Giant Sand Waves at the Mouth of San Francisco Bay

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A field of giant sand waves, among the largest in the world, recently was mapped in high resolution for the first time during a multibeam survey in 2004 and 2005 through the strait of the Golden Gate at the mouth of San Francisco Bay in California (Figure 1a). This massive bed form field covers an area of approximately four square kilometers in water depths ranging from 30 to 106 meters, featuring more than 40 distinct sand waves with crests aligned approximately perpendicular to the dominant tidally generated cross-shore currents, with wavelengths and heights that measure up to 220 meters and 10 meters, respectively.

Sand wave crests can be traced continuously for up to two kilometers across the mouth of this energetic tidal inlet, where depth-averaged tidal currents through the strait below the Golden Gate Bridge exceed 2.5 meters per second during peak ebb flows. Repeated surveys demonstrated that the sand waves are active and dynamic features that move in response to tidally generated currents. The complex temporal and spatial variations in wave and tidal current interactions in this region result in an astoundingly diverse array of bed form morphologies, scales, and orientations. Bed forms of approximately half the scale of those reported in this article previously were mapped inside San Francisco Bay during a multibeam survey in 1997 [*Chin et al.*, 1997].

Importance of the Golden Gate Sand Waves

The giant sand waves of the Golden Gate are fascinating geomorphic features that also have practical implications for a number of societal issues. The flux of sand and gravel between San Francisco Bay and the coastal ocean is an important component of the littoral sediment budget. Understanding the mechanisms of transport and the quantity of material transported is integral to the proper management of sediment in the region. Key issues related to sediment management include dredging of the navigation channel, local coastal erosion, sand mining for construction and fill, and sources of sediment for beach nourishment.

The giant sand waves are also expected to be important to the ebb and flood tidal currents at the entrance to San Francisco Bay because their effective roughness retards the flow, and eddies shed from flow separations near the crests cause substantial generation of turbulence. The flow and turbulence influenced by the giant sand waves probably affect the mixing and dispersion of pollutants and contaminants both within and outside the Bay.

The Golden Gate Setting

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 to a maximum depth of 113 meters, 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. The flow through this channel is forced by an enormous tidal prism of 2×10^9 cubic meters (528 billion gallons), resulting in tidal currents that typically exceed 2.5 meters per second. These strong flows effectively sweep all mobile sediment through the narrowest portion of the channel. However, the large sediment transport capacity of this channel diminishes as the channel emerges from it narrowest region, resulting in the formation of one of the largest sand wave fields in the world (Figure 1). Because the sand waves are generated by tidal currents, the ebb and flow of water across the channel creates sand wave fields on both sides of the Golden Gate.

Most of the sand and gravel that supplies this sand wave field presumably originates from the Sierra Nevada, and has been carried into San Francisco Bay via the San Joaquin and Sacramento river system, though the local erosion of the Marin Headlands (to the north) may also contribute sediment.

In the late 1970s, *Rubin and McCulloch* [1979] used rudimentary side-scan sonar to map sand waves inside San Francisco Bay, and they used several side-scan track lines and observations of flow conditions and sediment grain size to broadly assess bed form morphology at the mouth. Since that time, the advent of multibeam sonar systems has enabled imaging of the seafloor with incredible spatial coverage (more than one million depth points per square kilometer) and speed (3000 soundings per second), and with 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 [*Ashley*, 1990], and is highly unusual because of the combination of the following features: absolute depth and depth range (30–106 meters), number of sand waves (more than 40), modest tidal range (mesotidal, 2.65-meter range), strong bidirectional flow (peak 2–2.5+ meters per second during ebb and flood), the scale of the individual bed forms themselves (max λ = 220 meters, height = 10 meters), the aerial extent (four square kilometers) 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.

Examples of features of comparable scale have also been noted at Cook Inlet in Alaska [*Bouma, et al.*, 1977], the Bay of Fundy in Nova Scotia [*Dalrymple, et al.*, 1978], the Dutch coast [*Verhagen*, 1989], and the Messina Strait of Italy [*Santoro, et al.*, 2002], although none of these sites contains the combination of features comparable to the giant sand waves of the Golden Gate.

Giant Sand Wave Measurements

The entire mouth of San Francisco Bay was mapped for 44 days in the autumns of 2004 and 2005, a survey consisting of more than 1.1 billion soundings. A region along the centerline axis of the giant sand waves was mapped four times in 2004: on 17, 18, 25, and 30 October; and three times in 2005: on 17 and 18 September and 30 October. These surveys focused on 19 distinct contiguous bed forms (Figure 2) in water depths between approximately 35 and 80 meters. (For more details on the data processing and analysis techniques, go to http://walrus.wr.usgs.gov/coastal_processes/EOS_Transactions)

Grain-size measurements indicate that the bed surfaces of the giant sand waves are composed primarily of coarse sand and gravel (0.5 to 4 millimeters), distinctly different from nearby Ocean Beach (to the south) or the shallowest region of the ebb tidal shoal, where mean grain size is typically fine to medium sand (~0.25 millimeters). The average wavelength of the sand waves along the centerline axis is 82 meters (range 32 to 150 meters), the average height is six meters, and the sand wave shapes are strongly ebb-dominated close to San Francisco Bay but become more symmetrical moving seaward, with the steeper faces on the seaward side of the bed forms. The more gently sloping faces are commonly overlain by smaller sand waves (typical λ = ~5–10 meters) with crests parallel to those of the larger sand waves in the western half of the field and divergent (~34°) in the eastern half (Figure 2).

The profiles through the bed form field from the four surveys conducted over a 13-day period in 2004 indicate that the sand wave crests migrate in response to daily tidal currents. Between surveys spaced as little as 24 hours apart, crest position oscillates as much as three meters. The bottom panel of Figure 2 illustrates the differences in bathymetry that occurred between the first two surveys, approximately one day apart. The thicker blue and red bands represent accretion and erosion due to the seaward migration of a sand wave crest.

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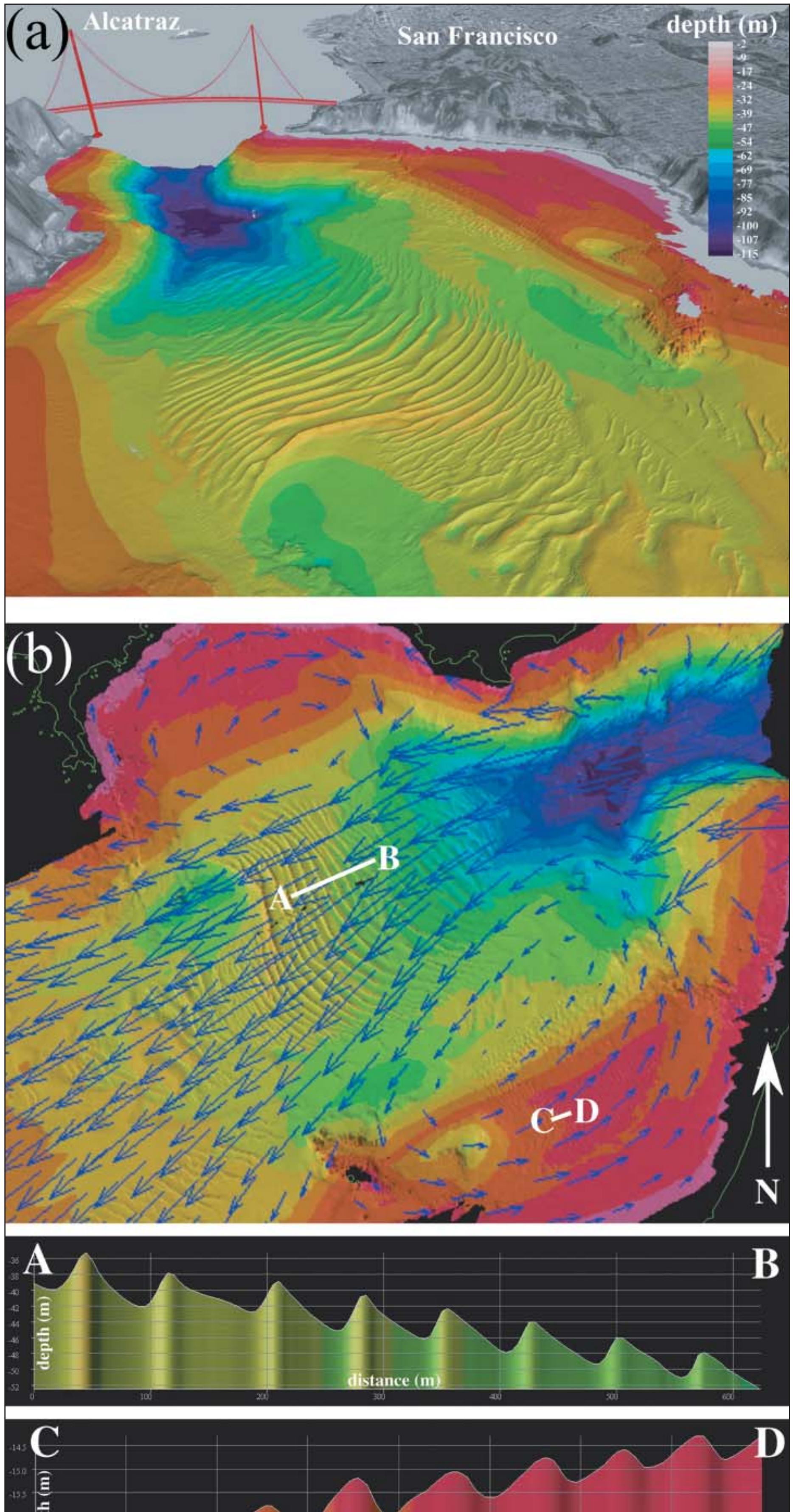

Fig. 1. (a) Oblique view of the giant sand waves and other bed forms at the mouth of San Francisco Bay. The view is from the northwest toward the Golden Gate Bridge. The city of San Francisco is in the upper right corner. The Golden Gate Bridge is approximately two kilometers long. The land was imaged using digital orthophotos draped over a U.S. Geological Survey digital elevation model. The Golden Gate Bridge model is courtesy of IVS 3D©. (b) Dominant transport directions at the mouth of San Francisco Bay illustrated by bed form orientation, ebb dominated in the center (transect A–B) and flood dominated along the periphery (transect C–D), due to persistent eddies. Predicted tidal currents from Delft3D are superimposed over the bathymetry, illustrating good agreement between peak flow vectors during ebbing tide and bed form morphology.

The finer-scale bands indicate the migration of smaller-scale sand waves up the more gently sloping side of the giant sand waves. There is an apparent correlation between instantaneous water level and crest locations during the four 2004 surveys, although a similar correlation is not apparent for the trough positions. This supports the supposition that the bed forms are actively responding to the unusually strong tidal currents, with small daily changes in shape.

Despite large daily oscillations, spatial lag correlation analysis conducted along the central axis of the sand wave field between the 2004 and the 2005 surveys indicates that there was a net offshore migration of only seven meters over one year. Assuming the migration rate can be extrapolated over the bed form field to estimate a total potential offshore sediment flux rate due to the migrating bed forms, this yields a total sediment flux of 32,000 cubic meters per year. However, the net transport clearly decreases away from the center of the tidal jet as the bed form morphology becomes increasingly symmetrical, and the net transport probably reverses in powerful flood-dominated eddies [*Rubin and McCulloch,* 1979] to the side of the main bed form field (Figure 1b).

The diversity of bed form morphologies, scales, and orientations at the mouth of San Francisco Bay is well illustrated in Figure 3. This wide array of bed form types represents an extremely dynamic coastal environment, reflecting the combination of extremely high gradients in tidal current velocity and direction, large waves, and ample sediment.

High-resolution multibeam imaging near the mouth of San Francisco Bay has revealed an extensive field of giant sand waves. The scale, migration rates, and diversity of bed forms at the mouth of San Francisco Bay reflect a highly energetic and dynamic coastal environment. This study demonstrates that repeat high-resolution surveys provide a powerful tool for measuring sand wave morphology and estimating bed form migration. The data demonstrate that the sand waves respond on a daily timescale to tidal current fluctuations, and the net migration is approximately seven meters per year in the offshore direction. The net migration indicates a significant flux of sand out of the Bay, with importance for a host of local and regional sediment management issues.

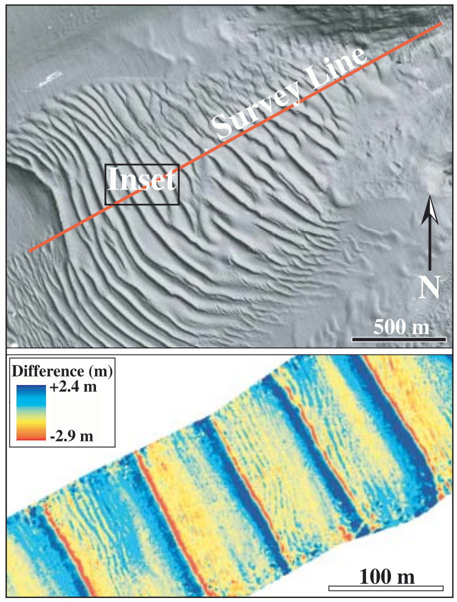

Fig. 2. Overview of large sand wave field and high-resolution difference map of two surveys approximately 21 hours apart illustrating both large-scale and small-scale sand wave migration and orientation. Migration is from right to left.

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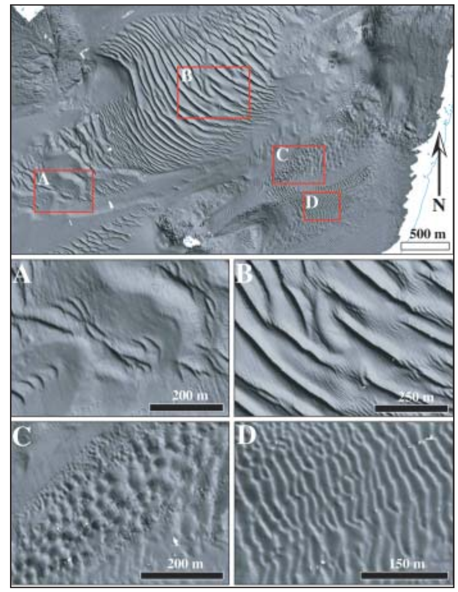

Fig. 3. Diversity of bed forms at the mouth of San Francisco Bay, just seaward of the Golden Gate Bridge. (a) Irregular sand waves seaward of the main sand wave field. (b) Up to 150 meter wavelength ebb-dominated sand waves with superimposed 5–10 meter scale sand waves. (c) Twenty to 30 meter wavelength scale linguoid-shaped sand waves. (d) Fifteen to 20 meter wavelength scale flood-dominated sand waves.

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