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Sediment transport in the San Francisco Bay Coastal System: An overview

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ABSTRACT

The papers in this special issue feature state-of-the-art approaches to understanding the physical processes related to sediment transport and geomorphology of complex coastal–estuarine systems. Here we focus on the San Francisco Bay Coastal System, extending from the lower San Joaquin–Sacramento Delta, through the Bay, and along the adjacent outer Pacific Coast. San Francisco Bay is an urbanized estuary that is impacted by numerous anthropogenic activities common to many large estuaries, including a mining legacy, channel dredging, aggregate mining, reservoirs, freshwater diversion, watershed modifications, urban run-off, ship traffic, exotic species introductions, land reclamation, and wetland restoration. The Golden Gate strait is the sole inlet connecting the Bay to the Pacific Ocean, and serves as the conduit for a tidal flow of ~8×10^9 m^3/day, in addition to the transport of mud, sand, biogenic material, nutrients, and pollutants. Despite this physical, biological and chemical connection, resource management and prior research have often treated the Delta, Bay and adjacent ocean as separate entities, compartmentalized by artificial geographic or political boundaries. The body of work herein presents a comprehensive analysis of system-wide behavior, extending a rich heritage of sediment transport research that dates back to the groundbreaking hydraulic mining-impact research of G.K. Gilbert in the early 20th century.

1. Introduction

San Francisco Bay (Fig. 1) is the largest estuary on the U.S. West Coast, and the 2nd largest in the United States (Conomos et al., 1985); combined with the contiguous Sacramento–San Joaquin Delta (Fig. 2) it covers a total surface area of ~4100 km^2 and a watershed area of ~162,000 km^2. It contains several economically significant harbors ($20 billion worth of cargo annually) in one of the most developed regions of the United States, with a surrounding population of over seven million people. San Francisco Bay and the adjoining Delta are among the most human-altered estuaries and hydrologic systems, respectively, in the world (Knowles and Cayan, 2004). Major historical changes were driven by the extensive hydraulic mining influx of sediment in the late 19th century (e.g., Gilbert, 1917), massive alteration of the drainages entering San Francisco Bay in the 20th century (e.g., Wright and Schoellhamer, 2004), and the enormous amounts of sediment removed throughout the San Francisco Bay Coastal System from the early part of the 20th century to the present (e.g., Dallas and Barnard, 2011). The system is well-advanced along the timeline of human development common to many estuaries, i.e., disruption (mining, deforestation, agriculture, urbanization) in the watershed that increases load, followed by dams, water diversions, and river management that reduce variability and thus sediment supply, and now restoration of damaged habitats. The many alterations to the system have resulted in significant changes to the Bay floor, area beaches, Bay-fringing tidal marshes, and ecosystems, serving as an example for understanding the evolution of other estuaries. Coupled with strong anthropogenic signals, distinct and powerful natural processes make this region the ideal scientific laboratory for analyzing sediment transport processes, including strong seasonal variability between wet and dry seasons, well-defined flow pulses, strong interannual variability of freshwater inflow, well-defined estuarine boundaries, and strong seasonal variations in wind strength. In addition to the above, intense resource management has provided a critical mass of modern data and studies.

This special issue is a culmination of nearly 100 years of sediment transport research in the San Francisco Bay Coastal System. Here we present ~20 papers, representing the state-of-the-art in sediment transport research on many topics, ranging from tidal marsh sustainability, suspended sediment transport variations, bedform migration and evolution, behavior of the open coast littoral system, and fluvial inputs. The intention of this introductory paper is to describe prior research that forms the basis of our understanding of the fundamental processes that shape this complex coastal–estuarine system, and to clearly identify the data gaps that are addressed in this special issue.

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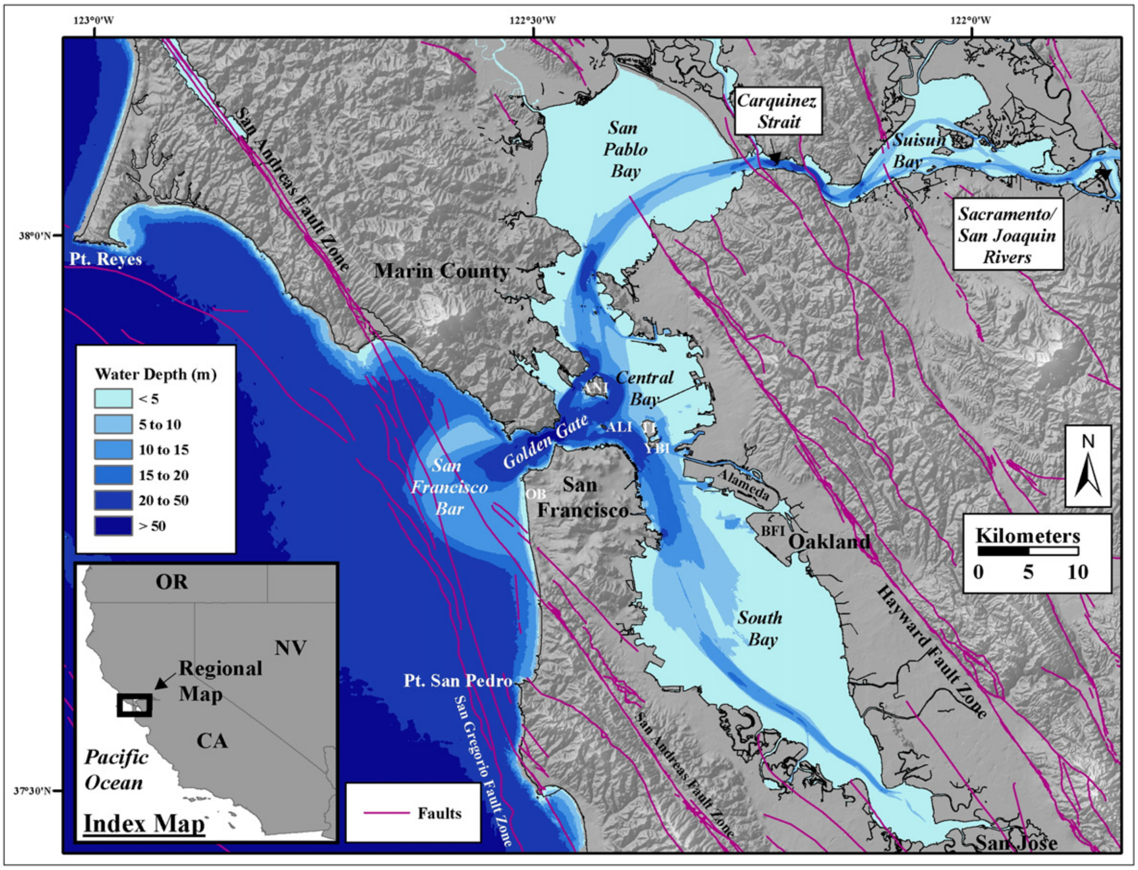

Fig. 1. The San Francisco Bay Coastal System, including major tributaries. Fault lines from U.S. Geological Survey (2006). (ALI = Alcatraz Island, ANI = Angel Island, BFI = Bay Farm Island, OB = Ocean Beach, TI = Treasure Island, YBI = Yerba Buena Island).

Despite the legacy of sediment transport research in the San Francisco Bay Coastal System, there are still some fundamental questions that remain unanswered, which this special issue addresses.

1) What are the primary sediment transport pathways, sources and sinks?
2) How has sediment delivery to the estuary changed over the course of the last century?
3) What is the net direction of sediment transport across the Golden Gate? Is the Bay a net importer or exporter of sand?
4) Is there a geochemical signature that can link sediment inside and outside the Bay?
5) What is the current trend of suspended sediment concentration in the Bay? What are the ramifications of this signal for marsh sustainability as sea level rises during the 21st century?
6) How will current trends in sediment transport dynamics and projected climate change affect the future morphological evolution of the San Francisco Bay Coastal System?
7) How do physical processes and topography control circulation and sediment transport patterns?
8) Can fine sediment transport and morphological evolution be effectively simulated with numerical models?

While this special issue will have direct implications for the regional management of the San Francisco Bay Coastal System, the techniques applied and physical processes analyzed throughout this special issue are on the cutting edge of sediment transport research, and add to the collective knowledge base and understanding of coastal–estuarine systems worldwide.

2. Historical geomorphology and sediment transport

2.1. Early history of San Francisco Bay

San Francisco Bay is situated in a tectonically active basin created from a structural trough that formed during the late Cenozoic (Lawson, 1894, 1914; Atwater et al., 1977; Atwater, 1979). It is bordered by the Hayward Fault Zone to the east and the San Andreas Fault Zone to the west (Fig. 1), which are both associated with the plate transform motion of the San Andreas Fault system (Parsons et al., 2002). The basin has been occupied by an estuary during interglacial periods, and was traversed by a fluvial system during glacial periods, with the current drainage configuration from the Central Valley established by ~0.4–0.6 Ma (Lawson, 1894, 1914; Atwater et al., 1977; Atwater, 1979; Sarna-Wojcicki et al., 1985; Harden, 1998; Lanphere et al., 2004). The open-coast shoreline was located approximately 32 km west of its present position during the Last Glacial Maximum (~18 ka), the current position of the continental shelf break. The basin was most recently flooded during the Early Holocene (Gilbert, 1917; Louderback, 1941, 1951), between 10 ka and 11 ka, as rising sea level inundated the Sacramento River channel that cuts through San Francisco Bay, through the Golden Gate straight, and across the continental shelf (Atwater et al., 1977). Schweikhardt et al. (2010) interpreted the oxygen isotopic composition of foraminifera in a sediment core taken from San Francisco Bay to indicate that the modern estuary was established by 7.7 ka, by 7.4 ka the estuary was highly stratified, and within another century a gradual decrease in water column stratification produced conditions that are similar to the modern, partially-mixed estuary. In the Delta, marshes began forming approximately 6.8 ka, which is likely

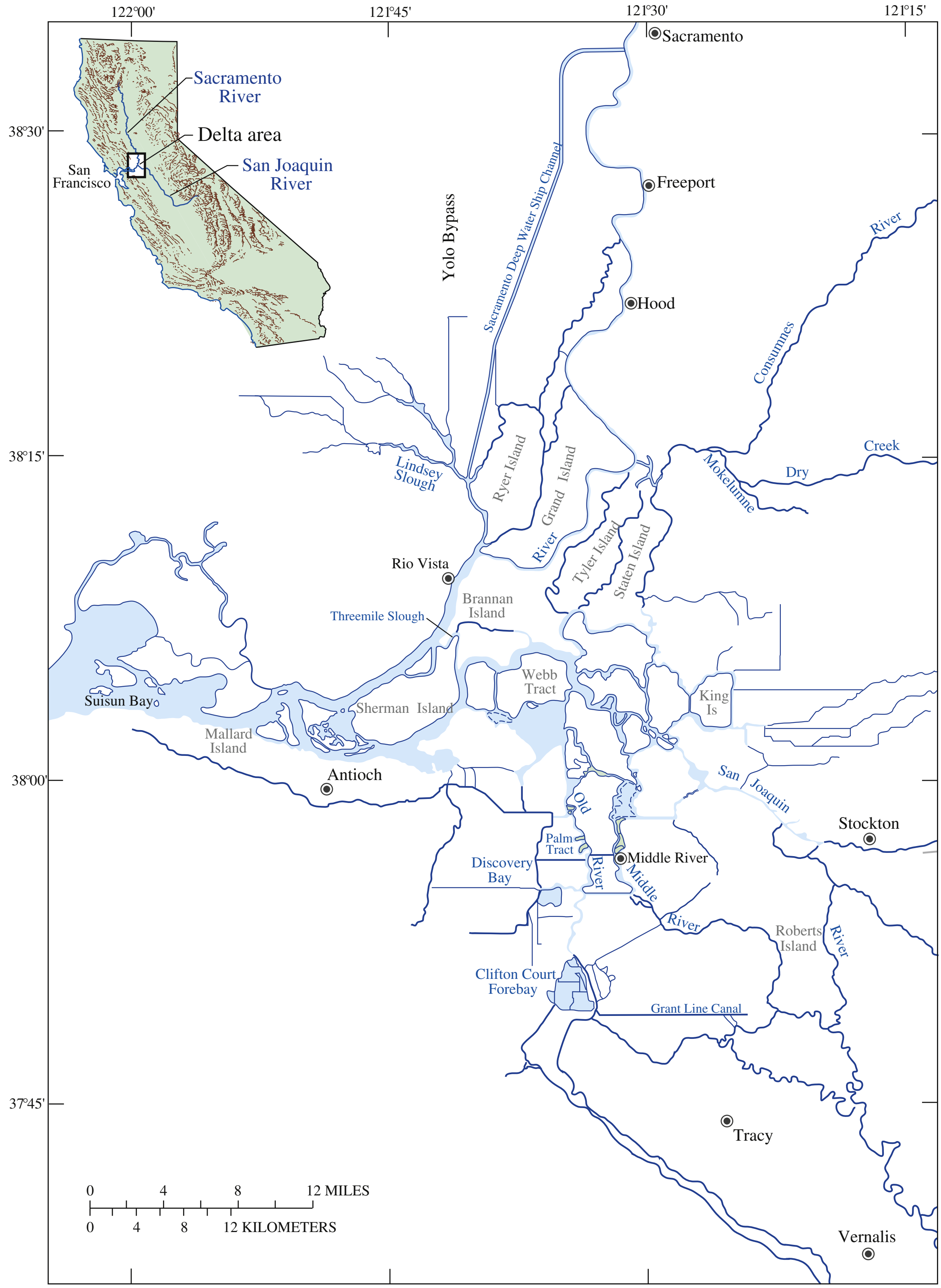

Fig. 2. The Sacramento–San Joaquin Delta.

related to inundation from rising sea-levels at that time (Drexler et al., 2009). After rapid sea level rise in the Early Holocene of up to 2 m per century (Atwater et al., 1977), Central Bay and San Pablo Bay had filled their current basins by ~5 ka (Atwater, 1979), with evidence suggesting the initial development of fringing tidal salt marshes at ~4.7 ka (Goman et al., 2008). McGann (2008) recognized numerous climate oscillations between warm/dry and cool/wet conditions over the last 3.9 ka, based on the faunal assemblages and an isotope record of a core from South Bay that are shaped by variations in fluvial discharge and water temperature. The top of the core is dominated by the invasive foraminifera *Trochammina hadai*, an indicator of pollution and eutrophication of the modern estuary, that is thought to have arrived in San Francisco Bay in the early 1980s (McGann et al., 2000).

2.2. Modifications to the natural system

2.2.1. Hydraulic mining

Major anthropogenic changes to the Bay (Fig. 3) began during the period of large-scale hydraulic gold-mining in the Sierra Nevada from 1852 to 1884 (Gilbert, 1917; Krone, 1979) and have continued to the present. Over 850 million m^3 of sediment was discharged into watersheds that drain into San Francisco Bay due to hydraulic mining (Gilbert, 1917), with a net sediment deposition of over 350 million m^3 in the Bay between 1856 and 1887 (Capiella et al., 1999; Foxgrover et al., 2004; Jaffe et al., 2007; Fregoso et al., 2008). This period of high sedimentation also coincided with abnormally high regional precipitation conditions: stations in Southern California established annual and monthly precipitation records in the 1880s, and the 3 largest floods in the historical record occurred between 1861 and 1891 (i.e., January 1862, December 1867, and February 1891). The first flood had well-documented massive, state-wide impacts (Engstrom, 1996), and the latter two were associated with El Niños (Sidler, 1968; Quinn et al., 1987). These resulting anomalous discharge conditions aided the movement of sediment into San Francisco Bay during this time period. Due to this enormous sediment influx, there was a dramatic seaward migration of the Bay shoreline, including the development of extensive intertidal flats and tidal marshes (Gilbert, 1917; Peterson et al., 1993; Jaffe et al., 2007). Bouse et al. (2010) quantitatively linked the sediment produced by hydraulic mining with the massive influx of sediment in San Francisco Bay using radionuclide dating, bathymetric reconstruction, and geochemical tracers, including mercury. In addition, surface sediment cores extracted in 1990 were still found to contain up to 43% hydraulic mining debris, indicating an ongoing remobilization and redistribution of this sediment within the system, with mercury contamination still posing a concern (David et al., 2009). Gilbert (1917) estimated that the effects of the mining would continue until ~1960s, and it has been demonstrated that the main pulse of bed sediment passed Sacramento by 1950 (Meade, 1982), aided by the construction of dams throughout the watershed (Wright and Schoellhamer, 2004).

2.2.2. Delta and other watershed modifications

Construction of dams, reservoirs, flood-control bypasses, and bank protection in the 20th century trapped and/or reduced the transport of sediment to the Bay (e.g., Brice, 1977; Wright and Schoellhamer, 2004; Whipple et al., 2012). Three of the largest dams in the Sacramento River watershed (Oroville, Folsom, and Englebright), which were constructed between 1940 and 1967, had impounded 85 Mm^3 of sediment by the end of the 20th century (~96 Mt, assuming a specific dry weight of the sediment deposit of 1121 kg/m^3; Vanoni, 1975) (U.S. Bureau of Reclamation, 1992; California Department of Water Resources, 2001; Childs et al., 2003). Not only do dams and reservoirs trap sediment, they also regulate down channel flows, often reducing or eliminating the peak flows that transport the majority of the sediment. However, there is no evidence of this in the Delta (Wright and Schoellhamer, 2004) where the frequency of high flows has been increasing (Schoellhamer, 2011). Canuel et al. (2009) determined that sediment accumulation rates in the Delta were 4–8 times greater prior to 1972 than after, and Jassby et al. (2002) noted a decrease in suspended-solid concentrations in the Delta from 1975 to 1995.

On the other hand, the extensive levee system in the Central Valley and Delta has served to isolate the flood plain from the main river

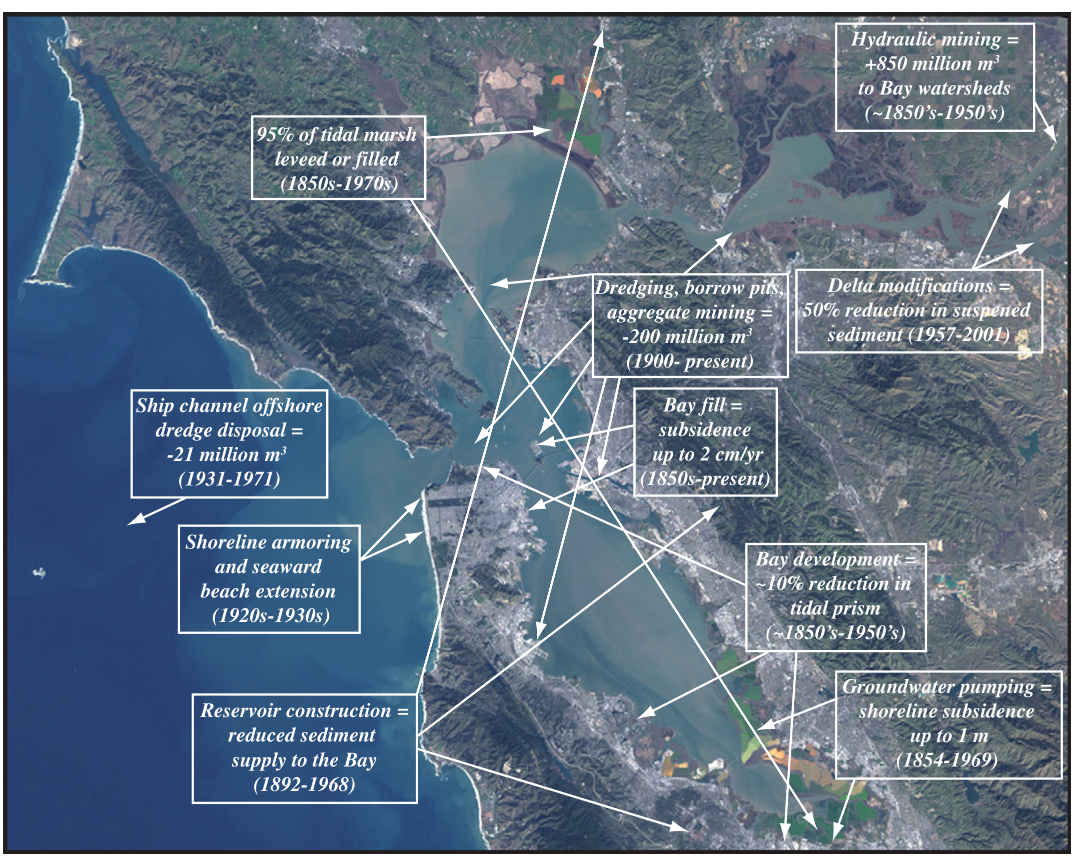

Fig. 3. Examples of major anthropogenic activities and approximate time period of influence to the San Francisco Bay Coastal System. See text for appropriate references.

channels, potentially increasing the sediment yield, along with logging, urbanization, agriculture, and grazing (Wright and Schoellhamer, 2004; Whipple et al., 2012). Construction activities and other forms of urbanization can generate sediment yields that are two orders of magnitude higher than erosion rates reported for stable urbanized areas, and even higher when compared to primarily natural areas with low or no measurable human impact (Lewicki and McKee, 2010). Suspended sediment yield from Guadalupe River, a small tributary watershed draining to the South Bay, was 4–8 times higher in the mid-20th century, during urbanization, than the early 21st century (McKee et al., 2004; Schoellhamer et al., 2008b), and yields from the Alameda Creek watershed also draining to the South Bay, Colma Creek, south San Francisco, and Cull Creek in the East Bay hills also appear to have decreased since the 1960s (Philip Williams and Associates and San Francisco Estuary Institute, 2006). However, overall it is not clear what the trends have been over the longer history of intensive local watershed development in the 9-county Bay Area since the 1850s.

2.2.3. Subsidence

Extensive groundwater pumping in the Santa Clara Valley, particularly from 1916 to 1966, led to as much as 4 m of local subsidence in San Jose, including up to 1 m of subsidence along the southern reaches of the South Bay shoreline, leading to the extensive flooding of low-relief land adjacent to the Bay (Poland and Ireland, 1988). In response, vegetation in South Bay shifted from high marsh vegetation to cordgrass but widespread marsh degradation did not occur because of rapid surface sediment accumulation (Patrick and DeLaune, 1990; Watson, 2004). Some of the submerged land has been recovered over the last several decades due to more responsible groundwater pumping practices (Galloway et al., 1999; Schmidt and Bürgmann, 2003). More recently, the largest vertical rates of change measured in the San Francisco Bay area are actually due to non-tectonic processes, particularly the consolidation of Bay mud and artificial fill that comprise a large proportion of the area's shoreline. For example, the northwestern tip of Treasure Island dropped ~2 cm/year from 1992 to 2000 (Ferretti et al., 2004), and subsidence up to 1 cm/year occurs along natural, mud-dominated shoreline areas (Bürgmann et al., 2006).

2.2.4. Direct sediment removal and Bay modifications

Over the last century, a minimum of 200 million m^3 of sediment has been permanently removed from the San Francisco Bay Coastal System through dredging, aggregate mining, and borrow pit mining, including at least 54 million m^3 of sand-sized or coarser sediment from Central Bay (U.S. Army Corps of Engineers, 1996; Friends of the Estuary, 1997; Chin et al., 2004; Dallas, 2009; Dallas and Barnard, 2009, 2011). From the mid-19th to late 20th century, the tidally-affected surface area was reduced by ~two-thirds due to ~95% of the tidal marsh in San Francisco Bay and the Delta being leveed or filled (Atwater et al., 1979).

Aggregate mining has been active in San Francisco Bay starting in the late 1800s, particularly on Point Knox and Presidio Shoals in Central Bay, with removal regulated since 1952. Aggregate mining currently removes approximately 0.9 million m^3/year of sediment in Central Bay and Suisun Bay (Hanson et al., 2004). Dredging removes about 3 million m^3/year of sediment out of navigation channels and from other channel and berth maintenance projects, with the majority of this material permanently removed from the San Francisco Bay Coastal System via deep-water disposal in the Pacific Ocean (Dredged Material Management Office, 2008; Keller, 2009; San Francisco Estuary Institute, 2009), roughly equivalent to the annual sediment supply from the Central Valley (Schoellhamer et al., 2005).

In Central Bay, human impacts include active sand mining, dredging and disposal, artificial shoreline fill, borrow pit mining, and underwater rock pinnacle blasting (Chin et al., 1997, 2004, 2010; Dallas, 2009; Dallas and Barnard, 2009, 2011; Barnard and Kvitek, 2010). From 1855 to 1979, 92% of tidal marsh and 69% of intertidal mud flats were eliminated from Central Bay by human development, resulting in total area loss of 4%. Bathymetric change at a borrow pit created near Bay Farm Island from 1947 to 1979 indicates the removal of 25 Mm^3 of sediment (Fregoso et al., 2008). Navigational dredging of Oakland Harbor began in 1874 and eventually at ~17 sites in Central Bay: a total of ~70 Mm^3 of sediment was removed from 1931 to 1976 (U.S. Army Corps of Engineers, 1975). Some of this material was used on land, some disposed of nearby, such as just offshore of Alcatraz Island and Yerba Buena Island that occasionally created dangerous shoals, and some at deep-water disposal sites. Borrow pits in Central Bay were utilized for numerous major developments, including the 22.5 Mm^3 dredged to create Treasure Island in 1935 (Scheffauer, 1954).

2.3. Changes to the historical sediment supply

Prior to the Gold Rush in 1849, Gilbert (1917) estimated that the sediment supply from the Delta to the Bay was ~1.5 Mm^3/year (or 1.3 Mt/year assuming a bulk density of 850 kg/m^3 per Porterfield, 1980). Based on bathymetric change data, Gilbert (1917) calculated a total sediment load of 876 Mm^3 between 1849 and 1914 (13.5 Mm^3/year, 11.5 Mt/year, 9 times the pre-Gold Rush rate), with 38 Mm^3 passed through to the Pacific Ocean. The sediment supply peaked near 1884 at > 24.9 Mt/year (Ganju et al., 2008).

Historically, the majority of the sediment load to San Francisco Bay was supplied from the Delta (Krone, 1979; Porterfield, 1980), with the Sacramento River producing seven times the sediment yield of the San Joaquin River (Oltmann et al., 1999). Porterfield (1980) used rating curves from individual Bay tributaries to estimate a total load of 6.6 Mm^3/year (5.6 Mt/year) from 1909 to 1966, 86% of this coming from the Delta. From 1957 to 1966 the load from the Delta was slightly less at ~83%. Porterfield (1980) sampled the Sacramento River bed numerous times in the 1960's during a range of flow conditions, and found the median grain size (D_{50}) to consistently range between 0.29 and 0.39 mm. From 1957 to 1966, bedload was estimated to account for 1.4% of the total sediment discharge, but sand discharge accounted for 52% of the total load. The San Joaquin River carried much less sand during this period, only 28% of the total load. Porterfield (1980) also used Gilbert's (1917) projections to estimate a total flux to the ocean of only 0.3 Mm^3/year from 1909 to 1966, 5% of the estimated supply that entered the Bay annually. Suspended sediment loads decreased by 50% from the Sacramento River from 1957 to 2001, from ~2-3 Mt to 1–2 Mt, or a total reduction of ~25 Mt (Wright and Schoellhamer, 2004; Singer et al., 2008). Schoellhamer et al. (2005) estimated that by the end of the 20th century, sediment supply to the Bay from the Delta and local tributaries was roughly equal, a trend that had been predicted by Krone (1979) and most recently confirmed by Lewicki and McKee (2010).

Ganju et al. (2008) used these prior studies as a guide to reconstruct decadal sediment loads for the Sacramento–San Joaquin Delta from 1851 to 1958, with measured data since 1958 (Ogden Beeman and Associates, 1992; USGS, http://waterdata.usgs.gov/nwis) used to complete the historical sediment load time-series (Fig. 4). Ganju et al. (2008) estimated a decrease in mean annual sediment loads to the Delta from a high of greater than 10 Mt/year in the late 19th century to less than 3 Mt/year in the latter half of the 20th century, with a dramatic decrease after 1910. The timing of dramatic changes in sediment loads is tied to the onset and subsequent cessation of hydraulic mining, followed by major Delta modifications, including the construction of reservoirs, in-stream diversions in the Sacramento and San Joaquin Valleys, and in-Delta withdrawals (e.g., freshwater pumping) (Knowles and Cayan, 2004).

2.4. Geomorphic response of the San Francisco Bay Coastal System

The precise impact of the aforementioned disturbances and changes to the sediment supply for the San Francisco Bay Coastal System is

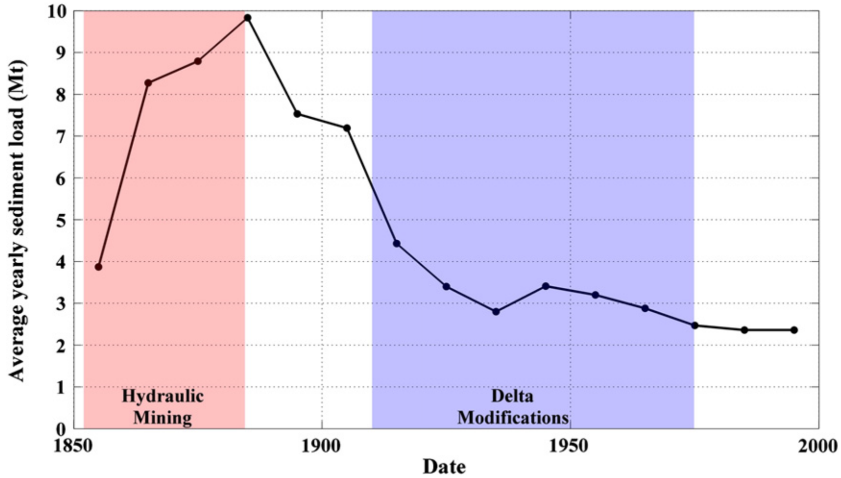

Fig. 4. Reconstructed decadal sediment load from the Sacramento and San Joaquin rivers (from Ganju et al., 2008, using bulk density estimates of 529 kg/m^3 per Schultz, 1965; Krone, 1979), with the major periods of hydraulic mining (1852–1884) and Delta modifications (1910–1975) highlighted.

difficult to quantify, although a series of bathymetric change studies have been effective in developing potential causal links. Net sediment volume changes to the Bay from 1855 to 1989 were derived from measured historic bathymetries by Capiella et al. (1999), Foxgrover et al. (2004), Jaffe et al. (2007), and Fregoso et al. (2008). These studies, coupled together, are summarized as follows: +350 Mm^3 (1855–1887) attributed to hydraulic mining; +10 Mm^3 (1887–1922) attributed to flushing out of hydraulic mining sediment into the Pacific Ocean; +120 Mm^3 (1922–1947) attributed to additional influxes of stored hydraulic mining sediment, and urbanization and increased agricultural land use in the watersheds; −180 Mm^3 (1947–1989) attributed to sediment trapping/diversion in the Delta, waning of the hydraulic mining and urbanization pulses, and direct removal of sediment from the Bay for dredging, aggregate mining, and borrow pits (Barnard and Kvitek, 2010; Dallas and Barnard, 2011; Schoellhamer, 2011).

After an estimated net of 115 Mm^3 of sediment was deposited in Suisun Bay from 1867 to 1887, the sub-embayment quickly began to erode, with a total net loss of ~262 Mm^3 from 1887 to 1990 (Capiella et al., 1999), largely attributed to the cessation of hydraulic mining and river management projects (Wright and Schoellhamer, 2004). San Pablo Bay only became net erosional in the mid-20th century (Jaffe et al., 2007).

Fregoso et al. (2008) demonstrated that Central Bay gained 42 Mm^3 of sediment from 1855 to 1979, but there were periods of erosion (−2 Mm^3/year, 1855–1895) and accretion (+3 Mm^3/year, 1895–1947). Most notably, the last time period was net erosional (−2 Mm^3/year, 1947–1979), particularly in West-central Bay (−31 Mm^3), coinciding temporally and spatially with the onset of large-scale aggregate mining.

Focusing on the last half-century for the entire San Francisco Bay Coastal System, sediment loss trends have been documented in North Bay (i.e., San Pablo (Jaffe et al., 2007) and Suisun Bay (Capiella et al., 1999)), Central Bay (Fregoso et al., 2008; Barnard and Kvitek, 2010), and the San Francisco Bar (i.e., mouth of San Francisco Bay: Hanes and Barnard, 2007; Dallas and Barnard, 2009, 2011), with only South Bay showing net accretion (Jaffe and Foxgrover, 2006) (Fig. 5). The mouth of San Francisco Bay lost over 90 million m^3 of sediment between 1956 and 2005 (Hanes and Barnard, 2007), Central Bay lost 52 million m^3 of sediment between 1947 and 1979 (Fregoso et al., 2008), and an additional 14 million m^3 of sediment between 1997 and 2008, linked directly to aggregate mining (Barnard and Kvitek, 2010). Applying rates of volume change for each sub-embayment and the San Francisco Bar from 1956 to 2005 would result in an estimated sediment loss of 240 million m^3 from the entire San Francisco Bay Coastal System. In 1999 there was a 36% step decrease in suspended sediment concentrations observed inside the Bay between the 1991–98 and the 1999–2007 water years, broadly attributed to the depletion of the 'erodible sediment pool' created by hydraulic mining and possibly urbanization, and further reduced by river bank protection, and sediment trapping behind dams and in flood bypasses (Schoellhamer, 2011).

For the open coast, there has been a net reduction of the surface area and volume of the ebb-tidal delta since the late 19th century, which has been linked to the decreasing sediment supply from San Francisco Bay and shrinking of the tidal prism (Gilbert, 1917; Conomos, 1979; Battalio and Trivedi, 1996; Hanes and Barnard, 2007; Dallas, 2009; Dallas and Barnard, 2009, 2011). As further evidence of the reduced sediment supply, the historical rates (late 1800s to 1998) of shoreline erosion south of San Francisco are the highest in California (Hapke et al., 2006, 2009) and have accelerated by 50% between Ocean Beach and Pt. San Pedro (Fig. 1) since the 1980s (Dallas and Barnard, 2011). Along with a reduced sediment supply, grain size, and tidal prism that have been linked to persistent regional erosion (Barnard et al., 2012b), scour associated with an exposed sewage outfall pipe that was constructed in the late 1970s offshore of Ocean Beach has locally exacerbated coastal erosion (Hansen et al., 2011).

The geomorphic and sedimentary changes caused by the hydraulic mining sediment pulse and its subsequent diminishment have affected the estuarine ecosystem. Hydraulic mining sediment contributed to the creation of 75 km^2 of tidal marsh habitat (Atwater et al., 1979). Mercury that was part of the mining debris continues to act as a legacy pollutant in the Bay and is found in elevated levels in Bay biota (Ely and Owens Viani, 2010). Suspended sediment in San Francisco Bay limits light availability, photosynthesis, and phytoplankton growth (Cloern, 1987). Decreased suspended-sediment concentration (SSC) after 1999 has contributed to increased chlorophyll concentrations, larger spring phytoplankton blooms, and reoccurrence of autumn blooms (Cloern et al., 2007; Cloern and Jassby, 2012). Reduced SSC may be one of several factors contributing to a collapse of several San Francisco Bay estuary fish species that occurred around 2000 (Sommer et al., 2007).

3. Present-day sediment transport and associated physical processes

3.1. The watershed

On average, San Francisco Bay receives >90% of its freshwater influx from the Sacramento–San Joaquin Delta (Conomos, 1979), with the remainder coming from >450 smaller drainages surrounding the Bay (McKee et al., 2013–this issue). The majority of sediment is

Fig. 5. Measured bathymetric changes over the last ~50 years in the San Francisco Bay Coastal System. See text for appropriate references.

delivered to the Bay in the highest flows during the wet season, from late fall-early spring (McKee et al., 2003, 2006; David et al., 2009), for which 87–99% of total load is suspended (Porterfield, 1980; Wright and Schoellhamer, 2004; Schoellhamer et al., 2005).

3.1.1. The Delta

The Sacramento–San Joaquin River Delta is a complex network of natural and man-made channels at the confluence of the two rivers (Fig. 2). The Delta is the outlet for 40% of California's drainage area and 92% of the San Francisco Bay drainage area (Porterfield, 1980). The annual mean freshwater discharge rate from the Delta into the Bay is 800 m^3/s and the record Delta outflow is 17,800 m^3/s in February 1986 (California Department of Water Resources, 2007). Levee construction and draining of marshlands began in the latter half of the 1800s (Atwater et al., 1979). As a result, the Delta today consists of a network of slough channels surrounding former marshlands commonly termed 'islands' which are primarily used for agriculture. Because of the high organic content of Delta soils, draining of marshes has resulted in significant land subsidence such that most of the islands are currently below mean sea level, some by as much as 4 m. The Delta also contains the pumping facilities that divert freshwater to the San Joaquin Valley and Southern California. The channels are tidal and freshwater flows are managed to prevent salinity from intruding landward of the western Delta. Wright and Schoellhamer (2005) used continuous measurements of suspended-sediment flux to develop a sediment budget for the Delta for water years 1999–2002. During that time period, 85% of the sediment that entered the Delta came from the Sacramento River, 13% came from the San Joaquin River, and the eastside tributaries (Cosumnes and Mokelumne rivers) supplied the remaining 2%. Riverine sediment delivery to the Delta was episodic with 82% of the sediment being delivered during the wet season (31% of the time). The lower Sacramento River is the primary sediment transport pathway because at least 82% of the sediment entering the Delta from the Sacramento River watershed either deposited along the Sacramento River or moved past Mallard Island and into San Francisco Bay. Of the sediment that entered the Delta, 67 ± 17% deposited there and the remainder entered the Bay. Schoellhamer et al. (2012) present a conceptual model of sedimentation in the Delta.

3.1.2. Recent sediment supply and delivery patterns

Recent estimates of suspended loads entering the estuary from the Sacramento–San Joaquin Delta range from 1 to 1.2 Mt/year (McKee et al., 2006; David et al., 2009) to 4 Mt/year (Shvidchenko et al., 2004), with most of this likely mud-sized. As suspended sediment loads from the Delta have diminished, the relative importance of loads from the small local tributaries has increased. Lewicki and McKee (2010) estimated that suspended sediment loads entering the Bay from local watersheds can vary by a factor of 2–4 inter-annually, with a mean rate of 1.3 Mt/year (35% associated with urbanized watersheds), significantly higher than the 0.3–1.0 Mt/year estimated in prior studies, summarized in McKee et al. (2003). These local watersheds may now account for ~56% of the total suspended load entering San Francisco Bay: the precise accounting has implications for the degradation of riparian habitats via siltation, the transport of particle-associated pollutants, dredging volumes, and accretion rates of tidal wetlands (David et al., 2009; Lewicki and McKee, 2010). These local watersheds typically produce 50% of their annual discharge and 90% of the sediment load (80% of which is mud; David et al., 2009; Lewicki and McKee, 2010) during only a few days (Kroll, 1975). More recent research by McKee et al. (2006) reinforces that episodic sediment loads dominate the sediment supply to the Bay, where 10% of annual load can be delivered in one day, and over 40% within seven days during an extremely wet year. Within this special issue, the latest observations of sediment supply volumes and trends will be presented (e.g., McKee et al., 2013–this issue), with particular focus on the resulting sediment transport processes and geomorphic evolution of the San Francisco Bay Coastal System (e.g., Hansen et al., 2013a–this issue; Schoellhamer et al., 2013–this issue).

The vast majority of sediment from minor drainages (~> 90%) is supplied as suspended load (McKee, 2006). Greater than 90% of suspended sediment in both Coyote Creek and Guadalupe River (larger South Bay tributaries) is silt- and clay-sized materials and 88% of suspended sediment is <0.02 mm in the Guadalupe River. Zone 6 Line B (another South Bay tributary) differs due to its small watershed size and steep stream slope; only 77% of suspended sediment transported is finer than 0.0625 mm. These data suggest that most of the suspended sediment loads are likely to pass through dredged channels and onto the Bay margin where they might be available for wetland maintenance or restoration (McKee, 2006). During average flows, sand is typically only a few % of the total load, but can be as high as 70% during high flows, and may account for 50% of the annual load during a very wet year, the remainder being mud (Porterfield, 1980). Sand and gravels are likely to be caught in flood control channels and removed by maintenance dredging of the larger and managed tributary systems (Collins, 2006; McKee, 2006); further research is needed to inventory these processes for individual channels and the Bay as a whole.

3.2. San Francisco Bay

San Francisco Bay consists of four sub-embayments, covering an area of 1200 km^2 (below MSL). In addition to the Bay, the San Francisco Bay Coastal System also includes the open coast littoral cell, extending from Pt. Reyes to Pt. San Pedro, the ebb-tidal delta (i.e., San Francisco Bar) at the mouth of San Francisco Bay, the inlet throat (i.e., Golden Gate), and the Sacramento–San Joaquin Delta mouth (Fig. 1). Morphologically, the mouth of San Francisco Bay is dominated by the San Francisco Bar, a massive sub-sea surface ebb-tidal delta that covers a region of approximately 175 km^2, with an average depth of 17 m. Sediments are derived from watersheds of the Sacramento–San Joaquin Delta (i.e., Sierran, notably granitic) and local tributaries (Gilbert, 1917; Yancey and Lee, 1972; Schlocker, 1974; Porterfield, 1980; McKee et al., 2003, 2006; Keller, 2009; Lewicki and McKee, 2010), and the local coast range that outcrops along the open coast in the Golden Gate and Central Bay (i.e., Franciscan Complex, notably chert and serpentine, and younger volcanic and sedimentary rocks). The modern Bay floor and adjacent open coast seafloor are primarily comprised of sand and mud, overlying metamorphic and sedimentary bedrock: the shallowest depths to bedrock and intermittent bedrock exposures are most common in Central Bay (Trask, 1956; Goldman, 1969; Carlson and McCulloch, 1970; Chin et al., 2004), within the Golden Gate (Barnard et al., 2006a,b), the northern open coast, and Carquinez Strait (Jachens et al., 2002). The bottom sediments are mud-dominated in South Bay and in the shallower (<4 m), lower tidal energy areas of Central Bay, San Pablo Bay, and Suisun Bay. Sand is prevalent in the open-coast littoral system, Golden Gate and San Francisco Bar, and the deeper portions of Central Bay, San Pablo Bay, and Suisun Bay, particularly within the main tidal channels (Conomos and Peterson, 1977) where large bedforms (~10–100 m wavelengths) are common (e.g., Rubin and McCulloch, 1979; Chin et al., 2004; Barnard et al., 2012a).

Tides at the Golden Gate (NOAA/Co-ops station 9414290) are mixed, semi-diurnal, with a maximum tidal range of 1.78 m (MLLW–MHHW, 1983–2001 Tidal Epoch). Minor tidal fluctuations extend up to Sacramento, 155 km from the Golden Gate. The tidal prism exceeds the volume of freshwater inflow by one to two orders of magnitude. Freshwater input represents less than 1% (~19% during record flow) of the spring tidal prism of 2×10^9 m^3 served by the Golden Gate tidal inlet (Barnard et al., 2007a). Tidal currents are therefore far stronger than freshwater flows except during extreme flow conditions upstream, and cause most of the mixing in the estuary (Cheng and Smith, 1998). Even during the highest river discharge events, water levels at the Golden Gate are only increased by a few centimeters, although freshwater surface flows may be significant (Kimmerer, 2004).

Though less dominant than tidal forcing, gravitational circulation can develop, particularly during strong stratification (e.g., Monismith et al., 1996) and neap tidal conditions. Gravitational circulation has been observed at deep locations in the estuary, such as the Golden Gate (e.g., Conomos, 1979) and Carquinez Strait (Smith et al., 1995). Schoellhamer (2001) demonstrated that estuarine turbidity maxima form when salinity and gravitational circulation are present but they are not associated with a singular salinity. Bottom topography enhances salinity stratification, gravitational circulation and estuarine turbidity maxima formation seaward of sills. The spring/neap tidal cycle also affects locations of estuarine turbidity maxima. Salinity stratification in Carquinez Strait, which is seaward of a sill, is greatest during neap tides, causing the tidally-averaged suspended-sediment concentration in Carquinez Strait to be less than that landward at Mallard Island in eastern Suisun Bay. Spring tides cause the greatest vertical mixing and suspended-sediment concentration in Carquinez Strait. Therefore, surface estuarine turbidity maxima always are located in or near the Strait during spring tides, regardless of salinity. During neap tides, surface estuarine turbidity maxima are landward of Carquinez Strait and in the salinity range of 0–2‰.

Wave energy throughout the Bay is mainly generated by local winds, while ocean swell penetrating through the Golden Gate can only significantly affect exposed portions of Central Bay, such as the north-facing San Francisco city shoreline (Hanes et al., 2011b) and the mudflats in eastern Central Bay (Talke and Stacey, 2003). Waves play a minor role in sediment transport throughout the deeper portions of the Bay. However, the impact of local, wind-generated waves and ocean swell can induce significant turbulence and sediment transport in shallow, fetch-exposed mudflats (Schoellhamer, 1996; Warner et al., 1996; Talke and Stacey, 2003).

The U.S. Geological Survey began measuring suspended sediment concentrations (SSCs) at several locations every 15 min in San Francisco Bay in 1991, an effort that continues to this day at seven locations (Schoellhamer, 2011; Buchanan and Morgan, 2012). Approximately 89% of the SSC variability in the Bay is associated with tidal cycles (i.e., semidiurnal, fortnightly, monthly, semi-annual), seasonal wind, and river supply (Schoellhamer, 2002). SSC is lowest during the summer and into the fall, as the supply of erodible sediment decreases (Schoellhamer, 2002), and overall, concentrations are highest in lower South Bay, moderate in Suisun and San Pablo Bays, and lowest in Central Bay (Schoellhamer, 2011).

3.2.1. Suisun Bay

The majority of Suisun Bay is shallower than 5 m and mud-dominated, with several deeper (10–15 m) sandy, bedform-covered channels running east–west through the sub-embayment that splits from the main Delta channel. Suspended sediment transport peaks during winter freshwater flows from the Delta into Suisun Bay, with a portion of the material passing through to San Pablo Bay. During the spring and summer, persistent onshore winds generate short-period waves, resuspending sediment in both Suisun and San Pablo Bays: landward near-bed flows and a gradient of suspended sediment concentration combine to transport sediment up estuary from San Pablo to Suisun Bay, but by the fall the finer fraction of the erodible sediment pool is significantly reduced (Krone, 1979; Ruhl and Schoellhamer, 2004; Ganju and Schoellhamer, 2006). Tidal currents in the channels approach 1 m/s and estuarine turbidity reaches a maximum along the north side of Carquinez Strait, due to high flow velocities (Schoellhamer and Burau, 1998). Moskalski and Torres (2012) found that wind, river discharge, and tides explained up to 75% of the variance of subtidal SSC. Ganju et al. (2009) established that tidal and wind-wave forcing, along with total load and peak flow magnitude, are the most important parameters for simulating geomorphic change. Carquinez Strait, which connects San Pablo Bay with Suisun Bay, reaches a depth of 35 m, and is flanked by rock (Kimmerer, 2004).

3.2.2. San Pablo Bay

San Pablo Bay contains a single main channel, 11–24 m deep with a mostly sandy bed, which connects Carquinez Strait with Central Bay (Jaffe et al., 2007). Extensive shallow areas (most <4 m deep) and tidal flats are mud-dominated and cover 80% of San Pablo Bay (Locke, 1971). In effectively modeling multi-decadal deposition patterns in San Pablo Bay, van der Wegen et al. (2011) found that river discharge and sediment concentration had a strong positive influence on sedimentation. The inclusion of waves in the model was found to decrease deposition rates, and along with tidal currents, had the most significant impact on sediment distribution. Waves are local, wind-driven with limited fetch, and have been measured as high as 0.6 m (Schoellhamer et al., 2008a). When tidally-driven mixing processes are weak, in particular during neap tides, stratification and gravitational circulation are common. Stacey et al. (2008) note that tidally-periodic stratification can also generate gravitational circulation, while Ganju et al. (2006) demonstrated that low river flow effectively reduced stratification in Carquinez Strait. Salt can intrude from the Pacific Ocean into Suisun Bay during the dry months but only reaches into San Pablo Bay during the wet months (Monismith et al., 2002), when water levels are elevated by ~20 cm and sediment transport is an order of magnitude higher. During high flows into Suisun Bay from the Delta, the sediment pulse takes multiple days to reach San Pablo Bay (van der Wegen et al., 2011).

3.2.3. South Bay

In South Bay, which receives considerably less river flow than the other sub-embayments (Kimmerer, 2004), spring tidal currents typically exceed 1 m/s in the channel and 0.4 m/s on the shoals (Schoellhamer, 1996). The South Bay floor is dominated by mud-sized sediments primarily derived from local watersheds, based on the heavy mineral assemblage featuring jadeite and glaucophane that is common in the bordering Coast Range to the southeast (Yancey and Lee, 1972), although contributions from the San Joaquin–Sacramento River watershed are also likely. Strong winds are typical during winter storms and summer sea breezes (~7 m/s), resulting in significant wave generation, sediment resuspension and basin wide circulation (Conomos et al., 1985), possibly directed landward in the shallower eastern channel and seaward in the main channel (Walters et al., 1985). Bottom currents are seasonally-reversing and slower than the other reaches, while surface non-tidal currents are primarily generated by prevailing summer and winter storm winds and winter freshwater flows from the Delta (Conomos, 1979). Sediment concentrations in South Bay are generally higher during flood tides as wind waves resuspend sediment during low water levels, particularly during the persistent westerly and northwesterly winds in the summer and fall, resulting in a net sediment flux toward the southeast (Lacy et al., 1996). While wind waves are important for cohesive sediment resuspension on shoals, large increases in sediment flux are due to the nonlinear interaction of both wind waves and tidal currents (Brand et al., 2010). In the channels, sediment concentration peaks during the lowest spring tides, when turbid water is advected from the shoals (Schoellhamer, 1996).

3.2.4. Central Bay

Landward of the Golden Gate, Central Bay is the deepest part of the Bay, contains the coarsest sediment, and the strongest currents (Chin et al., 1997, 2004). The western section is dominated by sandy bedform fields (up to 90-m wavelengths) and exposed bedrock, while the eastern Bay floor adjacent margins are primarily mud-dominated and featureless (Rubin and McCulloch, 1979; Barnard and Kvitek, 2010; Chin et al., 2010; Barnard et al., 2011b, 2012a). Sediment is up to 100 m thick (Carlson and McCulloch, 1970; Chin et al., 2004). Bedrock pinnacles and sandy shoals focus currents and produce a wide range of bedform morphologies that were first mapped in the late 1970's using side-scan sonar (Rubin and McCulloch, 1979) and several decades later in high resolution multibeam (Chin et al., 1997; Dartnell and Gardner, 1999; Barnard et al., 2011b, 2012a). Based on surficial grain size distributions and the multibeam, backscatter and sidescan data of Greene and Bizarro (2003), Chin et al. (2010) suggested that the sand in Central Bay is derived from either outside the Bay, shoreline sediments and outcrops in the vicinity of the Golden Gate (the coarser sands), or from San Pablo Bay (finer sands), with little mixing of the two fractions.

3.3. Golden Gate

Through the Golden Gate, the channel floor is bedrock with a maximum depth of 113 m, where tidal currents accelerate through the erosion-resistant rocky strait. The approximate depth and formation have been linked to either downcutting of the Sacramento River during the Last Glacial Maximum (Louderback, 1951) or a major fault (Schlocker, 1974), with ongoing minor incision due to tidal scour. As these currents decelerate, large bedforms are created on either side of the Golden Gate Bridge/strait, including one of the largest sand wave fields in the world (i.e., both spatial extent and wavelength) just seaward of the strait (Barnard et al., 2006a,b). Tidal currents in the inlet throat peak at over 2.5 m/s, and can exceed 1 m/s even on the edge of the ebb-tidal delta, over 10 km from the Golden Gate (Barnard et al., 2007a). These powerful and spatially variable currents result in an incredibly diverse array of bedform sizes and shapes both landward (Rubin and McCulloch, 1979; Chin et al., 1997) and seaward of the Golden Gate (Barnard et al., 2006a,b, 2012a).

The critical interface between San Francisco Bay and the open ocean (a.k.a., the Golden Gate) is particularly complex, with strong vertical stratification and lateral variability in current velocities and tidal phase (Largier, 1996; Petzrick et al., 1996). Exchange is influenced by a number of factors, including tidal flow, gravitational and lateral circulation (ebb-dominated on the northern side and flood-dominated on the southern side), wind stress, atmospheric pressure gradients, and changes in water levels due to spring–neap cycles (Conomos, 1979; Walters et al., 1985; Walters and Gartner, 1985; Largier, 1996; Petzrick et al., 1996). Residual flow through the Golden Gate is driven by subtidal processes such as tidal pumping, baroclinic flow, tidal trapping of an eddy, and enhanced frictional phasing by a lateral density gradient (Fram, 2005; Martin et al., 2007). While tidal forcing dominates circulation overall, baroclinic and barotropic components of wind-driven upwelling can play a critical role in the spring and summer, forcing denser water along the bottom into the Bay, inducing gravitational circulation (Largier, 1996).

Fram et al. (2007) ran transects parallel to the Golden Gate bridge with a boat-mounted acoustic Doppler current profiler (ADCP) and a suite of towed instruments to measure rms instantaneous discharges of 60,000 m^3/s, mean discharges of 600 m^3/s (net seaward), and a mildly stratified channel, with salinities ranging from 30 to 33‰ (top to bottom) in the summer and 32.0 to 32.4‰ in the fall. They also determined that both density gradients and bathymetry influence ocean-estuary exchange, and that overall tidal exchange (i.e., salinity variability between ebb and flood tides) is far less than prior studies indicated (Parker et al., 1972; Largier, 1996). During the same experiment, Martin et al. (2007) measured chlorophyll fluxes between Central Bay and the Golden Gate, and found that fluxes were dominated by tidal pumping, accounting for 64–93% of the net dispersive flux, and the direction of the net advective flux (i.e., the physical mechanism driving flow) was always seaward. Cheng et al. (1993) modeled neap and spring tidal discharge during low Delta flows (~200 m^3/s) at the Golden Gate of 42,000–95,000 m^3/s, and 5000–13,000 m^3/s in Carquinez Strait.

The only direct estimates of suspended sediment transport using in situ measurements across the Golden Gate were performed by

Teeter et al. (1996). During a two week neap–spring period of low Delta flow conditions, they performed repeated inlet cross-sectional transects using boat-mounted ADCP systems, observing a clear net seaward transport of suspended sediment of 188,000 metric tonnes, with fluxes during ebb flows 44% higher on average than during flood flows. No studies have made direct measurements of bedload transport across the Golden Gate, however, an extensive study of bedform asymmetry covering West-central Bay and the mouth of San Francisco Bay suggests a net seaward flux of bedload through the Golden Gate, further confirmed by applying a hydrodynamically-validated numerical model to estimate the net flux of suspended load and bedload across the inlet throat (Barnard et al., 2012a). The latest research on the net direction and volume of sediment flux across the Golden Gate will be presented in this special issue (Barnard et al., 2013a,b–this issue; Elias and Hansen, 2013–this issue; Erikson et al., 2013–this issue), essential information for quantifying the impact of a reduced sediment supply from the Bay to the open coast, with numerous estuary management implications (e.g., determining the appropriate location and volumes for responsible aggregate mining, dredging, and disposal).

3.4. The open coast

The open coast is a high-energy coastal environment comprising primarily sandy beaches and bluffs to the south of the Golden Gate, and rocky cliffs and pocket beaches to the north. The geology is controlled by active tectonics with the San Andreas Fault Zone and San Gregorio Fault Zone (Fig. 1) traversing directly through the region (Parsons et al., 2002). This area is susceptible to highly energetic waves, being exposed to swell from almost the entire Pacific Ocean. The average annual maximum offshore significant wave height is 8.0 m, and the annual average offshore significant wave height is 2.5 m (Scripps Institution of Oceanography, 2012). Tidal currents peak at 1.5 m/s immediately adjacent to the Golden Gate entrance along the northern extent of Ocean Beach, and still approach 1 m/s ~5 km north and south of the channel entrance (Barnard et al., 2007a), as is evident by the vast distribution of bedforms throughout the region (Barnard et al., 2012b). The combination of large waves, strong tidal currents, and active tectonics results in an extremely complicated coastal system that has only recently begun to be explored with a comprehensive study led by the U.S. Geological Survey initiated in 2003. This effort has focused on the physical processes controlling the sand waves in the Golden Gate (Barnard et al., 2006a,b; Sterlini et al., 2009; Hanes, 2012), the geomorphic evolution of Ocean Beach and a persistent erosion hot spot (Barnard and Hanes, 2005, 2006; Barnard et al., 2007a,b,c, 2009a,b, 2011a,c, 2012b; Erikson et al., 2007; Eshleman et al., 2007; Hansen and Barnard, 2009, 2010; Hansen et al., 2011, 2013b; Hansen et al., in review; Shi et al., 2011; Yates et al., 2011), and linking the physical processes in the Bay with the open coast (Hanes and Barnard, 2007; Dallas, 2009; Dallas and Barnard, 2009, 2011; Hanes et al., 2011a; Barnard et al., 2012a,b). Beach behavior at Ocean Beach is seasonally-modulated (Hansen and Barnard, 2010), with occasionally severe erosion during winter storms (Barnard et. al., 2011a) carrying large volumes of sediment offshore into an extensive nearshore bar system (Barnard et al., 2011c), while the beach recovers during the lower energy summer and fall (Hansen and Barnard, 2010). However, the morphology of the adjacent ebb-tidal delta affects the distribution of wave heights, which can vary by a factor of two, and sediment transport processes along Ocean Beach, exerting a dominant control on short and long-term beach evolution (Battalio and Trivedi, 1996; Eshleman et al., 2007; Hansen and Barnard, 2009; Jones, 2011; Shi et al., 2011; Hansen et al., 2013b; Hansen et al., in review). South of Ocean Beach, coastal bluff erosion and landsliding are a dominant geomorphic process, driven commonly by over steepening at the toe due to wave action, and/or precipitation-induced groundwater seepage (Collins and Sitar, 2008), sporadically providing significant volumes of sediment to the littoral cell.

3.5. Regional oceanography

Global sea level has been regionally-suppressed along the U.S. West Coast since ~1980 due to the persistence of strong, northwesterly winds (Bromirski et al., 2011). However, northward propagating, coastal-trapped waves can raise sea level along this portion of the California coast up to 30 cm during an El Niño winter (e.g., as occurred during 1982–83 and 1997–98) (Bromirski et al., 2003), with an additional 5–10 cm of decadal variability possibly associated with the Pacific Decadal Oscillation (Mantua et al., 1997). Non-tidal, water level extremes inside San Francisco Bay are dominated by storm surges that propagate from the open ocean into the Golden Gate, through the Bay, and up into the lower reaches of the Sacramento–San Joaquin Delta. Surge can force non-tide fluctuations as high as 70 cm at the Golden Gate, although during extreme events these levels are often exceeded in Suisun Bay due to both surge propagation into the constricted sub-embayment and the commonly coincident timing of high Delta discharge rates due to heavy rainfall (Bromirski and Flick, 2008). Along the exposed outer coast, long period ocean swell dominates the wave energy spectrum throughout the year, although local seas are often generated by strong northwesterly winds in the spring and summer that produce coastal upwelling and generally dominate shelf-scale circulation patterns (Largier et al., 2006; Kaplan et al., 2009) beyond the influence of the Golden Gate, with these persistent winds relaxing during the fall and winter (Largier et al., 1993).

4. Looking to the future-climate change impacts

Rising sea levels over the 21st century (e.g., Vermeer and Rahmstorf, 2009) will increase the frequency of extreme water level events in San Francisco Bay (Cayan et al., 2008), placing additional stress on the San Francisco Bay Coastal System's tidal marshes (including massive restoration projects currently underway), levees, shorelines, and ecosystems. Future warming scenarios for California consistently project more precipitation falling as rain in the Sierras, resulting in higher rainfall-related peaks earlier in the season and weaker snowmelt-related peaks of the Delta hydrographs, as well as higher estuarine salinity (e.g., Knowles and Cayan, 2002, 2004). These changes will undoubtedly impact circulation patterns and shift peak sediment loads to earlier in the year (Ganju and Schoellhamer, 2010).

Knowles (2010) indicated that the present day 100-year coastal flood event could occur annually by 2050, posing major threats to critical infrastructure that surrounds the Bay, including the international airports in Oakland and San Francisco, and placing 270,000 people and $62 billion of development at risk (San Francisco Bay Conservation and Development Commission, 2012). Knowles (2010) also noted that wetlands are particularly vulnerable, as they would require a total sediment input (i.e., organic matter and inorganic sediment) of up to 10.1 Mm^3/year (~2.6 cm/year) by 2100 to keep pace with the higher projections of sea level rise: presently only as much as 0.4 Mm^3/year is actually being deposited (Schoellhamer et al., 2005) while accretion rates of 0.2–0.5 cm/year have kept pace with recent rates of sea level rise (Callaway et al., 2012). Parker et al. (2011) added that the brackish and freshwater tidal wetlands, in particular, will be additionally stressed by higher salinities and temperatures, leading to lower plant productivity and correlative organic input to the wetland, requiring even higher rates of mineral sediment inputs for the wetland to keep pace with sea level rise.

Cloern et al. (2011) downscaled global climate models and linked them to a series of regional physical and ecological models to assess the impact of climate change for the San Francisco Bay region. Using both a low and a high-end emission scenario, they concluded that primary impacts to the San Francisco Bay Coastal System over the next century include reduced fluvial discharge from the Delta, increased Bay salinity, decline in suspended sediment concentration, and a marked increase in the frequency of extreme water levels.

Ganju and Schoellhamer (2010) modeled geomorphic change in Suisun Bay in response to future scenarios of climate change and sediment supply, demonstrating in all cases that net sediment deposition in the shallowest areas did not keep pace with sea level rise. The greater depths decreased wave-induced bottom shear stress and therefore sediment redistribution during the wind-wave season. This suggests that existing intertidal mud flats and tidal marshes may not be sustained in the future.

5. The special issue

As previously described, the San Francisco Bay Coastal System is a complex marine system with powerful waves and tidal currents, intricate estuarine circulation and sediment transport patterns, and significant anthropogenic influences. Several compilations of the physical processes of the Bay and watershed have been published (Conomos, 1979; Hollibaugh, 1996), however, until now, no synthesis of the past 20 years of science has been achieved. In the past 20 years, major wetland loss, seafloor and Bay floor sediment loss, and coastal erosion have been well documented, inspiring considerable work to understand the sources and transport pathways of sand- and mud-sized material, as well as the governing physical processes that control the evolution of the San Francisco Bay Coastal System. At the core of this research is a comprehensive, multi-faceted sand provenance study that includes a series of geochemical techniques, morphometric analyses, bedform asymmetry quantification, numerical modeling, physical process measurements, and faunal distribution analyses, synthesized in a unique approach to establish provenance and transport. This work is complemented by a series of focused efforts to understand fundamental sediment transport processes and circulation patterns at a range of spatial and temporal scales and within specific estuarine environments, including: the exposed outer coast, tidal flats and marshes, the inlet, Bay floor and Bay tributaries.

This special issue of *Marine Geology* is divided into four primary sections:

1) Introduction and framework geology
2) Sand provenance
3) Circulation patterns and geomorphic change
4) Fine sediment transport.

5.1. Section 1 — introduction and framework geology

The introduction explores the relevant research that has informed our present knowledge of the San Francisco Bay Coastal System, including landmark studies by Gilbert (1917), Conomos (1979), Krone (1979), and Porterfield (1980) summarized in this paper, outlines the framework geology of the region (Elder, 2013–this issue) and describes the sub-tidal habitats found at the core of the San Francisco Bay Coastal System (Greene et al., 2013–this issue). This knowledge has been greatly enriched due to the recent advances in high resolution bathymetric mapping technology. These papers provide the key boundary conditions for a more thorough understanding of the research presented in the subsequent sections.

5.2. Section 2 — sand provenance

After having established a temporal connection between a major reduction in the supply of sediment to San Francisco Bay since the late 19th century (e.g., Gilbert, 1917: Porterfield, 1980; Wright and Schoellhamer, 2004), the pervasive loss of sediment within the Bay (Capiella et al., 1999; Foxgrover et al., 2004; Jaffe and Foxgrover, 2006; Jaffe et al., 2007; Fregoso et al., 2008; Barnard and Kvitek, 2010), the adjacent ebb-tidal delta (Hanes and Barnard, 2007) and open coast beaches (Dallas, 2009; Dallas and Barnard, 2009, 2011; Barnard et al., 2012b), Section 2 presents a series of papers utilizing a wide variety of techniques to quantitatively establish the sources and sinks of beach-sized sand within the San Francisco Bay Coastal System. This section seeks to establish direct links between sediment found throughout the region, including all major drainages, the Bay floor, the open coast seafloor and beaches, and coastal cliffs. Techniques include traditional heavy mineral analysis (Wong et al., 2013–this issue) and X-ray diffraction (Hein et al., 2013–this issue), coupled with more sophisticated analytical techniques such as the signature of rare earth elements and strontium/neodymium isotopes (Rosenbauer et al., 2013–this issue), numerical modeling (Erikson et al., 2013–this issue), and nontraditional approaches such as bedform asymmetry (Barnard et al., 2013a–this issue) and biogenic sediment constituent distributions (McGann et al., 2013–this issue). By integrating all these techniques (Barnard et al., 2013b–this issue), a highly comprehensive understanding of sand transport sources, pathways, and sinks is established, thereby providing direct evidence for the regional impacts of sediment supply to and sediment removal from the San Francisco Bay Coastal System.

5.3. Section 3 — circulation patterns and geomorphic change

Section 3 explores the complicated feedback between physical forcing, geomorphology and resulting circulation patterns in the San Francisco Bay Coastal System. This includes investigations along the open coast and adjacent to the Golden Gate exploring sediment transport processes at the mouth of San Francisco Bay (Elias and Hansen, 2013–this issue) and the influence of changes in the long-term morphologic evolution of the ebb-tidal delta on nearshore processes (Hansen et al., 2013a–this issue).

5.4. Section 4 — fine sediment transport

Understanding suspended sediment transport in San Francisco Bay, particularly the mud fraction, is essential because it regulates primary productivity (Cloern, 1987), affects water quality (e.g., the availability and distribution of heavy metals: Schoellhamer et al., 2007), and is a primary factor in controlling the formation and erosion of wetlands and intertidal mud flats, crucial to ongoing extensive habitat restoration efforts (Callaway et al., 2012). Section 4 explores the state-of-the-art in our understanding of fine sediment transport, via studies focusing on the sources and supply of fine sediment to San Francisco Bay (McKee et al., 2013–this issue), anthropogenic influences on supply (Schoellhamer et al., 2013–this issue), and process measurements (Downing-Kunz and Schoellhamer, 2013–this issue; Hestir et al., 2013–this issue; Manning and Schoellhamer, 2013–this issue; Shellenbarger et al., 2013–this issue). In addition, Section 4 includes a series of numerical modeling studies that improve our fundamental understanding and representation of the physical processes that drive fine sediment transport, erosion, and deposition (Jones and Jaffe, 2013–this issue; Bever and MacWilliams, 2013–this issue; van der Wegen and Jaffe, 2013–this issue).

6. Summary

Despite the importance of estuaries as a critical physical, biological, and chemical interface between drainage basins and the coastal ocean, there is still a great deal to be learned about how they function, especially in light of the vast direct and indirect anthropogenic influences that have severely altered their functioning throughout human history. In this special issue, we present a series of papers that greatly improve our fundamental understanding of sediment related coastal–estuarine processes through state-of-the-art investigations of one of the most drastically altered estuaries in the world, the San Francisco Bay Coastal System.

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