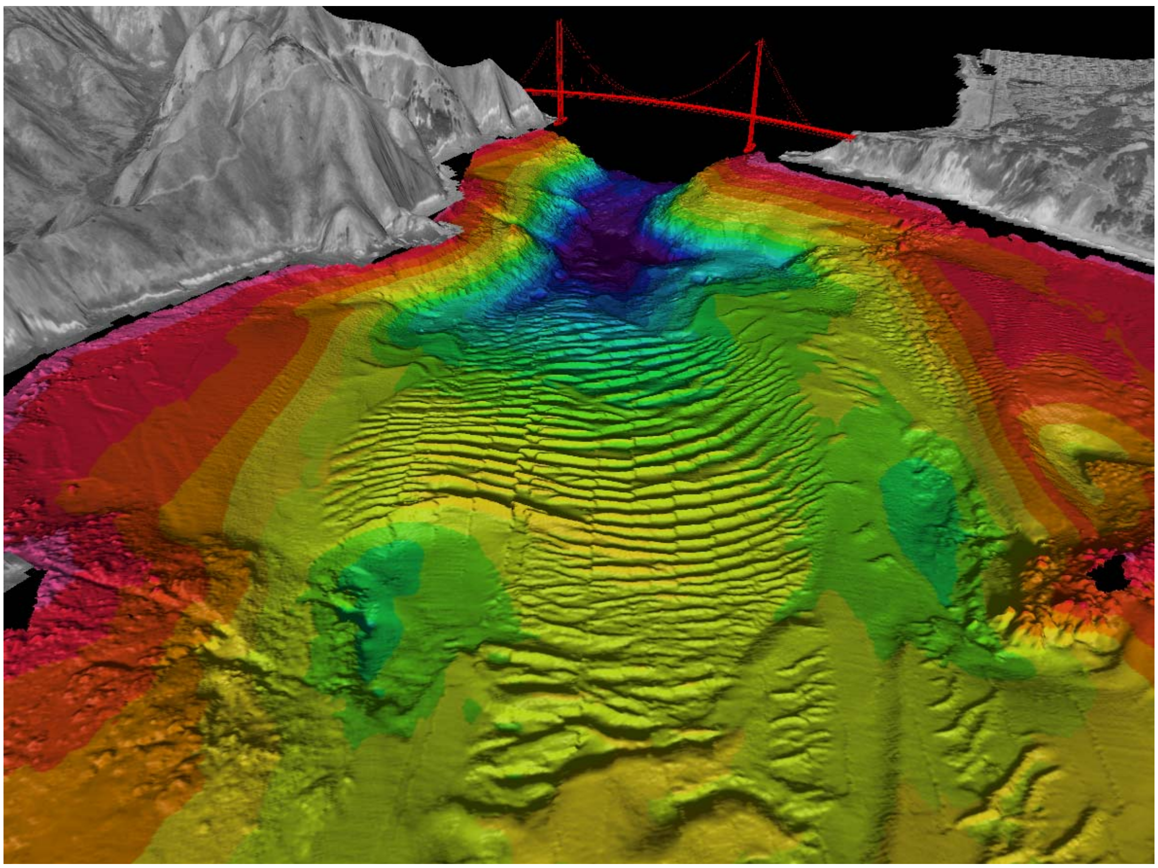
MODERN PROCESSES AT THE MOUTH OF SAN FRANCISCO BAY



ASBPA Field Trip
October 9, 2005

Patrick Barnard
Coastal Geologist
United States Geological Survey

Introduction

San Francisco Bay is a major estuary and one of the most developed in the country (Figure 1). Over 7 million people live in the immediate vicinity and over 10 million tourists visit the Bay Area every year (Chin et al. 2004). The Sacramento and San Joaquin Rivers, which empty into the bay, are the outlet for 40% of California's freshwater discharge. Major changes to the Bay began during the Gold Rush in the 19th century (Gilbert 1917) and have continued to the present. The influx of hydraulic mining 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.

This brief field trip guide will focus on the modern processes at the mouth of San Francisco Bay, highlighting recent work by the USGS as part of an ongoing coastal processes study in this region. This work includes some exciting new data sets and discoveries.

West-Central Bay

On our way out the Gate we will pass through West-Central San Francisco Bay. This region is the deepest part of the estuary and contains the coarsest sediment. Strong tidal currents that become focused through island channels and bedrock pinnacles have interacted with this sediment to produce a wide range of bedform morphologies that were first mapped by Rubin and McCulloch (1979) and later in high resolution multibeam by Chin et al. (1997) (Figure 2). In addition to interesting bedforms, this part of the bay also contains a series of bedrock knobs that rise to within 11 m (36 feet) of the surface, posing a major threat to navigation. These knobs have been lowered in the past by blasting, but as ship drafts keep increasing, the danger remains (Chin et al. 2004).

Figure 1. Satellite photo of the San Francisco Bay Area.

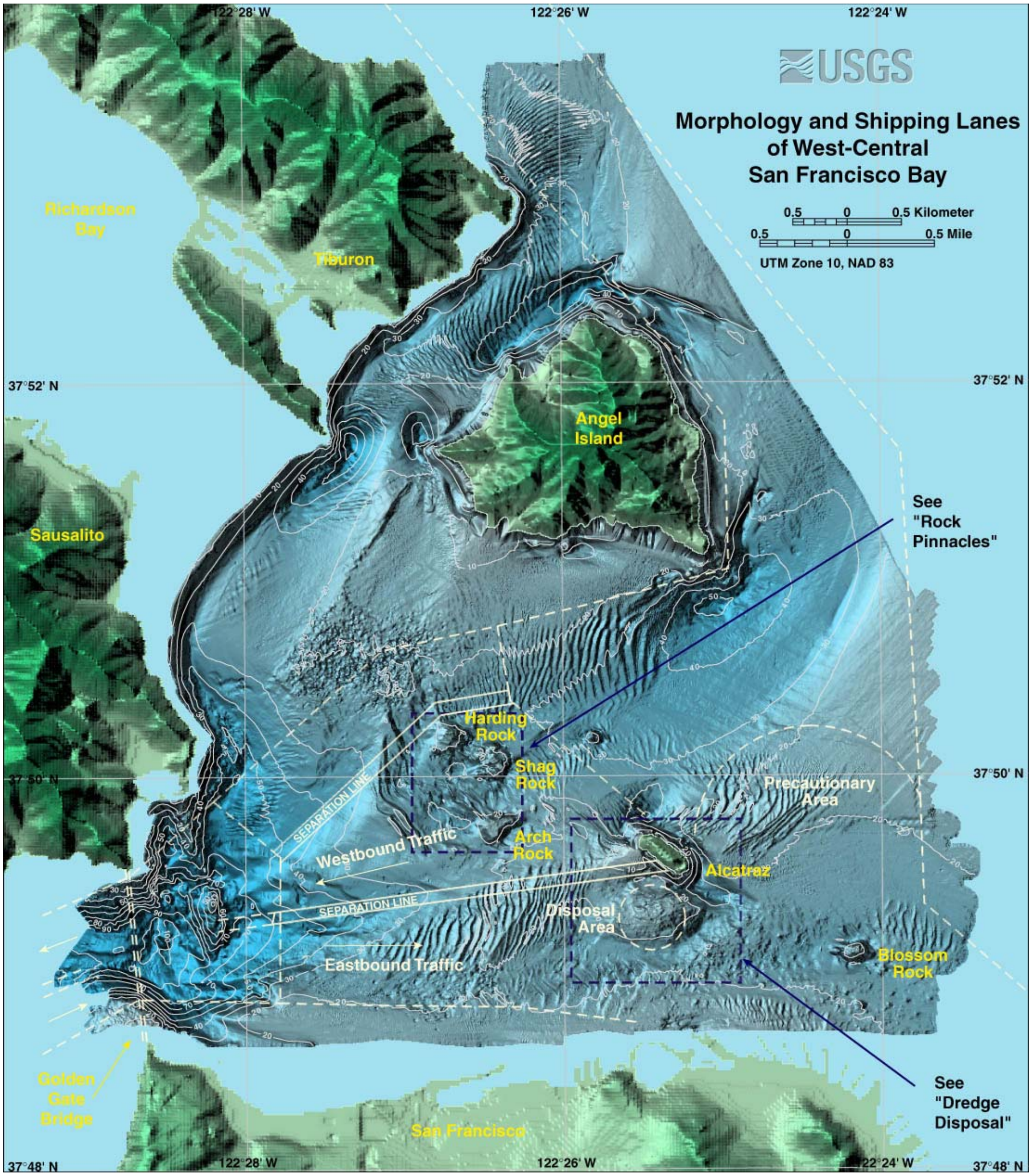


Figure 2. Shaded relief image of West-Central San Francisco Bay from USGS multibeam bathymetry (Chin et al. 1997).

Golden Gate Inlet Throat

Heading out to sea, the Golden Gate Bridge serves as the entrance to the mouth of San Francisco Bay, one of the most dramatic and dynamic coastal environments in the world. Tidal currents are extremely complex temporally and spatially, and can exceed 2.5 m/s (5.6 mi/hr) during peak ebb tidal flows at the Golden Gate (Figure 3). Wave heights on the continental shelf regularly exceed 6 m (20 ft) during major winter storms, and occasionally approach 9 m (30 ft) (Figure 4). The Golden Gate spring tidal prism is 2 x 10^9 m^3- that's 528 billion gallons of water moving in and out of the bay every 6.1 hours during peak flows- the equivalent of the volume of water required to fill 660,000 Olympic-sized swimming pools. Despite a high freshwater discharge rate into the bay of 800 m^3/s (211,000 gallons/sec) from the San Joaquin and Sacramento Rivers, this represents less than 1% of the overall tidal flow.

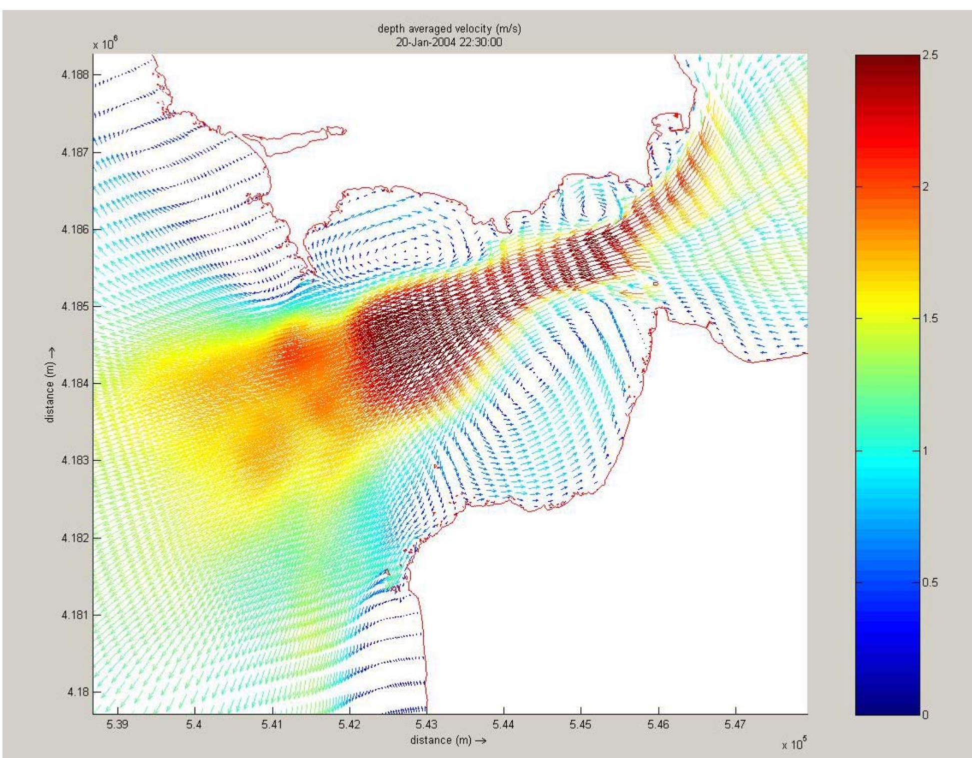


Figure 3. Predicted tidal current patterns during a peak ebb tidal flow at the Golden Gate using Delft3D.

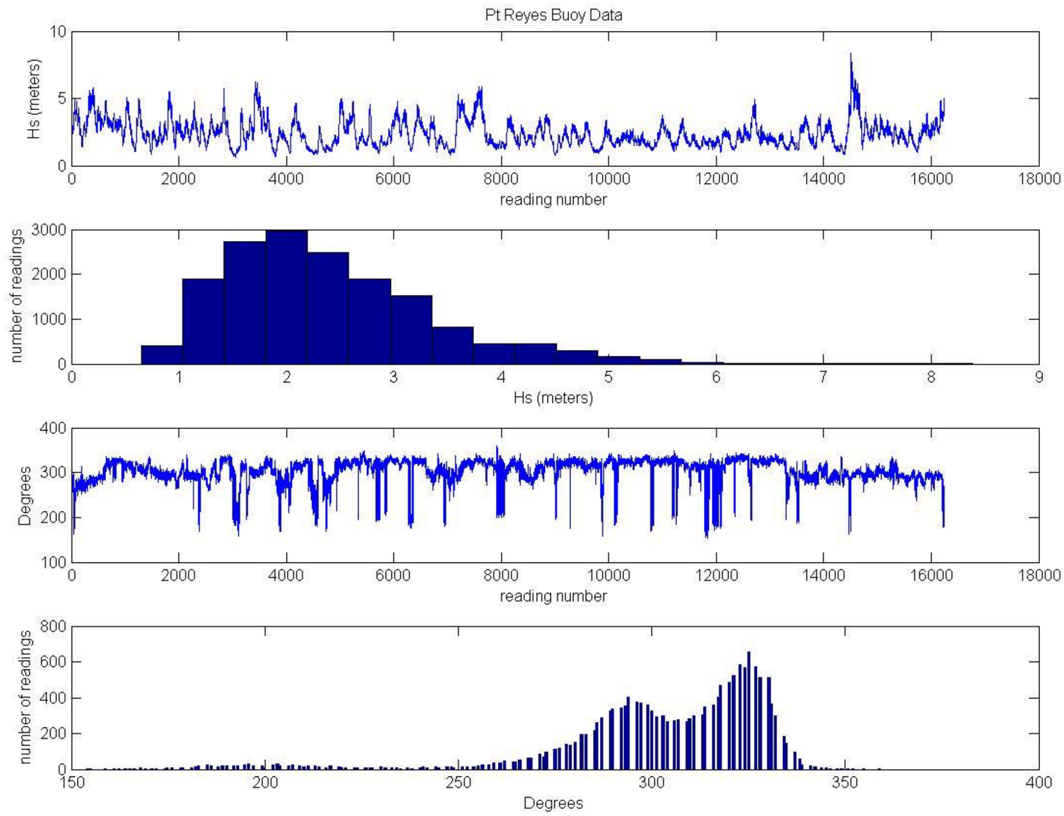


Figure 4. Offshore wave statistics during 2002 from the Pt. Reyes CDIP Buoy (Coastal Data Information Program 2004).

Underneath the Golden Gate, the strong tidal currents have scoured the channel bottom into bedrock to a depth of 113 m (370 ft), making the Golden Gate one of the deepest inlet channels in the world (natural or artificial). As the strong ebb tidal jet spreads out and velocities decrease west of the Golden Gate inlet throat (see Figure 3), the scouring potential sharply decreases, the coarse sediment load is dropped, and depths steadily decrease to 30 m (98 ft) over 2.5 km (1.5 mi). This combination of factors has resulted in one of the largest sand wave fields in the world (Barnard and Hanes 2005 (in press); Barnard et al. under review). The presence of large sand waves was first identified by Rubin and McCulloch (1979), but the features were mapped for the first time in high resolution multibeam in fall 2004 (Figure 5) by Rikk Kvitek from the Seafloor Mapping Lab at California State University, Monterey Bay, as part of a USGS-US Army Crops of Engineers (USACE) collaboration.

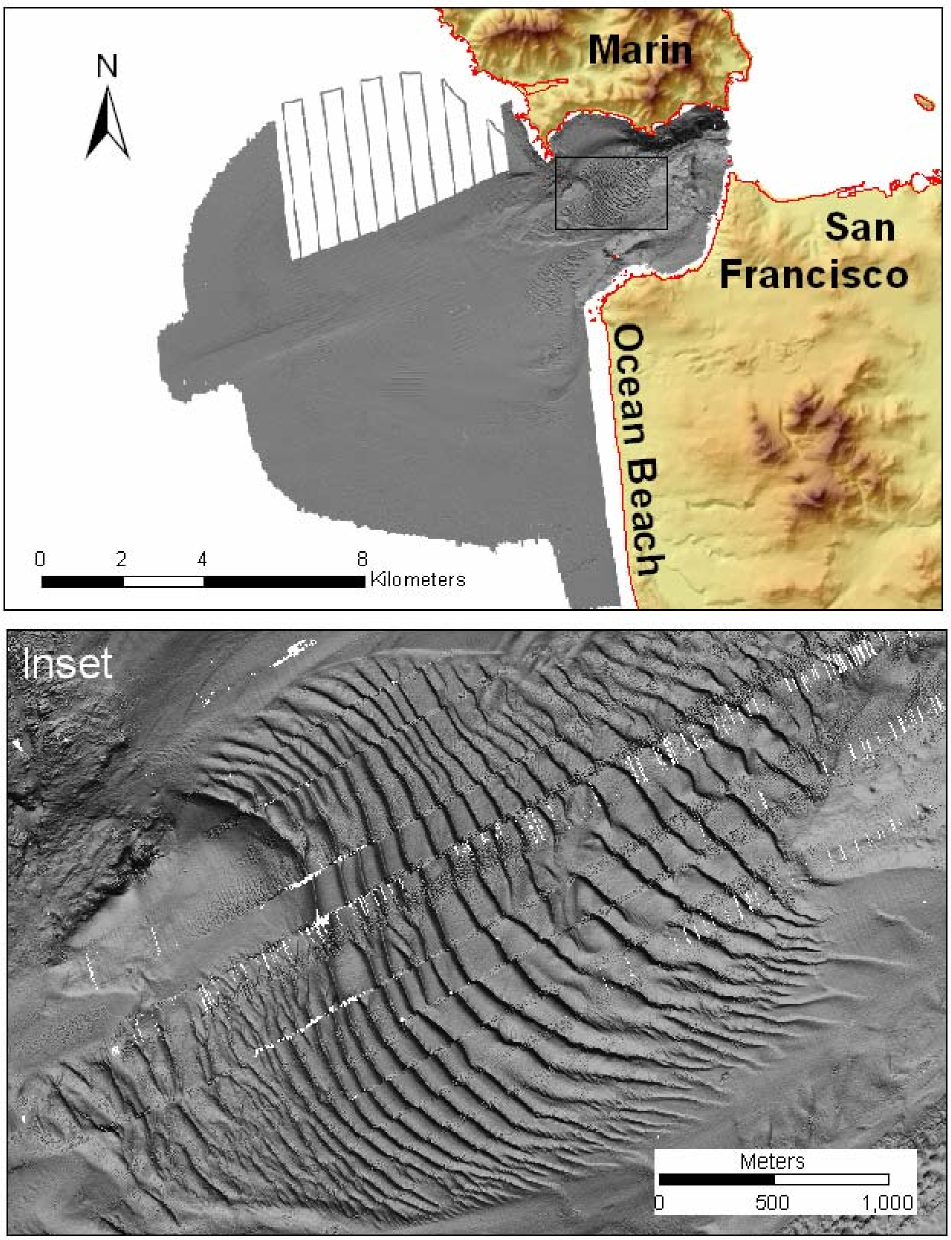


Figure 5. Overview of recent multibeam survey coverage area with inset showing large sand wave field.

Analysis of this massive bedform field shows that it covers an area of ~4 km^2 (1.5 mi^2) in water depths ranging from 30-106 m, featuring over 40 distinct sand waves with wavelengths and heights that measure up to 220 m and 10 m, respectively. This region shows an average wavelength of 82 m, height of 6 m, and strong ebb domination (ratio stoss:lee = 3) that decreases seaward. Bedform crests can be traced continuously for 2 km across the mouth of the inlet. Four passes over the center of this sand wave field were taken during a 13-day period to measure the dynamic nature of these features through time under varying tidal influences. The surveys demonstrate that average sand wave crest oscillation was ~4 m, with net migration ~3 m in the ebb direction during the study period. Difference maps show that sediment transport primarily occurs as smaller, ~ 5 m scale-wavelength, superimposed sand waves migrate over the much larger sand waves (Figure 6). However, the troughs are migrating at a much slower rate, which indicates that the crests move through an oscillation window that is controlled largely by the tidal stage, with the entire bedform field migrating seaward at much slower rate, approximately 80 m/yr, or one wavelength. Quantifying the net migration rate and direction of these bedforms is critical to evaluating their genesis and persistence through time, estuarine and coastal sediment supply rates, and for assessing how active similar features might be in other parts of the world (Barnard et al. under review).

The complex spatial and temporal variation in tidal current velocities at the mouth of San Francisco Bay (see Figure 3), that include strong eddies in both Bonita Cove and the cove at Baker Beach, have also resulted in an extremely diverse array of bedform morphologies (Figure 7). Scales range from m-wavelength-scale ripples to 200 m+ wavelength sand waves.

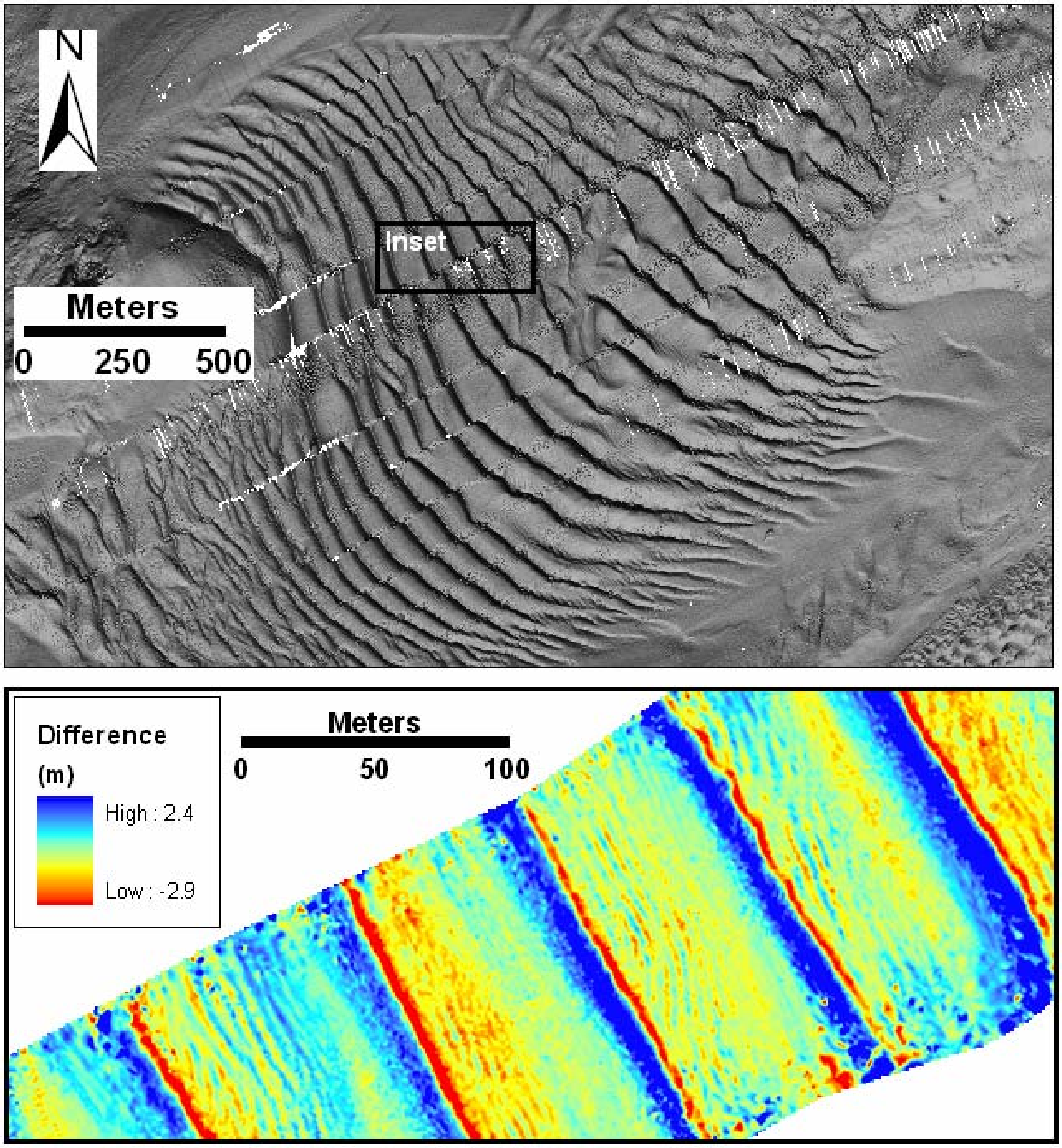


Figure 6. Overview of large sand wave field (top) and high-resolution difference map (bottom) of two surveys spaced 24 hours apart illustrating both large- and small-scale sand wave migration and orientation. Migration is from right to left (Barnard and Hanes 2005 (in press)).

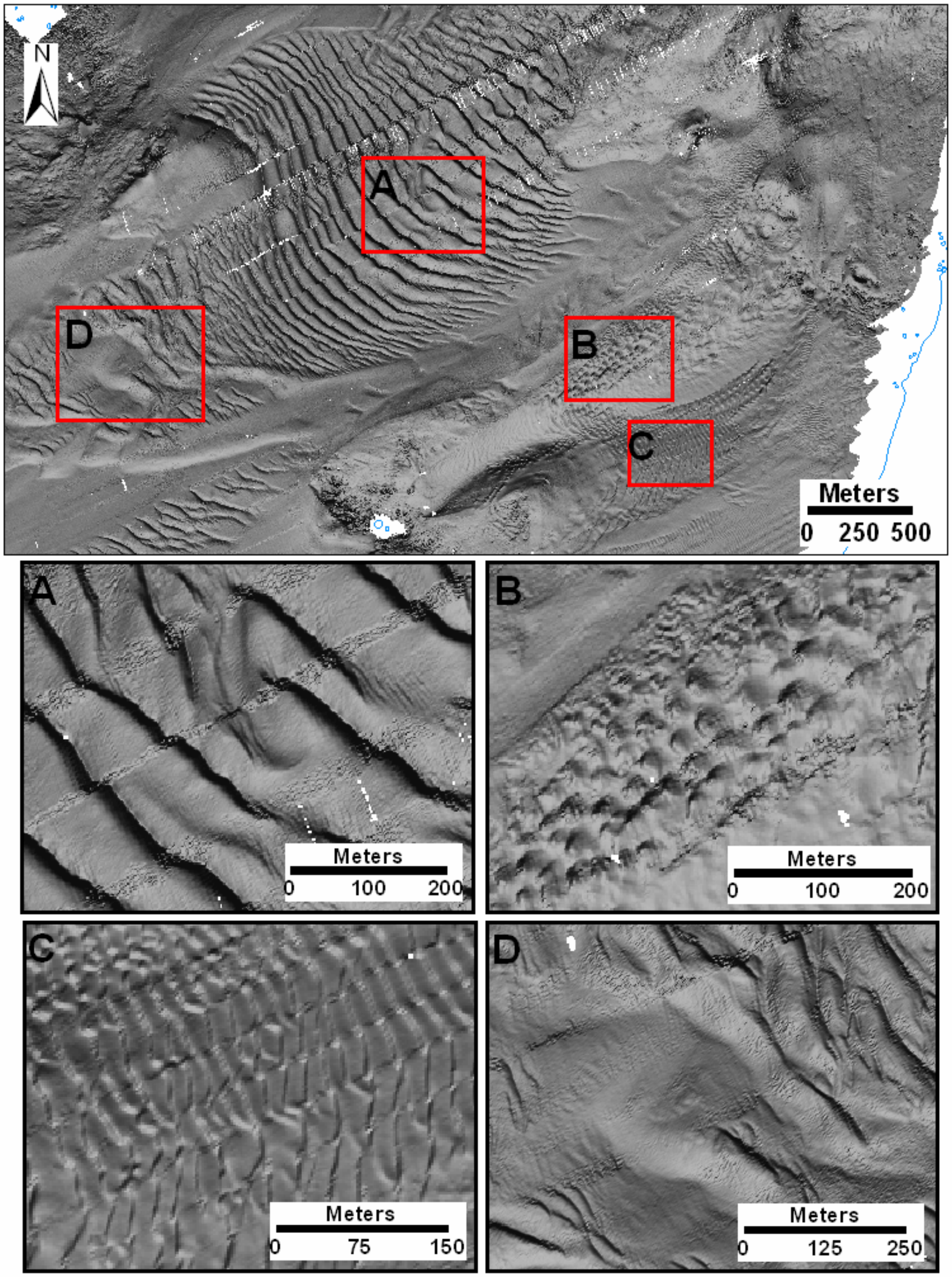


Figure 7. Diversity of bedforms at the mouth of San Francisco Bay. A) Up to 150 m ebb-dominated sand waves with 5 to 10-m wavelength superimposed sand waves. B) 20-30 m scale linguoid-shaped sand waves. C) 15-20 m scale flood-dominated sand waves. C) Irregular sand waves seaward of the main sand wave field with wavelengths up to 220 m (Barnard et al. under review).

Baker Beach

To the south lies Baker Beach, a pocket beach tucked between adjacent headlands. It is hypothesized that this beach is fed by sediment that leaks around Pt. Lobos from Ocean Beach. Further, recent shoaling at Crissy Field and at the San Francisco Yacht Harbor entrance indicate Baker Beach may becoming an increasingly major sediment pathway for sediment feeding the northern shoreline of the Marina District in San Francisco. This could be a result of more sediment leaking around Pt. Lobos (the northern part of Ocean Beach is wider than its been in over 20 years) or increased return flow from the strong eddy that spins in Baker Beach cove during the ebbing tide (Figure 8).

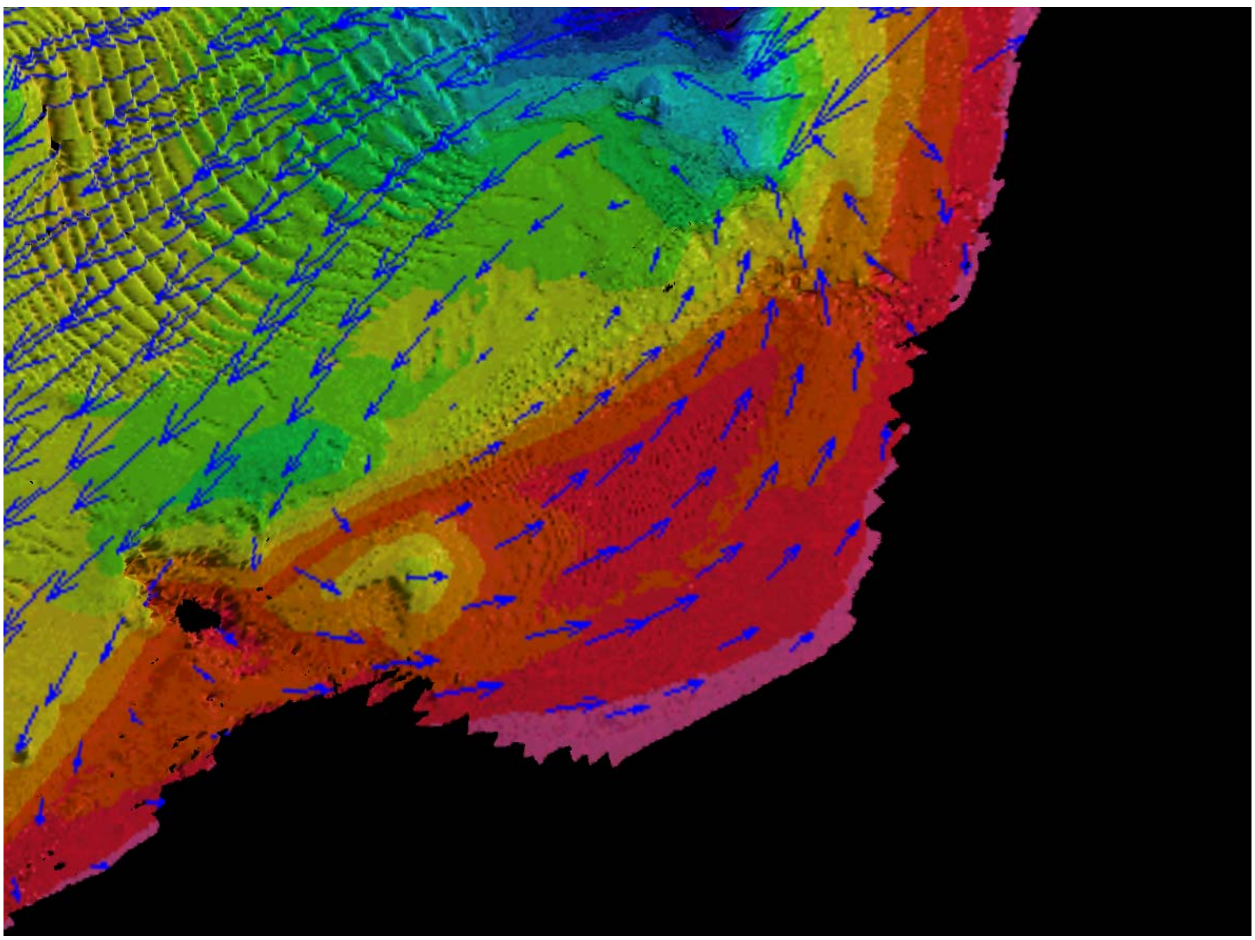


Figure 8. Dominant tidal current patterns during a peak ebb tidal phase predicted by Delft3D, with underlying bathymetry (Barnard and Hanes 2005 (in press)).

San Francisco Bar

As we move out past Pt. Lobos and Pt. Bonita into the open ocean we merge onto the San Francisco Bar (Figure 9), a huge ebb-tidal delta covering over 100 km^2 (39 mi^2) that is fed by sediment flushed out of San Francisco Bay, and shaped by strong tidal currents associated with SF Bay and waves originating from all corners of the Pacific. Moffatt and Nichol Engineers (1995) showed that a reduction in the SF Bay tidal prism and sediment supply from the Sierras resulted in a radial shrinking of the Bar towards the Golden Gate between the late 1800's and the 1950's. The fall 2004 multibeam survey, the first depth survey of the bar since 1956, indicates that this trend is continuing (Figure 10). The size and shape of the ebb-tidal delta has a direct influence on wave refraction and focusing patterns on adjacent beaches (Figure 11), as well as control dominant sediment transport pathways.

Ocean Beach

Ocean Beach is a 7 km-long north-south trending sandy beach that stretches south from a rocky headland at Point Lobos to the bluffs at Fort Funston (see Figure 9). It is strongly affected by tidal currents from the adjacent Golden Gate, as well as wave refraction around the ebb-tidal delta. Ocean Beach has undergone numerous significant anthropogenic alterations since the late 19^{th} century: highway construction, seawall construction, dune stabilization, dune removal, rip rap emplacement, beach nourishment, inlet fill, etc. (United States Army Corps of Engineers 1996). The most striking man-made feature we can observe from the boat, besides the Cliff House Restaurant atop Pt. Lobos, is the graffiti-covered, 1.5 km long O'Shaughnessy Seawall at the northern end of the beach. It was built from 1915-1929 to protect the Great Highway and is arguably one of the more successful seawalls in the country (Wiegel 2001). The beach has often

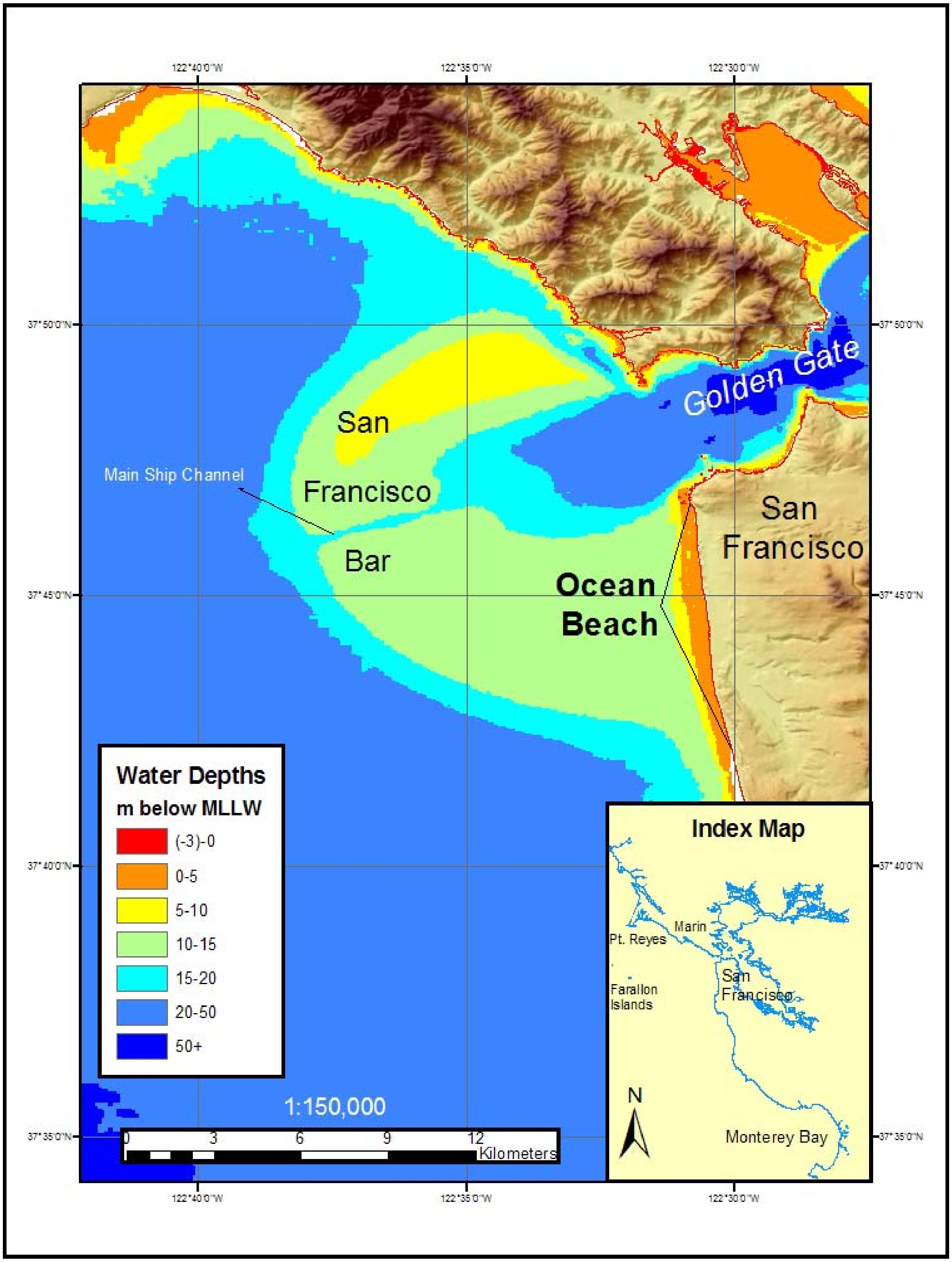


Figure 9. Location and bathymetry of the San Francisco Bar and adjacent Ocean Beach.

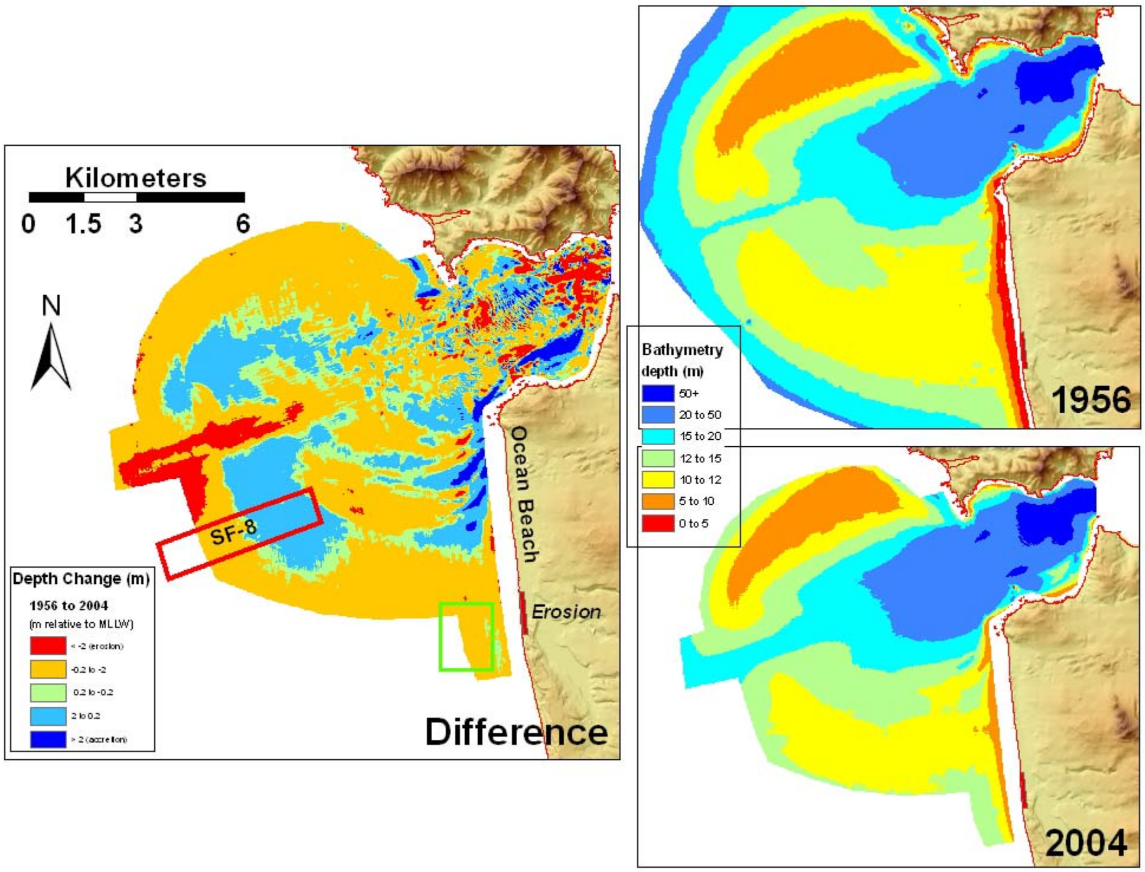


Figure 10. Depth change at the mouth of San Francisco Bay since 1956.

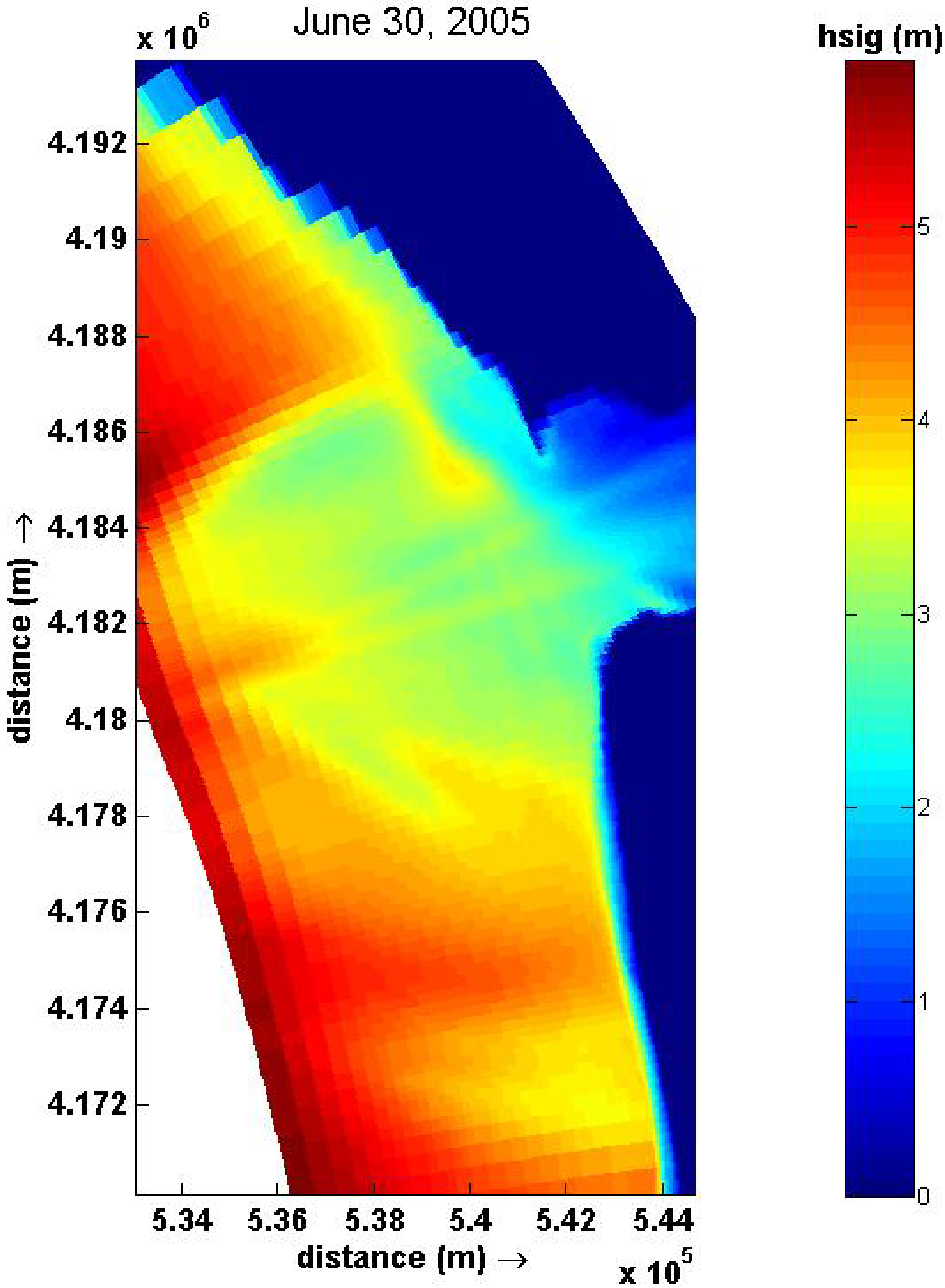


Figure 11. SWAN predictions of wave heights along the SF Bar during a large swell in June 2005, illustrating the dominant influence of the SF Bar on wave patterns.

maintained a healthy volume of sand in front of the seawall and no significant end-around erosion has been noted. The seawalls success can be attributed to several factors: it traps wind-blown sediment from leaving the beach system, Pt. Lobos acts as natural jetty to trap the dominant northerly littoral drift, and return flow from a strong eddy that spins off Pt. Lobos during the ebbing tide further feeds the beach (Figures 12-13).

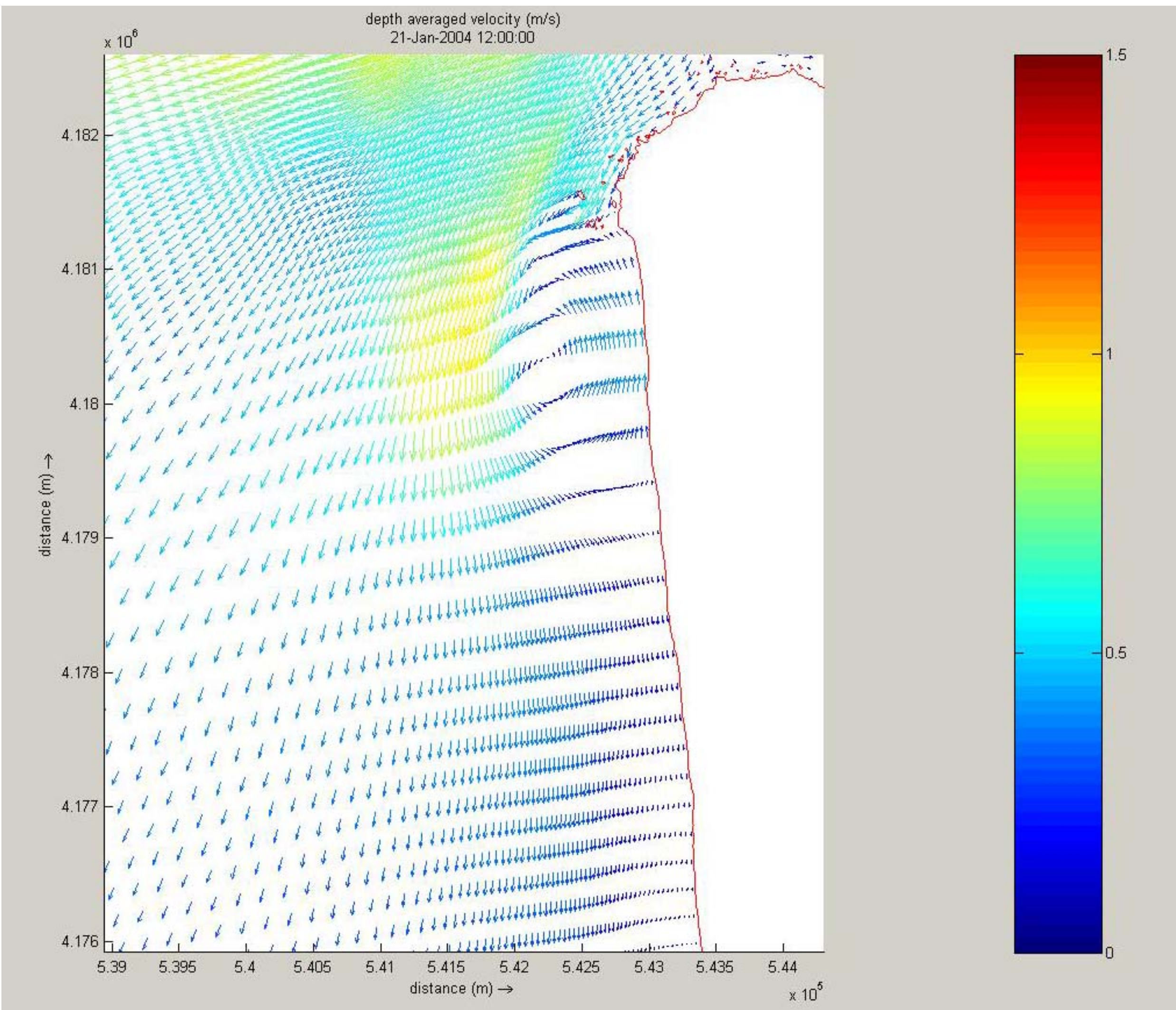


Figure 12. Strong eddy that spins off Pt. Lobos during peak ebb flow, resulting in significant volumes of northerly transport during a predominantly southerly flow.

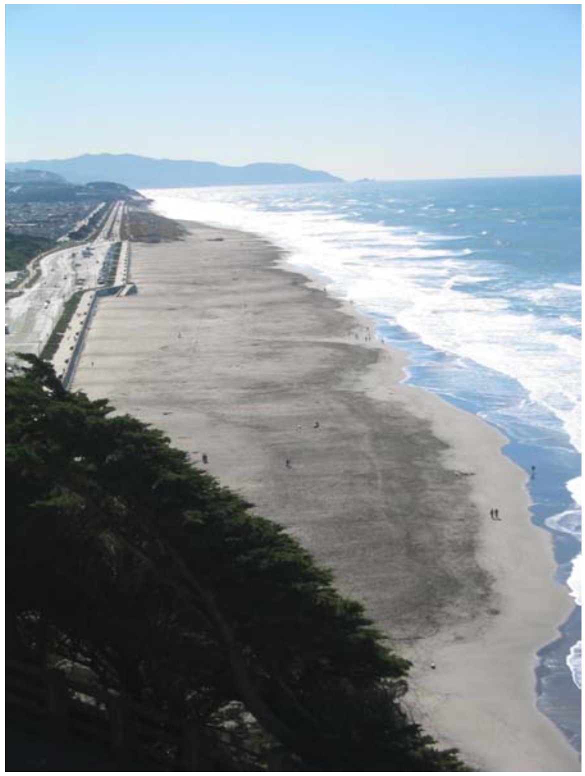


Figure 13. Wide beach at northern end of Ocean Beach. Possible result of return flow to northern part of beach from a strong, persistent cellular structure (see Figure 12).

Battalio and Trivedi (1996) estimated a sediment budget for Ocean Beach based on historical data that was summarized in Moffatt and Nichol Engineers (1994; 1995) . They estimated a net surplus between 1971 and 1992, believed caused by dredge material dumped on the southern lobe of the ebb-tidal delta migrating shoreward and possibly minor input from sea-cliff erosion to the south of Ocean Beach. Battalio and Trivedi (1996) estimated the potential shoreward transport from the ebb-tidal delta to range between 80,000 and 210,000 m^3/yr during this time. An average of 403,000 m^3/yr of sediment was dredged from the San Francisco Ship Channel between 1931 and 1994 (United States Army Corps of Engineers 1996). Major losses to the Ocean Beach system are thought to occur as littoral transport moves north past Point Lobos and by aeolian transport across the Great Highway driven by prevailing westerly and northwesterly winds (Domurat et al. 1979).

The shoreline at Ocean Beach has been experiencing areas of erosion for decades with recent (since mid-1990) severe effects focused south of Sloat Blvd, in front of the SF Zoo, which has destroyed and continues to threaten important local infrastructure (Figure 14). The greatest concern is the structural integrity of a 12-ft diameter sewage transport box that lies underneath the Great Highway. This ~ $10 million piece of infrastructure was exposed during the last 1997-98 El Niño winter, and carries 1/3 of the City of San Francisco's treated sewage out to sea. Emergency rip-rap was placed that winter, but that protection has steadily degraded. The City of SF and the USACE have been formally investigating shoreline protection strategies since the mid-1990's (Moffatt and Nichol Engineers 1995; United States Army Corps of Engineers 1996).

Figure 14. Severe erosion south of Sloat Blvd during the 1997-98 El Niño.

The USGS began a comprehensive field program two years ago to provide coastal managers with the scientific data to help mitigate the erosion problem. Regular topographic beach surveys, sediment analysis, nearshore depth surveys and numerical modeling quantified the processes controlling this dynamic system. Strong seasonal fluctuations in wave energy result in ~1,000,000 m^3 (1,308,000 yd^3) of net cross-shore transport each year along this 7 km stretch of coastline (Barnard and Hanes 2005 (in press)). Further, the fall 2004 multibeam survey indicated that not only has the ebb-tidal delta been further contracting since the 1950's, but there has also been extensive accretion on the SF Bar at the traditional dredge disposal site, SF-8 (see Figure 10). Sediment dumped at this site has not been dispersing sufficiently and may have become relatively immobile due to the steady reduction in tidal influence along the outer reaches of the SF Bar. This shoaling has made dredging operations increasingly dangerous in recent years. The constriction of the SF Bar is likely due to a reduction in tidal prism from SF Bay, and has resulted in new wave focusing patterns over the past few decades. The bar retreat has eroded shoals that once protected the Sloat region from direct wave attack from west and southwest swells. It has also served to shift a littoral drift nodal point from Ft. Funston north to the Sloat Region.

As a result of the new findings, the USACE implemented a new dredge disposal program in June 2005 to both reduce the strain on the existing dredge site and possibly feed sediment onto the eroding portion of Ocean Beach (Figure 15). Approximately 230,000 m^3 (300,000 yd^3) of sediment was placed in a nearshore disposal site (Figure 16)- numerical modeling suggests possible shoreward transport from this region. The California State University Monterey Bay Sea Floor Mapping Lab and USGS are currently monitoring and modeling the fate of the dredge disposal to help USACE determine if this new dredge disposal practice should be implemented permanently. This technique is a very progressive, low-impact form of shoreline protection that has been a successful form of beach nourishment in Holland for years (e.g. van Duin et al. 2004), but has rarely been implemented in the United States. The cost of dredge disposal at the offshore site is ~$7/yd^3, whereas direct beach nourishment costs upwards of $25/yd^3.

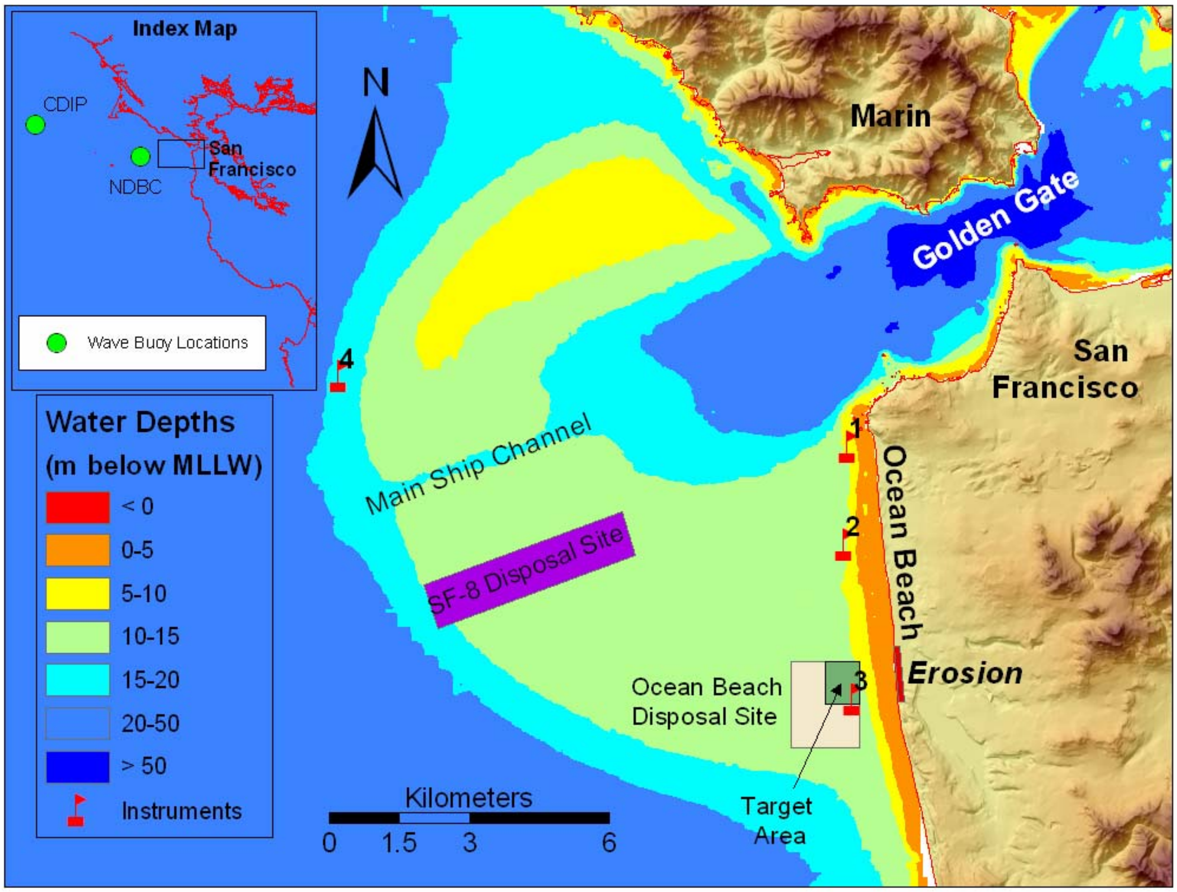


Figure 15. Overview of new dredge disposal program at the mouth of San Francisco Bay. Sediment is being taken from the main ship channel and disposed of in the target area immediately offshore of the erosion hot spot at Ocean Beach. The prior disposal site was SF-8. Red flags indicate the location of USGS instruments for measuring currents and waves during a recent experiment to help model sediment transport.

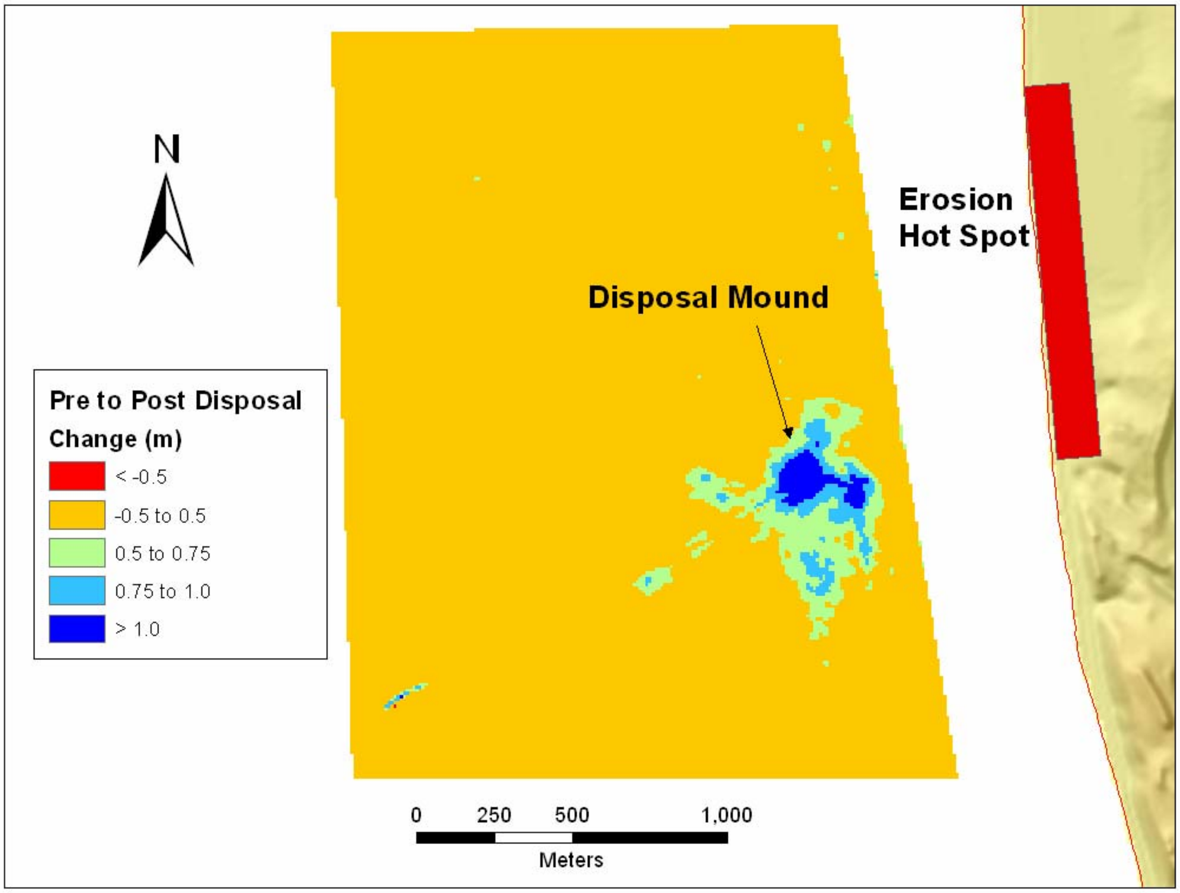


Figure 16. Difference map illustrating the location of the disposal mound created in June 2005 by the United States Army Corps of Engineers.

Additional Information

For more information regarding ongoing studies at the mouth of San Francisco Bay, see the following web sites:

USGS Ocean Beach Study- http://walrus.wr.usgs.gov/coastal_processes/intro.html

Web Cam at Cliff House- http://www.evsboca.com/usgs/default.htm

You can also contact me directly by email at pbarnard@usgs.gov.

References

Barnard, P. L., and Hanes, D. M. (2005 (in press)). " Integrating field research, modeling and remote sensing to quantify morphodynamics in a high-energy coastal setting, Ocean Beach, San Francisco, California.," 5th International Conference on Coastal Dynamics, American Society of Civil Engineers, Barcelona, Spain, 1-14.

Barnard, P. L., Hanes, D. M., Rubin, D. M., and Kvitek, R. (under review). "Giant dynamic sand waves at the entrance to San Francisco Bay.," *Science*, 1-3.

Battalio, R. T., and Trivedi, D. (1996). "Sediment transport processes at Ocean Beach, San Francisco, CA," Coastal Engineering 1996, Proceedings of the 25th International Conference, ASCE, Orlando, Florida, 2691-2707.

Chin, J. L., Carlson, P. R., and Wong, F. L. (1997). " Multibeam data and socio-economic issues in west-central San Francisco Bay (CA) [abs. and poster]," *EOS, Transactions, American Geophysical Union*, 78 (46), F349.

Chin, J. L., Wong, F. L., and Carlson, P. R. (2004). "Shifting shoals and shattered rocks- how man has transformed the floor of West-central San Francisco Bay, 30 pp.

Coastal Data Information Program (2004). http://cdip.ucsd.edu, Integrative Oceanography Division, Scripps Institution of Oceanography.

Domurat, G. W., Pirie, D. M., and Sustar, J. F. (1979). "Beach erosion control study, Ocean Beach, San Francisco, California," *Shore and Beach*, 47 (4), 20-32.

Gilbert, G. K. (1917). Hydraulic-mining debris in the Sierra Nevada, D. o. t. I. U.S. Geological Survey, p. 154.

Moffatt and Nichol Engineers (1994). "Shoreline Mapping for Ocean Beach, San Francisco, California, Final Report, 69 pp.

Moffatt and Nichol Engineers (1995). "Sediment transport processes study, Ocean Beach, San Francisco, California, Final Report, 69 pp.

Rubin, D. M., and McCulloch, D. S. (1979). "The movement and equilibrium of bedforms in central San Francisco Bay," San Francisco Bay: the Urbanized Estuary, Pacific Division of the American Association for the Advancement of Science, 97-113.

United States Army Corps of Engineers (1996). Ocean Beach Storm Damage Reduction Feasibility Study, in *Final Feasibility Study for the City and County of San Francisco*, S. F. District.

van Duin, M. J. P., N.R., W., Walstra, N. R., van Rijn, L. C., and Stive, M. J. F. (2004). "Nourishing the shoreface: observations and hindcasting of the Egmond case, The Netherlands," *Coastal Engineering*, 51, 813-837.

Wiegel, R. L. (2001). "Guide notes for coach tour of San Francisco coastal sites., 24 pp.