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Morphological Evolution in the San Francisco Bight

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ABSTRACT

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San Francisco Bight, located near the coast of San Franscisco, USA, is an extremely dynamic tidal inlet environment subject to large waves and strong currents. Wave heights coming from the Pacific Ocean commonly exceed 5 m during winter storms. During peak flow tidal currents approach 3 m/s at the Golden Gate, a 1 km wide entrance that connects San Francisco Bay to the Pacific Ocean. Flow structure in this region varies markedly spatially and temporally due to the complex interaction by wind, waves and tidal currents. A multibeam sonar survey was recently completed that mapped in high resolution, for the first time, the bottom morphology in the region of the ebb tidal delta. This data set includes a giant sand wave field covering an area of approximately 4 square kilometers. The new survey enables the calculation of seabed change that has occured in the past 50 years, since the last comprehensive survey of the area was completed. This comparison indicates an average erosion of 60 centimeters which equates to a total volume change of approximately 9.2×10^7 m^3. Morphologic change also indicates that flood channels have filled and that the entire ebb delta is contracting radially.

ADDITIONAL INDEX WORDS: *Sand waves, Tidal delta, Littoral, Sediment transport*

THE GOLDEN GATE AND S.F. BAY

San Francisco Bay (Figure 1) is a major estuary, an important commercial harbor, and is surrounded by one of the most developed urban centers in the United States. The Sacramento and San Joaquin Rivers, which flow into the NE edge of the bay, are outlets for 40% of California's freshwater discharge. Major geomorphic changes to the Bay began during the Gold Rush in the 19th century and have continued to the present. Influx of hydraulic mining debris from the Gold Rush in concert with major development of coastal wetlands in San Francisco Bay has exerted a strong influence on coastal processes at the bay mouth over the last 150 years in terms of sediment supply and tidal flushing capacity.

The Golden Gate is the sole tidal inlet in the present era that connects San Francisco Bay to the Pacific Ocean. At the mouth of San Francisco Bay, the channel has scoured down into bedrock a maximum depth of 113 m, where tidal currents accelerate through the narrow, erosion-resistant rocky strait spanned by the Golden Gate Bridge, forming one of the deepest natural channels in the world. Flow through this channel is forced by an enormous tidal prism of 2×10^9 m^3 , resulting in tidal currents that typically exceed 2.5 m/s.

The area also exhibits highly energetic waves, being exposed to swell from almost the entire Pacific Ocean. Average annual maximum offshore significant wave height is 8.0 meters, and the annual average offshore significant wave height is 2.5 meters. The combination of large waves, strong tidal currents, and ample sediment supply ensure active sediment transport in the region.

Figure 1: Satellite view of San Francisco Bay and the San Francisco Bight.

SAND WAVES

The large sediment transport capacity of tidal flow quickly diminishes as the channel emerges from it narrowest region, resulting in the deposition and persistence of one of the largest sand wave fields in the world, as shown in Figure 2. Most of the sand and gravel that supplies this sand wave field originates from the Sierra Nevada, and has been carried into San Francisco Bay via the San Joaquin and Sacramento river system, and through the local erosion of sea cliffs.

In the late 1970's, Rubin and McCulloch used rudimentary side-scan sonar to map sand waves inside San Francisco Bay, and they used observations of flow conditions and sediment grain size to predict bedform morphology at the mouth (RUBIN AND MCCULLOCH, 1979). Since that time, the advent of multibeam sonar systems enable both imaging of the sea floor with incredible spatial coverage (~1,000,000+ depth points per km^2) and speed (3,000 soundings/sec), and the potential of measuring depths with resolution of a few centimeters. Although sand waves are found in many marine and coastal environments, the sand wave field at the mouth of San Francisco Bay falls in the upper 10% of all sand waves in terms of wavelength, and are highly unusual (ASHLEY, 1990) because of the combination of the following features: absolute depth and depth range (30-106 m), number of sand waves (40+), modest tidal range (mesotidal, 2.65 m range), strong bidirectional flow (peak 2-2.5 m/s+ during ebb and flood), the scale of the individual bedforms themselves (maximum wavelength = 220 m, height= 10 m), the aerial extent (4 km^2) over which they persist, and the fact that the waves are apparently migrating up-slope from the channel beneath the Golden Gate Bridge toward the shallower submarine ebb-tidal delta located several kilometers offshore (BARNARD ET AL., 2006). Bedforms of approximately half the scale of those reported here were imaged inside San Francisco Bay during a multibeam survey in 1997 (CHIN, ET AL., 1997).

50 YEAR BATHYMETRIC CHANGE

By differencing the recent multibeam survey with the last comprehensive survey of the area, which was completed in 1956 by the National Ocean Service (U.S. COAST AND GEODETIC SURVEY, 1956) using single acoustic beam soundings, we calculate the patterns of net erosion and accretion over approximately the past half century, as shown in Figure 3. Overall there has been a loss of approximately 9.2 x 10^7 m^3 of sediment, which averages to 60 centimeters of erosion over the survey area. There are clearly recognizable patterns of erosion and accretion that relate to dredging activities, sediment transport, and the changing hydraulics of this system.

There is an overall indication that the ebb delta has contracted radially, as evidenced by the arc of erosion along the outer edge of the delta. We propose three hypotheses for the cause of this contraction. First, the entire delta might still be adjusting to a large input of sediment due to hydraulic mining in the Sierra Nevada during the gold rush of the late 19^{th} century (see GILBERT, 1917), and the ebb delta may still be slowing evolving back toward its equilibrium size. Second, the tidal prism of San Francisco Bay has been reduced due to construction, infilling, and sedimentation. In this case the ebb tidal delta would be shrinking toward a new equilibrium with the reduced tidal prism. Third, the sediment supply to the open coast has been reduced by damming in the rivers that feed San Francisco Bay, and the removal of sediment by sand mining directly from the San Francisco Bay floor. Over 50 millions m^3 of sediment has been removed since the mid- 1950's by sand mining operations. In the future we plan to investigate these hypotheses, all of which probably contribute toward the overall morphological evolution of the ebb tidal delta.

There are several locations that have experienced considerable erosion or accretion through either natural or man-induced processes. Foremost amongst the anthropogenically caused changes is the presence of a deep shipping channel incised through the central portion of the ebb delta. This channel has been maintained by dredging since 1922. Prior to 1971 the dredge spoils were disposed far offshore, but subsequently the dredged material has been place in the box marked SF-8 (Figure 3). Accretion at SF-8 is directly due to the dredge placement. Accretion north of SF-8 and north of the shipping channel is likely the result of tidally forced transport of material disposed within SF-8. Approximately 1.8 x 10^7 m^3 of sediment has been placed on SF-8 since 1971 (ARMY CORPS OF ENGINEERS, 1996).

Other regions of significant accretion appear along the coast on north and south sides of the inlet. These were previously primary flood channels that have been filled in over the past half century, likely related to the improved hydraulic efficiency of the main shipping channel due to its annual dredging. With the main channel more open to tidal flow, the flow in the peripheral flood channels would weaken, which would allow the infilling with sediment. We plan to conduct numerical modeling based investigations to explore this scenario.

There are small regions of accretion and erosion in the central part of the mouth of the inlet. We believe these are due to the migration of the giant sand waves discussed earlier.

Finally, there is a region of erosion in extremely deep water near the narrowest portion of the Golden Gate. We propose two hypotheses for this erosion. First, it is possible that regions that were covered with sediment 50 years ago have eroded down to bedrock since then due to the decrease in sediment supply. An alternative, but seemingly less likely explanation is that the energetic transport of sand and gravel through the mouth of the Golden Gate due to tidal currents is actively eroding the bedrock surface.

CONCLUSIONS

New multi-beam surveys of the San Francisco Bight completed in 2004-2005 have revealed a field of giant sand waves just seaward of the Golden Gate, and also provided a quantitative measure of the regions coastal morphological evolution over the past half century. The entire ebb delta has decreased in size and volume over the past 50 years. Several reasonable hypotheses for the causal mechanisms of this evolution have been proposed and will be explored in the near future.

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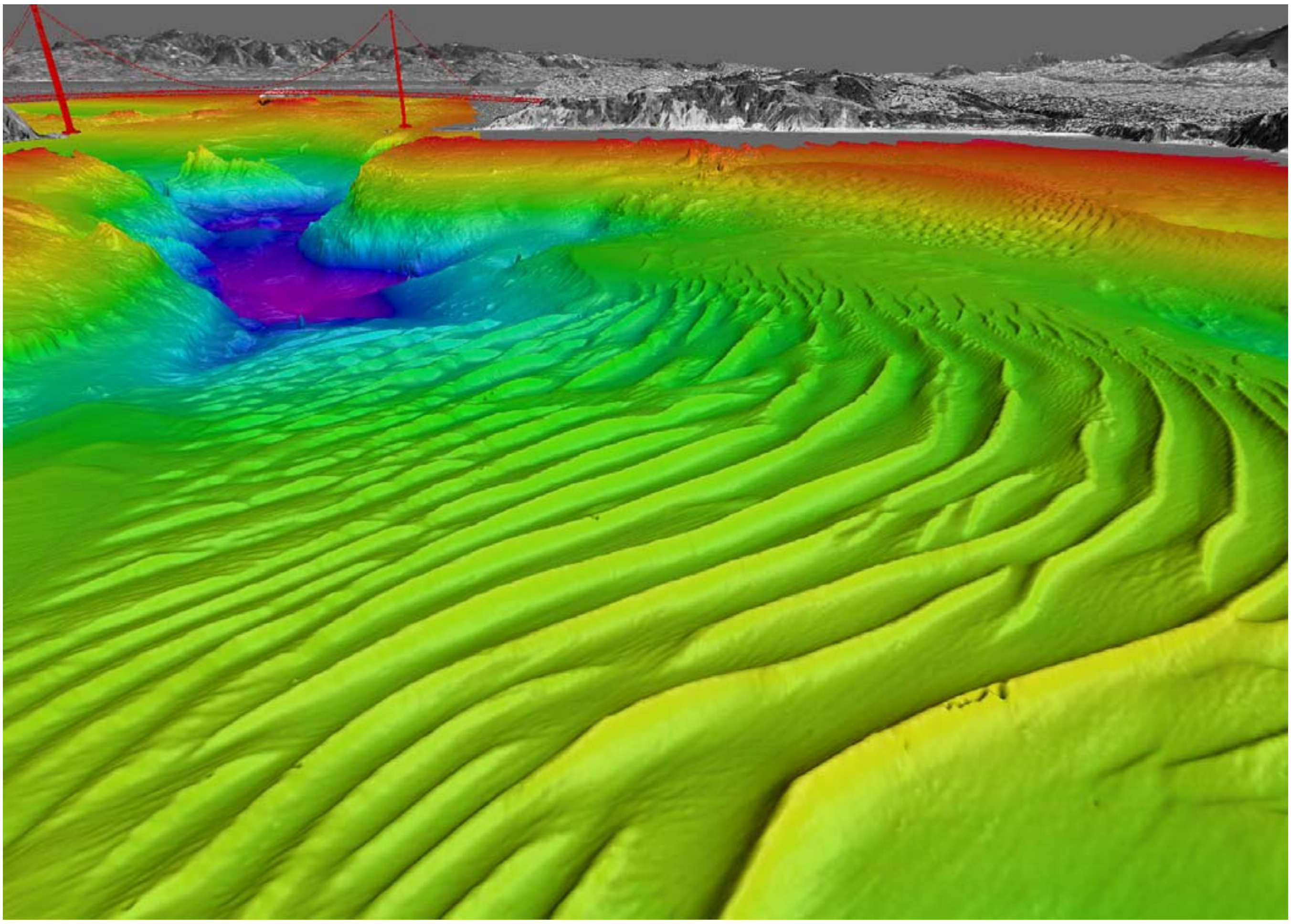

Figure 2: View toward San Francisco Bay of the massive sand wave field. The Golden Gate Bridge is approximately 2 km (1.2 mi) long. Shaded relief image created with a 2-m grid, 4x vertical exaggeration, sun azimuth of 240 degrees, and sun angle of 66 degrees. The land topography was generated by overlaying digital orthophoto quadrangles (DOQs) on USGS digital elevation models (DEMs), with a 2x vertical exaggeration. Bathymetry data inside the Bay (that is east of Golden Gate Bridge) is from DARTNELL AND GARDNER (1999). Golden Gate Bridge model courtesy of Interactive Visualization Systems.

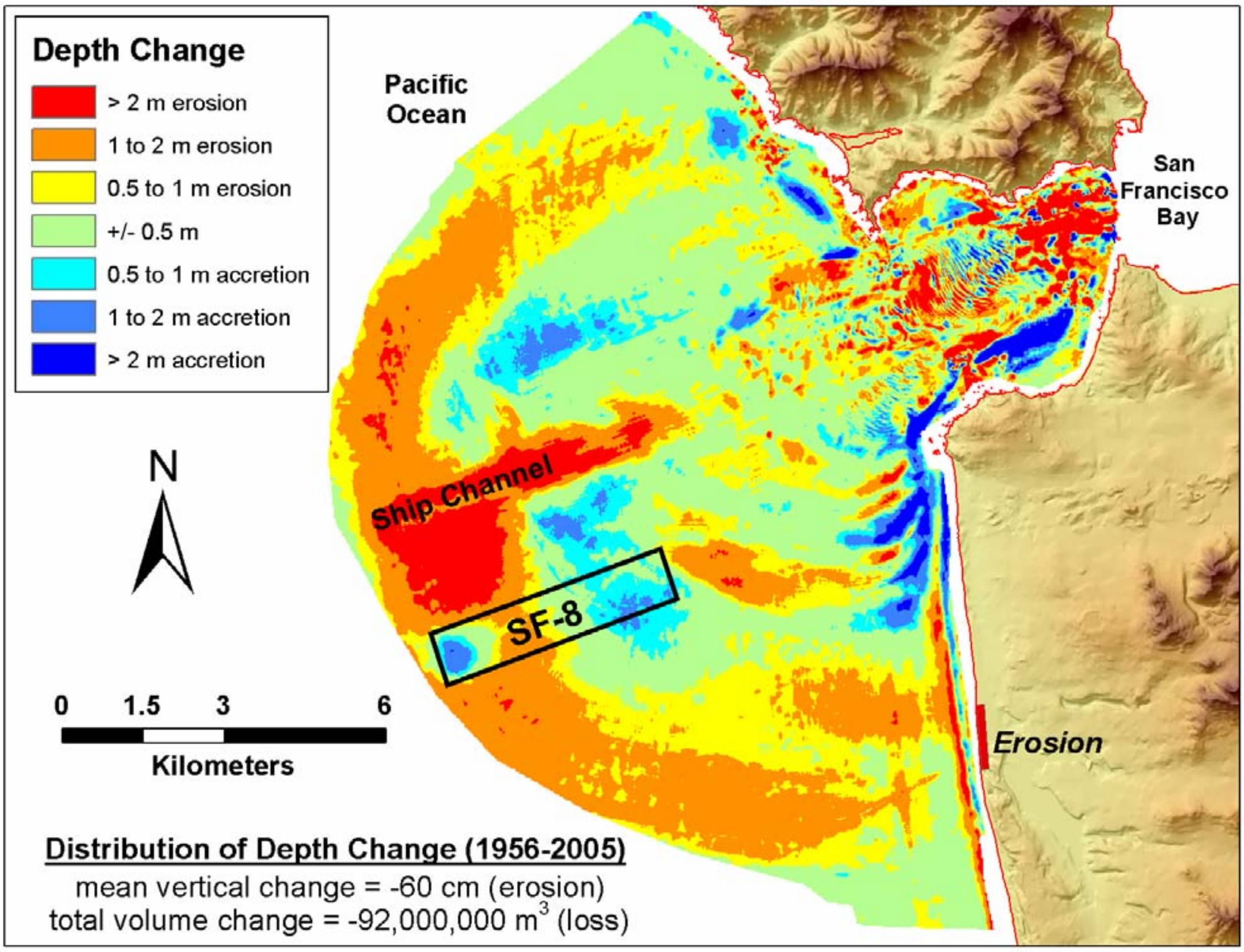

Figure 3: Vertical change in the region between approximately 1956 and 2005.