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Sand sources and transport pathways for the San Francisco Bay coastal system, based on X-ray diffraction mineralogy

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ABSTRACT

The mineralogical compositions of 119 samples collected from throughout the San Francisco Bay coastal system, including bayfloor and seafloor, area beaches, cliff outcrops, and major drainages, were determined using X-ray diffraction (XRD). Comparison of the mineral concentrations and application of statistical cluster analysis of XRD spectra allowed for the determination of provenances and transport pathways. The use of XRD mineral identifications provides semi-quantitative compositions needed for comparisons of beach and offshore sands with potential cliff and river sources, but the innovative cluster analysis of XRD diffraction spectra provides a unique visualization of how groups of samples within the San Francisco Bay coastal system are related so that sand-sized sediment transport pathways can be inferred.

The main vector for sediment transport as defined by the XRD analysis is from San Francisco Bay to the outer coast, where the sand then accumulates on the ebb tidal delta and also moves alongshore. This mineralogical link defines a critical pathway because large volumes of sediment have been removed from the Bay over the last century via channel dredging, aggregate mining, and borrow pit mining, with comparable volumes of erosion from the ebb tidal delta over the same period, in addition to high rates of shoreline retreat along the adjacent, open-coast beaches. Therefore, while previously only a temporal relationship was established, the transport pathway defined by mineralogical and geochemical tracers support the link between anthropogenic activities in the Bay and widespread erosion outside the Bay. The XRD results also establish the regional and local importance of sediment derived from cliff erosion, as well as both proximal and distal fluvial sources. This research is an important contribution to a broader provenance study aimed at identifying the driving forces for widespread geomorphic change in a heavily urbanized coastal-estuarine system.

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1. Introduction

Over 150 million m^3 of sand-sized sediment has been lost during the last half century from the central area of the San Francisco Bay (SF Bay) coastal system (Hanes and Barnard, 2007; Fregoso et al., 2008; Dallas and Barnard, 2009, 2011). Over the same time period, widespread erosion occurred on adjacent beaches, wetlands, and submarine deposits (Atwater et al., 1979; Hapke et al., 2006; Barnard and Kvitek, 2010; Dallas and Barnard, 2011; Barnard et al., 2012a, 2012b). These impacts to the outer coast may be the result of anthropogenic modifications within the system such as delta damming, sediment mining, offshore dredge disposal, and the restoration of salt ponds formerly surrounded by levees (e.g., Knowles and Cayan, 2004; Wright and Schoellhamer, 2004; Dallas and Barnard, 2011), but no direct linkages have previously been established.

The Golden Gate strait is the sole connection of SF Bay with the Pacific Ocean, where over 7.57 km^3 of water is transported daily along with mud, sand, biogenic material, and pollutants (McHugh, 2001). SF Bay and the adjacent ocean have typically been treated as separate entities. However, recent research documents the dynamic processes that occur at the mouth of SF Bay, which highlights the connection of physical processes between SF Bay and the adjacent coastal ocean (e.g., Barnard et al., 2007; Dallas and Barnard, 2011; Barnard et al., 2012b).

Sediment within the SF Bay coastal system is derived from diverse sources and undergoes complex transport and mixing processes. Sources range from rivers that erode the distal Sierra Nevada granitic and metamorphic rocks and feed into the two major rivers of the Great Valley (the Sacramento and San Joaquin Rivers), local watersheds draining the Pacific Coast Ranges that are composed of the heterogeneous Franciscan Complex, displaced Sierran granitic rocks, and Mesozoic and Cenozoic sedimentary rocks, and sediment transported alongshore in the coastal ocean (Gilbert, 1917; Yancey and Lee, 1972; Schlocker, 1974; Porterfield, 1980; Graymer et al., 2006).

X-ray diffraction mineralogy is used here to determine the characteristic minerals for each of the predominant source regions throughout the study area, including all major drainages and rock types. The mineralogical compositions of the source regions are then compared with those of the beach and seabed sands to provide estimates of mixing using statistical analyses. That information is further used to trace sources of

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sand-sized sediment deposited around the SF Bay coastal system and to infer dispersal pathways.

This mineralogical study is part of a multi-faceted, multi-disciplinary provenance study designed to establish the primary sources, sinks, and inferred transport pathways of sand in the region, and thereby establish links between anthropogenic activities and geomorphic change (Barnard et al., 2013-in this issue-a). The program is based on comprehensive sampling of sediment including the seabed, bayfloor, beaches, representative rock units, and all major and some minor drainages. Our approach is unique in using bulk XRD mineralogy of sand (a technique generally applied to finer size fractions) and cluster analyses of XRD spectra to determine these sources and transport pathways. Heavy minerals and isotopes are more typically used for this purpose.

2. Methods

2.1. Sample collection

The 119 samples analyzed are geographically representative of the SF Bay coastal system (Fig. 1). Beach sand was collected by hand scoop (n = 27), and seafloor/bayfloor samples (n = 61) at variable water depths by using a Smith–MaIntyre grab from which the surface 10 cm was subsampled. Source rock sampling (n = 18) followed the distribution of rock types displayed on a geological map of the area; rock types representative of all formations in the area were sampled (chert, basalt, various types of sandstone, serpentinite, and granitic rocks displaying various stages of weathering) from outcrops near beach sand locations along the coast. Streambed sediments (n = 13) were collected by hand scoop along the water's edge, with the exception of the Sacramento and San Joaquin Rivers, where several were collected by boat in the center of the channel.

2.2. Analytical techniques

All sediment sample analyses were performed on a consistent size fraction, 0.15–0.5 mm (mean D_{10}–D_{90} range of outer coast beach samples), after the shell was removed by weak hydrochloric acid leach. Potential source rocks were analyzed in bulk. All samples were ground in a McCrone micronizing mill with 4 ml of methanol for 5 min. The powder was then dried at 80 °C overnight, and was further ground with a

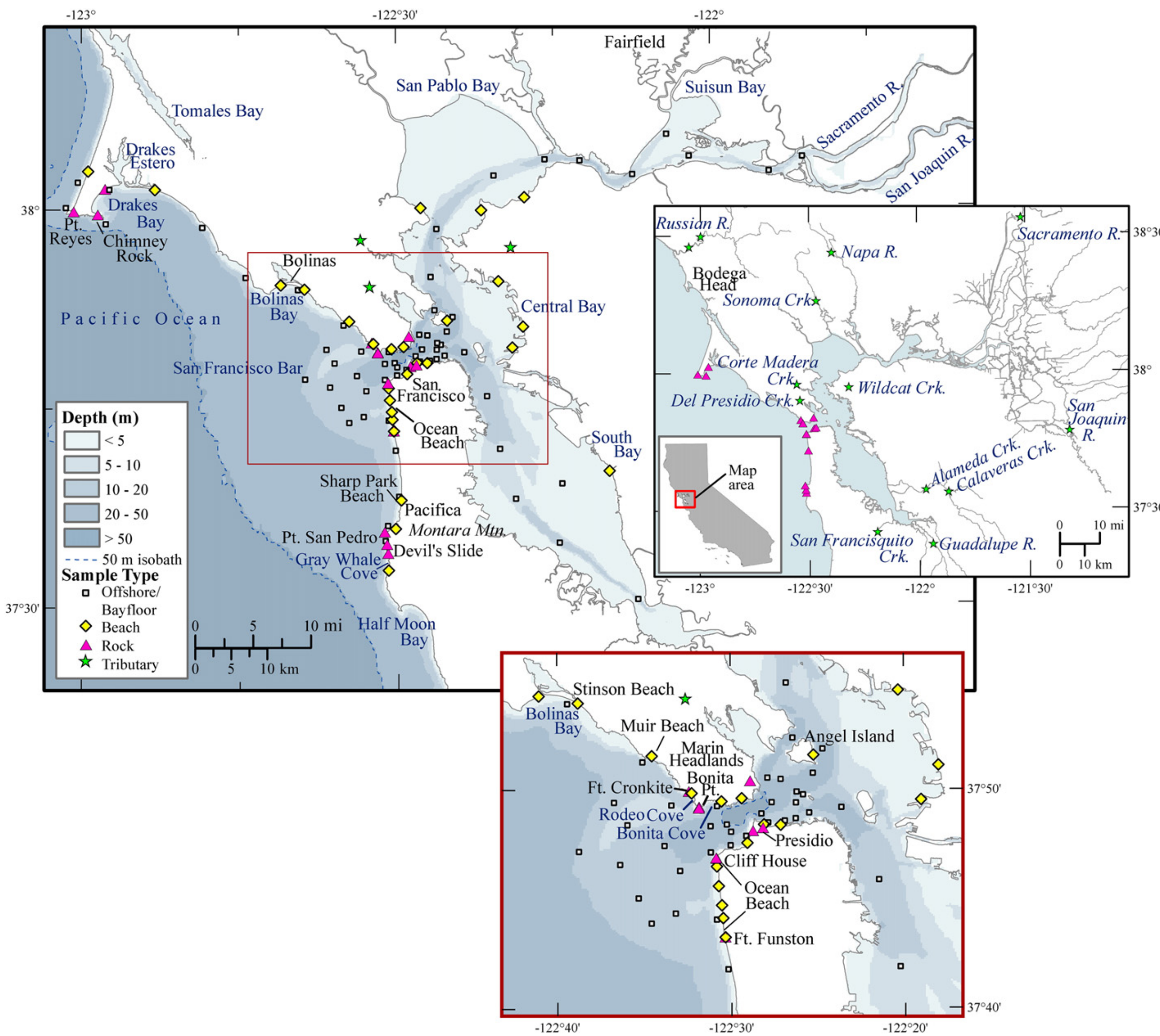

Fig. 1. Map showing all sample locations used in this study as well as water depth.