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The sand-covered floor of Central San Francisco Bay is molded by tidal currents into a series of bedforms, each of which is stable through a discrete range of tidal velocity, grain size, and water depth. Many of the bedforms move during average tide cycles, and do not require storms, floods or abnormal flow conditions to be active. The net direction of bottom sediment transport has been deduced from bedform asymmetry. The geometry of Central Bay exerts considerable control on the sediment transport pattern. Tidal flows accelerate as they pass through the narrow Golden Gate and produce ebb and flood jets that transport sediment away from the Gate. Lower velocity flows that occur between the shoreline and the jets are ebb dominant within the Bay, and flood dominant outside the Gate, and these flows transport sediment toward the Gate.

In Central Bay, where many of the bedforms are active during average tide cycles, sediment turnover, which is important in organic and inorganic exchange between the sediment and the water column, results largely from bedform migration. This rigorous hydraulic regime also acts to reduce biological turnover by benthic organisms by producing an environment more suited to animals that extract nutrients from the water column and surface and suspended sediment, rather than from buried sediment.
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Sediment on the floor of San Francisco Bay is an active element in the organic and inorganic processes that go on in the estuary. The sediment provides a repository through which there is a flux of plant and animal nutrients, trace metals (McCulloch et al. 1971; Peterson et al. 1972; Moyer and Budinger 1974; Girvin et al. 1978; Luoma and Cain 1979), and man-made synthetic organic compounds. It also provides a domicile for a varied benthic community (Nichols 1979).

The sediment is dynamic; it responds to physical stirring by organisms, to estuarine circulation, to oscillating tidal flows, and to wind-generated waves. In some areas the tidal flow produces hydraulic sorting of the bed load which largely determines the local grain-size of the sediment, and also the pattern, rate, and total flux of the sediment through that reach of the estuary. This hydraulic sorting, which separates mudflats from sandy bottoms, exerts marked control on the distribution of benthic species. Hydraulic conditions also affect the distribution of benthic species by controlling the duration of bottom stability (Nichols 1979).

PURPOSE

In Central Bay, the area described in this chapter, where tidal currents are strong and the Bay reaches its greatest depth, the sediment is generally sandy. The sandy sediment responds to the local hydraulic regime by forming several distinct types of bedforms, each of which is stable, or in equilibrium, for some discrete range of water depth, flow velocity and grain size. Thus, knowledge of the distribution of these bedforms not only indicates the local hydraulic environment that prevailed when the bedforms were produced, but with some reservations, can be used to estimate sediment transport rates.
Fig. 1. Track-line locations. Light lines were run once. Heavy lines were run throughout tidal cycles.

This chapter discusses the kinds and distribution of bedforms in Central Bay, the directions of bedload transport, some rates of sand-wave migration, how often the sand waves move, and the hydraulic factors that control bedform distribution. A more detailed quantitative discussion is given elsewhere (Rubin and McCulloch in press).

PROCEDURE

Bedforms were mapped with a side-scanning sonar system that bounces a high frequency (100 kHz) sonic signal off the seafloor and produces a continuously recorded oblique view of the sea floor on both sides of the survey vessel. The vessel location (Fig. 1) was continuously recorded with an electronic dual transponder range-range system that has a precision of about 5m. Bedload transport directions were inferred from the orientation of the crests and the asymmetry of sand waves. Sand-wave movement was studied by resurveying selected sonar lines through several tide cycles, and by making longer term observations from a fixed point with a bottom-mounted rotating side-scan sonar system (Rubin et al. 1977). Bedforms in any given area were related to sediment grain size, water depth, and depth-averaged current velocity in order to determine equilibrium
bedform conditions. Depth-averaged velocities were calculated from unpublished National Ocean Survey current velocity data by plotting semilog velocity profiles and averaging the velocities read from the plot at each tenth of the flow depth from 1/10 to 9/10.

SETTING

Central Bay is one of four bays in the San Francisco Bay complex. Within this complex the deepest water (Fig. 2), the coarsest sediment (Fig. 3), and the highest velocities (Fig. 4) occur where flow is constricted by bedrock at the Golden Gate, the entrance to Central Bay. The eastern and northern margins of Central Bay are lined with broad muddy flats in relatively shallow slow-moving water. Between these broad, shallow, muddy flats, and the steep, rocky Golden Gate, the Bay is floored with sand and has tidal currents that peak at about 70-200 cm·s⁻¹ during average tides.

Fig. 2. Bathymetry of Central Bay.

BOTTOM TYPES

As sandy sediment is exposed to increasingly strong flows it responds by forming a progression of bedforms, from low regime flat beds or ripples, to sand waves, and finally, when bed
irregularities are unstable, to upper regime flat beds. The progression is well demonstrated in laboratory flumes and is observed in natural flows (see later discussion). Limited observations by divers and underwater television indicate that these same bedforms occur on the Central-Bay floor. Unfortunately, for mapping purposes we were limited by the resolution of the sonar system that cannot differentiate lower from upper regime flat beds, and has insufficient definition to recognize ripples. Thus, only sand waves and flat beds are shown in Fig. 5.

Sand Waves

Sand waves, first reported in Central Bay by Gibson (1951), cover approximately half of the area surveyed in Central Bay (Fig. 5). In plan view as seen by the side-scan sonar, the sand waves are straight-crested (Figs. 6, 7) sinuous, catenary, or barchan-like (Fig. 8). In cross section, they are triangular (Fig. 6) or convex upstream (Fig. 8). Their heights range from less than 20 cm to more than 8 m, and height-to-wave length ratios are typically 1/10 to 1/40. Although the sand waves

1 We recognize that some workers subdivide the larger bedforms (e.g., megaripples, dunes, etc.) but for simplicity these additional forms are included with sand waves in this discussion.
Fig. 4. Peak depth-averaged tidal currents in the Central Bay during an average tide. Current velocities were measured by the National Ocean Survey (unpublished data).

vary in size, in any given area they are approximately the same size and can be divided and mapped by size (Fig. 4).

Flat Beds

Beds that appear flat are the second most abundant bottom type observed in Central Bay. The theoretical resolution of the side-scan system is approximately 10 cm, and the smallest sand waves visible on the side-scan records are 10-20 cm high. Beds with bedforms less than 10 cm high, small sand waves and all current ripples, would therefore be expected to appear flat. Despite this lack of resolution, the extensive flat bed areas can be grossly separated into two types; one contains boulders and bare bedrock and lies in the high-velocity tidal currents in and adjacent to the Golden Gate, the other is free of bedrock and boulders, and lies in an area of weaker tidal currents along the eastern fringe of Central Bay. Upper regime flat beds occur in the former, and current ripples predominate in the latter.

Bedrock and Boulders

As noted above, bedrock and boulders occur mostly in the Golden Gate area where fast
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currents keep the bed swept clear of sand. In some areas, boulders are numerous enough to form a boulder pavement. In other areas, boulders and bedrock locally protrude through a sand veneer. Turbulence developed at these protuberances downmixes fast-moving water and, in some places, the resulting increase in flow velocity at the bottom is sufficient to scour away the thin sand veneer downstream from obstructions and to produce rock or boulder-floored sharp pointed depressions (Fig. 9) called comet marks (Wemer and Newton 1975).

Fig. 5. Distribution of bedforms mapped by side-scan sonar. Flat-appearing beds in the Golden Gate area are upper flow regime flat beds, and in this same area boulders and bare bedrock occur on the Bay floor. Other flat-appearing beds are inferred from Fig. 12 to be rippled.

Other Bottom Features

At several locations in Central Bay the bottom is dominated by forms produced by processes other than flowing water. On Southampton Shoal in the northeast corner of Central Bay there is a field of holes up to 4 m in diameter and 0.5 m in depth that resemble holes formed by feeding bat rays in nearby Bodega Bay (Nichols 1979, Fig. 7). In this same area, adjacent to an oil refinery pier off Richmond, the bottom has been grooved by numerous ships as they plow their keels through the sediment. Our side-scan profiles show that similar keel plow marks are common off the mouth, and throughout the Oakland Estuary, and in this same area a long chain of large cycloidal bottom
gouges appear to have been made by the propeller of a large ship (Hartman 1976, Figs. 1.2 and 1.3).

**Bedload Transport Directions**

Directions of bedload transport can be estimated by assuming that bedload sediment is transported normal to a sand-wave crest. Although the current reverses direction during each tide cycle, and transport may occur in both directions, the net transport occurs down the steeper slope of the sand waves. Net bedload transport directions inferred from sand-wave geometry are shown in Fig. 10. Because the sediment transport rate increases as a high power of the velocity of a flow, sediment transport is strongly biased in the direction of the peak-velocity tidal current. Consequently, sediment transport directions inferred from sand-wave orientation are generally within 15° of the directions measured by current meters of the strongest near-bottom currents (Fig. 10).

![Side-scan record of straight-crested sand waves. Sand wave heights are 0.5 m; wavelength is 5-10 m; depth is 20 m. Transport is from left to right.](image)

The bedload transport pattern in the Golden Gate area is dominated by high velocity flows generated by jet currents that are formed by both the ebb and flood tides as they flow through the Golden Gate. During flood flow (Fig. 11A), ocean water enters the Gate and accelerates because the channel decreases in cross-sectional area. This jet current enters the Bay with depth-averaged velocities of more than 200 cm·s⁻¹ and is maintained for some distance by its momentum. Flood velocities north and south of the jet current are lower, or about 50-100 cm·s⁻¹. During ebb flow (Fig. 11B), Bay water converges radially toward the Golden Gate with peak velocities of 100-150 cm·s⁻¹. Consequently, east of the Gate, where the jet current flows, flood velocities exceed ebb velocities, but in the adjacent areas north and south of the jet, ebb velocities exceed...
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East of the Golden Gate the jet current maintains a channel that is deeper than the adjacent ebb-dominated shoals. The resulting bedload transport pattern forms a cell similar to that observed in other tidal inlets where transport in jet-dominated channels is away from inlet openings (Dean and Walton 1975; Wright and Sonu 1975) and transport in adjacent shoals is toward inlet openings (Fig. 11C).

During ebb flow (Fig. 11B) the velocity is also increased by the constriction of the Golden Gate, and a high velocity flow is formed along the north side of the Gate west of the constriction. North and south of the jet, surface current data (U. S. Coast and Geodetic Survey 1964) indicate counter-rotating eddies that are driven by the jet flow. Bedforms beneath the northern eddy were not observed, but bedforms beneath the southern counterclockwise eddy indicate that the counter-clockwise circulation dominates. Because of the formation of the jet flow and the fact that the most rapid changes in sea level occur in the downward direction, ebb flow dominates, and the directions of sand transport closely resemble the directions of ebb circulation. Thus, within the Golden Gate, as within the adjacent Bay, sand is circulated in a cell, with jet transport away from, and adjacent transport toward the inlet opening.

Between the inward and outward flowing jets lies the deepest channel of San Francisco Bay, at a depth of about 110 m. Side-scan sonar profiles and high resolution sub-bottom acoustic profiles (Carlson and McCulloch 1970) indicate that the bedrock channel floor is swept partially free of sediment. Flat beds accompanied by boulders also reflect the high velocities of the jets. Although the bedforms define the transport cells as both sides of the Golden Gate, they do not

Fig. 7. Side-scan record of sand waves with reversed crests. Dominant transport is left to right. Record shows the reversal of the sand-wave crests caused by right-to-left flow. Maximum sand-wave height is 5 m, and water depth is 40 m.
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define the net direction of bedload transport through the Gate.

Because sand is moved mainly by peak-flow currents, its net transport direction may vary from the net transport direction of near bottom suspended sediment that depends solely on net water circulation. The San Francisco Bay estuary enjoys estuarine circulation with a seaward flow of brackish surface water over a compensating landward flow of more saline bottom water (Conomos 1979). As demonstrated by the movement of seabed drifters (Conomos 1979, Fig. 23) the bottom flow transports the near-bottom suspended sediment landward (Conomos and Peterson 1977). Thus, in ebb-dominated areas of Central Bay the tractive bedload and the near bottom suspended sediment have opposite net transport directions.

Fig. 8. Side-scan record of barchan-like sand waves. Maximum bedform height is 2.5 m; water depth is 30 m, and transport is from left to right.

SAND-WAVE MOVEMENT RATES

Sand-wave migration rates are very difficult to measure from a vessel, because even with very precise navigation the error in determining the vessel’s position may exceed the distance that sand waves move in many months. However, one can determine whether or not sand waves move without measuring their migration by observing short-term changes in sand-wave shape. During average and spring tides, the crests of many sand waves in Central Bay reverse orientation daily in response to the oscillating tidal currents (Fig. 7), indicating that these sand waves are active under average tidal conditions. Sand-wave movement, or lack of movement, during neap tides has not been studied.

As noted above, the measurement of sand-wave migration rates is difficult. Tidal sand waves typically move only a few centimeters or tens of centimeters per day (Jones et al. 1965; Boothroyd and Hubbard 1975; Bokuniewicz et al. 1977). With commonly available navigation systems one would need a long elapsed interval of months or years between repeated observations, and
even then the navigation problem may make a significant uncertainty in measured migration rates. In order to overcome the navigational uncertainty, sand-wave migration in a portion of Central Bay was measured with a rotating side-scan sonar system (Rubin et al. 1977) that was placed on the Bay floor about 2.5 km east of the Golden Gate and about 400 m offshore of San Francisco. The sonar system was wired to shore where a recorder provided images of a 400-m-diameter circular area of the Bay floor. The side-scan system was in water about 20 m deep and sand waves in the field of view were approximately 0.6 m in height and 18 m in wavelength. Sediment at the site had a median grain size of approximately 0.3 mm. During a two-month observation period from this fixed position sand-wave crests moved 0.6 to 2.4 m, with average rates of 1 to 4 cm-d⁻¹. The site of this study was chosen for its proximity to shore, and current velocities at the site are lower than at many other sand-wave fields. Consequently, sediment transport rates and bedform migration rates at the side-scan site may be relatively low.

CONTROL OF BED CONFIGURATION AND DISTRIBUTION

Sedimentologists and engineers working with flumes have found that specific kinds of bedforms reproduced with a given flow (velocity, depth, and viscosity) and sediment (grain size, density, and sorting). This has led to many studies designed to determine how flow and sediment parameters are related to bed configuration (Allen 1963, 1968; Raudkivi 1963, 1966; Yalin 1964; Harms and Fahnestock 1965; Simons et al. 1965; Guy et al. 1966; Hill 1966; Znamenskaya 1966; Harms 1969; Hill et al. 1969; Kennedy 1969; and Southard 1971, 1975). These experimental
Fig. 10. Map showing the orientation of sand waves and the orientation of the strongest near-bottom currents. Symmetrical sand waves occur along the boundaries between ebb- and flood-dominant areas.

Fig. 11. A. Generalized diagram showing water-circulation pattern in the Golden Gate area during maximum flood. Water enters the Bay in a jet current. B. During ebb circulation west of the Golden Gate water exits the Bay as a jet with adjacent counter-rotating eddies. C. Flow directions of the strongest currents beneath the jets are flood oriented in the Bay and ebb oriented west of the Golden Gate. Strongest currents adjacent to the jets are ebb oriented in the Bay and flood oriented west of the Golden Gate.
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studies were generally limited to flow depths of less than 0.5 m, and extrapolation of bed phase boundaries to greater depths was largely conjectural. In 1975 Boothroyd and Hubbard extended these studies to flows of several meters depth in describing bed phases in two shallow New England tidal estuaries. Rubin and McCulloch (1976) described bed-phase boundaries in San Francisco Bay where flow depths reach 80 m, and with these deeper flow data they proposed an extension of previously established shallow flow bed phase boundaries to deeper flows (Fig. 12). The phase

Fig. 12. Plots of bed configuration as a function of depth and velocity for two sediment-size ranges. Triangles and circles represent San Francisco Bay sand waves and flat-appearing beds respectively; squares are points from bed-phase boundaries on grain size vs. velocity plots for additional bay data; x’s are points on bed-phase boundaries determined by Boothroyd and Hubbard (1975); dots are points on bed-phase boundaries measured or interpolated from Southard (1975, Figs. 2-2, 2-3, and 2-5); circles with dots are points from boundaries separating ripple, dune, and flat-bed phases determined by Dalrymple, et al. (1978). Flume velocities are depth-averaged for steady flow; bay velocities are depth-averaged during peak flow of average tides. High-velocity, shallow flows that produce in-phase waves (also called antidunes) have not been seen in San Francisco Bay.

boundaries they proposed are shown in Fig. 13 where phase boundaries and sand-wave height are related to sediment size, depth, and velocity. More recent work by Dalrymple et al. (1978) describes bed phases in intermediate depths up to about 14 m in the Bay of Fundy. Allowing for differences in bedform nomenclature, and the fact that smaller straight-crested bedforms they call
Type I megaripples would appear as flat beds to the side-scan sonar, their data fit the trends of the phase boundaries based on flume and Bay data.

The construction of Fig. 13 is not meant to imply more than correlation between the related parameters. It should be clearly understood that although it is valid to draw such a figure, and that such a figure might be used for predictive purposes, there is very little that is understood about the details of the specific mechanisms that generate bedforms.

SEDIMENT TURNOVER

For some biological and chemical processes that involve exchange between sediment on the floor of the Bay and the water column, sediment turnover rates are more important than the rate of net sediment transport over the Bay floor. Physical overturning of sediment accompanies bedform migration, but is also caused by benthic organisms. In physically stable environments such as deep subtidal areas, equilibrium faunas can be effective in turning over the sediment (Nichols 1974). But in Central Bay, where the benthic population is dominated by siphon feeders that extract nutrients from surface or suspended sediment and from the water column, rather than from buried sediment (Nichols 1979), benthic stirring is of less importance than bedform migration. Central Bay sediment is highly dynamic. Where tidal-current velocities are high, sand waves as much as 1 m in height have been observed to reverse their asymmetry in a single tide cycle. This requires turning over the bulk of the sediment within the sand wave. Thus, locally, turnover may reach a depth of 1 m·d\(^{-1}\). In general, however, physical turnover is lower, the principal process being the migration of current ripples that turn over only the upper 2-5 cm of sediment each day.

Although difficult to quantify, a total Central Bay turnover rate estimated from these observations would be consistent with a rate calculated from the amount of radon contributed to the water column by Central Bay sediment (Hammond and Fuller 1979). By assuming a rate of radon production for sandy sediment (1000 atoms·m\(^{-3}\)·s\(^{-1}\)) they estimate that approximately 40 cm of
As noted earlier, sediment dynamics are important in determining the composition of the benthic fauna. In the Bay mudflats, where sediment is generally fine-grained, episodes of physical turnover or disruption are related to storms or seasonal wind patterns. Although less dynamic on a daily basis than Central Bay, sediment turnover in South Bay may be caused largely by physical stirring (storm resuspension) rather than biological stirring. The South Bay benthic community is composed of opportunistic pioneering species adapted to fine-grained sediment that can re-establish themselves rapidly after disruption (Nichols 1979). Rhoads et al. (1978) have shown that pioneering species like those in South Bay have little effect below the surface of the bottom, and make only minimal contribution to sediment turnover.

SEDIMENT TRANSPORT RATES

Because both the rate of sediment transport and bed phase are functions of velocity, depth, and sediment size, they can be directly compared. In Fig. 14, empirically determined and extrapolated sediment transport rates from Colby (1964) are superimposed on bed-phase plots. These plots give an estimate of the rate of sediment transport for flows in equilibrium with specified turnover must occur every few days.

Fig. 14. Plots of bed phase and sediment transport rate (dashed lines) as a function of depth and velocity for two sediment sizes. Transport rates in kg·m⁻¹·s⁻¹ are from Colby (1964).
beds. Equilibrium is stressed because bedforms can persist in flow velocities higher and lower than those which produced them, and the transport rates apply only to the time interval during which the form was in equilibrium with the flow. In tidally oscillating flows, where most transport occurs during peak flow, this interval may be short, and total transport over long time periods is difficult to establish.

FUTURE RESEARCH

The present study was limited to sedimentary processes active in sandy areas of Central Bay. Little is known about those processes active in other sandy areas in San Francisco Bay, and even less is known about sedimentary processes active in the muddy areas that predominate in the Bay. In general, the sedimentary processes that have been identified are known only qualitatively, and the rates at which they operate are only beginning to be quantified.

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LITERATURE CITED

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