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Sand Waves at the Mouth of San Francisco Bay, California

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Background

A multibeam bathymetric survey that produced unprecedented high resolution images of the mouth of San Francisco Bay was conducted in 2004 and 2005. The survey, performed over forty-four days by the Seafloor Mapping Lab at California State University, Monterey Bay, consisted of 1,138 track lines, 1.1 billion soundings, and covered an area of 154 km^2 (60 mi^2). The goals of this survey were to analyze sediment transport pathways at the mouth of San Francisco Bay and to calculate bathymetric change since the last survey was completed in 1956. The survey showed that significant bathymetric changes have occurred over the past 50 years. It also revealed that the study area contains sand waves that are among the largest and bedform morphologies that are among the most varied in the world.

Figure 1. Location of the study area.

Bedform Diversity

The complex temporal and spatial variations in wave and tidal current interactions at the mouth of San Francisco Bay result in a diverse array of bedform morphologies, scales, and orientations (Barnard and others, 2006). Strong tidal currents peak at over 2.5 m/s (5.6 mi/hr) and rocky headlands and embayments help to create strong eddies and reverse flows, all of which combine to form highly variable bottom features.

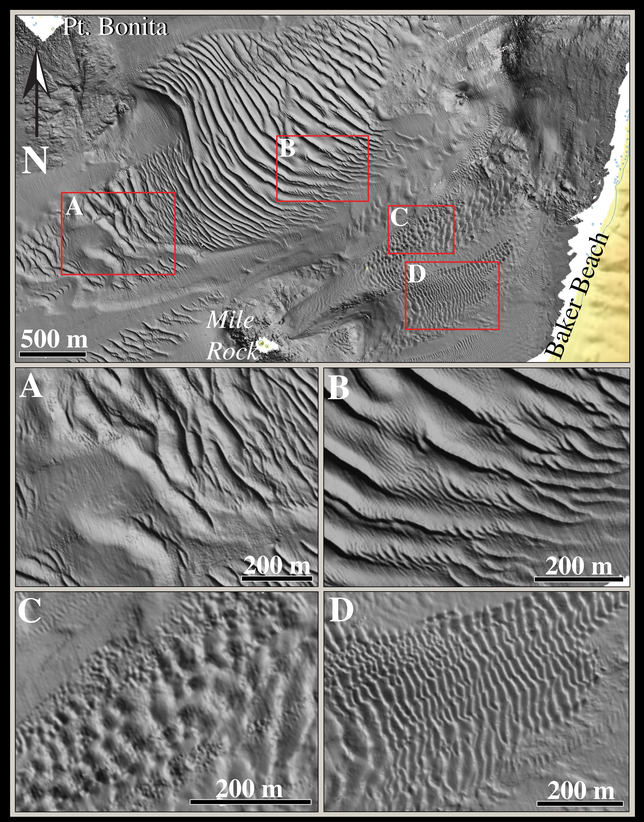

Figure 2. Diverse sand waves at the mouth of San Francisco Bay, seaward of the Golden Gate Bridge. Shaded relief image created with 5x vertical exaggeration, sun elevation of 45 degrees, and sun azimuth of 45 degrees. (A) Irregular sand waves seaward of the main sand wave field. (B) Ebb-dominated sand waves with wavelengths as great as 150 m with superimposed sand waves of 5- to 10-m wavelength. (C) Linguoid sand waves, 20- to 30-m in wavelength. (D) Flood-dominated sand waves, 15- to 20-m in wavelength.

Massive Sand Waves

Some of the largest sand waves in the world are located just west of the Golden Gate Bridge—these waves have been formed by abundant sediment and extremely powerful tidal currents. The data are shown in the figure below as a perspective color shaded relief image. This massive sand wave field covers an area of approximately 4 km^2 (1.5 mi^2) in water depths ranging from 30 m (98 ft) to 106 m (348 ft). More than 40 distinct sand waves were identified; the waves have an average wavelength of 82 m (269 ft) and an average height of 6 m (20 ft). The maximum wavelength and height are 220 m (722 ft) and 10 m (33 ft), respectively. Put another way, the largest crest to crest distance is well over two football fields long and more than three stories high! Sand wave crests can be traced continuously for as much as 2 km across the mouth of this energetic tidal inlet, where each tide forces 2 billion m^3 (528 billion gallons) of water through the Golden Gate—that's the equivalent of the volume of water required to fill 660,000 Olympic-sized swimming pools! The resulting strong currents sweep large volumes of sediment between the narrow rocky headlands, spanned by the Golden Gate Bridge, into the Bay during the flooding tide and toward the Pacific Ocean during the ebbing tide.

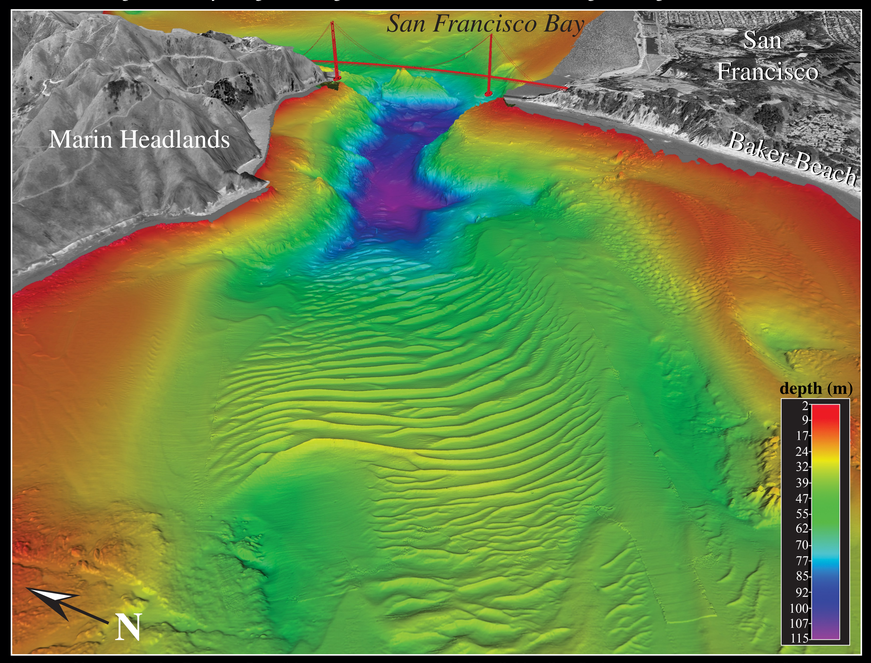

Figure 3. View toward San Francisco Bay of the massive sand wave field. The Golden Gate Bridge is approximately 2 km (1.2 mi) long. Shaded relief image created with a 2-m grid, 4x vertical exaggeration, sun azimuth of 240 degrees, and sun angle of 66 degrees. The land topography was generated by overlaying 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. See figure 5 for a close-up view of some of the sand waves.

Sand Wave Migration

Multiple surveys of a 2.5 km (1.6 mi) track line through the center of the massive sand wave field were completed in 2004 and 2005. Analysis of these surveys enables the calculation of short- (daily) and long-term (annual) rates of bedform migration and sediment transport. In 2004, surveys repeated as frequently as 24 hours (figure 4) showed that crests shifted as much as 3 m (10 ft), whereas over the entire 13-day sampling period the average migration of each sand wave was just 1.4 m (4.4 ft), or 11 cm/day (4.3 in/day). However, the 2005 surveys indicate that the net migration rate, when averaged over an entire year, is just 7 m (23 ft), or less than 2 cm/day (0.7 in/day) seaward. These data show that strong tidal fluctuations cause daily sand wave oscillations that are a significant percentage of annual migration rates, but flow reversals result in a relatively low rate of net sand wave migration annually (Barnard and others, 2006).

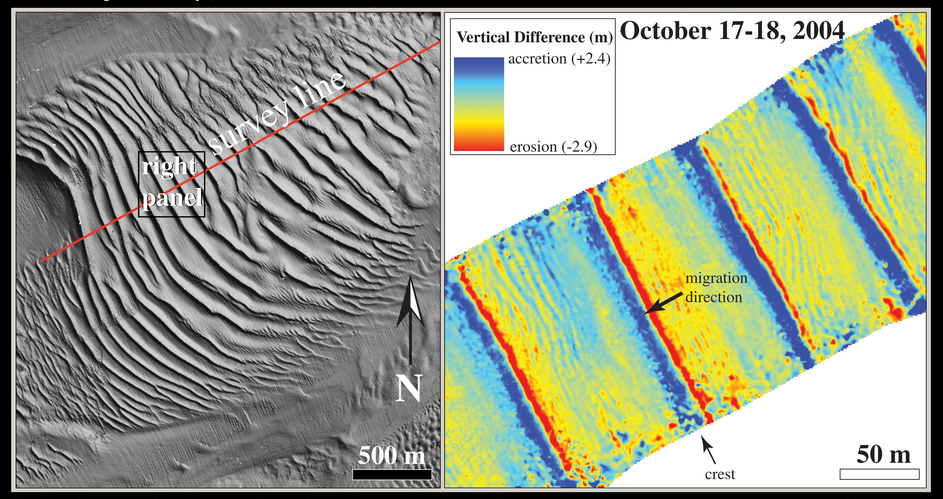

Figure 4. Overview of large sand wave field (left panel) and high-resolution difference map (right panel) of two surveys approximately 21 hours apart illustrating both large-scale and small-scale sand wave migration and orientation. Migration is from right to left (seaward).

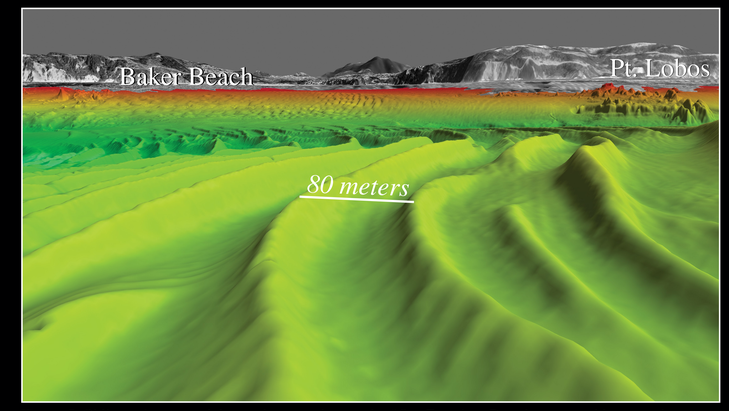

Figure 5. Oblique view toward the south across the mouth of San Francisco Bay along several large sand wave crests. See figure 3 for depth scale and image details.

Depth Change (1956-2005)

The bathymetry at the mouth of San Francisco Bay has changed considerably since the last complete survey was conducted by the NOAA National Ocean Service (NOS) in 1956. The large-scale morphological trend is sediment loss (figure 6). The average depth change in the region was -70 cm (-2.3 ft, erosion), which amounts to about 105 million m^3 (137 million yd^3) of sediment loss in the common survey area in 50 years. The outer lobe of the ebb tidal delta (that is, the bar at the mouth of San Francisco Bay) is completely dominated by erosion. Several likely causes for the observed trend include the reduction in tidal prism or currents of approximately 30 percent due to San Francisco Bay development, a decrease in sediment supply due to removal by sand mining inside the bay of approximately 50 million m^3 (65 million yd^3) since the middle of 20th Century (Chin and others, 1998; 2004), and a reduced influx of hydraulic mining debris from the Sacramento River (Gilbert, 1917). There are two distinct accretionary mounds just south of the main shipping channel, presumably the result of the annual dredge disposal of shipping channel sediments in this area, that have totaled about 18 million m^3 (24 million yd^3) since disposal commenced on this site (SF-8) in 1971 (United States Army Corps of Engineers, 1996).

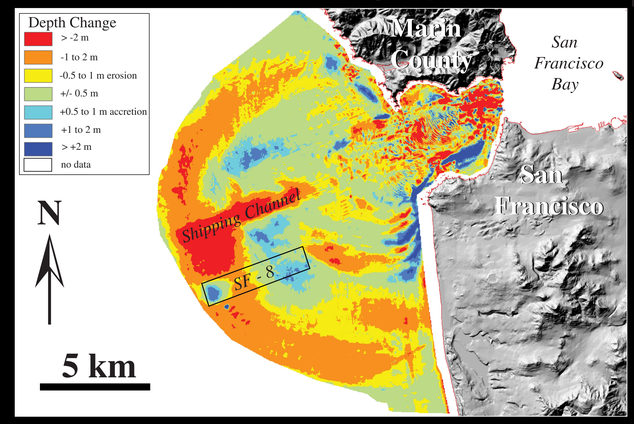

Figure 6. Difference map between the 1956 NOAA NOS survey and the multibeam survey completed in 2005.

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For more information on this study, go to http://walrus.wr.usgs.gov/coastal_processes/

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