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Integration of bed characteristics, geochemical tracers, current measurements, and numerical modeling for assessing the provenance of beach sand in the San Francisco Bay Coastal System☆

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ABSTRACT

Over 150 million m^3 of sand-sized sediment has disappeared from the central region of the San Francisco Bay Coastal System during the last half century. This enormous loss may reflect numerous anthropogenic influences, such as watershed damming, bay-fill development, aggregate mining, and dredging. The reduction in Bay sediment also appears to be linked to a reduction in sediment supply and recent widespread erosion of adjacent beaches, wetlands, and submarine environments. A unique, multi-faceted provenance study was performed to definitively establish the primary sources, sinks, and transport pathways of beach-sized sand in the region, thereby identifying the activities and processes that directly limit supply to the outer coast. This integrative program is based on comprehensive surficial sediment sampling of the San Francisco Bay Coastal System, including the seabed, Bay floor, area beaches, adjacent rock units, and major drainages. Analyses of sample morphometrics and biological composition (e.g., Foraminifera) were then integrated with a suite of tracers including $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopes, rare earth elements, semi-quantitative X-ray diffraction mineralogy, and heavy minerals, and with process-based numerical modeling, in situ current measurements, and bedform asymmetry to robustly determine the provenance of beach-sized sand in the region.

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1. Introduction

A definitive understanding of sediment sources, sinks, and pathways in urbanized coastal–estuarine systems is essential for assessing the current and future effects of sediment-impacting activities, such as dredging operations, aggregate mining, shoreline armoring, and watershed modifications (Duck et al., 2001). More informed management of sediment resources can promote the sustainability of fringing tidal wetlands and beaches, the first line of defense as sea level rises (Vermeer and Rahmstorf, 2009) and potentially larger storms (Graham and Diaz, 2001) increase the vulnerability of coastal environments over the next century and beyond (Jevrejeva et al., 2012), enhancing threats to public safety, vital infrastructure, and ecosystems (Nicholls and Cazenave, 2010).

The physical, biological, geochemical, and mineralogical composition of coastal sediment is a product of multiple factors, including river catchment petrology (Cho et al., 1999), cliff and seafloor geology, biogenic contributions (Lackschewitz et al., 1994), oceanographic and climatic conditions (Bernárdez et al., 2012), residence time, grain size, shape, density, and local hydrodynamics (Steidtmann, 1982). Therefore, understanding the sources of beach sediment can yield important information about transport pathways and anthropogenic impacts, littoral transport directions, and local erosion.

Spatial variations in grain size parameters (i.e., mean grain size, sorting, and skewness) have been used as tool for decades to infer sediment transport pathways, with insight into local sources and sinks (e.g., McLaren and Bowles, 1985; Gao and Collins, 1992; Le Roux, 1994). However, this approach suffers from severe limitations, such as lack of validation data sets for the multiple approaches, uncertainty as to whether the grain size variability is associated with a modification of the hydrodynamic energy or with sediment reworking processes, input uncertainties such as sampling and measurement error, and model uncertainties (Poizot et al., 2008). Preferential sorting on beaches has established heavy mineral analysis as a common tracer for establishing provenance (e.g., Rao, 1957; Morton, 1985; Frihy et al., 1995), where storms, frequent washing of sediments, and wind erosion can focus more dense, darker grains in distinct layers (Da Silva, 1979; Li and

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Komar, 1992). However, from source to sink, the effects of weathering, transportation, deposition and diagenesis must be considered in interpretations (Morton, 1985), and the mechanisms of beach deposition are still poorly understood (Gallaway et al., 2012). Andrews and Eberl (2012) used quantitative X-ray diffraction (qXRD) and SedUnMix, an Excel Macro program, to gain a greater understanding of provenance in a complicated glacial marine system, but were not able to capture exact source rock compositions, a common shortcoming of qXRD. Magnetic properties of sediment have been used as a fast, low cost means to explore sediment provenance in estuaries (Jenkins et al., 2002) and beaches (Rotman et al., 2008), although magnetic signatures are not useful if the magnetic susceptibility of source areas is not distinct, and the results are complicated by the natural particle size variability of the samples (Oldfield and Yu, 1994). Rare earth elements (REE) have been used as a tracer to determine sediment transport pathways (Ronov et al., 1967; Piper, 1974), with numerous studies using REEs to determine coastal sediment provenance (e.g., Munksgaard et al., 2003; Prego et al., 2012), but their universal applicability can be limited by natural abundance. Isotopic analysis (e.g., $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) has often been used in recent years, particularly for mud-dominated seafloor sediments and eolian dust (e.g., Lee et al., 2005; Saitoh et al., 2011), due to their stability and reflection of minerals and rocks with different ages and compositions (Grousset and Biscaye, 2005), but the analysis is expensive and the results can be difficult to interpret (Farmer et al., 2003).

The only means to implement effective local and regional sediment management plans that promote the sustainability of coastal environments is to understand the entire coastal system, from source to sink. However, because any given provenance technique limits the relevance and applicability of the results to discrete portions or processes within a complex coastal–estuarine system, recent studies have utilized multiple techniques. For example, Duck et al. (2001) used bedform asymmetry, grain size distribution, and magnetic susceptibility measurements in an attempt to distinguish the relative contribution of marine and fluvially-derived bedload in a channel of the Tay Estuary, Scotland. Bernárdez et al. (2012) incorporated grain size, total carbon, particulate organic and inorganic carbon, particulate organic nitrogen, X-ray diffraction, heavy mineral separation, and flame atomic absorption spectrometry for metals analysis to determine the provenance of marine sediments off the coast of the northwest Iberian Peninsula. The results of these provenance studies clearly were strengthened by the use of multiple techniques, but the integration of the results in these prior studies was only qualitative.

In this study we present a uniquely extensive, complex, and robust approach to determining sediment provenance in the San Francisco Bay Coastal System, focusing on the pathways for the movement of beach-sized sand from the watershed, through the estuary, and onto open-coast beaches. This study was motivated by major anthropogenic changes to the Bay that began with the influx of hydraulic mining-related sediment from the Gold Rush in the 19th century (Gilbert, 1917), and have continued to the present with extensive indirect and direct impacts on the Bay sediment supply, including widespread watershed modifications (e.g., Wright and Schoellhamer, 2004), and Bay floor aggregate mining and dredging (Dallas and Barnard, 2011), reflected by ~150 million m^3 of erosion from the floor of San Francisco Bay over the last half of the 20th century (Barnard and Kvitek, 2010). This significant erosion of the Bay floor is temporally correlated with similarly high volumes of erosion of the ebb-tidal delta at the mouth of San Francisco Bay (Hanes and Barnard, 2007; Dallas and Barnard, 2009), as well as widespread erosion of adjacent, open-coast beaches (Hapke et al., 2006; Dallas and Barnard, 2011; Barnard et al., 2012a). However, a quantitative physical or geochemical connection has not been established between sediments inside and outside the Bay, nor a definitive causal link driving regional coastal erosion.

Using extensive regional sediment sampling, geochemical and mineralogical analyses, multibeam bathymetry mapping, physical process measurements, and numerical modeling, we developed a semi-quantitative method to integrate and cross-validate the results of nine separate techniques for establishing sand provenance:

1) Grain size morphometrics
2) $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios
3) Rare earth element (REE) composition
4) Heavy minerals
5) Semi-quantitative X-ray diffraction (XRD)
6) Biologic, anthropogenic, and volcanic constituents
7) Bedform asymmetry
8) Acoustic Doppler velocity measurements
9) Modeled residual sediment transport

The multifaceted approach results in a definitive understanding of sand movement in the coastal–estuarine system, thereby providing essential information to promote more efficient management of sediment resources. This unique and complex approach can serve as a model for provenance studies worldwide.

2. Study area

2.1. Physical setting

San Francisco Bay is the largest estuary on the U.S. West Coast (Conomos et al., 1985), and is among the most developed and human-altered estuaries in the world (Knowles and Cayan, 2004). The San Francisco Bay Coastal System comprises four sub-embayments, as well as 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). The region is subjected to highly energetic physical forcing, including spatially and temporally variable wave, tidal current, wind, and fluvial forcing. The open coast at the mouth of San Francisco Bay is exposed to swell from almost the entire Pacific Ocean, with annual maximum offshore significant wave heights (h_s) typically exceeding 8 m, and mean annual $h_s = 2.5$ m (Scripps Institution of Oceanography, 2012). Inside the Bay, wave forcing is less important, except on shallow Bay margins where local wind-driven waves, and occasionally open ocean swell can induce significant turbulence and sediment transport (Talke and Stacey, 2003; Hanes et al., 2011). 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), but due to the large Bay surface area (1200 km^2 at MSL), the Golden Gate strait serves a spring tidal prism of 2×10^9 m^3. This powerful tidal forcing results in peak ebb tidal currents that exceed 2.5 m/s in the Golden Gate, peak flood tidal currents of 2 m/s just inside Central Bay, and even 1 m/s on the edge of the ebb-tidal delta, 10 km from the inlet throat (Rubin and McCulloch, 1979; Barnard et al., 2007). The strongest tidal currents throughout the other sub-embayments are focused in the main tidal channels, commonly approaching 1 m/s (e.g., Wright and Schoellhamer, 2004). Bedforms dominate the substrate (Rubin and McCulloch, 1979; Chin et al., 2004; Barnard et al., 2006, 2011b, 2012b) where sand is prevalent among the highly energetic areas throughout the region, including at the mouth of San Francisco Bay and the deeper portions of Central Bay, San Pablo Bay, and Suisun Bay (Fig. 1), particularly within the main tidal channels. 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 (Conomos and Peterson, 1977).

Sediments are derived from watersheds of the Sacramento–San Joaquin Delta (i.e., Sierran, notably granitic) and local tributaries, 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) (Gilbert, 1917; Yancey and Lee, 1972; Schlocker, 1974; Porterfield, 1980; McKee et al., 2003; Graymer et al., 2006; Keller, 2009). The modern Bay floor and adjacent open coast seafloor are primarily composed of sand and