Current Patterns Over the Continental Shelf and Slope

Marlene A. Noble

Summary and Introduction

The waters of the Gulf of the Farallones extend along the central California coast from Point Reyes southeastward to Año Nuevo (fig. 1). This unique region of coastal ocean contains valuable biological, recreational, commercial, and educational resources. Sandy beaches provide living space for a wide variety of organisms. Seabirds nest along the beaches, in the rocky cliffs above them, and on the Farallon Islands. Animals ranging from the small anemones found in tide pools to the elephant seals off Año Nuevo live in these waters. This coastal region is also a playground for people, Californians and visitors alike. In addition, fishing and commercial shipping activities are an integral part of the economy in the region.

Tides are the most familiar ocean phenomenon. They are easily seen at the sea shore; beaches are covered and exposed twice a day. Tidal currents, the largest currents in San Francisco Bay, move water in and out of the estuary. At the Golden Gate, ebb-current velocities during spring tide can reach 6 knots. Small sailboats bucking a strong tide can have trouble just getting back in through the Golden Gate. Timing of the return is critical. Outside the Golden Gate, in the coastal ocean, tidal currents are strong near the coastline. They diminish offshore, becoming overwhelmed by steadier currents as water depth increases.

Tidal currents and waves are important in the coastal ocean. They mix the water column, allowing nutrients near the seabed to reach plants growing in the lighted surface regions. Tides move nutrients and other suspended materials vertically and back and forth, but they generally do not transport these materials large distances.

On the Continental Shelf and Slope in the Gulf of the Farallones oceanic currents flow through the area transporting suspended sediment, nutrients that allow plants to grow, and possible pollutants. Until recently, however, not much was known about how strong the currents are, in what direction they flow, or how rapidly flow patterns change with time or location. Even less was known about how current patterns affect the many creatures that live in the coastal ocean, how currents modify the natural sediment on the sea floor, or about the eventual fate of natural sediment or materials dumped in the gulf. Knowledge is needed about these important factors so that people can make reasonable decisions about how to manage the coastal waters, ensuring that recreational and commercial activities do not harm the environment.

During the 1990's, several programs were undertaken by the U.S. Geological Survey and other organizations to gather information about how currents, nutrients, and suspended material move through the Gulf of the Farallones. The area studied by the USGS covers about 1,000 square nautical miles of the gulf and ranges in water depth from 200 to 3,200 m (660 to 10,500 ft). These studies showed that the general features of the complex current patterns in the area are similar to those observed elsewhere along the central and northern California continental margin.

Currents over the Continental Shelf tend to flow southeastward and slightly offshore in summer, causing nutrient-rich cool waters to upwell onto the shelf. Shelf currents flow mostly northwestward in winter. Tidal currents are strong over the shelf and tend to be the dominant features in flow patterns near the shoreline or within estuaries. The strong waves that occur during winter storms commonly cause sediment on the sea floor to be resuspended and carried both along and off the shelf.

The currents on the Continental Slope flow dominately northward in all seasons. Tidal currents over the slope are weak except for regions near the seabed or within the conspicuous submarine canyons that cut into the continental margin.

However, many of the current patterns in the Gulf of the Farallones are altered by the region's unique sea-floor topography; therefore, the local characteristics of flow, such as the amplitude of currents, their detailed response to winds, and the strength of the summer upwelling, are specific to an area. In summer, the promontory of Point Reyes causes shelf currents to turn offshore and flow over the slope. The abrupt steepening of the slope in the northern part of the area studied also causes northwestward-flowing slope currents to turn toward the deep ocean. Both of these features enhance the exchange of water, nutrients, and other suspended materials among the shelf, slope, and deep ocean relative to what happens along the simple, straight shelf more common north of the gulf.

The complex current patterns in the Gulf of the Farallones help to make the coastal waters of the area a truly unique resource. Knowledge of these patterns is essential if competing demands on this resource are to be balanced.

Instrumentation Design And Methods

The modest amount of information now available about how water and other materials move through this section of the coastal ocean is amalgam of many complex data-gathering projects. The study area is large, extending 128 km (80 mi) along the coast from Point Reyes to Año Nuevo and as far as 80 km (50 mi) offshore. Water depth ranges from 10 to 3,000 m (33–9,840 ft). Currents have many different flow patterns. The largest changes occur between sites separated by many kilometers (miles). Even at the same site, near-surface currents can have a different strength or flow direction from currents moving near the sea floor. Moreover, current patterns change over time, and summer patterns may not resemble winter patterns.

In a typical program to discover how ocean currents move in the study area, moorings containing various instruments are deployed in three to eight sites simultaneously on the sea floor (fig. 2). Moorings are generally spaced more closely across than along the Continental Shelf because current patterns are anisotropic; that is, they tend to change more rapidly away from, rather than parallel to, the coast. Moorings are commonly left out for 4 to 8 months; they are then recovered, refurbished, and redeployed for the rest of the year. Thus, both the mooring and the instruments on the mooring have to be rugged enough to withstand high winds, large waves, and the heavy corrosion caused by the saltwater environment. The housing for an instrument deployed in relatively shallow water (200 m [660 ft]) has to withstand a force equal to 20 times atmospheric pressure. At typical slopewater depths of 3,000 m (9,800 ft), the housing withstands 300 times atmospheric pressure. A styrofoam head lowered to these depths will be shrunk by pressure forces to the size of a coffee cup (fig. 3).

A typical mooring in water depths less than 200 m (660 ft) spans the entire water column, from the sea surface to the sea floor. As shown in figure 4, a large, lighted buoy is placed at the top of the surface mooring. The buoy has enough flotation to keep everything below it suspended in the water column. The buoy is attached to an anchor resting on the sea floor by a line composed of steel cable, elastic tethers, and thick chain. Instruments are attached to or hung between sections of this line. A currentmeter is commonly hung 6 m (10 ft) below the buoy to monitor water properties near the sea surface. This instrument has external sensors that measure current speed and direction, water temperature, and salinity every few minutes for the entire duration of the program. Currentmeters and other instruments are attached to the mooring line at various depths in the middle of the water column. A more complex instrument package that contains a currentmeter, a pressure sensor, and devices to measure water clarity (transmissometer) and to capture suspended sediment is attached to the mooring line near the seabed. This package monitors near-bottom processes so that models can be developed which predict how often sediment and other materials on the sea floor are picked up by the currents and transported. An acoustic release is placed between the last instrument and the anchor.

All measurements from the instruments are recorded on internal computers powered by small batteries. The computers are efficient enough to record data for 1 to 2 years, although the moorings in shallow water are seldom left out that long. Marine plants and small animals grow on the instruments, fouling the sensors and interfering with the measurements. Moorings deployed in 30 to 200 m (100–660 ft) are generally recovered within half a year. To recover them, a coded acoustic release signal is sent through the water from a nearby ship. When the release mechanism receives the signal, it decouples from the anchor. Subsurface floats attached near the instruments bring all the line and equipment to the surface, which are then picked up. Both a deployment and a recovery operation are shown in figure 5.

Moorings deployed in water depths deeper than 500 m (1,640 ft) are generally too short to reach the surface. The mooring configuration is similar to that described above, except that a large number of smaller glass floats built to withstand the enormous pressures in deep water replace the surface float. These glass floats are covered by yellow or orange "hardhats" to protect them from breakage. Unlike shelf moorings, these instruments can be deployed for the year or two their battery capacity allows. Light, which allows plants to grow on and foul the shelf instruments, does not reach these dark depths. Marine animals that grow on these instruments are sparse.

Water properties are important but are not the only thing measured in the coastal ocean. Wind, which causes waves and coastal currents, also has to be monitored so as to understand how the coastal environment works. The U.S. National Oceanic and Atmospheric Administration (NOAA) and the U.S. National Oceanic Data Center (NODC) have maintained four wind buoys in the study area for the past 15 years and will continue to maintain at least one buoy in the future. Two buoys are located off San Francisco, one off Monterey, and one north of Point Reyes (fig. 6). Each buoy continuously measures wind velocity, air temperature, atmospheric pressure, and such water properties as temperature and wave height. Sailors, fishermen, and others can obtain recent measurements from these buoys over the World Wide Web (http://facs.scripps.edu/surf/nocal.html). The buoy data are also recorded and stored. When currentmeters are recovered, the past year's wind and wave information is also downloaded from NODC.

Typical Water-Flow Patterns

Just as winds can blow strongly in San Francisco, yet be calm in nearby Oakland, waters in the study area have complex flow patterns. These patterns are a function of location, time of day and season. Surface waves, the highest frequency water movement, are ubiquitous. Typical wave periods range from 3 to 18 s; the most common wave period is 12 s. Waves break on and erode coastal bluffs. Large waves scour the sea floor, stirring and resuspending bottom sediment out to water depths of 100 m (330 ft) (fig. 7).

Tides are the most familiar ocean phenomenon. They are easily seen at the sea shore; beaches are covered and exposed twice a day. Tidal currents, the largest currents in San Francisco Bay, move water in and out of the estuary. At the Golden Gate, ebb-current velocities during spring tide can reach 6 knots. Small sailboats bucking a strong tide can have trouble just getting back through the Golden Gate. Timing of the return is critical. Outside the Golden Gate, in the coastal ocean, tidal currents are strong near the coastline. They diminish offshore, becoming overwhelmed by steadier currents as water depth increases.

Tidal currents and waves are important in the coastal ocean. They mix the water column, allowing nutrients near the seabed to reach plants growing in the lighted surface regions. Tides move nutrients and suspended material vertically and back and forth, but they generally do not transport these materials large distances. Lower-frequency, subtidal currents that move in one direction, generally parallel to the coastline, for periods ranging from 2 days to a few months are the main sediment-transport mechanism in the coastal ocean.

Crucial questions occur to those who wish to understand, manage, or utilize resources in our coastal ocean. What current patterns occur where? What causes them? How do they change with location and season? How do currents effect and (or) change the environmental processes we are interested in?

To answer these questions, we first have to determine the topography, or physical shape, of the area of interested. The Continental Shelf (gently sloping sea floor out to 200 m [660 ft]) in the study area is the broadest in the Western United States, but it narrows in both directions. Point Reyes juts out to the north, cutting across part of the shelf. To the south, the shelf effectively disappears. Monterey Canyon, the largest canyon in the contiguous United States, cuts all the way to the coastline. The entrance to San Francisco Bay makes a gap in the coastline south of Point Reyes. Farther offshore, the sea floor drops steeply from 200 m (660 ft) to the ocean floor, to water depths greater than 3,000 m (9,800 ft). These topographic features control and constrain how currents move over and through the study area. In particular, flows over the Continental Shelf and Slope are distinct. Local processes tend to control flow over the shelf, whereas oceanic processes tend to control flows over the slope. The flow patterns on the shelf and slope are not strongly connected.

Currents Over the Continental Shelf

The currents that flow over the Continental Shelf can be divided into the two basic types mentioned above—tidal currents and lower-frequency, subtidal currents. Tidal currents dominate the flow over the inner and middle parts of the shelf. Semidiurnal tides (currents that oscillate with an approximately 12-hour period) are the largest currents near the entrance to San Francisco Bay. The Moon drives the largest semidiurnal constituent, named M_2, at a 12.4-hour period. These tidal currents are large near the coast in water depths shallower than 30 m (100 ft) (fig. 8).

Strong semidiurnal tidal currents are expected on the shelf because sea level along the coast rises and falls twice a day. Water must move with the same frequency. Farther offshore, however, something unexpected happens: The diurnal, or daily, tidal currents on the midshelf are as large as or larger than semidiurnal tidal currents, even though the daily variation in sea level at the coast is smaller than the semidiurnal variation. This situation is unusual. Tidal currents over the shelf usually have the same amplitude ratios as in coastal sea level. The exact mechanisms that cause the relatively strong diurnal tidal currents are presently unknown. The topography of the study area may cause the currents to resonate at the diurnal frequency. Alternatively, especially during the summer, near-surface diurnal currents may be enhanced by strong diurnal afternoon winds that are generated when the hot, rising air in the inland valleys pulls replacement air off the cold ocean.

Over the shelf, subtidal currents are generally smaller than tidal currents but are just as important. Subtidal currents are responsible for moving nutrients and suspended material onto and off of the Continental Shelf in the study area (fig. 9). When winds are calm, the low-frequency currents tend to flow northwestward, parallel to the coast. In winter, winds tend to blow in the same direction, enhancing the poleward flow. Average current speeds commonly exceed 20 cm/s for several days in a row, replacing the water on the shelf in less than a week.

In March or April, winter storms dissipate. An atmospheric high sits offshore and causes the coastal winds to blow persistently southeastward for the next several months. Wind-driven, southeastward-flowing currents are generally strong enough to override the poleward flow on the shelf. The net current is equatorward until the winds die and the poleward flow returns. The southeastward winds not only force currents in the main part of the water column to move equatorward, but also, owing to the Earth's rotation, cause currents within 10 m (33 ft) of the surface to move offshore. Where does the replacement water come from?

The near-surface water that moves off the shelf is replaced by water from the slope that moves onshore (upwelling conditions). This water is drawn from a water depth of 150 to 250 m (490–820 ft). Thus, the water is colder, saltier, and more nutrient rich than the water it replaces. This upwelled, deep water moves across the shelf, staying in the lower half of the water column all the way to the coastline, where it reaches the surface. As a result, water near the beaches is cold in summer. If the southeastward winds continue to blow, the newly cooled surface waters flow southeastward along the shelf and offshore, toward the surface layers of the deep ocean. A satellite photograph taken in summer shows this cold band of surface water near the coast and spreading offshore (fig. 10).

Satellite photographs also show that narrow jets of cold coastal water move offshore in summer at sites near coastal promontories, such as Point Reyes and Point Sur. These jets can be several hundred kilometers long, swirling out into the deeper ocean. The jets sometimes carry barnacle larvae, other zooplankton, and phytoplankton (small plants) off the shelf. Generally, unless these small life forms can make it back near the shore, they die. The jets can draw phytoplankton deep beneath the ocean's surface, where the light needed for growth disappears. Barnacle larvae cannot find a suitable shallow rock to attach to or grow on. The cold water that remains near the surface in filaments is nutrient rich. These nutrients enhance the growth of the other plants native to the deeper ocean.

The cold water along the coast changes our summer climate. As moist air moves over the coastal ocean, it cools and generates a persistent fog. The daily onshore winds carry the fog inland through gaps in the coastal hills, cooling the surrounding towns. Mark Twain once remarked that the coldest winter he ever spent was a summer in San Francisco. The winds reverse in winter and do not bring the deep, cold slopewater onto the shelf. Our coastal ocean tends to be actually a few degrees warmer in winter than in summer.

Cold water does not always appear near the coast in summer. During a strong El Niño, water over the slope is warmer than usual, and so the water brought onto the shelf from depths is not so cold. El Niño conditions also tend to weaken, even reverse, the generally southeastward summer winds (fig. 11). Thus, the southeastward wind-driven currents do not appear in summer; cold oceanwater does not upwell onto the shelf. Fog does not develop so often.

In spring, the snow melts and flows into the local rivers. Eventually, part of this freshwater reaches San Francisco Bay, where it mixes with the more saline estuarine waters, then flows out into the coastal ocean. Because the estuarine water is less salty than seawater, it is lighter and flows over oceanwater. On those rare spring days when fog does not obscure the coastal ocean, satellite photographs show that a tongue of warm freshwater exits San Francisco Bay and turns southward as it joins the southeastward-flowing coastal currents. During major storms, such as those that occurred in December 1996 and January 1997, the plume of Sacramento River water that exits San Francisco Bay is colored brown because fine silt and mud are suspended in the river water. This plume commonly extends out onto the shelf, to the 30- or 40-m isobath (fig. 12). Because the river water and shelf water have different densities, they do not mix easily. The edges of the plume are sharply differentiated from the underlying shelf water.

Currents Over the Continental Slope

Currents that flow over the Continental Slope are confined on the inshore edge by shelf currents and on the offshore edge by the California Current. The California Current is part of a permanent, oceanwide gyre in the surface waters of the North Pacific. It forms the east boundary of this gyre, which is defined in the west by the Kuroshio (Pacific Gulf Stream), in the north by the Kuroshio Extension/North Pacific Current, and in the south by the North Equatorial Current (fig. 13). The mean flow in the upper few hundred meters (feet) of the California Current is a slow flow to the southeast. Current velocities averaged over space and time are less than 10 cm/s. Higher-speed jets and eddies as much as several hundred kilometers (120 mi) in diameter are embedded within the California Current. The eddies can drift over the slope and draw slope water offshore.

The slope currents are quite distinct from the southeastward-flowing waters in the California Current. The slope currents are confined to a relatively narrow band that parallels the shelf break, and flow poleward in a stream called the California Undercurrent, which has been observed everywhere along the west coast of the United States. The position, strength, and speed of the undercurrent vary from place to place and seasonally. Off San Francisco, the undercurrent is generally found over the slope and above 800 m (2,600 ft) water depth. The undercurrent flows northwestward parallel to the topography (fig. 14). The slope currents oscillate on time scales of weeks to months, periods much longer than the 3- to 10-day oscillations seen over the shelf. In the study area, we only have 1 year of observations, too short to develop a reliable understanding of the flow, although some trends have been noted. Slope currents were strongest in spring and early summer; flow speeds exceeded 30 cm/s for days at a time. The currents became weaker and more disorganized in August, then returned to the persistent poleward flow direction in the fall. The currents formed a single flow pattern that spanned entire slope from the surface to 800-m (2,600 ft) water depth (fig. 15). The inshore boundary of the wedge was farther offshore to the north, possibly because the sea floor in the northern part of the study area has much steeper, more complex topography with shorter spatial scales than in the south. Currents are less likely to flow parallel to topographic features when these conditions exist. In the summer, offshore jets from Point Reyes may interact with the undercurrent and enhance the tendency for it to move offshore.

The strong southeastward winds that cause southeastward flow over the shelf in summer do not significantly affect surface currents over the slope. Currents tend to flow poleward despite strong equatorward winds. The one distinct equatorward current pulse seen for several weeks in April 1991 down to 250-m (820 ft) water depth was not caused by wind. This flow event is too strong, deep, and persistent. Instead, the inshore edge of a counterclockwise rotating eddy or a southward-flowing filament generated at Point Reyes probably passed through the study area in April.

Subtidal currents over the slope but below the undercurrent were much weaker and more disorganized than currents in shallower water. Subtidal current speeds were less than 10 cm/s (0.02 mph). Current patterns observed at one site differed from those observed at other sites. Mean currents were insignificant. The steady northwestward flow observed at shallower water depths was absent.

Tidal currents are weaker over the slope. During the year of observations, tidal currents were less than 8 cm/s (0.17 mph). Most of the oscillating tidal currents are not strong enough to reverse the generally poleward flow over the slope. However, within 10 m (33 ft) of the seabed, tidal-current speeds can increase significantly. For example, in 2,000 m (6,560 ft) water depth, at a site where a small canyon cuts into the slope, tidal-current speeds increased from 3 to 14 cm/s (0.03–0.12 mph) just above the sea floor. At another site in 400 m of water, tidal-current speeds increased from 6 to 15 cm/s (0.05–0.13 mph). These faster tidal currents, which were strong enough to reverse the flow near the seabed, also enhanced the ability of currents to stir sediment up off the seabed, dispersing and mixing suspended material that falls to the sea floor. These strong near-bed tidal currents were not observed at every site. Generally, the sea floor has to have a small to medium-size canyon or a special topographic slope, near 1° to 3°, to generate strong, depth-dependent tidal currents.

Conclusion

The general features in the complex current patterns in the Gulf of the Farallones study area typify current patterns observed over the central and northern California continental margin. Currents over the Continental Shelf tend to flow southeastward in summer, causing nutrient-rich cool waters to upwell onto the shelf. Shelf currents tend to flow northwestward in winter. Tidal currents are strong over the shelf and tend to be the dominant features in the flow near coastal boundaries or within estuaries. The strong waves that occur during winter storms commonly cause sediment on the sea floor to be resuspended and carried both along and off the shelf. The slope currents tend to flow poleward in all seasons. Tidal currents over the slope are weak except for regions near the seabed or within the conspicuous submarine canyons that cut into the continental margin.

However, the detailed characteristics of flow in the study area, such as the amplitudes of currents, their response to wind driving, and the strength of the summer upwelling, are specific to the region because many of the current features are altered by the unique topography of the study area. In summer, the promontory off Point Reyes tends to cause shelf currents to turn offshore and flow over the slope. The abrupt steeping of the slope topography in the northern part of the study area also causes northwestward-flowing slope currents to turn toward the deep ocean. Both of these features enhance the exchange of water, nutrients, and other suspended materials among the shelf, slope, and deep ocean relative to the simple, straight shelf more common north of the study area. The complex current patterns in the Gulf of the Farallones help to make the coastal waters of the area a truly unique resource.

Further Reading

Brink, K.H., 1983, The near-surface dynamics of coastal upwelling: Progress in Oceanography, v. 12, p. 223–257.

Collins, C.A., Garfield, N.R., Paquette, G., and Carter, E., 1996, Lagrangian measurements of subsurface poleward flow between 38°N and 43°N along the west coast of the United States during summer, 1993: Geophysical Research Letters, v. 23, no. 18, p. 2461–2464.

Hickey, B.M., 1979, The California Current system—hypotheses and facts: Progress in Oceanography, v. 8, p. 191–279.

Largier, J.L., Magnell, B.A., and Winant, C.D., 1993, Subtidal circulation over the northern California shelf: Journal of Geophysical Research, v. 98, no. C10, 18,147–18,179.

Lentz, S.J., ed., 1991, The coastal ocean dynamics experiment (CODE): Collected Reprints [see Journal of Geophysical Research, v. 92, no. C2, p. 1987].

———1995, U.S. contributions to the physical oceanography of continental shelves in the early 1990's. Reviews of Geophysics, Supplement, p. 1225–1235.

Noble, M.A. and Gelfenbaum, G., 1990, A pilot study of currents and suspended sediment in the Gulf of the Farallones. U.S. Geological Survey Open-File Report 90–476.

Noble, M.A. and Kinoshita, K., 1992, Currents over the slope off San Francisco CA: U.S. Geological Survey Open File Report 92–555.

Noble, M.A., Ramp, S.R., 2000, Subtidal currents patterns over the central California—evidence for offshore veering of the undercurrent and for direct, wind-driven slope currents: Deep-Sea Research II, v. 47, p. 871-906.

Noble, M.A., Ramp, S.R., and Kinoshita, K., 1992, Current patterns over the shelf and slope adjacent to the Gulf of the Farallones; executive summary: U.S. Geological Survey Open File Report 92–382.

Paduan, J.D., and Rosenfeld, L.K., 1996, Remotely sensed surface currents in Monterey Bay from shore-based HF radar (CODAR): Journal of Geophysical Research, v. 101, p. 20,669–20,686.

Rosenfeld, L.K., Schwing, F.B., Garfield, N., and Tracy, D.E., 1994. Bifurcated flow from an upwelling center; a cold water source for Monterey Bay: Continental Shelf Research, v. 14, no. 9, p. 931–964.

Ryan, Holly, Gibbons, Helen, Hendley, J.W., II, and Stauffer, P.H., 1999, El Niño sea-level rise wreaks havoc in California's San Francisco Bay region: U.S. Geological Survey Fact Sheet 175-99, 4 p.

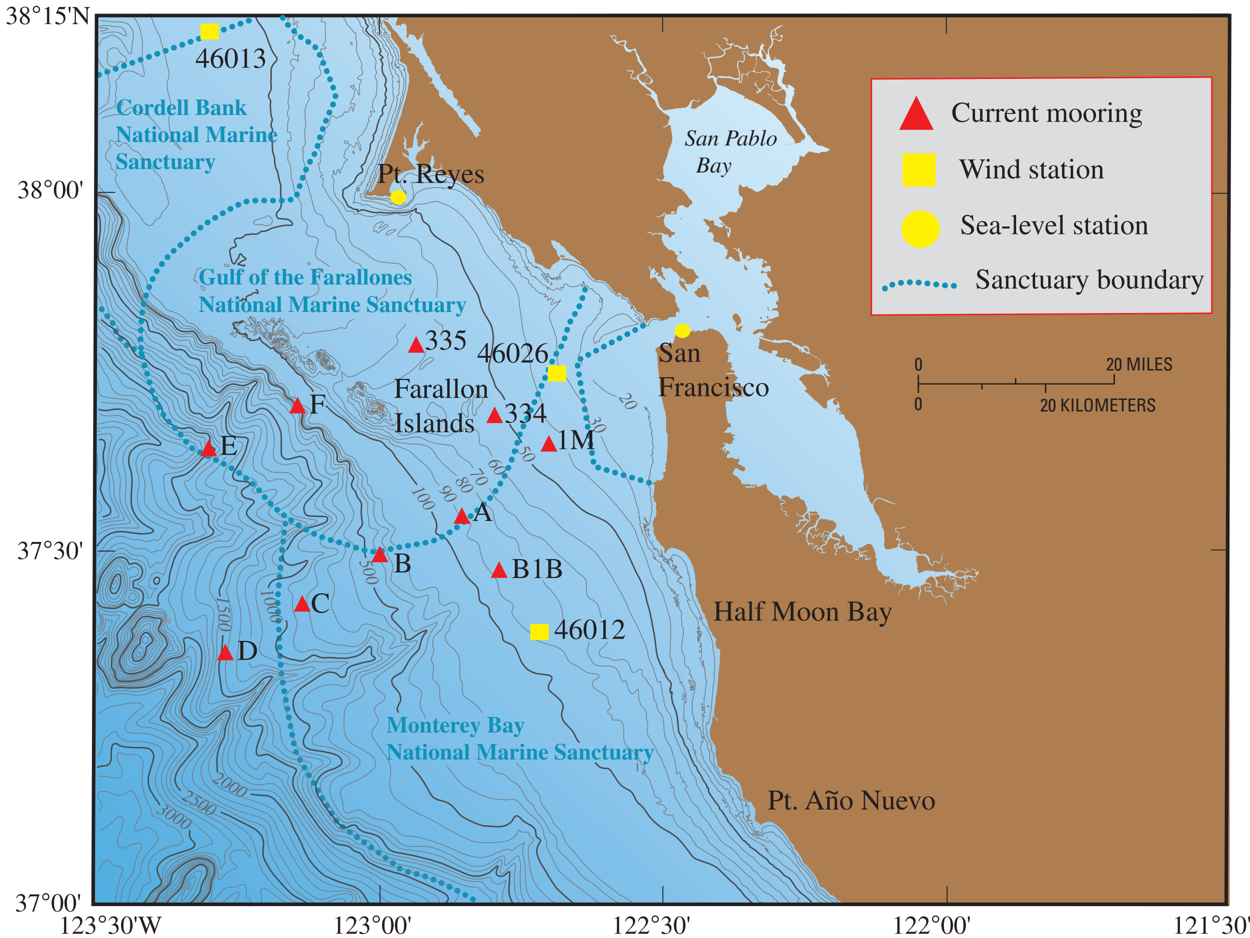


Figure 1. Gulf of the Farallones study area, showing locations of various types of measurement stations. Contour intervals: for water depths down to 100 m (330 ft), 10 m (33 ft); for water depths below 100 m (330 ft), 100 m (330 ft).

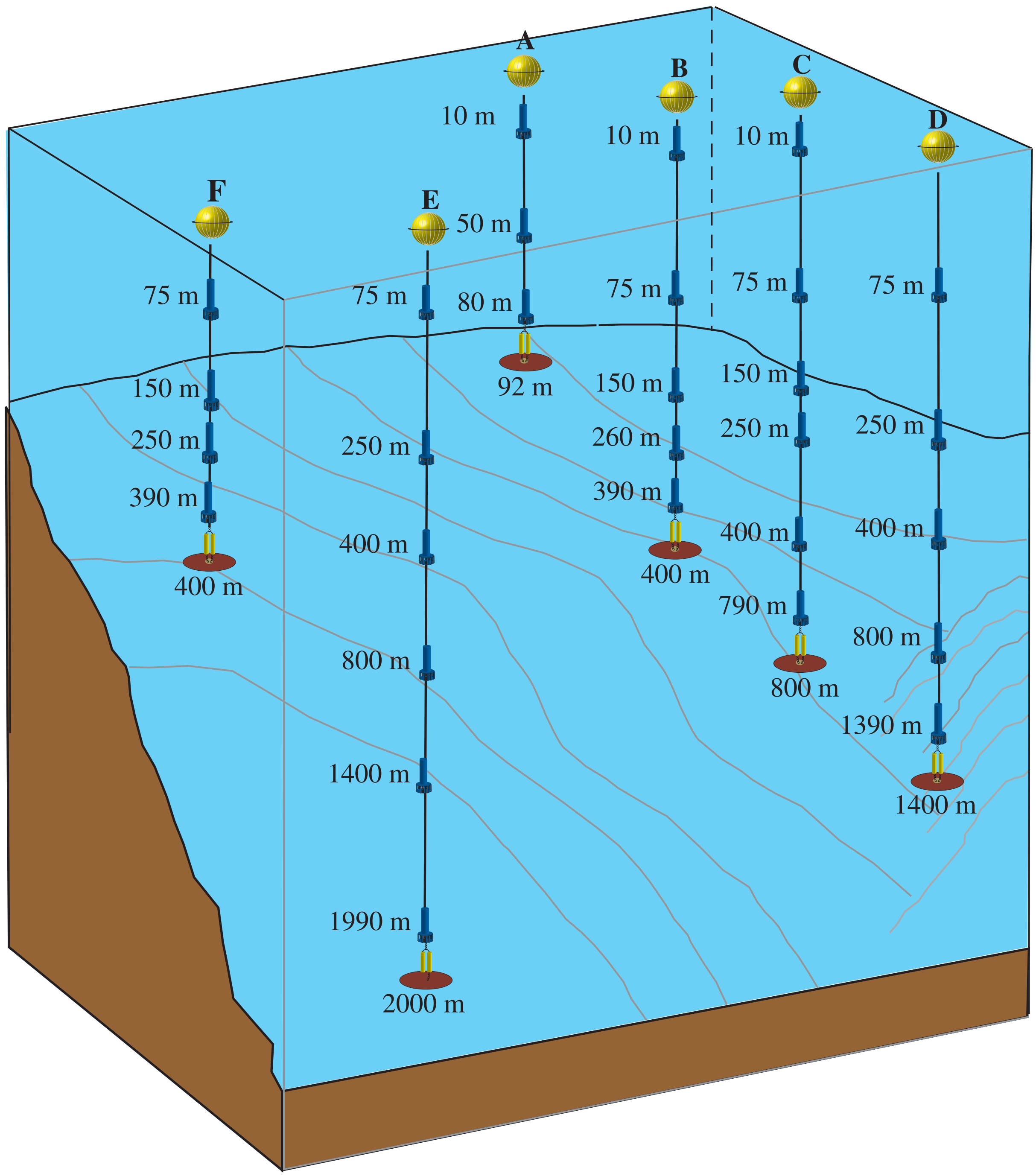


Figure 2. Block diagram showing moorings deployed in Gulf of the Farallones study area (see fig. 1 for locations). Moorings A through D were deployed in a line 12.8 km (8.0 mi) long, perpendicular to coastline; moorings D and F were deployed in a similar line, displaced approximately 24 to 32 km (15–20 mi) to the northwest.

Figure 3. Two styrofoam heads. Head on right shows effect of pressure at 2,000-m (6,560 ft) water depth.

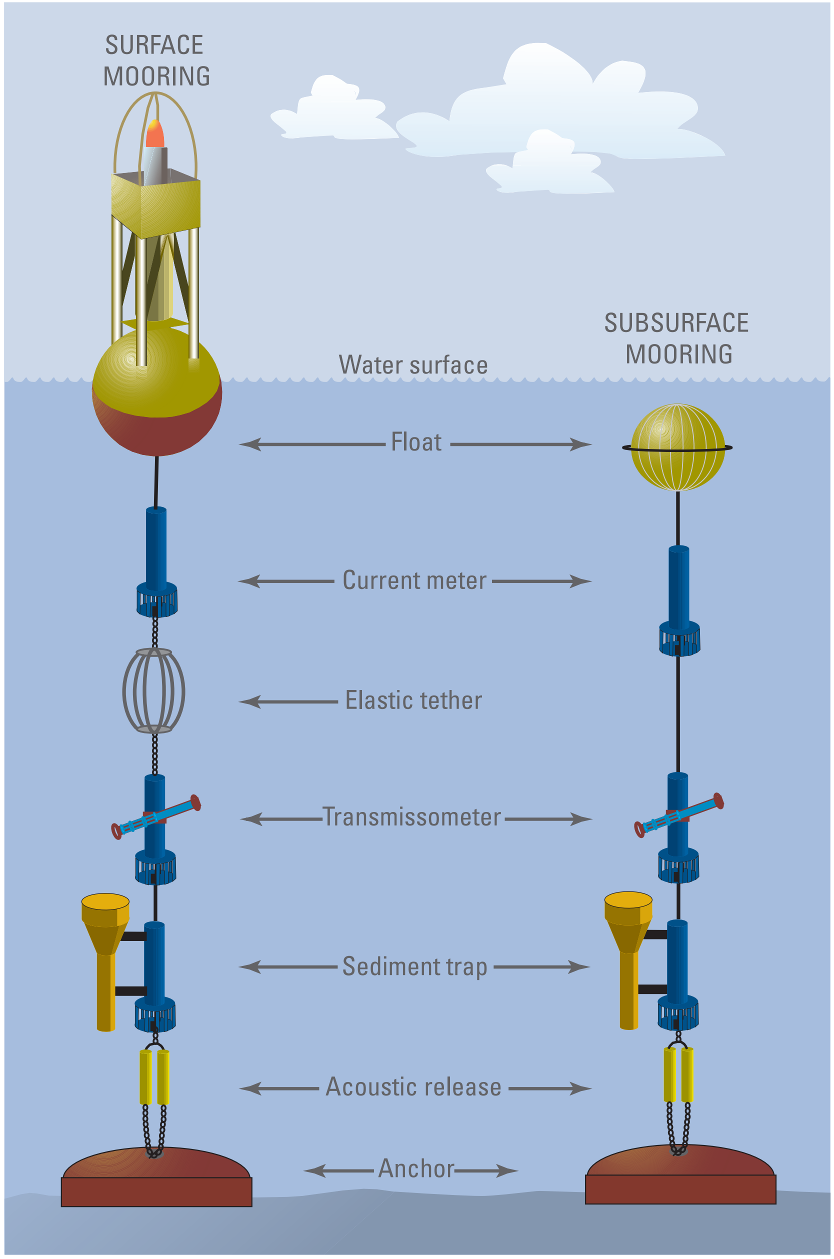
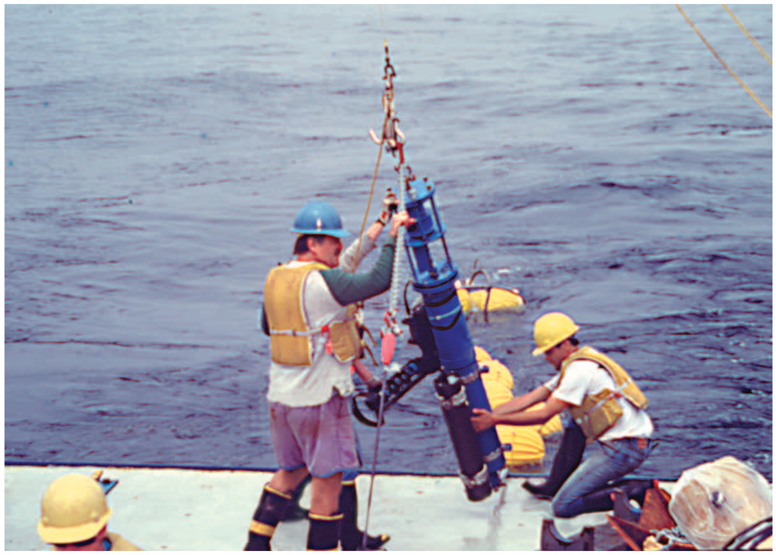


Figure 4. Typical surface and subsurface instrument moorings deployed in the Gulf of the Farallones study area.



A

B

Figure 5. Mooring deployment. *A*, Instrument is a current meter with an attached transmissometer. *B*, Yellow spheres are subsurface floats.

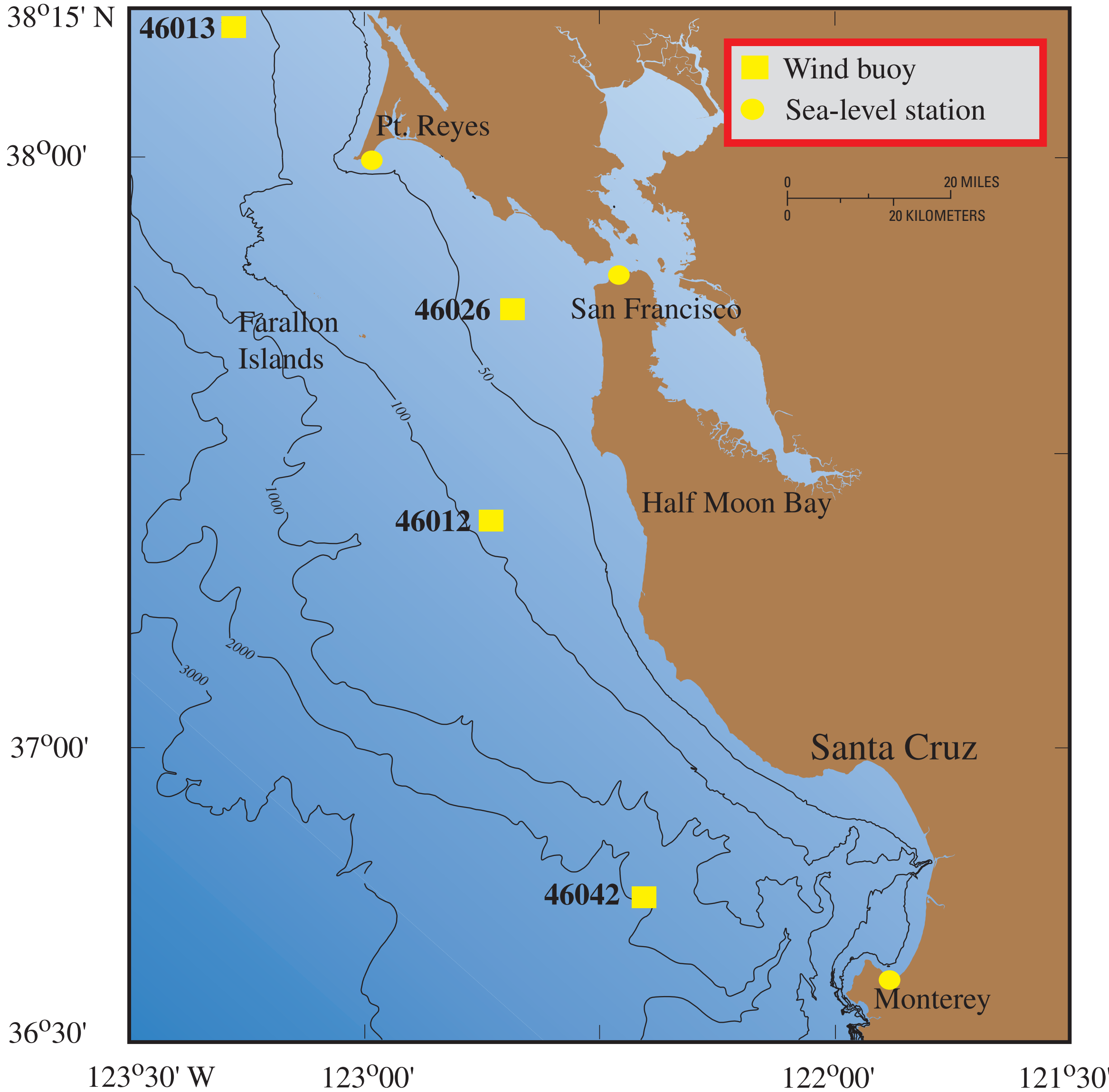
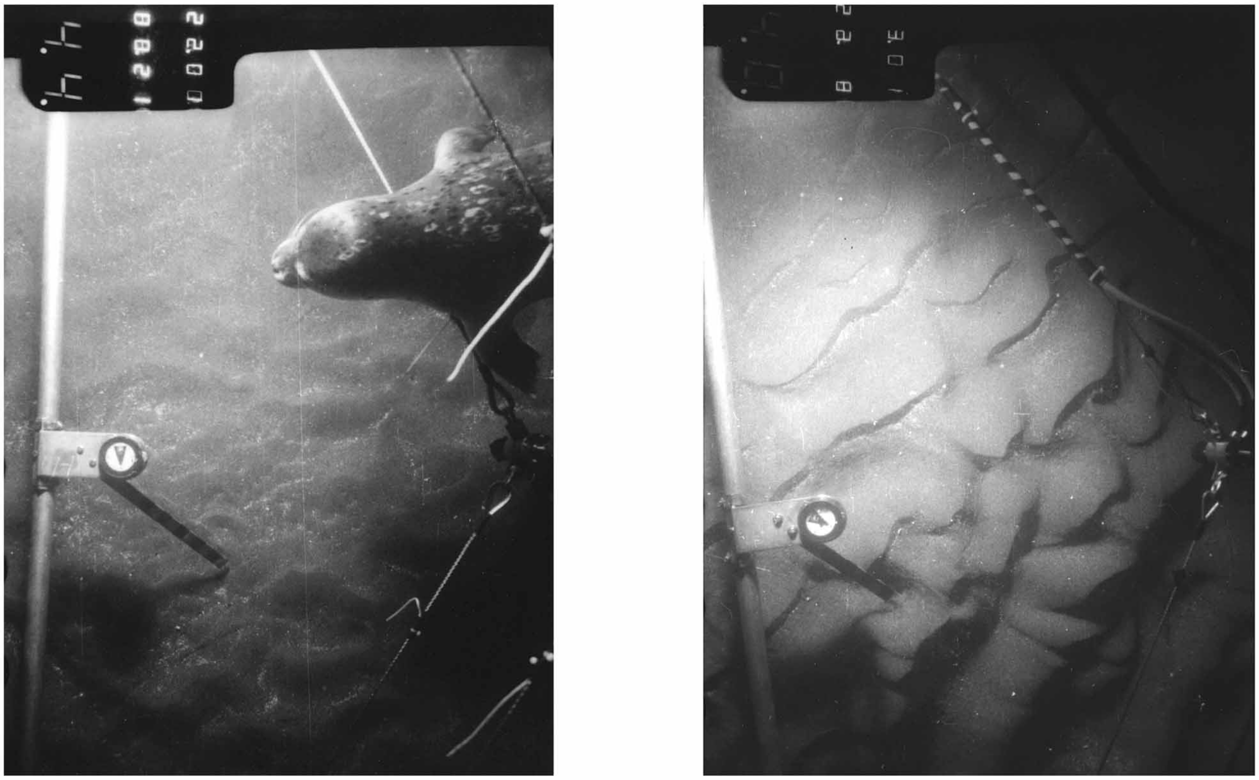


Figure 6. Gulf of the Farallones study area, showing locations of wind buoys and sea-level stations offshore San Francisco and Monterey. Bathymetry in meters (1 m = 3.281 ft).



A ***B***

Figure 7. Sea floor, showing relatively smooth surface when current is absent or quiet (*A*), and large ripples that may form when waves or currents are strong (*B*).

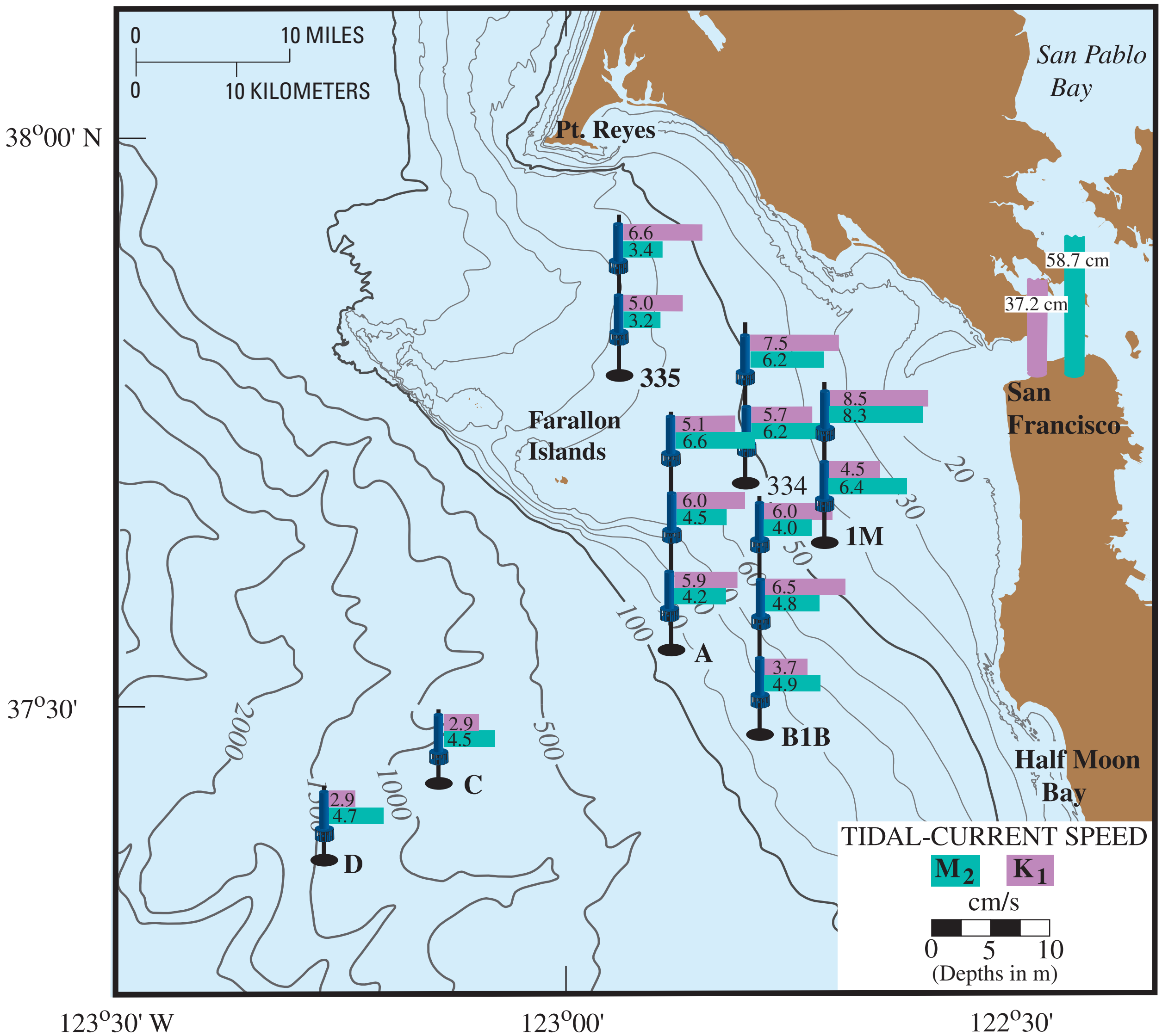


Figure 8. Gulf of the Farallones study area, showing tidal-current amplitudes at diurnal (lunar-solar; K_1) and semidiurnal (principal lunar; M_2) frequencies, as well as sea-level amplitudes at the Golden Gate. Bathymetry in meters (1 m = 3.281 ft).

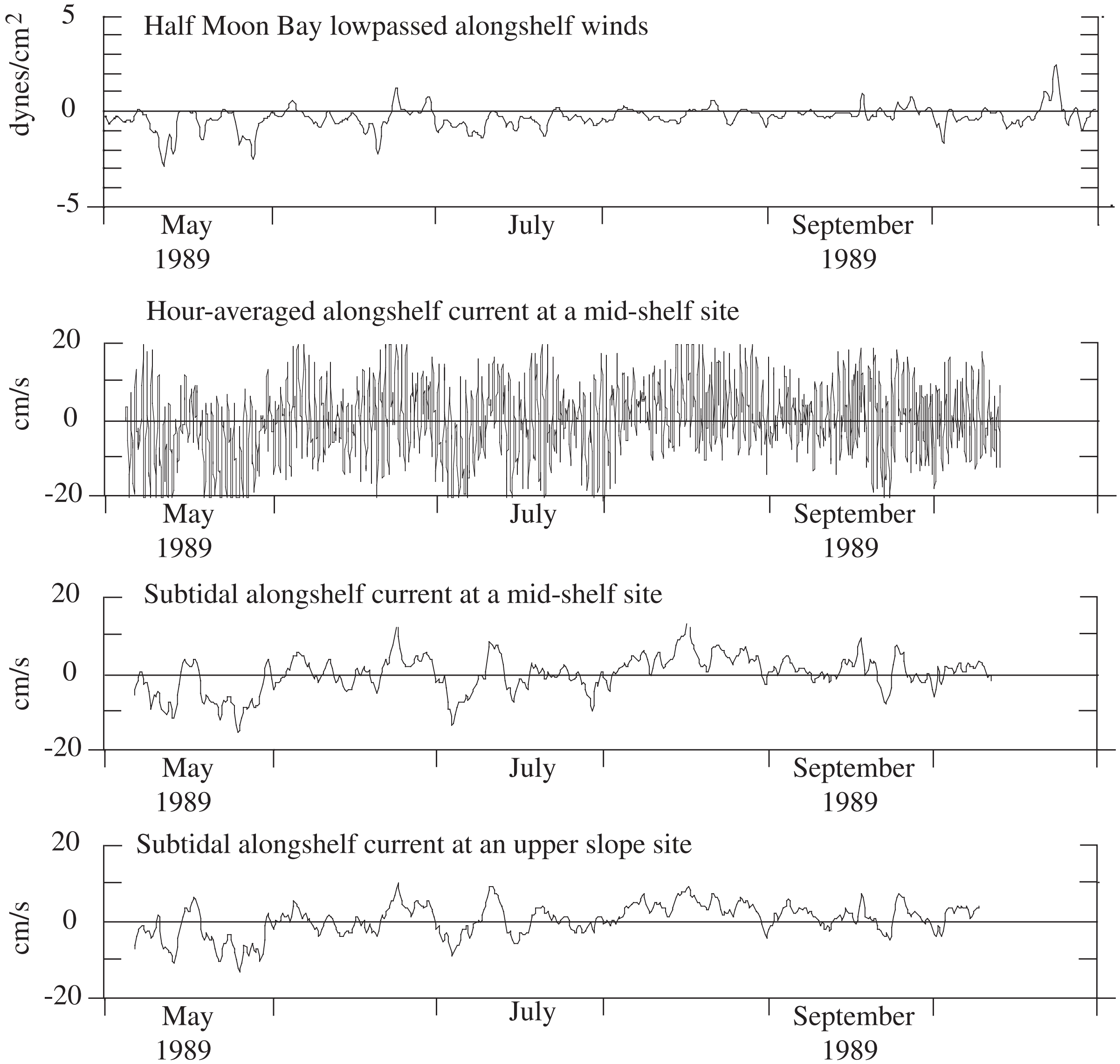


Figure 9. Hour-averaged current records, showing strong tidal currents. Tidal oscillations have been removed from subtidal-current record.

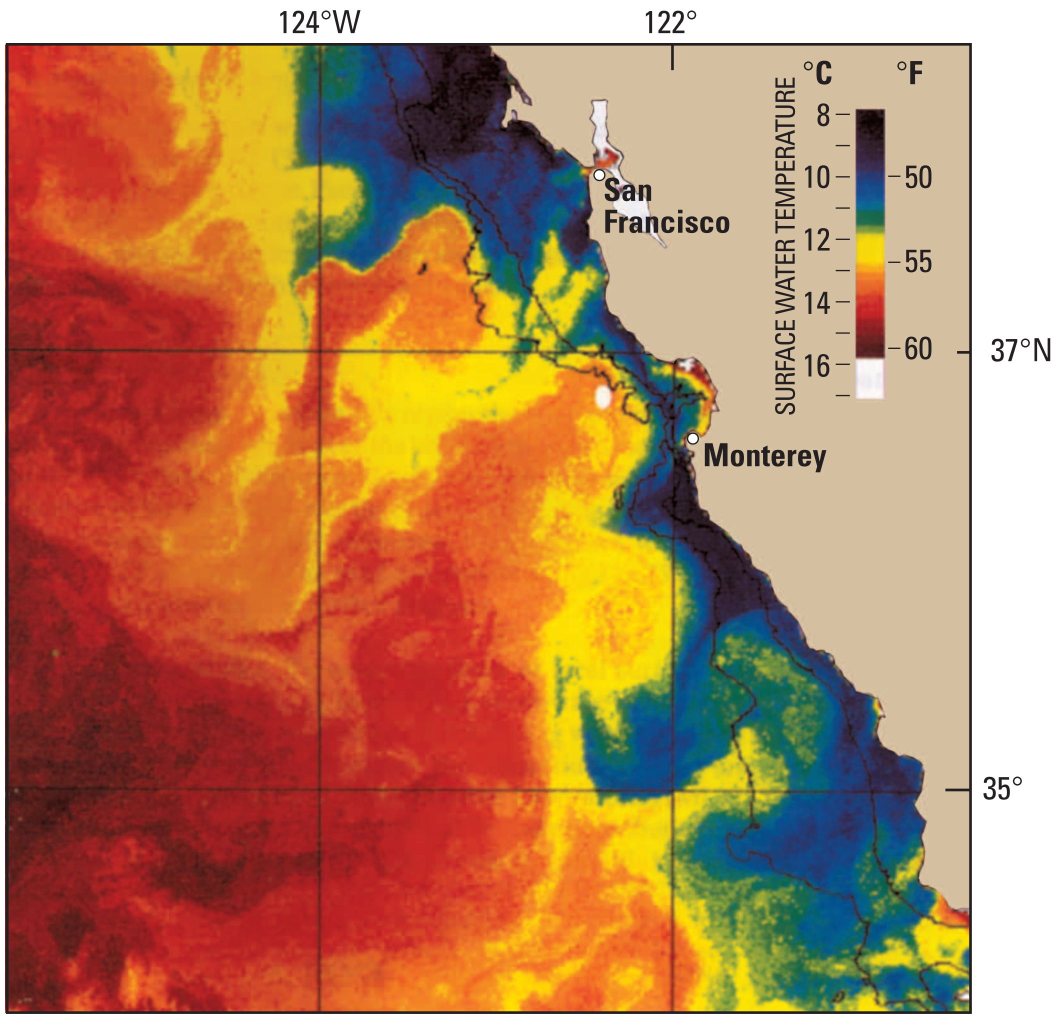


Figure 10. Satellite image of Gulf of the Farallones study area, showing water temperature (blue is cold, red is warm) along central California coast in summer. Note filaments of cold, upwelled water along coast that spread out onto surface layers of ocean (NOAA AVHRR satellite data, processed at Naval Postgraduate School, modified from Rosenfeld and others, 1994).

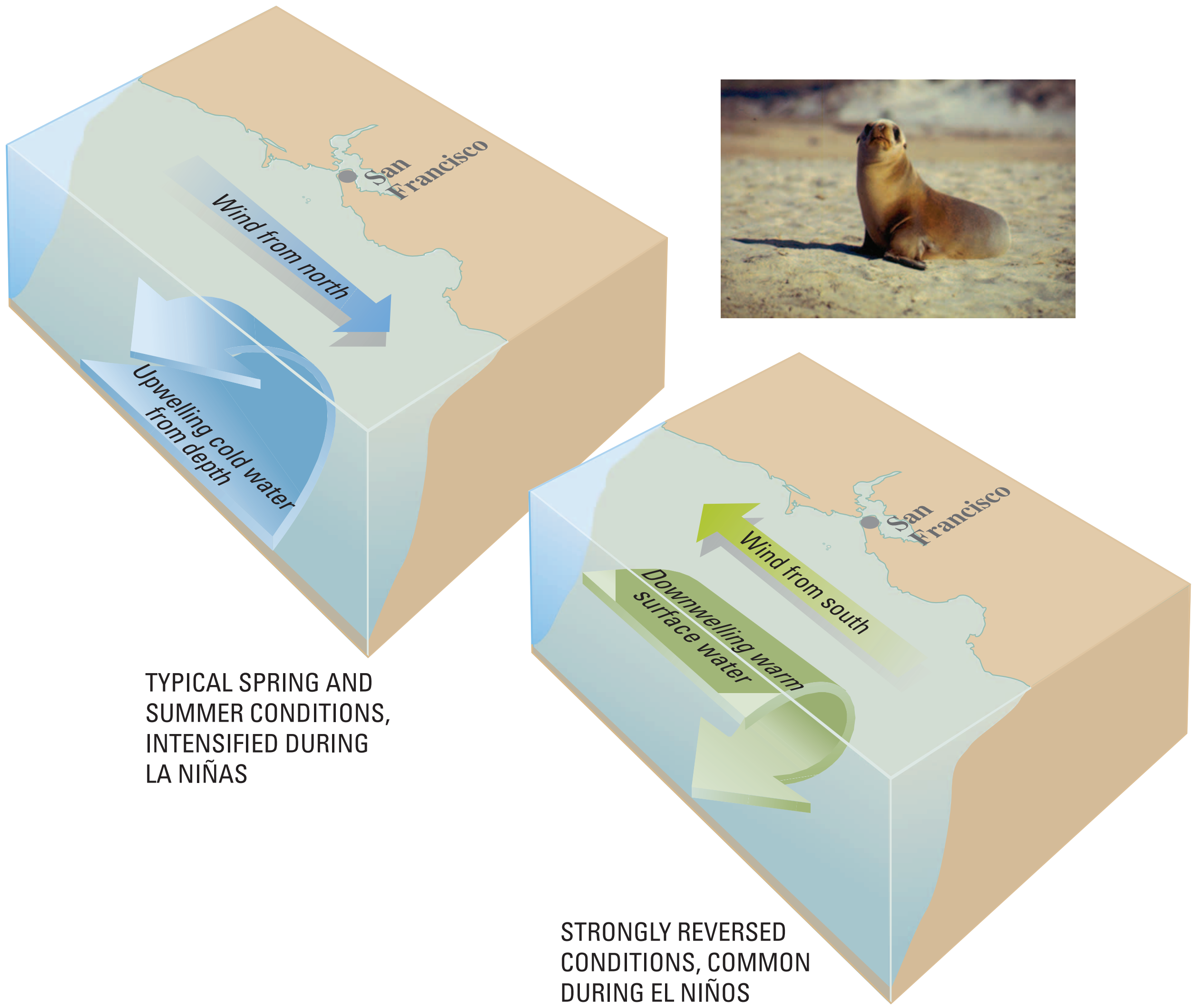


Figure 11. The normal spring drop in sea level along the California coast results from the onset of strong winds blowing toward the equator. These winds together with the Coriolis effect (the tendency of winds and currents to veer to the right in the Northern Hemisphere and to the left in the Southern Hemisphere) push surface water away from the coast. To fill its place, colder water rises to the surface in the yearly upwelling that makes the ocean off northern California so cold in spring and summer. During La Niñas, upwelling conditions are intensified. Higher sea levels in autumn and winter are produced by relaxation of the alongshore winds that push surface water away from the coast and by expansion of the water caused by summer and fall warming. Northward and onshore flow of warmer surface water during El Niños intensifies these effects and causes downwelling, which prevents the replenishment of nutrients to surface waters and can have a major impact on sea life. For example, in 1997–98, thousands of seals and sea lions starved to death when downwelling warm water drove away many of the fish and squid on which they normally fed. Young animals, such as the sea lion pup shown here, were particularly vulnerable. (From Ryan and others, 1999.)

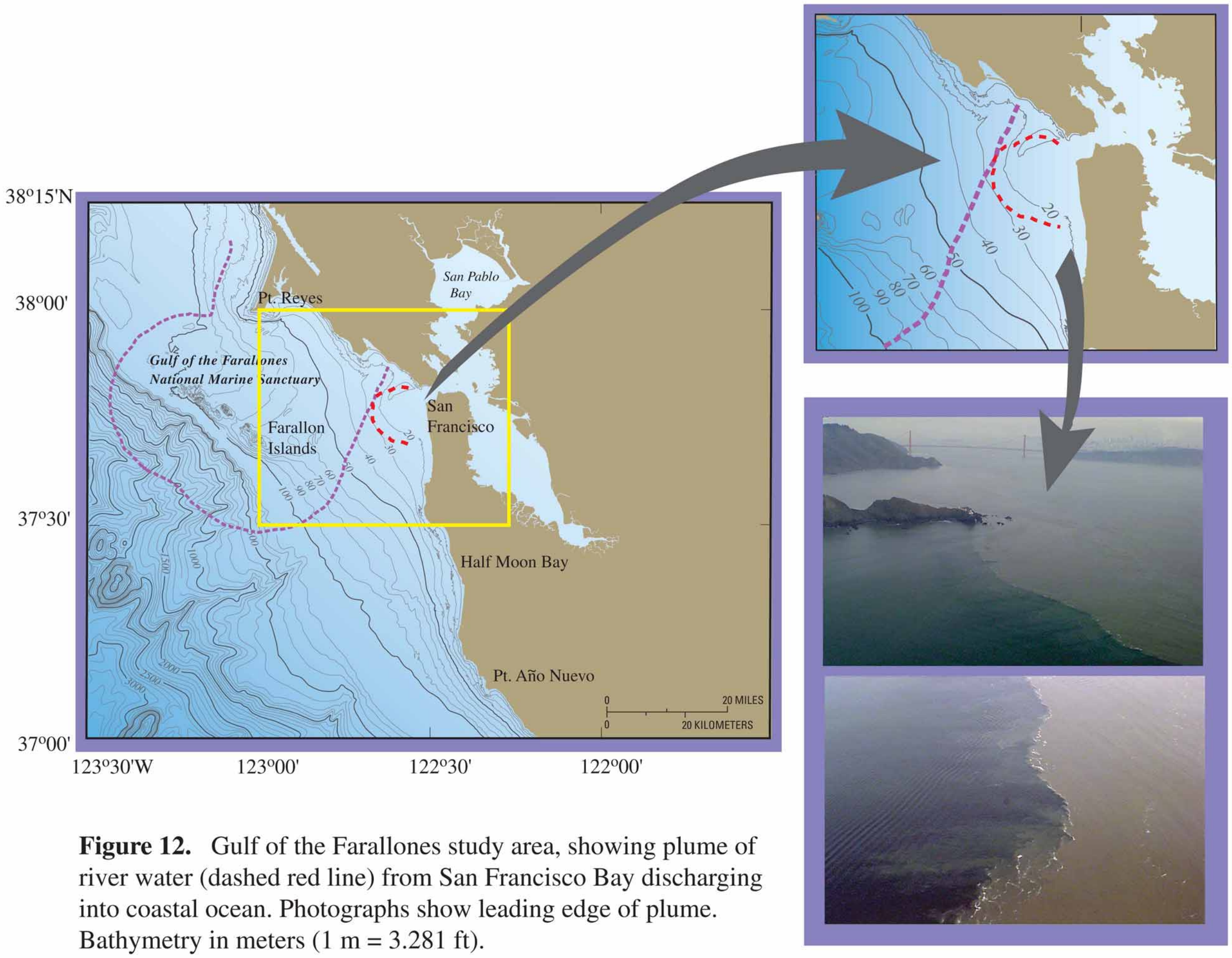
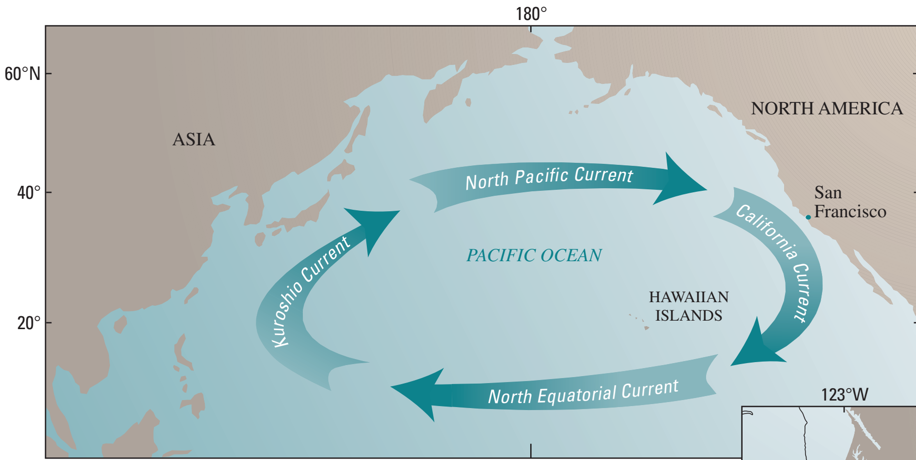


Figure 12. Gulf of the Farallones study area, showing plume of river water (dashed red line) from San Francisco Bay discharging into coastal ocean. Photographs show leading edge of plume. Bathymetry in meters (1 m = 3.281 ft).



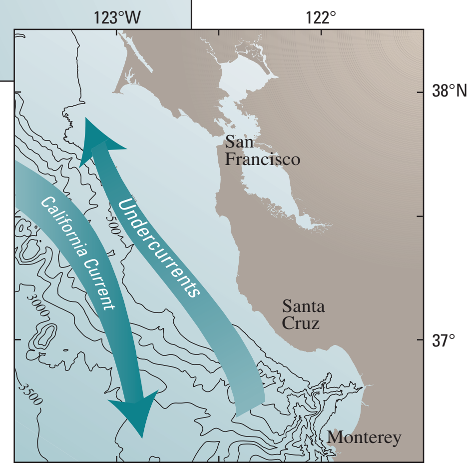


Figure 13. The California Current is part of a major gyre in the central Pacific Ocean. The California Undercurrent (inset) flows over the Continental Slope from southern California to Washington State in a direction opposite to the California Current. Bathymetry in meters (1 m = 3.281 ft).

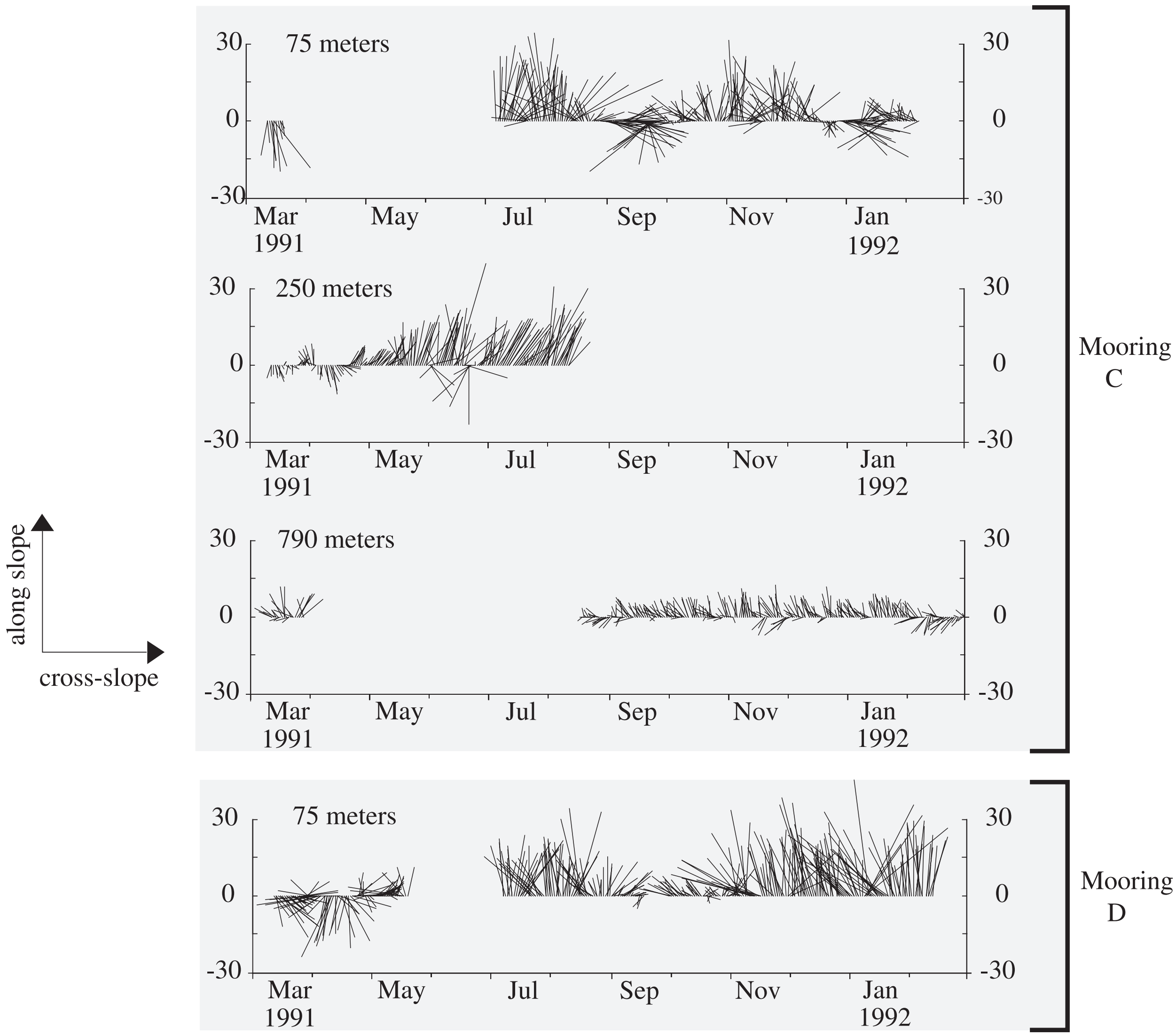


Figure 14. Subtidal-current vectors from moorings in 800-m (2,600-ft) and 1,400-m (4,600-ft) water depth. Unit of measurement is centimeters per second.

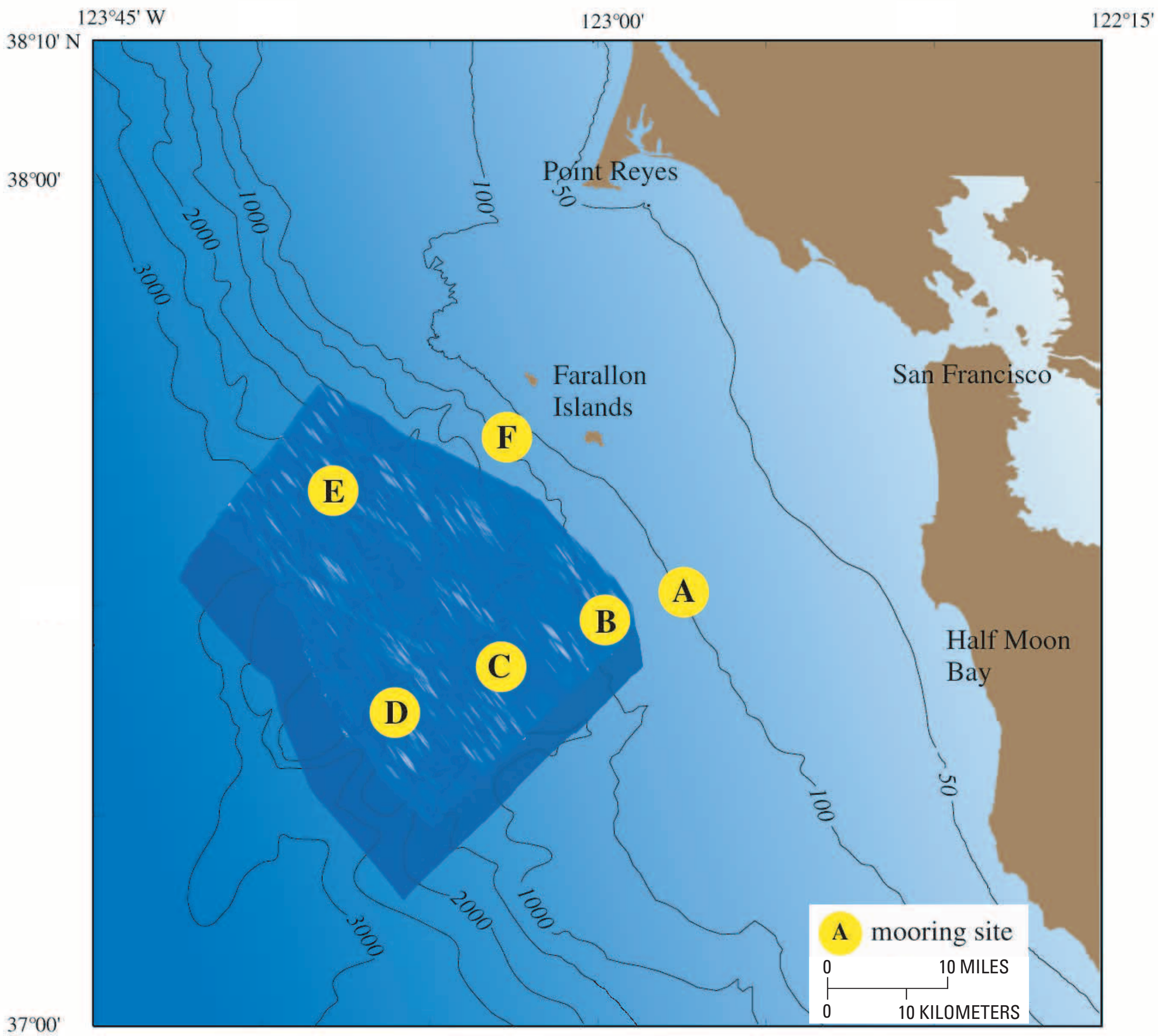


Figure 15. Gulf of the Farallones study area, showing the area of correlated middepth flow over the Continental Slope (dark blue area). Bathymetry in meters (1 m = 3.281 ft).