject to pre- and post-land use change. Twelve sediment cores were collected from the McCormack-Williamson Tract (MWT) leveed farmland and Delta Meadows (DM) tidal wetland in the upper deltaic plain of the SSJD. Multiple environmental proxies were obtained from the cores to assess habitat spatio-temporal variability. Floodplain predominately characterized MWT during the late-Holocene as evidenced by sedimentary and geomorphic structures preserved in deposited sand, silt, and clay. Pollen analysis reveals that a mosaic of habitats persisted in the region in the past. Dry upland sites supported *Pinus* woodlands whereas local riparian forests of *Quercus* and *Salix* lined the river edges. Composites colonized the expansive floodplains and freshwater wetlands of Cyperaceae and *Typha* were widespread. Comparison against the regional sea-level history suggests that the upper delta came under tidal influence within the last 2,500 years. Despite this observation, floodplain landforms and habitats, not those of tidal wetlands, prevailed at DM from 3,650-280 calendar years after which wetlands are observed to expand. In recent times, the upper deltaic plain at MWT has been profoundly disturbed by agriculture and other human activity. Pollen flux shows a dramatic decline in overall productivity, likely related to landscape modification and loss
of habitat. An increase in *Zea* and Chenopodiaceous pollen in the agricultural horizon testify to the changing nature of the landscape as riparian forests, floodplains, and wetlands were destroyed or converted to crop fields. At DM, sedimentation rates and organic accumulation are shown to increase concurrently with the recent wetland expansion. Pollen from DM records the local existence of different habitats. The concentrations of Hg, Pb, and As pollutants as well as P are elevated several-fold in the study area’s surficial sediments at all coring locations compared to late-Holocene background levels, with unknown implications for restoration. The significance of these findings is that restored upper Delta wetlands will face a high-energy floodplain-type disturbance regime that will preclude simple stability by design for any given site. Also, it is imperative that research be performed right away to determine the significance of the pollution in Delta Meadows so this may serve as a template of what to expect in restoring Delta tracts.

**Keywords:** California, floodplain, delta, tidal freshwater wetland, agriculture, grain-size, pollen, pollutants
INTRODUCTION

The Californian landscape and associated waterways have experienced profound modification during the last 150 years. Forests of the Sierra Nevada have been actively logged since the mid-nineteenth century (Mudie and Byrne, 1980; Barbour et al., 1998) and fire disturbance has been suppressed since 1925 (Biswell, 1989; Taylor, 1998; Minnich et al., 2000). At lower elevations, the Central Valley that once flourished with native grasses (Jepson Prairie Docent Program, 1998) has been almost completely converted into agricultural land. Logging profoundly increased watershed erosion and the delivery of sediment to rivers (Lewis, 1998). Hydraulic gold mining in the Sierra Nevada in the late 1800's had a devastating impact as slopes were destabilized, river channels redirected and aggraded, and the San Francisco Bay estuary disturbed (Gilbert, 1917; Nichols et al., 1986). The sediment that was mobilized by hydraulic mining was rapidly and widely deposited in San Francisco Bay (Jaffe et al, 1998). At present, more than 60% of the rivers flowing out of the Sierra Nevada toward the Pacific Ocean are dammed primarily for water supply and secondarily for flood control, electric power generation, and recreation. Increased salinity noted in the San Francisco Estuary since 1860 is likely related to the upstream storage and diversion of water (Byrne et al, 2001).

In coastal regions, the impact of short-term human activity is particularly acute (Nichols et al, 1986). Ninety-one percent of California’s wetlands were destroyed (Dahl, 1990). Many wetlands, such as those in the Sacramento-San Joaquin Delta (SSJD), were extensively leveed and drained, thus exposing regularly inundated and buried organic matter to oxidizing conditions. In addition to the direct loss of wetland habitat, the ensuing oxidation caused significant subsidence in the delta (Atwater and Belknap,
Statewide efforts are now underway to improve ecosystem health and reduce flood-damage losses by rehabilitating degraded habitats and restoring lost landscapes.

Past research on the San Francisco Bay estuary has focused on such diverse issues as the evolution of the estuary (Atwater, 1979; Atwater et al., 1979), river inflow and salinity (e.g. Ingram et al., 1996; Goman and Wells, 2000; Byrne et al., 2001), salt marsh vegetation communities and landforms (e.g. Atwater et al., 1979; Malamud-Roam and Ingram, 2001), as well as the impacts of deleterious human activity (e.g. Nichols et al., 1986; Jaffe et al. 1998; van Geen and Luoma, 1999). Tidal wetland deposits and vegetation communities in the SSJD have been thoroughly investigated by Atwater (1980) and Atwater and Belknap (1980). Together, these investigations provide critical insight into the estuary-delta interface. More recently, Florsheim and Mount (2002) and Tu (2000) investigated floodplain evolution and riparian forest succession at sites upstream of the SSJD and show that flooding generates variable floodplain relief, features, and habitat. Unfortunately, unlike the estuary, lower delta, and upland floodplains, the upper deltaic zone has received little attention.

The upper delta is uniquely positioned in a tidal freshwater zone that experiences both riverine and tidal influence, rendering a complex combination of processes. Work by Brown and Pasternack (submitted) reveals that the upper deltaic plain in the SSJD is characterized by biogeomorphic profiles that are highly variable through time. They show that flooding was an important disturbance agent prior to levee construction and that the modern upper deltaic plain in the SSJD is relatively young, only coming under tidal influence during the last few millennia.
The basic research presented in this contribution is part of a larger restoration project that aims to convert upper deltaic floodplain tracts currently used for agriculture to tidal wetlands by breaching levees. The restoration project generally assumes that such tracts were tidal wetlands historically and ought to be that way now. The ultimate goal of successful restoration requires an understanding of how such wetlands evolved because this information can provide critical insight into post-restoration disturbance regimes, site stability, and potential impacts of land use change. Existing basic research on these topics is limited to and primarily comes from the Atlantic Coast (e.g. Orson et al., 1992; Khan and Brush, 1994; Pasternack et al. 2001). Thus, we sought to document the variability and recent evolution in the upper deltaic plain with particular attention paid to tidal freshwater wetlands. In addition, concern has been raised about the impact of wetland restoration on organic Hg toxicity due to reduction and bioactivation of inorganic Hg pollution derived from the gold mining era. We sought to address this concern within the context of the historical analysis to ascertain the pre- and post-mining levels of Hg and other pollutants.

The overall objective of this contribution is to characterize the spatial variability of an upper deltaic plain and to document environmental perturbation associated with distal land use change and local agriculture. Specifically, we aim to (1) develop an age-depth model for the site; (2) document changes in late-Holocene sedimentation rates and the relative role of watershed flux versus in situ organic accumulation, (3) examine topographic, landform, and habitat variability through time, and (4) quantify the level of toxic metal (Hg, Pb, and As) and phosphorus nutrient pollution at the site. Once these objectives are fulfilled, we combine that information to describe the evolution of the site
and contrast the late-Holocene interval that was not profoundly disturbed by humans with the upper cores sections that record both immediate and distal human-induced disturbance. Paleoenvironmental reconstruction is the primary tool for investigating past hydrogeomorphic conditions (Orson, 1996) and it will be employed here.

**SETTING**

The McCormack-Williamson Tract (MWT; Fig. 1) is owned by The Nature Conservancy, a nonprofit, tax-exempt corporation that has preserved more than 37 million ha of land and water worldwide, and is slated for full-scale restoration to tidal freshwater and floodplain habitat consistent with the tract’s landscape position. This site has been targeted for restoration because it is the downstream terminus of the well-protected Cosumnes River and could yield critical tidal freshwater wetland habitat that has been all but eradicated from the region. Because the Cosumnes River is undammed and its floodplains are being passively restored using levee breaches in the zone upstream from MWT (Florsheim and Mount, 2002), it is anticipated that historical processes including tidal exchange, channel migration, seasonal overbank flooding, and sediment transport and deposition can be partially to fully restored to MWT. It is further hoped that the restoration of fluvial and geomorphic processes to the site will create aquatic and riparian habitats favorable to native wildlife and fish species. The tidal influence is significant because one of the restoration objectives is to generate functional tidal freshwater habitat with associated aquatic and riparian habitat. Delta Meadows (DM) is a tidal freshwater wetland that is located just west of MWT. It is diurnally saturated by 1-1.4 m tides and dominated by *Scirpus*. 
The study site has been highly impacted by human activity and the modern landscape bares only little resemblance to historical conditions (United States Geological Survey, 1911). Limited riparian vegetation can be found along the levees impounding MWT. Some of the more common trees found at the site include *Quercus lobata* (valley oak), *Populus fremontii* (Fremont cottonwood), *Platanum racemosa* (western sycamore), *Acer negundo* (box elder), *Fraxinus latifolia* (Oregon ash), and *Alnus rhombifolia* (white alder). Many trees are enveloped with *Vitis californica* (California grape) and *Arceuthobium* (mistletoe). Common understory shrubs include *Rosa californica* (California rose), *Rubus discolor* (himalayaberry), and several species of *Salix*. *Cephalanthus occidentalis* (bottonbush) was noted close to the channels and *Chenopodium ambrosioides* (Mexican tea) occupies open disturbed sites. Nearby wetlands consist predominately of *Scirpus acutus* (common tule).

**METHODS**

**Field Methods and Core Processing**

To characterize the spatio-temporal variability of the upper delta plain, 12 sediment cores (MWT-1 to MWT-11 and DM-1) were collected. The MWT cores were distributed over the surface of the tract for maximum coverage, whereas DM-1 was collected from DM (Fig. 1). A second core was collected from DM, but was found to be identical to the first one upon further examination. Of the 11 cores collected from MWT, 3 cores (MWT-2, -6, -8) were analyzed for a suite of proxy environmental indicators including bulk density, loss-on-ignition (LOI), magnetic susceptibility, grain-size, geochemistry, and pollen. The vibracore DM-1 was similarly analyzed. The remaining 8
MWT cores were visually described and archived for possible future analysis. Stratigraphic description of the cores provides tentative insight into the recent spatial variability of the study site (Fig. 1). We elect to present only the top 200 cm of core stratigraphy in figure 1 because according to the age-models presented by Brown and Pasternack (submitted) and in this contribution (reported later), the top 200 cm can represent between 4,700-1,700 years of depositional history. Thus, if we present more than 200 cm of record we would be documenting mid-Holocene history at some sites but not at others and, similarly, less than 200 cm of record would result in only the latest late-Holocene profiles at some sites. The 200 cm cutoff is the most accommodating selection given our understanding of the age-depth relationships of the cores that were dated.

The MWT cores were all collected incrementally using a Geoprobe drilling rig that enabled the retrieval of coarse sediment in 122 cm long plastic liners. Sediment compaction or expansion during coring was measured as the difference between pushed distance and core length on a section-by-section basis. Delta Meadows was vibracored because it was physically and legally challenging to take the Geoprobe coring rig into this protected wetland. Vibracoring obtains continuous sediment by vibrating a core barrel into the substrate. The vibracore consisted of an aluminum tube, a small Honda motor, and a vibrating hose. The tube was vertically erected and driven into the ground via vibrations that were generated by the motor and transferred to the tube by the vibrating hose. The vibracore easily cut through organic layers but had difficulty penetrating inorganic dominated sediment. Compaction was noted as the difference between the distance pushed and sediment recovered. The vibracore was manually extracted using an old-style “bumper” car jack.
All cores were stored in a cold room at ~4 °C. Cores were split longitudinally using a circular saw and a nylon string was passed down the middle to split the sediment. Any smeared sediment was carefully removed using plastic spatulas and the cores were photographed and visually described. MWT-2, -6, -8 and DM-1 had plastic u-channels pushed longitudinally into each core section to retrieve samples for magnetic susceptibility. The u-channels were transferred to a magnetics laboratory where the sediment was measured for susceptibility using a Bartington MS-2 magnetometer. All of the MWT cores were then subsampled in 10-cm intervals whereas DM-1 was subsampled in 4-cm intervals because it was a shorter core and higher resolution was sought for the preserved wetland history. Sediment bulk density (g cm$^{-3}$) was determined for all cores at this time by weighing a subsample and measuring its volumetric displacement in a 50 ml graduated cylinder. The subsamples were placed in labeled plastic bags for cold storage.

**Analytical Methods**

MWT-2, -6, -8 and DM-1 had samples sent to Beta Analytic Inc., Florida for accelerator mass spectrometry (AMS) radiocarbon dating (Table 1). The radiocarbon dates were converted to calendar ages using a calibration program (Stuiver and Reimer, 1993). Non-linear age-depth models were developed for these cores by fitting a locally weighted smoothing function to the reported dates (Fig. 2). Subsequent measurements of sedimentation rates (g cm$^{-2}$ yr$^{-1}$), organic accumulation (g cm$^{-2}$ yr$^{-1}$) and pollen flux (grains cm$^{-2}$ yr$^{-1}$) were determined using the established age-depth model.
Following determination of down-core trends in bulk density and magnetic susceptibility, the cores were sampled for loss-on-ignition (LOI). Samples were weighed wet, dried overnight at 60 °C, and weighed dry, yielding the water content of the sample. Next, the dried sample was combusted for 6 hours at 600 °C in a muffle furnace and reweighed, yielding the organic matter content.

Grain-size percentages were determined for each sample using methods adapted from Folk (1974) coupled with empirical measurements by a laser granulometer. Organics were initially removed from the samples using 30% hydrogen peroxide (Black, 1965; Pasternack and Brush, 2002). Next, the samples were suspended in 500 ml 0.5% sodium metaphosphate to disaggregate particles and passed through a 63 μm sieve to separate sands from fines (silt and clay). Sands were collected, rinsed, dried, and weighed to determine total mass of sand. The fines suspended in the sodium metaphosphate were retained after wet separation and subsequently transferred into a graduated cylinder to determine total suspended volume. The fines were then transferred into a plastic bottle that was vigorously shaken to homogenize the suspension. Two 20-ml subsamples of the suspended fines were collected rapidly before any sediment settling occurred in the bottle. One of the subsamples was pipetted into a weighing dish, dried, and weighed. The subsample mass was calculated as the dry mass minus the mass of 20-ml of 0.5% sodium metaphosphate. The total mass of fines was calculated by multiplying the mass of the dry fines in the 20-ml pipetted subsample by the total volume of the sample divided by the subsample volume. The other 20-ml subsample was placed in a laser granulometer to determine the relative percentages of silt and clay in the sample and these values were then multiplied by the mass of the fines to determine the mass of
silt and clay. The mass of the measured sand, silt, and clay relative to the total mass of the sample was used to determine the relative percentage of sand, silt, and clay in the sample.

Information about habitat variability in the upper delta was realised through pollen analysis. Pollen preparation followed standard procedures (Moore et al., 1991; Brown and Hebda, 2002). All pollen samples were spiked with *lycoperdium* tablets containing 10,679±953 spores each (University of Uppsala, Quaternary Geology Department, Batch Number 938934) so pollen flux could be calculated. Fossil pollen was measured and identified using a Nikon Eclipse E200 microscope at 400x magnification and the University of California Museum of Paleontology Pollen Reference Collection respectively. Because pollen was rare in some levels, we have elected to present the pollen data as flux instead of relative percentages. Pollen flux was determined using the number of *lycoperdium* spores encountered compared to the number of pollen grains multiplied by the sedimentation rate to yield grains cm⁻² yr⁻¹.

Determinations of the Al, P, Hg, Pb, and As elemental concentrations with 20-cm resolution for MWT and 4-cm resolution for DM were carried out by Chemex Labs, Inc of Sparks, Nevada. The procedure involved drying the samples and sieving them through a #80 mesh to obtain the fraction smaller than 0.177 mm in diameter, treating them with hot concentrated nitric acid to destroy organic matter and oxidize sulfide material, and adding concentrated hydrochloric acid (3 times the volume of the nitric acid) to generate the aqua regia (3 HCl + HNO₃ = 2 H₂O + NOCl + Cl₂) which was used to digest the material. Total sediment digestion was achieved for all elements except Al, as assessed using a nearby reference soil sample (San Joaquin Soil Standard Reference Material
2709) from the National Institute of Standards and Technology processed using the same procedure. After digestion sample solutions were analyzed by inductively-coupled argon plasma and atomic emission spectroscopy to obtain the concentrations of Al, P, Pb, and As. Hg was analyzed by cold volatilization atomic adsorption spectroscopy to achieve a detection limit of 10 ppb. Final concentrations were adjusted for their organic content to give an organic-free concentration to eliminate this source of difference in the analysis. Anthropogenic enrichments were calculated as the element ratio of the top-most sample to the average of the deepest samples from the 4,000-3,000 calendar years before present (cal BP) interval with measurable concentrations for each core. Documentation of pollutants in the cores, as indicated by elevated enrichment ratios, can either be indicative of the age of pollution onset or the limit of stratigraphic consideration if core sediment has been mixed by tilling.

MWT-2, -6, and -8 were previously zoned using a stratigraphically constrained clustering algorithm (Brown and Pasternack, submitted). The parameters used for zoning included LOI, magnetic susceptibility, percentage fines (silt and clay), and Al percentage. These variables were selected because they are continuous throughout the cores and not modified by down-core compaction. DM-1 is similarly clustered and zoned in this contribution.

RESULTS

Because the cores are widely distributed over MWT and DM (Fig. 1), it is possible to examine the general spatial characteristics of the site through time culminating in agricultural landscape utilization, though this is tempered somewhat
because only 4 of the 12 cores were radiometrically dated (Table 1). The results of this investigation are divided into several sections. First, the stratigraphic profiles from the upper 200 cm of all of the cores are examined to provide tentative insight into the spatial variability and evolution of the area. Next, a late-Holocene age-depth model for the radiometrically dated MWT-2, -6, and -8 cores and DM-1 is described and the temporal changes in sedimentation rates, organic accumulation, grain-size are examined. After that, MWT cores are examined in greater detail because their established chronologies enable greater insight into the temporal variability of the site during the last 4,000 years and to provide a basis for comparison against DM. Brown and Pasternack (submitted) described the entire Holocene records for MWT-2, -6, and -8, so only the pre- and post-agriculture characteristics are summarized in Table 2 for these cores. Finally, previously undescribed DM-1 stratigraphy and core characteristics are presented in detail (Table 2).

**Landform Evolution**

The general predominance of silt and clay with some sand in all MWT cores below the upper mixed layer (Fig. 1) together with a lack of organic material suggests that the tract was mainly floodplain below the agricultural horizon. Variations in the color of the sediment and the degree of mottling between cores are due to past local conditions specific to each coring site. Isolated parcels containing sand are noted in MWT-2 and MWT-10 at about 163-148 and 200-178 cm depth respectively and these deposits may reflect sand splays. The thin layer of gravel observed in MWT-8 at about 58-52 cm depth is not considered a paleochannel deposit because it is too thin. Instead, it may reflect either splay deposition or possibly human land use. Contrary to the
expectation from Atwater and Belknap’s (1980) investigation of delta cores two decades ago, the agricultural topsoil noted in the MWT cores is surprisingly thin, often penetrating only 20-30 cm deep. In comparison, the basal section of DM-1 also consists of fine floodplain sediment (Figs. 1 and 3), though these are replaced up-core by wetland peat. Agricultural topsoil is not observed in the DM-1 core.

The age-depth model (Fig. 2), based on radiocarbon dates in Table 1, reveals that the DM-1 core is considerably shallower compared to the MWT cores. Over the last 3,650 years, the elevation of DM-1 was always less than MWT-6. In contrast, the elevation of DM-1 was greater than those of MWT-2 and MWT-8 between 3,500-700 cal BP, after which the surface elevations of these cores converged. MWT-2 and MWT-8 have had remarkably similar elevations during the late-Holocene. Mean higher high water is ~0.5-0.7 m above mean sea level in this region, implying that the study area may have first experienced small tides ~2,500 cal BP (Fig. 2). All core sites appear tidal by ~750 cal BP, a relatively recent phenomenon given the long-term evolution of MWT (Brown and Pasternack, submitted). The slopes of the accretion rate curves are not equal to that of the relative sea level rise curve until ~ 500 years ago.

In general, sedimentation rates (Fig. 4) gradually increase in DM-1, decrease in MWT-6, and remain roughly constant in MWT-2 and MWT-8 through time. Between 3,500-1000 cal BP sedimentation rates in DM-1 hover around 0.05 g cm$^{-2}$ yr$^{-1}$, but then increase during the last 1,000 years to modern values of 0.15 g cm$^{-2}$ yr$^{-1}$. In MWT-6, sediment accumulation decreases through time from 0.1 g cm$^{-2}$ yr$^{-1}$ at 4,000 cal BP to about 0.05 g cm$^{-2}$ yr$^{-1}$ at present. Sedimentation rates are comparable in DM-1 and MWT-6 between ~2,500-1,500 cal BP. In contrast, rates of sedimentation during the
late-Holocene in MWT-2 and MWT-8 are two to four times greater than those of DM-1 and MWT-6, averaging around 0.2 g cm\(^{-2}\) yr\(^{-1}\).

Low LOI values (Table 2; Fig 3) reveal that little organic matter accumulated on the late-Holocene upper deltaic floodplain. LOI values also indicate that upper core sections have greater organic content compared to lower sections, with a sharp boundary between these zones indicating changing supply rates and going against organic losses. The relative contribution that organic matter has made to overall sedimentation has been relatively low on the floodplain as evidenced at all the core sites where values are typically <0.015 g cm\(^{-2}\) yr\(^{-1}\) (Fig. 4). The exceptions are in the bottom of MWT-8 and the top of DM-1. In MWT-8, sediment deposited before 3,500 cal BP consists of 0.015-0.03 g cm\(^{-2}\) yr\(^{-1}\) organic matter. The tidal freshwater wetland deposits in DM1-4 record markedly more organic matter accumulation, ranging between 0.03-0.04 g cm\(^{-2}\) yr\(^{-1}\). The organic matter contribution to the agricultural horizon is intermediate between floodplains and tidal freshwater wetlands, averaging 0.01 g cm\(^{-2}\) yr\(^{-1}\) but ranging between about 0.005-0.02 g cm\(^{-2}\) yr\(^{-1}\).

MWT-2, -6, and -8 Stratigraphy and Core Characteristics

Clays containing organics were deposited from 427-220 cm in MWT-2, representing the 4,000-1,900 cal BP interval. A thin sand layer is observed at 307-299 cm depth and was likely deposited at about 2,600 cal BP. Interbedded sand and silt deposited between 1,800-700 cal BP are noted in the core from 220-96 cm depth. Clays with high organic content occur in the top of the core from 96-0 cm. In contrast, the last 4,000 years of depositional history is more homogenous in MWT-6 where mottled clays
are noted to occur until about 300 years ago, after which they are overlain by mixed
organic topsoil between 50-0 cm depth. Increased variability recurs in MWT-8. Peat
deposited from 5,400-4,100 yields to clay containing organics and visible wood
fragments from 4,100-2,000 cal BP at 480-231 cm depth. Mottled clay from 231-65 cm
depth occurs between 2,000-500 cal BP whereas clay with interbedded pebbles and
gravel is noted from 65-20 cm depth. Organic topsoil characterizes the core from 20-0
cm.

Bulk density and Al do not change markedly across the agricultural boundary on
MWT from deeper undisturbed deposits to upper highly impacted sediment (Table 2). However, many other proxy indicators do indeed exhibit a change across the boundary.
Magnetic susceptibility decreases slightly across the agricultural boundary in MWT-2
and increases slightly in MWT-6. In MWT-8, the thin gravel deposit in the upper part of
the core results in a noticeable increase in up-core susceptibility. In terms of grain-size
(Fig. 5), MWT-2 is characterized by 21% sand, 53% silt, and 24% clay between 4,000-
1,900 cal BP. Sand increases to 42% from 1,900-700 cal BP, whereas silt and clay
decrease to 38% and 20% respectively. Sand is absent at the top of the core whereas silt
and clay increase to 66% and 31% respectively. MWT-6 consists of roughly 6% sand,
60% silt, and 34% clay throughout the late-Holocene. In contrast, MWT-8 shows some
variability in grain-size with the interval from 4,000-2,000 cal BP containing 4% sand,
73% silt, and 23% clay. Between 2,000-1,000 cal BP, sand increases to 18% whereas silt
and clay decrease slightly to 64% and 18% respectively. The last 1,000 years are
characterized by 5% sand, 49% silt, and 45% clay. Less sand and more clay is generally
noted in the agricultural horizon compared to pre-agricultural floodplain layers (Fig. 6).
Changes in total pollen flux and flux for individual taxa characterize the agricultural boundary on MWT (Fig. 7). Pollen flux was not determined for MWT-2 because pollen was rare throughout that core. However, pollen extracted from MWT-6 and MWT-8 show several trends. In general, pollen flux was greater in pre-agricultural sediment compared to agricultural horizon. Arboreal, riparian, and wetland taxa such as *Pinus*, *Quercus*, *Salix*, Cyperaceae, and *Typha* all show a reduction in flux across the agricultural boundary, whereas agricultural and disturbance indicators such as *Zea* and Chenopodiaceae show an increase. Composites surprisingly decrease across the agricultural boundary.

The analysis of pollutant concentrations in MWT shows elevated levels in the topsoil of all cores relative to the background levels for Hg, Pb, and P (Fig. 8). MWT-2 has 293 ppb Hg (12.8x), 15.2 ppm Pb (2.3x), and 956 ppm P (2.7x), with anthropogenic enrichments given in parentheses. MWT-6 has 253 ppb Hg (11.8), 13.2 ppm Pb (1.5x), and 1043 ppm P (4.1x). MWT-8 has 192 ppb Hg (5.7x), 14.9 ppm Pb (1.5x), and 799 ppm P (1.9x). As was not present in basal layers of MWT-2 or MWT-6. In the latter case, As concentration drops from 11.0 to 2.17 ppm from present day to 1,300 cal BP (5 to 45 cm depth), showing an anthropogenic effect. For MWT-8, As is present throughout, but the surficial sediment is 3.6 times more enriched (19.2 ppm) than the basal layers. The depth of pollutant penetration in the cores was found to be 30 cm for MWT-2, 50 cm for MWT-6, and 100 cm for MWT-8.
DM-1 Stratigraphy and Core Characteristics

DM-1 is 205 cm long (Fig. 3). Olive-red mottled clay is observed between 3,650-2,500 cal BP at 205-178 cm depth. A gradual color change is noted in DM-1 with olive clay occurring between 2,500-1,200 cal BP at 178-122 cm. Mottled dark grey clay is present between 1,200-350 cal BP. Fibrous plant fragments that were laid down between 350-250 cal BP are noted between 52-40 cm depth. The fibrous plant unit is replaced by dark grey-black clay between 250-100 cal BP. Peat that was deposited during the last 100 years is observed in the top of the core from 22-0 cm depth.

The stratigraphically constrained cluster diagram combined with visual inspection of the core yields four distinct zones for DM-1 (Table 2; Fig. 3; DM1-1 to DM1-4). Zone DM1-4 is further divided into 3 subzones (DM1-4a to DM1-4c). Zone DM1-1 occurs from 204.5-185 cm depth, spanning the interval from 3,650-2,750 cal BP. Pollen is rare in this zone at the 1 cm$^{-3}$ resolution and magnetic susceptibility is highest in the core. DM1-2 occurs from 185-101 cm depth, covering the interval from 2,750-880 cal BP. Pollen remains rare in this zone. Magnetic susceptibility decreases from DM1-1 to an average of 23 x10$^{-5}$ SI units. One other notable feature in this zone is the decrease in percentage silt and clay and increase in sand from 159-151 cm depth. Pollen is detected in upper half of zone DM1-3, which persists from 880-280 cal BP (101-45 cm depth), for the first time in the core. The most abundant taxa in this zone are *Quercus* and composites. A noticeable increase in pollen flux is evident in the DM1-4, which comprises the top of the core from 45-0 cm depth spanning 280-0 cal BP. Other noteworthy features of DM1-4 include an increase in organic content as evidenced by the highest LOI values for the core. The pollen stratigraphy in DM1-4 varies considerably
between the subzones. DM1-4a has lower pollen flux compared to DM1-4b and DM1-4c, though many of the pollen types observed in DM1-4a are also observed in the other subzones. DM1-4b and DM1-4c have distinguishable pollen assemblages. DM1-4b is characterized by Pinus, low levels of Quercus, composites, Rubiaceae, and Typha whereas DM1-4c contains Pinus, more Quercus, Salix, Alnus, Poaceae, Typha, and Cyperaceae.

Bulk density gradually decreases up-core in DM-1 from 1.8 g cm\(^{-3}\) in the base of the core to 0.9 g cm\(^{-3}\) at the top, whereas MWT shows little up-core variability. A similar pattern is noted in LOI where greater values are observed in the upper wetlands (~24 %) compared to deeper more inorganic deposits (~5 %). Magnetic susceptibility is markedly higher in the basal section of the DM-1 core, averaging 67 x10\(^{-5}\) SI units in zone DM1-1 compared to the upper wetlands (DM1-4c) that have a magnetic susceptibility of about 8 x10\(^{-5}\) SI units. The fibrous plant remains in zone DM1-4a do not have a magnetic signature. These trends are generally consistent with the MWT cores that show higher LOI and susceptibility in the upper disturbed layer compared to basal sediment. DM-1 has a highly consistent grain-size profile throughout the late-Holocene that is comparable to MWT-6, consisting of approximately 2% sand, 65% silt and 33% clay. The wetlands in DM1-4 have slightly more silt and less clay compared to the agricultural sediment on MWT and less sand compared to the undisturbed floodplains that characterized the region in the past (Fig. 6).

Al generally increases up-core from a basal low of 1.7 % in DM1-1 to a high of 6.0 % near the top of the core in DM1-4c. Hg, Pb, As, and P are greater in the upper wetlands compared to the deeper floodplain sediment. The concentrations of these
elements in the DM1-4c wetland are all equal or greater than those in the top-most agricultural sediment on MWT, revealing that DM-1 has experienced the most severe pollutant enrichment of all cores (Fig. 8). The surficial concentration and enrichment ratio for Hg were 257 ppb and 24.5 respectively. For Pb, they were 23.3 ppm and 3.7. For P they were 1604 ppm and 4.2. Enrichment ratios drop to background levels by 140 years ago (27 cm depth). The surficial concentration of As was 12.9, with a spike to 22.7 occurring 55 years ago and none present before 90 years ago.

DISCUSSION

The 12 cores collected from MWT and DM provide critical insight into the spatio-temporal evolution of an upper deltaic plain in the SSJD. The following discussion will first examine the general nature of MWT prior to human disturbance and this will be compared to similarly old sediment from DM, thus establishing a late-Holocene spatial reconstruction of the study site. Next, the upper disturbed layer on MWT is examined and contrasted to the underlying undisturbed sediment. Finally, tidal wetland development in the upper part of DM is examined.

Late-Holocene Floodplains

The age-depth model developed by Brown and Pasternack (submitted) reveals that the past surface topography of the upper deltaic plain was well above the influence of sea level for most of the last 10,000 years. This suggests that relative sea level rise and local sedimentation were independent processes through that period, with the former occurring significantly faster than the latter. Since relative sea level rise has been fairly
constant in the last 4,000 years, the recent matching of the curves must be due to a significant increase in sediment supply. This change in supply is most likely due to increased erosion and disturbance caused by land use but it could possibly be due to changing deltaic local geomorphic conditions, renewal of accommodation space, and associated reduction in sediment bypassing.

The differences in the age-depth model reveal that the past surface topography of the upper deltaic floodplain was spatially variable, likely because different geomorphic features such as levees and channels were affected by processes such as flooding and lateral channel migration that characterized the site (Brown and Pasternack, submitted). Late-Holocene grain-size profiles from MWT-2, -6, and -8 (Figs. 5 and 6) coupled with the visual descriptions of the upper 200 cm from the remaining MWT cores (Fig. 1) reveal that silt and clay, and to a lesser extent sand, were widely dispersed throughout the late-Holocene, with a corresponding very low amount of organic material present. Though there are subtle variations between the cores, we interpret these deposits as past floodplain because tidal wetlands are highly enriched in organic content (Pasternack and Brush, 2001). The greatest amount of sand accumulated at the southern end of the tract at MWT-2, whereas the most amount of silt was deposited in the northwest corner of the tract around MWT-8 (Table 2; Figs. 1, 5, and 6). The highest clay content is found in the middle of the tract at MWT-6. Changes in average magnetic susceptibility in the floodplain sediment (Table 2) also record the spatial distribution of different sized sediment since magnetic susceptibility is shown to increase with increasing grain-size on MWT (Brown and Pasternack, submitted).
In general, sand is not very abundant in the DM-1 core (Table 2; Figs. 3 and 6). Instead, silt dominates much like in nearby MWT-8, suggesting that floodplain habitat constituted the DM site in the recent past as well. This result is somewhat surprising since it demonstrates that the tidal wetlands in DM must be relatively young habitat. The main difference between DM-1 and MWT-8 is that clay is the next most abundant grain-size after silt in DM-1, whereas sand and clay are similarly abundant at MWT-8. In addition, high basal magnetic susceptibility values in DM1-1 are replaced by values consistent with those of MWT-8 in zone DM1-2 (Table 2; Fig. 3). The higher content of sand at MWT-2 and silt at MWT-8 and DM1-1suggests that these sites were generally more proximal to active channels compared to MWT-6. Further, changes in grain-size throughout the late-Holocene, such as the increase in sand content in MWT-2 between 1,700-700 cal BP could reflect increased proximity to a channel or the local formation of a levee or sand splay complex (Asselman and Middelkoop, 1995; Steiger et al., 2001; Pasternack and Brush, 2002). Together, these observations reveal that the tract was geomorphically active in the late-Holocene.

Little organic accumulation occurred on the floodplain as evidenced by low LOI values (Table 2; Fig. 3). The amount of organics that were accumulating on the floodplain are very consistent with a sedimentary endmember mixing line previously developed by Brown and Pasternack (submitted), suggesting that most of the organic matter on the floodplain is reflective of particulate organic matter derived from landscape wash load. MWT-6 deviates the most from the mixing line and has the highest LOI values noted on the past floodplain, implying that more organic matter may have accumulated at this site. However, when adjusted for sedimentation, all sites generally
show comparable amounts of organic accumulation (Fig. 4). The highest amount of organic matter occurs in the bottom of MWT-8, which is not surprising since this site previously supported wetlands in the late mid-Holocene (Fig. 6; Brown and Pasternack, submitted). Late-Holocene sedimentation rates are lower at MWT-6 and DM-1 compared to MWT-2 and MWT-8 (Fig. 4) simply because these sites are at higher elevations (Fig. 2) and experienced slower accretion.

Pollen is rare in the late-Holocene floodplain sediment, likely because of the grains were degraded through oxidation and mechanical abrasion. In fact, little to no pollen was observed in MWT-2 and the bottom of DM-1 at the 1 cm$^3$ sampling resolution. Fortunately, pollen was observed in MWT-6, MWT-8, and in zone DM1-3 (Figs. 3 and 7) and these grains provide additional information about the late-Holocene variability in the upper delta. The $Pinus$ pollen largely observed in MWT-8, is likely derived from drier upland sites that supported pine woodlands. $Quercus$ pollen coupled with lower levels of Chenopodiaceae further imply the presence of nearby dry slope habitat. The presence of $Quercus$ and $Salix$ pollen suggest that well developed riparian forests bounded nearby rivers (Atwater, 1980). The high flux of Cyperaceae and $Typha$ pollen indicates that bulrush and cattail dominated freshwater wetlands abounded the upper delta. The presence of composites implies that open areas such as floodplains, were extensive, though some of the composites may have persisted in wetlands too.

Together, these observations suggest that floodplains were widespread over much of the upper delta in the late-Holocene. These floodplains exhibited topographic relief and variations in grain-size and rates of sediment accumulation. Little organic matter accumulated permanently on the floodplain, and what did was likely delivered as wash
load during flood events. In addition to floodplains, pollen observations suggest that riparian forests and wetlands were also common forms of habitat.

**Upper Agriculturally Disturbed Horizon**

The top-most sediment on MWT related to agriculture is not only widespread on MWT but also markedly different from the lower floodplain layers. The amount of organic matter in the agriculturally mixed layer is noticeably higher compared to the subsurface floodplain sediment (Table 2; Fig. 4). At all sites on the tract, silt constitutes roughly two-thirds of the sedimentary matrix with clay comprising the remainder (Table 2; Figs. 5 and 6). Sand is virtually absent in the agricultural profile. The pollen records also record a noticeable change. Overall pollen flux is greatly reduced (Fig. 7), suggesting a reduction in landscape productivity. This reduction in flux, however, could also result from increased oxidation and mechanical breakdown of pollen due to invasive practices such as tillage. However, marked declines in *Pinus*, *Quercus*, *Salix*, Compositae, Cyperaceae, and *Typha* imply some loss of habitat. Noticeable increases in *Zea* pollen testify to the conversion of once pristine floodplains to agricultural fields. A dramatic increase in Chenopodiaceae exemplifies the degree of human induced disturbance and clearly illustrates that the vegetation communities common in the upper delta today are profoundly different from those that persisted in the region for millennia.

Perhaps most disturbingly is the dramatic increase in chemical pollutants noted in the agriculturally mixed horizon. Hg, Pb, As, and P all show elevated concentrations compared to late-Holocene background levels. This might be a problem for wetland restoration, as restoration will impose reducing conditions that promote toxification. The
sources of Hg to the study area are from Hg mining in the Coastal Range located northwest of the delta. Hg was transported directly through streams such as Cache Creek and though its translocation and use in gold mining in the Sierra Nevada. The sources for the elevated concentrations of Pb include industrial air pollution and car emissions, whereas the As comes from industrial combustion and high temperature processes as well as insecticides, weed killers, fungicides, and wood preservatives. Phosphorus is derived primarily from agricultural and lawn fertilizers.

**Tidal Freshwater Wetlands**

Unlike the MWT that was leveed, drained, and converted into agricultural pasture, DM is in somewhat more intact, though not necessarily healthier. DM gradually came under tidal influence as sea level transgressed throughout the late-Holocene, likely around 1,500 years ago (Fig. 2). By about 500 years ago DM was keeping pace with the changing sea level. *Typha* wetlands and meadows thrived in this environment starting about 280 years ago and continuing until present-day (Fig. 3). Cyperaceae, or more specifically *Scirpus*, wetlands started to expand at about the same time but developed more extensively only recently, about 120 years ago as indicated by pollen and the deposition of peat. Sediment not only changed from inorganic silts to silts and clay with high organic content (Table 2; Figs. 3, 5, and 6), but it also began to accumulate more rapidly (Fig. 4). Magnetic susceptibility subsequently decreased. These observations reveal that the wetlands around DM are very recent landscape features. Pollen from the DM core also reveals that some *Pinus* woodlands and riparian forests containing *Quercus*, *Salix*, and *Alnus* also survived nearby. The increase in pollutants is even more
noticeable in DM compared to MWT, revealing that these wetlands, often considered relatively pristine by the public, are in fact highly polluted. As such, they may make excellent restoration models if they are studied in detail to understand how such wetlands are functioning now in the face of such strong physical disturbance and chemical pollution.

CONCLUSIONS

A comparative analysis was performed between the history of MWT farmland and the adjacent protected DM tidal freshwater wetland covering the last 4,000 years to assess spatio-temporal variability in landforms and habitat conditions. Amazingly, topsoil and wetland peat is present only as a thin veneer at both sites respectively. In fact, AMS radiocarbon dating of the base of the peat shows that the tidal wetland at DM is less than 100 years old. The elevational history of DM also shows that it did not come under tidal influence until the most recent anthropogenic period, suggesting that the wetland itself was a result of human impact, most likely gold mining sedimentation. This finding is very similar to results reported for Atlantic tidal freshwater wetlands of Chesapeake Bay, Delaware, and New Jersey. A mosaic of habitats including open floodplains, riparian forests, *Scirpus* wetlands, and upland woodlands prevailed throughout much of the late-Holocene, though in the modern era these are more restricted and less productive. Whereas MWT shows the potential for becoming a polluted marsh risking wetland biota, DM is in fact already a highly polluted biohazard. Hg, Pb, As, and P all show extremely high concentrations relative to pre-anthropogenic background levels. The restoration significance of these findings is that there are no long-term, stable tidal freshwater wetlands on the upper deltaic plain of the SSJD. Such wetlands are
geomorphically ephemeral, but part of an overall habitat patchwork. Also, it is imperative that research be performed right away to determine the significance of the pollution in Delta Meadows so this may serve as a model for what to expect in restoring Delta tracts.

ACKNOWLEDGEMENTS

The authors kindly thank The Seaver Institute, University of California, and CALFED (Ecosystem Restoration Program Co-op Agreement no. 114200J095) for providing funding for this research. J. Mount kindly contributed considerable financial resource for analytical equipment used in this investigation. K. Verosub graciously permitted access to his magnetics laboratory and use of his equipment. We sincerely thank The Nature Conservancy and Ramona Swenson for access to their land and continued support during this investigation. We would also like to thank Ellen Mantalica, Kaylene Keller, Derek Sappington, Mike Bezemek, Laurel Aroner, Wendy Trowbridge, Jim MacIntyre, Jose Constantine, and the numerous other volunteers for their assistance.
REFERENCES


Atwater BF. 1979. Ancient processes at the site of Southern San Francisco Bay, movement of the crust and changes in sea level. In San Francisco Bay-The Urbanized Estuary, Conomos TJ (ed). American Association for the Advancement of Science, Pacific Division: San Francisco; 31-45.


Brown KJ, Pasternack GB. The geomorphic dynamics and environmental history of an upper deltaic floodplain tract in the Sacramento-San Joaquin Delta, California, USA. Submitted to Earth Surface Processes and Landforms.


Tu I. 2000. Vegetation patterns and processes of natural regeneration in periodically
flooded riparian forests in the Central Valley of California. Ph.D. dissertation,
University of California, Davis. pp. 180.

van Geen A, Luoma SN. 1999. The impact of human activities on sediments of San
Table 1. AMS radiocarbon dates for cores MWT-2, MWT-6, MWT-8, and DM-1 with 1 standard deviation statistics where ybp is radiocarbon years before present and cal BP is calendar years before present. The radiocarbon dates were converted into median calendar ages using a calibration program developed by Stuiver and Reimer (1993).

<table>
<thead>
<tr>
<th>Sample Number</th>
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<th>Material</th>
<th>Depth (cm)</th>
<th>Conventional $^{14}$C date (ybp)</th>
<th>Median Calendar Age (cal BP)</th>
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<td>Beta-160023</td>
<td>MWT-2</td>
<td>Organic sediment</td>
<td>1060-1070</td>
<td>12420 ± 90</td>
<td>14670</td>
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<tr>
<td>Beta-160024</td>
<td>MWT-2</td>
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<td>23550 ± 210</td>
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<td>6530</td>
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<td>Beta - 160030</td>
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<td>Peat</td>
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<td>120.2 ± 0.4</td>
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<td>Beta - 160031</td>
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<td>Organic sediment</td>
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Table 2. Core characteristics for MWT-2, -6, and -8 across the agricultural boundary where BD is bulk density (g cm\(^{-3}\)), LOI is loss-on-ignition, MS is magnetic susceptibility (x10\(^{-5}\) SI units), and n/a is not available because values were so low they were not reported during analysis. All of the zones identified in DM-1 are presented since this site was not disturbed by agricultural activity. All listed values are averages.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Depth (cm)</th>
<th>Age (cal BP)</th>
<th>BD</th>
<th>LOI</th>
<th>MS</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Al (%)</th>
<th>Hg (ppb)</th>
<th>Pb (ppm)</th>
<th>As (ppm)</th>
<th>P (ppm)</th>
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<tbody>
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<td><strong>MWT-2</strong></td>
<td></td>
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</tr>
<tr>
<td>Agriculture</td>
<td>0-30</td>
<td>-50-200</td>
<td>1.8</td>
<td>8.3</td>
<td>26</td>
<td>4</td>
<td>58</td>
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<td>3.3</td>
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<td>942</td>
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<tr>
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<td>200-4000</td>
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<td>3.2</td>
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<td>25</td>
<td>50</td>
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<td>2.3</td>
<td>23</td>
<td>6</td>
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<tr>
<td><strong>MWT-6</strong></td>
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<tr>
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<td>-50-1700</td>
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<td>8.4</td>
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<td>4</td>
<td>61</td>
<td>35</td>
<td>2.9</td>
<td>222</td>
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<td>1700-4000</td>
<td>1.8</td>
<td>8.1</td>
<td>10</td>
<td>8</td>
<td>58</td>
<td>34</td>
<td>2.6</td>
<td>31</td>
<td>10</td>
<td>n/a</td>
<td>345</td>
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<tr>
<td><strong>MWT-8</strong></td>
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<td></td>
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</tr>
<tr>
<td>Agriculture</td>
<td>0-110</td>
<td>-50-900</td>
<td>1.8</td>
<td>6.0</td>
<td>54</td>
<td>6</td>
<td>53</td>
<td>39</td>
<td>3.2</td>
<td>238</td>
<td>14</td>
<td>19</td>
<td>756</td>
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<tr>
<td>Pre-Agriculture</td>
<td>110-460</td>
<td>900-4000</td>
<td>1.7</td>
<td>5.2</td>
<td>25</td>
<td>8</td>
<td>69</td>
<td>23</td>
<td>2.6</td>
<td>27</td>
<td>9</td>
<td>6</td>
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<td>-50-90</td>
<td>0.9</td>
<td>24.4</td>
<td>8</td>
<td>1</td>
<td>64</td>
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<td>12.7</td>
<td>4</td>
<td>1</td>
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<td>220-280</td>
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Figure 1. Location map of the study site. The McCormack-Williamson Tract (MWT) is located in the Sacramento-San Joaquin Delta, which is marked by a star in the California inset map. MWT is bounded by the Cosumnes River to the east and Snodgrass Slough to the west. Delta Meadows is located along the western banks of Snodgrass Slough at the site marked by the DM core. The locations and simplified top 2 m lithologies are shown for all cores.
Figure 2. The left panel shows the late-Holocene non-linear calendar-year age-depth model for the MWT-2, -6, and -8 geoprobe cores, as well as the DM-1 vibracore. The sea-level curve is from Atwater (1979). The age-depth models were constructed by fitting a smoothing algorithm to the calendar dates obtained for the cores. The graph on the right reveals the elevation differential between the cores and sea level. The horizontal line represents the 70 cm higher high water mark. Values >70 cm imply no tidal influences, whereas those <70 cm imply some tidal influence.
Figure 3. Stratigraphically constrained cluster diagram for DM-1 where LOI = loss on ignition and MS = magnetic susceptibility. Pollen estimates are presented as flux (grains cm\(^{-2}\) yr\(^{-1}\)).
Figure 4. Sedimentation and organic accumulation rates of all cores during the last 4,000 years.
Figure 5. Late-Holocene changes in percent sand, silt, and clay.
Figure 6. Ternary diagram showing the grain-size distribution for the various environments identified in the cores.
Figure 7. Changes in pollen assemblages across the agricultural boundary for MWT. The “pre” suffix reflects the pre-agricultural conditions whereas the “post” suffix represents the post-agricultural or mixed interval.
Figure 8. Down-core changes in pollutant geochemistry.
Shallow Seismic Reflection Survey Research On An Upper Deltaic Plain In Aid Of Wetland Restoration Planning

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Abstract

Pairing of a CALFED grant (Ecosystem Restoration Program Co-op Agreement no. 114200J095) with a generous private grant from The Seaver Institute to The Nature Conservancy and University of California at Davis enabled an expansion of the McCormack-Williamson Tract (MWT) restoration planning project to combine state-of-the-art seismology with paleoenvironmental reconstruction techniques to yield a cutting-edge environmental perspective on the restoration potential for the site. In the first phase, the seismographic technology was tested using a rented system and promising results were found. In particular, we imaged underground river channels and sedimentary layers, but they turned out to be much too deep to be of relevance for restoration. In the second phase, the physical limits of near-surface data collection were contested using highly customized equipment to image near-surface substrate, yielding excellent raw data. The amount of seismic data collected using very high sampling resolution appears to exceed undisclosed built-in limits in the low-cost Winseis processing software used to convert field derived raw seismic data into polished seismic imagery. In consequence, an alternate means of analyzing the high-resolution data has yet to be identified, but efforts are still underway to find an alternative approach. Without having the data analyzed, it is not possible to evaluate the depth of the survey or the resolution of sedimentary layers. Consequently, while this project has yielded some very interesting results that will inform wetlands restoration at the McCormack-Williamson Tract, it has revealed a limitation of seismic technology for routine evaluations of potential restoration sites: unreliability of low-cost software and complexity of methods required for analysis and interpretation by skilled geologists. We were excited to have this opportunity to test out this cutting-edge technology in a novel application. However, we must conclude at this time
that seismology is of much less value than sediment coring in revealing and understanding subsurface structure.
INTRODUCTION

Critical among the problems that face environmental restoration specialists are those related to selecting the most promising sites for successful restoration coupled with choosing the most appropriate techniques for site evaluation. Restoration of riparian habitat is an expensive business that can cost from $2,000 to $10,000 per acre, so it is vital for conservationists not to waste scarce resource on non-viable sites. Often, restoration planners try to select sites by visiting the site and consulting aerial photographs. This approach, while important, cannot guarantee success and cost efficiency. Knowing the nature of the subsurface is critically important since it can provide detailed insight into past conditions, habitats, and processes at the site. If too little is known of subsurface conditions and structures, restoration ecologists may find themselves working on unpromising sites with techniques poorly suited to the location.

Taking soil cores and digging trenches are two methods often used to learn about subsurface conditions. But coring and trenching provide knowledge of only a few isolated points or cross-sections. Scientists must extrapolate what they learn from these limited investigations to the rest of the site. Time and expense limit the number of core samples that can be taken and the number of trenches that can be dug, and using too many of either can damage the environment. Moreover, trenches are often too shallow to reveal deeper structures. So relying only on these methods can easily lead to errors. Important subsurface structures such as ancient riverbeds and hardpan layers may go entirely undetected.

The Potential for Seismic Technology

To detail subsurface conditions more extensively, exploration seismography has been frequently been employed (Pullan et al. 1990). The most promising new seismographic
technology uses both refracted and reflected sound waves to provide detailed, three-dimensional images of underground features.

Seismic surveys use sound waves to collect information about the shape and texture of underground features. A sound wave is propagated by striking a metal plate on the ground or firing a downward shot from a specialized gun. A series of geophones distributed across the field detect slight vibrations associated with the generated signal as they bounce off different soil layers and return to the surface. The signal is relayed to a computerized seismograph, which measures, displays, and interprets the returning echoes. Three-dimensional images can be generated either from a grid arrangement of geophones or from several transects using specialized software.

There are two types of seismic surveys: refraction and reflection. Refraction surveys interpret the refraction of sound waves as they encounter different materials. Greater resolution is provided with reflection surveys, which use the echo of sound waves that bounce back from the underground material to the surface, but this method requires more data and is therefore more time-consuming to conduct. Seismic surveys, particularly reflection surveys, can extend several hundred feet deep, but there is a tradeoff between depth and resolution of image. We are interested in shallow surveys (up to 50 feet deep) because the features important to ecosystem restoration are closer to the surface. For example, while tree roots can penetrate as much as 30 to 40 feet deep in search of groundwater, younger plants need shallower groundwater to become established.

Seismic technology has not been previously employed in ecosystem restoration, but it could be a very valuable innovation in this field. The images it produces allow scientists to reconstruct the geological history of an area and map present underground features, such as ancient stream beds, slough channels, or layers of impermeable hardpan supporting perched watertables. With this information, restoration specialists could target sites whose combined soil, subsurface, and water
conditions offer the best chances of successful, cost-efficient restoration. In addition, they could refine the restoration goals and techniques best suited to the site. In the MWT study it was hypothesized that a shallow seismic reflection survey could greatly enhance the understanding of the subsurface structure of the restoration site beyond what could be obtained from a coring study alone.

STUDY AREA

Tidal freshwater wetlands are a critical component of the coastal ecosystem in the San Francisco Bay (SFB) and Sacramento - San Joaquin Delta (SSJD) on the west coast of the United States. These wetlands exist primarily in the upper tributaries of estuaries, where salinity is less than 0.5 ‰ and water levels fluctuate in response to tidal exchange, local wind forcing, and winter river floods. They contain a wide array of nutrient rich aquatic and riparian environments, have the highest plant diversity of any coastal wetland type, and are critical buffer zones that protect estuaries against sediment, nutrients, and toxics from deleterious human activities. Although only a small area of the SFB-SSJD region contains tidal freshwater wetlands today, early explorers reported vast expanses. In the SSJD alone, land-use and pollution have destroyed 700,000 acres of overflow and seasonally inundated land, largely tidal freshwater marshes. Where tidal freshwater marshes were converted to farmland, agriculture faces significant and increasing exposure to floods and earthquakes.

The CALFED Bay-Delta Program, an element of a consortium of state and federal agencies, calls for ecosystem restoration in part to protect levee infrastructure and agricultural land. The Nature Conservancy, a private conservation group, has purchased the ~1,600 acre McCormack-Williamson Tract (MWT) in the northern Delta to restore it to tidal freshwater...
wetland. Knowing where on the tract restoration efforts should be focused would greatly reduce costs and significantly increase the likelihood of success. To provide The Nature Conservancy with the critical baseline data necessary for successful restoration, scientists from the University of California, Davis have joined ecologists and managers from The Nature Conservancy on investigative field research projects designed to reveal the chemical, physical, and biological dynamics of the MWT.

MWT (Fig. 1) is uniquely located at the head of the delta downstream from the confluence of the Cosumnes and Mokelumne rivers and adjacent to the Sacramento River. The Cosumnes River is the only major river flowing out of the Sierra Nevada whose mainstem is undammed. MWT is ~650 ha in area and is bordered by the Mokelumne River to the east, Snodgrass Slough to the west, and artificial dredge channels to the north and northeast. Historic maps show that MWT supported freshwater wetland in the early 20th century (United States Geological Survey, 1911). The wetland was likely tidal, as the adjacent channels are presently tidal for several miles upstream. Subsequently, the tract was leveed, drained, and converted into agricultural land. After drainage, MWT and other delta islands experienced subsidence as surface organic sediment was oxidised and decomposed (Rojstaczer et al., 1991).

PROJECT ACHIEVEMENTS

Geophysical Work- Phase 1

During the first phase of geophysical work, a StrataView seismograph system was rented to learn the technique, collect trial seismic lines on MWT, and to process the data to determine its relevance, if any. Geometrics, the top company selling seismographic systems, provided training and assistance on the methods for collecting seismic data. Subsequently, 5 seismic lines were
surveyed using the rental system and a sledgehammer seismic source (Fig. 1). Walkaway tests to optimize the return seismic signal yielded a typical offset of 40 ft between hammer location and the first geophone. Geophones were distributed along the selected transects in 3-5 ft increments. Generation of the seismic sound signal involved 6 hammer swings. Afer the signal was collected at one location the entire line was extended the length of the geophone increment and resampled, thus propagating the seismic sampling across the study site. . The numbers of spots per survey line ranged from 140-1100, yielding thousands of exhausting hammer swings per seismic line.

After the data was collected, a computer program, Winseis, was purchased and used to process some of the seismic lines to evaluate the performance of the approach with respect to restoration goals. Winseis was selected because it is the software that was written and used by leading government experts on seismic reflection. For comparison, commercial data processing software used in the oil exploration industry costs between $10,000-$100,000, which greatly exceeded our budget. Also, private consulting firms could process our seismic lines at a cost of ~$5 per shot, which corresponds to $1000-5000 per survey line, which would quickly exceed the cost of software and labor. The government experts, employees of the Kansas Geological Survey, provided some training on the use of Winseis and helped us process our trial survey data. Spectral analysis of the resulting seismic signal showed low energy in the high frequencies (Fig. 2), not conducive to near-surface profiling. The resulting seismic images showed near-horizontal subsurface strata and features to a depth of ~100 m (Fig. 4). The gently dipping u-shaped features are interpreted as wide, ancient channels deposits. These channels likely crosscut the MWT in the past. The presence of these paleochannels is consistent with the view that the MWT has been flooded frequently and cross-cut by channels many times in the past. These data suggested that
any future restoration activity on the MWT should consider restoring channels and associated
fluvial processes to the site.

**Geophysical Work- Phase 2**

Though the phase 1 research revealed some insight about past fluvial processes on the
MWT, such as channel incision and migration, the images were too deep to be directly useful for
comparing with the sediment cores and for guiding the on-going restoration effort. The primary
reasons for the deep imaging with too little resolution are directly related to the seismic source and
the geophones. Working in consultation with both the Kansas Geological Survey and Geometrics,
a significantly improved seismographic system was designed and built to acquire near-surface high-
resolution data. Key features of this system included higher frequency (40 Hz) geophones, a
custom-built seismic-rifle, digital seismograph technology, and a 72-channel seismograph. Several
technological and logistic hurdles had to be addressed before this cutting-edge approach could
work, as several elements of the system were completely new technology. Eventually all data
collection hurdles were overcome.

During the spring of 2002 the new seismographic system was used to develop a surveying
methodology for collecting seismic lines. Because live ammunition is used to generate the seismic
signal (Fig. 4), the effort was also coordinated with University of California police. In addition,
every member of the field crew participated in a fire-arms safety course and became NRA certified
for small-arms fire. To increase the resolution and decrease the depth of the survey, we had to
reduce the geophone spacing from 4 ft to 8 inches, with rifle-to-geophone offset of 18 ft.
Thankfully, the increase in the number of shot locations was exactly counteracted by the reduced
number of repeat shots necessary at each location- from 6 for the hammer down to 1 for the rifle,
as the rifle generated substantially greater energy per shot. However, the rifle barrel had to be placed into the ground for every shot, which required augering a 6-inch hole at every shot location using a gas-powered industrial auger. This proved difficult since the shot holes were so closely spaced, augering one hole would often cause the adjacent hole to collapse. Firing a single rifle shot is quicker, less tiring, and actually safer than making several swings of the hammer. Thus, overall the surveying time was slightly streamlined and more effective even though many more shot locations were sampled. The principle downsides were the cost of bullets and balloons (to protect the gun barrel from backsplash after firing into the ground), which amounted to $1 per shot. However, in the future this can easily be budgeted into the cost of using the system. To provide a consistent approach to data collection for future use by any TNC or UCD staff, we wrote a manual that explains the surveying process and includes many photos illustrating the procedure (Appendix A).

During the summer of 2002 seismic data was collected from MWT. We had originally proposed in our previous annual report to shoot 3 lines to delineate a paleo-wetland that was uncovered in the sediment cores (Fig. 1), but the estimated cost of performing such a survey based on a $1 per shot estimate (plus labor cost) was prohibitive given the remaining funds. Instead, we decided to use the system to shoot a single line over a section of one of the survey lines from phase 1 for three reasons. First, we wanted to have a direct comparison between the two systems so we could evaluate the improvement. Second, aerial photos suggested the presence of a near-surface paleo-channel at this location. We were interested to see if the new system could detect and profile this feature. Third, we had collected a core along this transect and could use the known lithology to help interpret the seismic line. For this new line we shot 1560 points, which amounted to more shots compared to any sledge-hammer line, confirming the efficiency of the new system.
The raw data had the best signal response we have seen, and a new software tool that came with the system showed that the rifle was in fact generating significant high frequency signals as hoped. As soon as the field surveying was finished, we started trying to process the data, but we ran into significant hurdles using WinSeis, and these problems have not been resolved. In collecting the field data we chose to record all the highest frequency features of the data, as needed for our restoration objectives, but this yielded much more data than in phase 1 and more than is commonly analyzed. Each shot is stored on the computer as an individual file, with each file being ~ 1-3 MB in size. With 1560 shots, the combined file size is close to 2 GB. Apparently, WinSeis has many built-in problems analyzing such large files, and it seems that there is a 2 GB limit for some commands. We have tried to obtain help from KGS to resolve our problems, but despite our previous payment for their help last year, they are not willing to help guide us through this new data analysis. Even with the help of a geophysics professor at UC Davis, Dr. Jim McClain, we could not get WinSeis to work properly. We have even offered to fly to Kansas at our own expense to obtain further help in data processing from the geological survey, but they surprisingly refused the offer stating that they only provide assistance with software defects and installation problems.

CONCLUSIONS

This project involved side-by-side collection and processing of sediment core data and seismic reflection data. The strength of the sediment coring approach is that you actually have the material to observe and analyze using many different techniques. The results are real and provide detailed insight into the history and evolution of the study site. As paleoenvironmental researchers, we use the sediment cores to travel back through time to observe the processes and
diversity that characterized MWT in the past. However, the weakness of this approach is that it is costly and was too time consuming to analyze all 12 cores that were collected in full multi-proxy detail. Instead, we elected to thoroughly study three long cores distributed longitudinally along MWT and the vibracore from Delta Meadows using the large range of scientific analyses possible at UC Davis. The remaining MWT cores were studied using a subset of analyses. The outcome of the coring investigation is a huge wealth of information on the history and geomorphic dynamics of MWT. These findings are in various stages of peer-reviewed publication at this time.

By contrast, seismic surveying was ultimately found to provide a characterization of the spatial extent of subsurface conditions. Unfortunately, the analysis of that characterization hinged on an inherently complex software package that consisted of multiple stand alone modules and no instruction manuals. To successfully process any data with this software would require written software manuals for reference, software training sessions, and a cooperative software support team to help with trouble-shooting. Kansas Geological Survey scientists have reported using a lower-technology surveying system compared to ours, and then using Winseis to analyze their data to yield very shallow images of subsurface conditions. We cannot confirm their reported findings, because Winseis has too many software bugs and is too convoluted for use by any persons outside of the original programmers and their immediate associates.

Our original plan was to test the seismic method at MWT, then apply this to other TNC restoration sites, but the problem of data analysis has rendered the system useless until this problem can be resolved. The final effort to work with Winseis ended in March. Three alternatives are being pursued. First, colleagues at Stanford University (with the collaboration of UC Davis) have submitted a proposal to the National Science Foundation for over $1 million for equipment and facilities for “near-surface characterization” of the earth’s surface. The project
funded by the Seaver Institute was several years ahead of this new Stanford initiative, and thus puts us in a terrific position to benefit from this new possibility. Second, we have contacted a colleague in the oil industry because commercial seismic software packages are industrial-strength utilities designed for the express purpose of production-level seismic processing. We are asking if she can provide technical assistance using their state-of-the art software for free or at a substantially reduced cost. Finally, we have recently learned of a freeware seismic processing program called CWP/SU Seismic Un*x that may be better than Winseis, but that is not yet known.

The grand conclusion for the seismic surveying approach is that the field data collection is affordable and practical for even non-technical staff to perform, but that extension of the technique for use throughout The Nature Conservency is limited by the current lack of means for processing the data.

ACKNOWLEDGEMENTS

The authors kindly thank The Seaver Institute, University of California, and CALFED (Ecosystem Restoration Program Co-op Agreement no. 114200J095) for providing funding for this research. Karen Burrow, Ron Huggins, Craig Lippus, Jianghai Xia, Jose Constantine, and Jim McClain provided suggestions on seismic analysis. We thank our collaborators at The Nature Conservancy—notably Ramona Swenson and Keith Whitener- for their joint participation as well as The Nature Conservancy in general for access to their land, help in field logistics, and partnership in research, outreach, and education. We are grateful to Ellen Mantalica, Kaylene Keller, and Diana Cummings for logistic support. We thank numerous volunteers for help in the field, including Derek Sappington, Laurel Aroner, Andy Ho, Colin Amos, Gwen Pikkarannien, Dave Benner, Jose
Constantine, Gerrit Schoups, Chuck Young, Brett Valle, and Eriko Suzuki plus the many others who volunteered their time.

APPENDIX A: Multiple Geode Operating System (MGOS) Manual
By
Kendrick Brown

1.0 Introduction

The Multiple Geode Operating System (MGOS) is a relatively simple software package designed for refraction and reflection geophysical field surveys. This manual will document the step-by-step deployment of a 72-channel seismograph and the subsequent collection of shallow reflection seismic data.

This manual is meant to complement the original manual, Geode™ and StrataVisor™ NZ Operations Manual, which accompanied the MGOS package. The original manual should be read before employment of the system in the field. Chapter 1 in the original manual is a good introduction to seismic research and provides an overview of the system. Chapter 2 emphasizes refraction studies whereas Chapter 3 emphasizes reflection studies. The original manual adequately introduces the reader to the MGOS system but does not detail the actual field deployment of the seismograph and software. Section 2.0 of this manual lists the contact information of persons who participated in the original development and deployment of our MGOS system and are useful sources of information for any future seismic study. Section 3.0 comprehensively lists the equipment that is necessary for the collection of seismic data with our system. Section 4.0 outlines the step-by-step setup procedure of the seismograph and associated field equipment as determined through a 4-week research operation in May, 2002. Section 5.0 details the software setup. Section 6.0 expands on Sections 4.0 and 5.0 by describing the actual field and software operations of a reflection survey. Section 7.0 concludes the field element of seismic signal collection.

2.0 Contact Information

As a precursor to any field research, it is important to have contact phone numbers in case of field emergencies and these should be determined at the start of any new investigation. Listed below are the phone numbers, names, and affiliations of persons involved in the original deployment of the seismograph. These numbers and personnel may change through time and should be checked and updated before any field excursions.

Contact: Dr. Greg Pasternack
Affiliation: University of California, Davis faculty member. Primary purchaser of seismic equipment and general contact person/coordinate for seismic equipment.
**Contact:** Dr. Ramona Swenson  
**Affiliation:** Ecologist at The Nature Conservancy (TNC). The seismograph, computer, and software are actually owned by TNC. Dr. Swenson was involved with the purchase of the equipment and should always be kept informed about its usage  
**Phone:** 916-684-4012

**Contact:** Jody Williams  
**Affiliation:** TNC employee. Purchased the equipment and has access to purchase records and receipts.

**Contact:** Craig Lippus  
**Affiliation:** Employee at Geometrics, the San Jose based company that sold the 72-channel seismograph and accompanying software to UCD and TNC. Can provide field assistance if requested.
**Phone:** 408-428-4244

**Contact:** Deb Underwood  
**Affiliation:** Employee at Geometrics, the San Jose based company that sold the 72-channel seismograph and accompanying software to UCD and TNC.
**Phone:** 408-428-4245

**Contact:** Ron Freshour  
**Affiliation:** Freshour Manufacturing Inc. located in Texas. Manufactured the seismic rifle and can be consulted about its design and general usage and maintenance.
**Phone:** 409-945-7726

**Contact:** The Shooting Gallery, Inc.  
**Affiliation:** Located at 27 Commerce Place, Vacaville, CA, 95687. The Shooting Gallery is the firearm store that registered the rifle. Also a good source for ammunition and rifle cleaning products (ammunition is about $2/box of 20 rounds cheaper if purchased at Wall-Mart)
**Phone:** 707-449-4867

**Contact:** Michael Oreschak  
**Affiliation:** University of California Police Department. Mr. Oreschak is the officer who provided information about the storage, transport, and usage of the seismic rifle and ammunition.
**Phone:** 530-752-1727

**Contact:** Jianghai Xia  
**Affiliation:** Kansas Geological Survey. Can help with post-collection data processing.
**Phone:** 785-864-2057
3.0 Equipment List

The equipment list is divided into 3 separate sections, including field, computer, and laboratory categories. This is a complete list of the equipment used during our trial deployment, though additional items may be necessary for the needs of other surveys.

3.1 Field Equipment

1. 72 40-Hz geophone (it is advisable to bring a few extra geophones on any field outing)
2. 3 geophone cables
3. 3 geodes
4. 3 geode patch cables
5. 3 geode-battery connectors
6. 1 geode-laptop adapter
7. 6 Yuasa sealed rechargeable lead-acid batteries
8. 3 tape measures (50 m+)
9. 1 trigger cable
10. trigger switches (two exist: a geometrics manufactured trigger and geophone that has been rigged to serve as a trigger)
11. 1 strike plate
12. 1 hammer
13. 1 seismic rifle (stored in pelican case). The following items should always be stored in the pelican case:
   a. 1 rifle barrel(s)
   b. 1 action (bolt assemblage and trigger. Note: The action should always be locked when not in use and during transport with a trigger lock)
   c. 2 trigger lock keys (Dr. Greg Pasternack retains extra keys in case of emergency)
   d. go-no-go cartridge (only one exists so be extra careful with this critical item)
   e. Allen keys (3/4 and 3/16 size)
14. 1 seismic rifle base plate
15. 30.06 ammunition (the amount should be determined at the beginning of any survey)
16. 1 can WD-40 lubricant
17. rifle cleaning supplies (brush, cloth tips, gunkout)
18. 1 auger
19. auger 2-stroke fuel (stored in labeled red gas container)
20. extra auger oil canister
21. 1 broom
22. several pairs of gloves
23. several pairs of ear-plugs
24. 1 GPS
25. first aid
26. water, sunscreen, hat

3.2 Computer Equipment (take into the field)
1. Gateway laptop computer with MGOS software installed
2. 6 Gateway computer Solo 9500 batteries

3.3 Laboratory Equipment
1. Schumacher 2/10/50 Amp Battery Charger

4.0 Field Equipment Setup

Several steps are required to setup the seismic equipment so that signal can be collected in the field. The following text details a sequence of steps required to set up the seismic equipment in the field.

1) Choose the site of the line (previous subsurface knowledge and airphotos may help in this endeavor).
2) Lay the tape measure out along the desired line. This should start at the first shot location and run to the 72nd geophone.
3) Place the geophones (spike first) into the ground along side the tape measure. Use the tape measure to ensure that the geophone spacing is even and regular.
4) Lay the geophone cable out next to the array of geophones that are planted firmly in the ground. Each cable has the capacity to connect to 24 geophones. The cables are considered “high end” cables, which means that they should be arranged according to geophone attachment slots. These slots range from a low of 1 at the start of the line to a high value of 24 at the end of the line. Examination of the cables reveals that each geophone slot is labeled with numbers 1-24. In addition (and incase the numbers rub off the geophone cable), it should be noted that the cables have attachments at both ends, one black and one red. The black attachment is at the low end (1) and does not plug into anything. The red attachment is at the high end (24) and plugs into a geode.
5) Connect geophones to the cables as illustrated below.
6) Connect geodes together using geode patch cables.
7) Connect one battery to each geode using the geode battery connector (red-on-red; black-on-black).
8) Run a patch cable from the first geode to the geode-laptop adapter.
9) Plug the geode-laptop adapter into the computer.
10) Connect the trigger cable to the first geode in the line.
11) Run the trigger cable to the first shot point.
12) If using the rifle, then auger seismic holes at desired intervals and move tape measure to end of the line. If using hammer leave tape measure out to assist with properly spacing the shots.

The next step is to assemble the rifle.
1) Remove the action trigger lock and place the key back in the pelican case.
2) Place the go-no-go cartridge in the top of the open barrel.
3) Screw the action onto the barrel with the go-no-go cartridge still in it. Make sure that the bolt is closed at this time.
4) When the action gets really tight loosen the action just a bit and then tighten the action onto the barrel using the 3/16” Allen key. Do not pull the trigger because the action’s firing pin may get damaged when it strikes the solid go-no-go cartridge.
5) Open the bolt and the go-no-go cartridge should pop out. Put the go-no-go cartridge back in the pelican case.
6) Loosen the bolt on the base plate.
7) Take the assembled action-barrel and place the barrel in the base plate, positioning it at the desired depth and lining up the barrel notches with the base plate clamp.
8) Turn the base plate clamp and tighten with a 1/4” Allen key. Tighten the bolt for extra safety (this acts as a lock).
9) Carry the gun out to the first shot location and place it in the augered hole.

The next step is to turn on the geodes (blue lights should be flashing) and then turn on the computer (check the battery to make sure it is at 100%). Launch MGOS software and proceed to Section 5.0 Computer Software Setup.

If the computer does not detect all of the geophones then it can be one of several things:
1) Check to make sure the geophones are all attached properly.
2) Make sure the geophones cables are properly connected to the geodes. From experience, these cables may appear screwed in, but if they are slightly crooked then some geophones may not register.
3) Make sure the geodes are properly connected together.
4) Check the geode computer connection.

5.0 MGOS Computer Software Setup

After the MGOS software is turned on, four windows should appear on screen, including a text, shot, noise, and spectra window. Reshape the shot window so it is a vertically oriented rectangle because this is the best configuration for viewing the data.

The text window can be used to view the initiation of the system to check that all geophones are registered and to track data collection.

The noise window should ALWAYS BE KEPT OPEN. If it is minimized then a resource leak is initiated in the software (this is a bug in the software) and the computer will eventually crash. The noise window is used to ascertain that all geophones are properly connected and attaining signal.

The spectra window shows the source frequency.
The shot window shows the actual data that is being collected with each shot and will change from shot to shot.

The first step is to set up the parameters for your survey. This is fairly simple, though several parameters must be set. The following list details those parameters starting at the left pull down menu and going to the right.

**Survey Menu:**

- Start a new survey and give it a name.
- Set initial line number to 1.
- Set initial tape number to 100 (though this does not matter because we are not saving to tape).

**Geom Menu:**

- Set survey mode to reflection.
- Set group interval to the value of the geophone spacing i.e. if the geophones are 1 m apart then set this value to 1 or if the are 80 cm apart set this value to 0.8.
- Skip group/shot location for now.
- Set phone increment to 0.
- Set shot increment to the same value as group interval. This value represents the distance between shots.
- Set gap to 0 for both hi and low settings.

**Observer Menu:**

- You can fill in a description of the survey under Edit Survey Description or simply skip this menu.
- Set the line number to 1 under New Line Number and set the starting file number to 1 plus some multiple of 1000. Geometrics suggests that the numbering system should be in the thousands, so the first file in a line should be, for example, 1001 or 5001 etc…

**Acquisition Menu:**

- In the sample interval/record length menu define the parameters that apply to the survey i.e. 125 ms sample interval; .5 or .25 sec record length; delay 0 sec.
- Set acquisition filters as needed though they do not need to be used because filters will be applied to the data in the post-collection processing phase.
- Correlation should be off (do not tick on) and set pilot to –1.
- Under the stack options menu select auto stack and set the stack limit equal to the number of shots per site.
- Skip specify channels for now.
- Select desired preamp gains to desired level i.e. all 24 dB.
- Set stack polarity positive; look in the text window to make sure this has been set.
File Menu:

- Under storage parameters:
  - Set the next file to be written to the same as the first file (i.e. 1001 or 5001). This parameter may have to be reset by 1 (i.e. 1536 back to 1535) during a survey if the software rolls right when data is not collected.
  - Set auto save on. Set stack limit to the same value as under the Acquisition Menu.
  - Set data type to seg-2.
  - Select save to disk and specify a path and directory.
- The Read Disk option allows the user to open a seismic data file (*.dat). This file can be viewed in the Shot Window.

Display Menu:

The display menu is simply a way of viewing the data and the parameters that are set under this menu and do not modify the raw data in any way. There are several submenus under the Display Menu and for best viewing these should be set as follows:

- **Shot Parameters**
  - Display boundary should be set from 1-72 channels and the time 0-.5 or .25 sec.
  - Gain style should be set to AGC with AGC window in samples = 250 and trace overlap = 1.
  - Set trace style to variable and do not clip.
  - Set the display filter as follows: select enable display filters and set roll-off at 24dB. Next set the high cut filter at 250 Hz, the low cut filter at 10 Hz, and the notch to out.

- **Spectral Parameters**
  - Set the start and end channels to 1 and the Hz range to 0-500.
  - Set the trace style to variable.
  - In the analysis parameters set the start time to 0 and the end time to 0.5. Also select horizontal trace display.
  - Select autoscale traces under display gains.

- **Noise Monitor Parameters**
  - Set the plot blue trace to 12 traces.
  - The noise scale values can be adjusted by activating the noise monitor and using the up and down arrow keys to examine the noise. The best configuration is where the amplitude of the noise is equal to about 0.5 the trace width.

Do Survey Menu:

This menu provides the user with short-cut keys that can be used during a survey instead of the mouse. Some shortcut keys worth remembering include:

- Arm/Disarm: by pressing “1” the software can be manually armed or disarmed. When the software is armed it is capable of attaining signal. When disarmed, the software
is in a deactivated mode and cannot collect data even if a seismic source is set off (i.e. a shot fired).

- Shot Location: Key “3” is used to quickly show the next shot location to be written.
- Noise Display: The noise display can be displayed by pressing “4”.
- If the traces do not appear or appear as straight lines in the shot window during a survey then they can be displayed by pressing the auto scale traces key “6”.
- Save: The next file to be saved can be displayed by pressing “7”.
- Channels (geophones) can and must be advanced along a line using roll right or reversed using roll left if accidentally moved forward or if a shot has to be redone. The END key causes the software to roll right whereas the HOME key causes the software to roll left.

**Window Menu:**

Various windows including noise, trace, spectra, and log can be activated using this menu. The various windows can also be tiled and restored through this menu.

**Answers Menu:**

A help menu for refraction surveys.

**Print Menu:**

 Allows individual shots and spectra to be printed.

**System Menu:**

Various survey parameters can be set under this menu. The most important include:

- The date, time and units setting. This is where the survey units (either feet or meters should be set).
- The trigger option is also very important. The trigger should be set to automatic with a 0 second holdoff. Trigger sensitivity will have to be determined for the type of trigger that is being used but a value of 20 (relatively low) is a reasonable starting value. This value will enable slight movement in the trigger without accidentally setting it off whereas a higher value like 95 will make the trigger very sensitive and it could easily be initiated by slight movement.

**Final Preparation:**

The final step is to check the configuration of the survey. This can be done in either the **Geom Menu: Group/Shot Locations** or in the **Acquisition Menu: Specify Channels**. This should be done at the start of any survey and then the software will continually update the configuration as
the survey progresses, though it is advisable to check the configuration periodically or after a line is moved.

1) Make sure the shot coordinate is set to the offset distance between the shot and the first geophone. For example, if the shot is 10 m behind the first geophone, then the shot coordinate is set to 10. Make sure that the proper units (meters versus feet) are set (if not, then set this parameter under the System Menu).

2) The interval values are the distance between shots. This value should be constant along the line. Enter this value in each space.

3) The geophone coordinate represents the spatial distribution of geophones along the line. The first geophone is positioned at the start of the line and should be labeled as 0. By pressing the right arrow key, the other fields should be filled in automatically. These values should increment according to the interval value.

4) The gain is set under the Acquisition Menu.

5) The “use” option is where the desired geophones are activated. For example, in a typical survey 3 geodes are spread out along a seismic line and each geode is connected to 24 geophones for a total of 3 geodes x 24 geophones/geode = 72 geophones. Therefore, when shooting a line geophones 1-48 are active at the start and 49-72 are inactive for the first shot. For the second shot geophones 2-49 are active and geophones 1 and 50-72 are inactive. During the third shot, geophones 3-50 are active and 1,2, and 51-72 are inactive, etc…The 24th shot will have geophones 24-72 active and 1-23 inactive. Therefore, at the start of a line it is important to activate and inactivate the appropriate geophones. In the use option, press “1” to activate the geophones and then use the slide scale bar and move to geophone #49, place the cursor in the geophone 49 slot and press “4”. This action will inactivate every geophone from #49 to the end of the line. Activated geophones are ready to collect “data” whereas “inactivated” geophones will be labeled accordingly.

6) Set freeze to no.

6.0 Conducting A Reflection Survey

The system should now be set up properly to conduct a survey. There are several simple steps that now must be followed.

1) Activate the software so it can receive signal by pressing “1”, again note that the software will signal that it is “busy” on the bottom left corner. Simply wait a few seconds as it prepares for signal acquisition.
2) Generate the seismic signal (i.e. swing the hammer or shoot the rifle).
3) Examine the signal in the shot window. If it looks good, roll the software right to activate the next group of geophones (i.e. 1-48; 2-49; 3-50 etc…) by pressing the end key.
4) Clear the window by pressing the “enter” key on the laptop.
5) Activate the software again by pressing “4”.
6) Generate the next seismic signal
7) Proceed in this fashion, repeating steps 1-6 until the end of the line is reached. This will happen after 24 seismic signals have been fired.
8) Make sure all data was saved in the “File Menu”-Read Disk directory.
9) Turn the computer off to save battery power.
10) Next move the first geode and 24 geophones to the end of the line where geophone number 72 is located, and set them up again as described in the Field Equipment Setup. Essentially the first geode and 24 geophones are being appended to the end of the line so that the line can be extended in a leap-frog fashion.
11) Turn the computer on check the configuration in either the Geom Menu: Group/Shot Locations or in the Acquisition Menu: Specify Channels, being sure that the proper geophones are activated. All other setting will be saved and do not have to be adjusted.
12) Start shooting the line again as in step 1.

7.0 Post-Collection Data Processing

After the seismic survey is completed, the raw seismic data has to be processed using WinSeis or some other seismic processing softer. Dr. Greg Pasternack (see Section 2.0) has a hardcopy manual that documents the processing steps required by the WinSeis software.
Figure 1. Arial photograph of the MWT showing core locations (blue dots), summer 2000 seismic lines (red lines), and planned Summer 2002 seismic lines (green lines). The Geoprobe cores that were analyzed in the laboratory are labeled 2, 6, and 8 whereas the analyzed Delta Meadows vibracore is labeled DM.
Figure 2. Frequency spectrum of the raw seismic data. Most of the energy generated by the sledgehammer yielded waves in the 5-35 Hz range. The send-phase seismic-gun generated more energy in the >40 Hz range. 40-Hz geophones then captured the widest spectrum of usable data (thick line is zone of best reading and thin line shows range of observation) whereas 100-Hz geophones would miss a lot of potential information. This new configuration optimized the effort to image the shallow subsurface relevant to restoration.
Figure 3. Seismic image of the MWT showing gently dipping u-shaped features, possibly representing ancient channels (shown in white boxes) that have cross-cut the tract.
Figure 4. The "seismic-rifle" used during seismic profiling.