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Beyond the Golden Gate—Oceanography, Geology, Biology, and Environmental Issues in the Gulf of the Farallones

Circular 1198

U.S. Department of the Interior
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Beyond the Golden Gate—Oceanography, Geology, Biology, and Environmental Issues in the Gulf of the Farallones

Edited by
Herman A. Karl, John L. Chin, Edward Ueber,
Peter H. Stauffer, and James W. Hendley II

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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Gulf Of The Farallones National Marine Sanctuary
Cordell Bank National Marine Sanctuary
National Marine Fisheries Service

National Park Service

Point Reyes Bird Observatory

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Foreword

Both scientists and decisionmakers have become increasingly aware of the need to understand the complexity of natural systems when considering actions that affect individual aspects of resources and the environment. The interconnectedness of the physical and biological elements of a natural system is often appreciated in the abstract, but sometimes not as much as it should be in scientific studies. Too frequently, how the interaction of all elements of a system influence the organism, habitat, or process being focused on is given only lip service or general observations. Although not intended to be an integrated study, this report on oceanographic, geological, biological, and environmental aspects of the Gulf of the Farallones is an excellent example of a study describing the many facets of a complex marine system.

In marine systems, the geologic foundation and sediment dynamics of the sea floor define the basic environment for communities of bottom-dwelling organisms, which are influenced by circulation patterns that also affect organisms living in the water column. Decreased light penetration caused by turbidity affects the plankton, the base of the marine food web, and thus affects fish and other marine populations. We sometimes consider the most dynamic and influential elements of marine systems to be the currents, waves, and mobile species that are monitored regularly because they change frequently on a human time scale. However, this report demonstrates how geologic processes, including crustal processes manifested as earthquakes, can also be influential on the same time scale. The inclusion of a chapter on tectonics brings this point home.

This report also demonstrates the impact that a past tendency towards an "out of sight, out of mind" approach to the use of the ocean floor for waste disposal has had on future use of marine resources and how new technology can improve the situation. Concerns over possible leakage from drums of radioactive waste dumped until about 1970 on the ocean floor in the Gulf of the Farallones affected the marketability of fish caught in the area. Technology has only recently enabled scientists to locate the drums and begin assessing the actual risk. Similarly, new technology has allowed proposed sites for disposal of dredged material to be evaluated with a more thorough understanding of bottom conditions and processes.

Studies that help provide an integrated knowledge of complex natural systems, like these on the Gulf of the Farallones, give decisionmakers and the public an enhanced ability to avoid the mistakes of the past and promote sustainable use of environments and resources essential to human society.

Charles G. Groat
Director, U.S. Geological Survey

Beyond the Golden Gate—Introduction

Herman A. Karl and Edward Ueber

The beauty and power of the ocean fascinate many people. The sea has been a source of sustenance, recreation, contemplation, and inspiration, as well as a challenge for exploration and discovery, for mankind since prehistory. Although much has been discovered and reported about them, the sea, the life in the sea, and the landscape beneath the sea continue to be largely shrouded in mystery. Despite the fact that the oceans occupy 71 percent of the Earth's surface and are crucial to our survival, we invest more in learning about other planets than we invest in learning about the world beneath the sea.

Perhaps more than any other open space remaining on our planet, the oceans are a common-use area for both work and play for much of the world's population. This observation is particularly true in those areas of the coastal ocean off major urban complexes. In these multiuse "urban oceans," environmental and ecological concerns must be balanced against the human, economic, and industrial demands of adjacent large population centers. With ever-increasing stress being placed on the ecosystems of the oceans by human activities, many areas of the oceans around the United States have been designated as protected sanctuaries and reserves. Three contiguous National Marine Sanctuaries—Cordell Bank, Gulf of the Farallones, and Monterey Bay—stretch more than 185 miles from Bodega Bay north of San Francisco to Cambria south of Monterey. They protect an area larger than the States of Connecticut and Rhode Island combined, about 7,000 square miles of the California coastal ocean.

The U.S. Geological Survey (USGS) began a major geologic and oceanographic study of the Gulf of the Farallones in 1989. This investigation, the first of several now being conducted adjacent to major population centers by the USGS, was undertaken to establish a scientific data base for an area of 1,000 square nautical miles on the Continental Shelf adjacent to the San Francisco Bay region. The results of this study can be used to evaluate and monitor human impact on the marine environment.

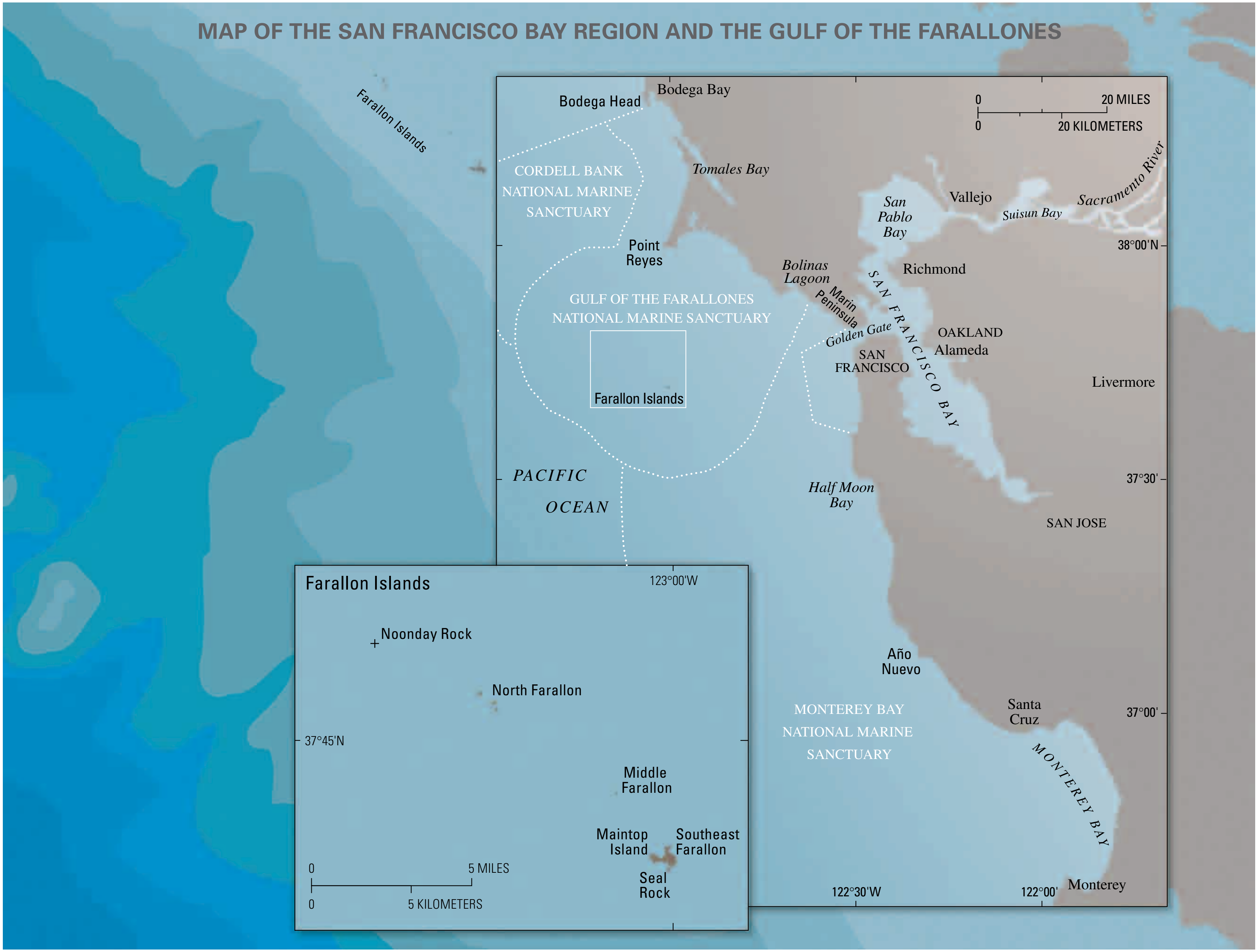
In 1990, the project expanded in scope when the USGS sponsored a multidisciplinary investigation with four other Federal agencies—Environmental Protection Agency, Army Corps of Engineers, U.S. Navy, and Gulf of the Farallones National Marine Sanctuary (part of the National Oceanic and Atmospheric Administration)—to survey and sample the Continental Slope west of the Farallon Islands. This study was primarily designed to provide information on the location and distribution of approximately 47,800 containers of low-level radioactive waste and obtain data on areas being considered as potential sites for the disposal of sediments dredged from San Francisco Bay.

Many other organizations eventually participated in this work, including Point Reyes Bird Observatory, California Department of Health Services, and the British Geological Survey. The information from these studies is being used by the Gulf of the Farallones National Marine Sanctuary to better manage and protect the unique ecological resources of the gulf. This information was also used in 1994 by the Environmental Protection Agency in designating the first deep-ocean disposal site for dredged material on the Pacific coast of the United States, west of San Francisco on the Continental Slope outside the boundaries of the sanctuary.

This USGS Circular endeavors to pull back the shroud of mystery that covers the ocean waters seaward of the Golden Gate, revealing to the reader some of the diverse habitats and ecosystems in the Gulf of the Farallones and discussing issues of contamination and waste disposal. The sections of this book cover the topics of Oceanography and Geology, Biology and Ecological Niches, and Issues of Environmental Management in the Gulf of the Farallones.

The chapters in the paper version of the book are short, less technical summaries. The full chapters are contained on the CD–ROM in the pocket at the back of the book. Links to the complete Circular and related topics can be found at http://walrus.wr.usgs.gov.

Acknowledgments.—The view of the Gulf of the Farallones presented here resulted from the efforts of scores of people over a 12-year period, from the first sampling and surveying cruise in 1989 to final publication of this book in 2001. It is not possible to single out each person who contributed in one way or another to this endeavor. The work of each is greatly appreciated, but some deserve special mention. William Schwab, David Twichell, David Drake, and David Rubin served as co-chief scientists with John Chin and Herman Karl on the 1989 and 1990 cruises and contributed significantly to their design and implementation. William Danforth and Thomas O'Brien led the teams that processed sidescan-sonar data in near-real time while at sea. Arthur Wright of Williamson and Associates provided helpful insights during the search for barrels of radioactive waste using the SeaMARC1A sidescan sonar. Pat S. Chavez, Jr., and his group did preliminary computer enhancements of sidescan images that helped identify nongeologic features on the sea floor, such as radioactive waste barrels. John Penvenne of Triton Technologies developed the principal methodology to detect barrels and classify objects in the SeaMARC1A imagery. Kaye Kinoshita and Norman Maher supported the early stages of assembling this book. William van Peeters coordinated the use of the U.S. Navy's DSV *Sea Cliff* and Advanced Tethered Vehicle. The USGS Marine Facility in Redwood City, California, provided operational support on shore and at sea. The officers and crews of the USGS ship R/V *Farnella*, NOAA ship R/V *McArthur*, the Navy's ship *Pacific Escort*, and the support vessel *Laney Chouest* greatly aided the work in the gulf.


MAP OF THE SAN FRANCISCO BAY REGION AND THE GULF OF THE FARALLONES
Farallon Islands
Bodega Head
Bodega Bay
0 20 MILES
0 20 KILOMETERS
Tomales Bay
CORDELL BANK NATIONAL MARINE SANCTUARY
San Pablo Bay
Vallejo
Suisun Bay
Sacramento River
38°00'N
Point Reyes
Bolinas Lagoon
Richmond
Marin Peninsula
SAN FRANCISCO BAY
GULF OF THE FARALLONES NATIONAL MARINE SANCTUARY
Golden Gate
OAKLAND
Alameda
SAN FRANCISCO
Livermore
Farallon Islands
PACIFIC OCEAN
Half Moon Bay
37°30'
SAN JOSE
Año Nuevo
MONTEREY BAY NATIONAL MARINE SANCTUARY
Santa Cruz
37°00'
MONTEREY BAY
122°30'W
122°00'
Monterey
Farallon Islands
123°00'W
Noonday Rock
North Farallon
37°45'N
Middle Farallon
Maintop Island
Southeast Farallon
Seal Rock
0 5 MILES
0 5 KILOMETERS

Techniques and Technology of Exploration in the Gulf of the Farallones

Kaye Kinoshita and John L. Chin

Although the oceans occupy 71 percent of the Earth's surface, they continue to be largely shrouded in mystery. From the surface it is impossible to see into the ocean depths, and actually going into those depths is both costly and hazardous. Because the oceans are crucial to our survival, we must try to understand the interactions of their complex physical and biological systems. In pursuit of this understanding, scientists seek many kinds of information—the depth, composition, temperatures, and movements of the water; the shape and composition of the sea bottom; and the types and abundances of the animals and plants living in the water and at the bottom. Some of these kinds of information can be obtained at the surface from ships, others require the lowering of cameras and sampling devices, and still others are best acquired through exploration in submersible vehicles, both manned and unmanned. Exploration in the Gulf of the Farallones has made use of a wide variety of such techniques.

When collecting multiple sets of geophysical and geological data over a wide area of the sea floor, precisely determining the location of an object or feature is critical. Navigation was therefore the common denominator that linked all data types together in a spatial frame of reference. Four types of navigation sensors were used to determine the locations of objects and features on the sea floor—Global Positioning System (GPS) satellites, Loran-C, and two ranging navigation systems (Del Norte and Benthos). The output from the GPS, Loran-C, and Del Norte systems was fed directly into a navigation program running on a microcomputer. This program provided important real-time location information, which was relayed to computers in onboard science laboratories and the ship's bridge. The Benthos system was a standalone system, which had its own program and display and ran separately from the integrated navigation system.

Two types of equipment using sound waves—sidescan sonar and seismic-reflection systems—were used to map the sea floor in the gulf. Images from three different sidescan systems were cut and pasted together to create "mosaics," which provide excellent map views of the area of sea floor studied in the gulf. Both 3.5-kilohertz (kHz) and 4.5-kHz high-resolution seismic-reflection systems were used to profile and look at the shallow subbottom (uppermost 160 feet) of the sea floor. A 10-kHz system was also used to provide accurate bathymetric information.

A towed seabed gamma-ray spectrometer belonging to and operated by the British Geological Survey, called the EEL because of its eel-like appearance, was used to measure the radioactivity of the sea floor. The gamma detector can measure both natural and artificial radioactivity in surficial sea-floor material to an effective maximum subbottom depth of about a foot. As the probe is towed, data are sent up the towing cable to a shipboard computer and recorded continuously.

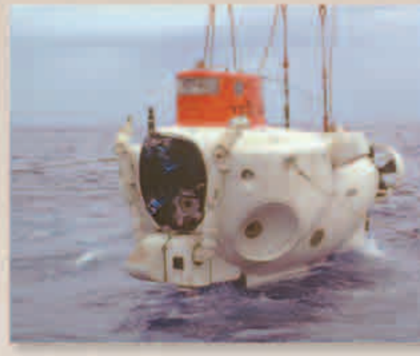
Physical samples of the sea bottom were taken with two devices. A gravity corer, driven into the bottom by a heavy weight, was used to obtain round cores about 4 inches in diameter and as much as 10 feet long. This type of coring device was used where the sediment was expected to be soft and muddy. The other sampling device used was a Van Veen grab sampler, which works very much like a clam shell. When the two sides of the shell touch the sea floor they close and scoop up a sample. This device was used where the sea floor was expected to be sandy, because sand would not easily be penetrated by or retained in a gravity corer.

Instrument packages were attached to lines moored to the sea floor to measure the velocity and direction of ocean currents in the Gulf of the Farallones. These instrument packages also measured water clarity, conductivity, salinity, and temperature.

A camera sled designed and built by the U.S. Geological Survey was towed from a research vessel along a preplanned trackline to take pictures of the sea floor in the gulf. Video was recorded continuously and still photographs were taken every 10 to 15 seconds. The images of the sea floor obtained with the camera sled were used to visually verify information collected from both sidescan-sonar mapping and physical sampling.

Visual observations were also made with *Sea Cliff*, a manned deep-submergence vehicle (DSV) operated by the U.S. Navy. *Sea Cliff* also had the capability to take physical samples with the use of mechanical arms. The Navy's unmanned Advanced Tethered Vehicle (ATV) was also used to obtain additional video and photographs of the sea floor. The ATV can be remotely "driven" to a specific site, and it proved to be the most precise way used so far in the Gulf of the Farallones to view objects on the sea floor.

Two types of equipment using sound waves—sidescan sonar and seismic-reflection systems—were used to map the sea floor in the Gulf Of the Farallones. Each system is housed in a hydrodynamic “towfish” that is towed just below the ocean surface from a ship. The SeaMARC1A sidescan-sonar system is shown here outside of its protective shell. The inset shows the towfish that was used for high-resolution seismic-reflection systems.



Sea Cliff (above), a manned deep-submergence vehicle operated by the U.S. Navy, was used to directly observe the sea bottom and to take physical samples with its mechanical arms. The Navy’s unmanned Advanced Tethered Vehicle (above right) was also used to take video footage and still photographs of the sea floor.

This U.S. Geological Survey camera sled, towed from a research vessel along pre-planned tracklines, was used to take pictures of the sea floor in the Gulf of the Farallones.

Samples of the sea bottom were taken with two devices. A gravity corer (above) was used where the sediment was expected to be soft and muddy. A clam-like Van Veen grab sampler (left, in closed position), used where the sea floor was expected to be sandy, collected samples such as the sand and brittle stars shown (top).

Oceanography and Geology of the Gulf of the Farallones

The San Francisco Bay region of California is famous for its stunning landscapes and complex geology. Adjacent to this region, in the watery world of the Pacific Ocean beyond the Golden Gate, lies the Gulf of the Farallones, a physical environment equally complex and fascinating, but less obvious, less visible, and therefore more mysterious.

Scientific studies are revealing that the sea floor of the gulf, like the region onshore, was crafted by geologic forces that include movements of the San Andreas Fault system, major changes in sea level, and the action of rivers. The ceaseless work of oceanic currents has further sculpted the sea bottom in the gulf into landscapes that today range from flat plains and giant sand ripples to deep canyons and rugged mountains, some of whose highest summits poke above the water to form the Farallon Islands.

Oceanography and Geology of the Gulf of the Farallones

Regional Setting

John L. Chin and Russell W. Graymer

The Gulf of the Farallones lies in the offshore part of the San Francisco Bay region just beyond the Golden Gate. The bay region is home to more than 6 million people and has long been regarded as one of the most beautiful regions in the United States. It annually draws hundreds of thousands of tourists from all over the world to enjoy its hilly, often fog-shrouded terrain and its mild, Mediterranean climate, as well as to experience its cultural richness and diversity. The historical settlement of the bay region is intimately related to its geography, natural harbors, and mild climate.

The San Francisco Bay region extends from the Point Reyes Peninsula southward to Monterey Bay and from the coast eastward to the Sacramento-San Joaquin Delta and also includes the offshore area out to a water depth of about 11,500 feet, which is the outer edge of the Continental Slope. This offshore area, where many residents of the region and tourists go to watch the annual migration of whales, as well as to boat and fish, includes the Gulf of the Farallones and the Farallon Islands. Although the sea floor in this area cannot be visually observed, scientists have learned much about it by using acoustic instruments (instruments that utilize sound sources and listening devices) and underwater cameras and video equipment.

The landscape features of the San Francisco Bay region are the cumulative result of millions of years of Earth history, involving the building and subsequent wearing down of mountains, volcanic eruptions and resulting outpourings of lava, large and small earthquakes, and the never-ending processes of wind and water erosion and deposition. Many of these processes are occurring today, although some of them occur at rates so slow that little change may be perceived over the course of a human lifetime. The sedimentary deposits and rocks of the region range in age from hundreds of millions of years to those still forming today. The entire spectrum of rocks present in the region records only a fraction of the Earth's history. The rock types range from the salt-and-pepper granitic rocks at Point Reyes and on the Farallon Islands, through various types of volcanic rocks (such as the pillow basalts in the Marin Headlands), to sedimentary rocks, such as the red to brown bricklike chert that forms the cliffs of the Marin Headlands and many of the hills of San Francisco, and the young sand-dune deposits that occur along the Pacific Coast.

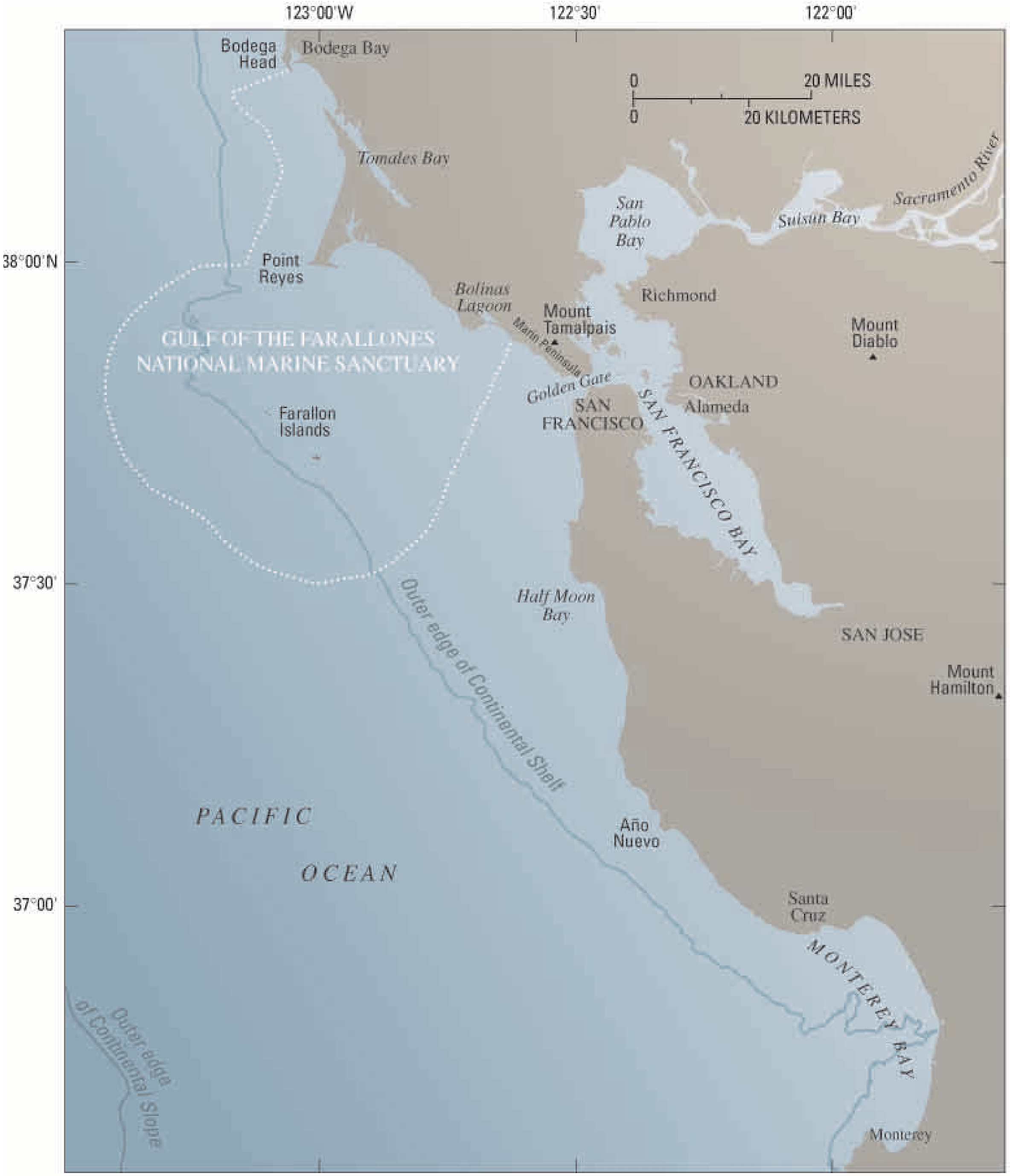
The San Francisco Bay region straddles the boundary zone between two of the Earth's major tectonic plates. The Pacific Plate is slowly moving northward relative to the North American Plate, and this motion takes place along the San Andreas Fault and a network of associated subparallel faults, collectively called the San Andreas Fault Zone (see chapter on Earthquakes, Faults, and Tectonics). Rocks east of the San Andreas Fault Zone were mainly formed in approximately their present positions. However, many of the rocks found within the zone, like the Franciscan chert at the Marin Headlands, are ocean-floor rocks that have been scraped off onto the edge of North America over the past 150 million years.

The oldest of the rocks found west of the San Andreas Fault were formed hundreds of miles to the south, some near the present site of Los Angeles, and subsequently transported northward by movement along the San Andreas and its associated faults. Rocks west of the fault are, in fact, still being transported northward at about 2 inches per year and after millions of years may reach the area where Alaska is today.

Mountain ranges in the San Francisco Bay region trend mostly northwest and are separated by broad basins and narrow valleys. Many of the ridgecrests in the Coast Range, the major mountain range in the region, rise above 1,000 feet, and a few above 4,000 feet. The highest peaks include Mount Hamilton at 4,373 feet, Mount Diablo at 3,849 feet, and Mount Tamalpais at 2,606 feet.

As recently as about 10,000 years ago, at the end of the last ice age, great sheets of ice (glaciers) covered much of Earth's northern hemisphere. Because so much water was stored in these glaciers, sea level was about 300 feet lower than at present, and the coastline of the San Francisco Bay region was situated as much as 35 miles seaward of its present position, near coastal hills whose tops are now the Farallon Islands. The melting of the ice sheets caused worldwide sea level to rise, forming the Gulf of the Farallones and San Francisco Bay.

If the vast volume of ocean water that now covers the floor of the gulf could be removed, people would see a varied landscape. That landscape is as rich in diversity and rugged splendor as that on the nearby shore (see chapter on Landscape of the Sea Floor).



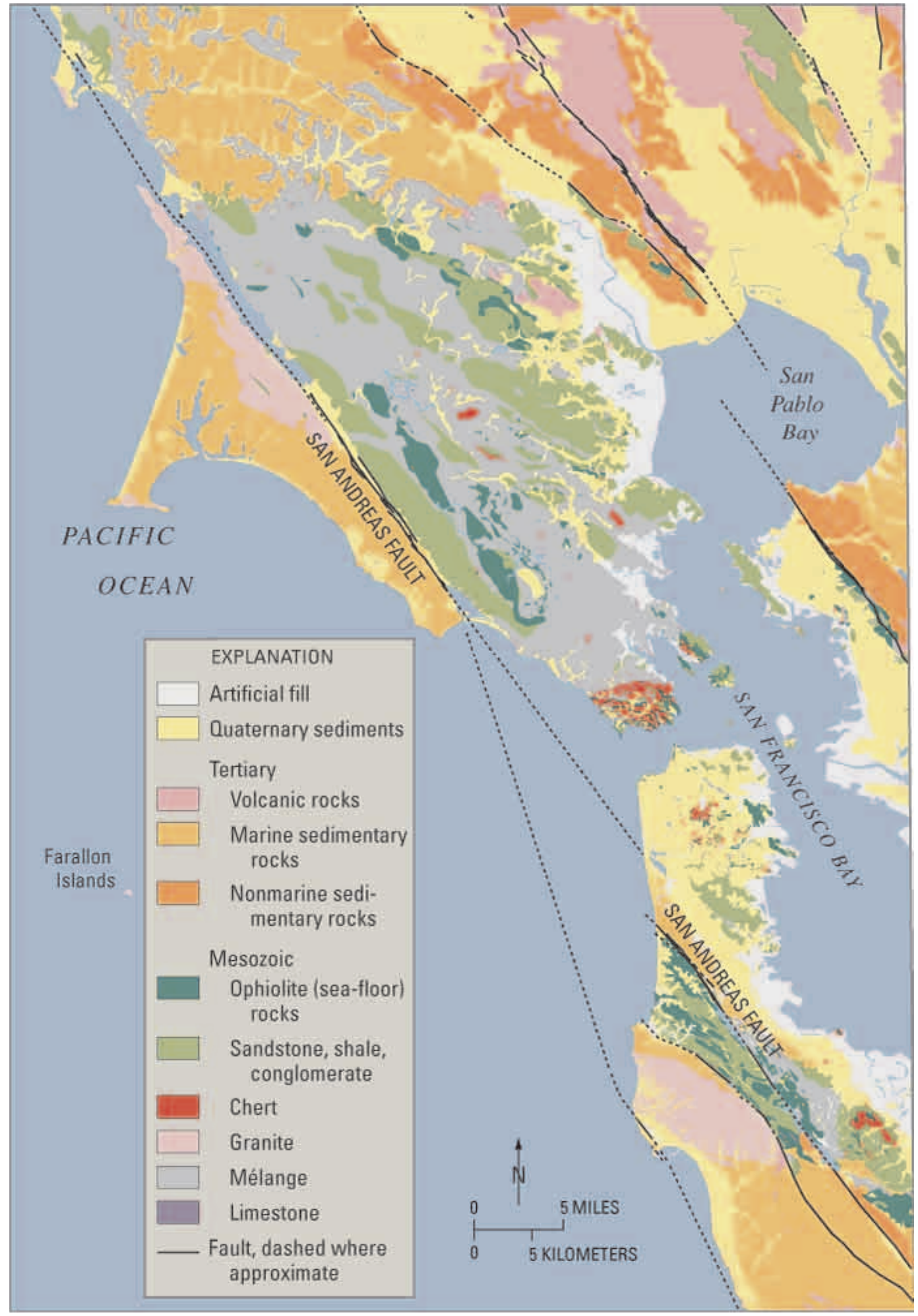
The Gulf of the Farallones lies in the offshore part of the San Francisco Bay region (see map at left) just beyond the Golden Gate (views above). *A*, View eastward from the Marin Headlands toward the Golden Gate Bridge and downtown San Francisco; Alcatraz Island can be seen at the upper left, Treasure and Yerba Buena Islands and the San Francisco Bay Bridge are seen in the middle distance, and the hills of the heavily populated east bay, which includes the city of Oakland, can be seen beyond the Bay Bridge. *B*, View westward through the Golden Gate looking out into the Gulf of the Farallones. *C*, Closeup westward view of the Marin Headlands taken from a similar vantage point as photograph *A*; the headlands are mostly composed of Franciscan chert and pillow basalts (see next page). (U.S. Geological Survey photographs by Phil Stoffer.)

◄ Some rocks of the San Francisco Bay region dating from the Mesozoic Era (250 to 65 million years ago): Franciscan cherts (top left) and pillow basalts (bottom left) of the Marin Headlands, which were originally formed on the ocean floor 150 to 100 million years ago. (U.S. Geological Survey photographs by Bruce Rogers.)

Some sedimentary rocks of the San Francisco Bay region dating from the Tertiary Period (65 to 1.6 million years ago). Above, deposits of an approximately 50-million-year-old submarine landslide exposed near Año Nuevo on the coast south of San Francisco; left, a beach cobble of the Purisima Formation on the coast south of San Francisco containing abundant fossils, mostly clams, that lived in shallow marine waters a few million years ago and are similar to those living in the region's coastal waters today. (U.S. Geological Survey photographs by Phil Stoffer.)

Quaternary (less than 1.6 million years old) deposits of the marine and coastal Merced Formation in an eroded seacliff at Fort Funston Beach in San Francisco (U.S. Geological Survey photograph by Phil Stoffer). The white band in the middle of this approximately 150-foot cliff is the Rockland Ash, a layer of volcanic ash from a powerful eruption that occurred in the Lassen area of northern California about 600,000 years ago. That eruption was 50 times larger than the 1980 eruption of Mount St. Helens, Washington, and because the winds at the time of the eruption were blowing southward, ash several inches thick was deposited as far south as the San Francisco Bay area. Map shows known distribution of the Rockland Ash, and inset shows particles from it magnified about 70 times.

Geologic map of San Francisco Bay region, showing the San Andreas Fault, related faults, and regional rock types. ►



Oceanography and Geology of the Gulf of the Farallones

Earthquakes, Faults, and Tectonics

Holly F. Ryan, Stephanie L. Ross, and Russell W. Graymer

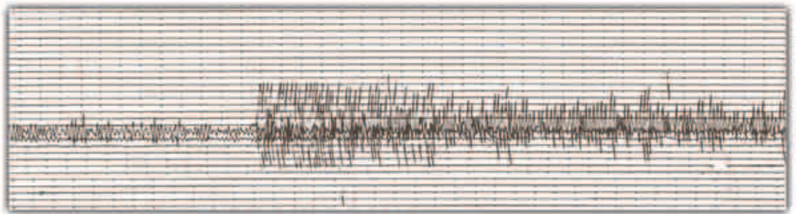
On April 18, 1906, the San Francisco Bay region was rocked by one of the most significant earthquakes in history. This magnitude 7.8 earthquake began on a segment of the San Andreas Fault that lies underwater in the Gulf of the Farallones, just a few miles offshore of San Francisco. The quake ruptured nearly 270 miles of the fault from San Juan Bautista to Cape Mendocino. Damage from the intense shaking during the earthquake, along with the devastation from the ensuing fire, wreaked havoc in San Francisco, a city of 400,000 inhabitants at the time. Although the official death toll from the earthquake was reported to be about 700, it is now widely believed that the actual loss of life was three to four times greater. In addition, more than 50 percent of the population of the city was homeless following the earthquake.

Today, a large metropolitan area of more than 6 million people covers more than 7,000 square miles around San Francisco Bay. Many small earthquakes occur in the bay region every year, although only those greater than about magnitude 3 are usually felt. The 1989 magnitude 6.9 Loma Prieta earthquake was a strong reminder of the potential for large, destructive earthquakes in the region. The Loma Prieta earthquake killed 63 people, injured more than 3,700 others, and caused property damage in excess of $6 billion. It should be kept in mind, however, that devastation occurred only in limited areas because the epicenter of this earthquake was on a somewhat remote segment of the San Andreas Fault, 70 miles south of San Francisco in the Santa Cruz Mountains. An earthquake of similar magnitude located closer to the center of a densely populated urban area is capable of causing much greater damage and loss of life. This was shown by the 1995 Kobe, Japan, earthquake (magnitude 6.9), which caused more than 6,000 deaths, injured 35,000 people, resulted in $100 billion in property damage, and destroyed the homes of more than 300,000 people.

The rigid outer shell of the Earth is made up of large "tectonic plates" that move horizontally relative to one another. The Gulf of the Farallones includes part of the boundary between two of the Earth's largest tectonic plates. Tectonic motion along this boundary is what makes the San Francisco Bay region so susceptible to earthquakes and is a significant factor in creating the geology and geomorphology of the region. The Pacific and North American Plates are sliding relentlessly past each other at an average rate of about 2 inches per year. Most of this motion occurs in catastrophic bursts of movement—earthquakes—along the San Andreas Fault system. Near San Francisco, the San Andreas Fault system is a complex zone of faults about 50 miles wide. It stretches from offshore to as far east as the cities of Vallejo and Livermore. In addition to the San Andreas Fault, the numerous faults that are part of the San Andreas Fault system include the San Gregorio, Hayward, Rogers Creek, and Calaveras Faults.

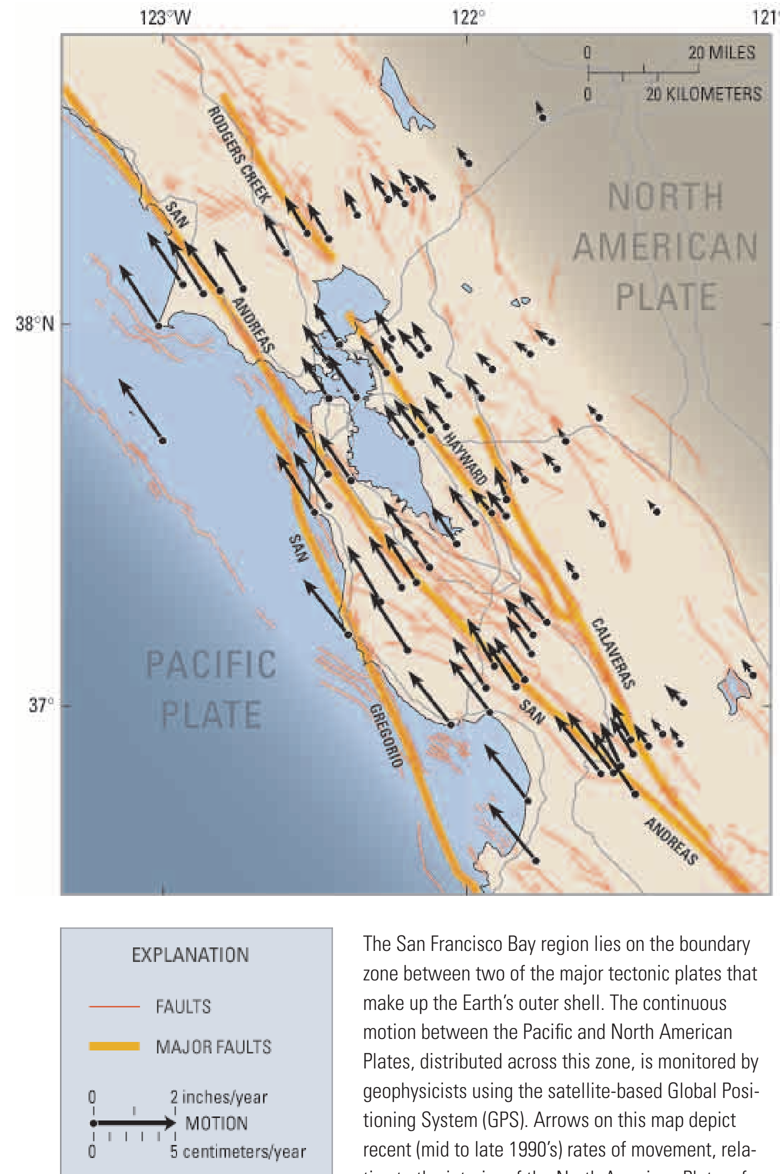
Much of the geomorphology (surface features) of the San Francisco Bay region is a consequence of the location and motion of past and presently active faults within the San Andreas Fault system, and of the juxtaposition of blocks of different rock types by movements along these faults. For example, the Farallon Islands offshore and Montara Mountain located onshore north of Half Moon Bay are parts of large fault blocks that contain granitic rocks believed to be originally derived from the southern Sierra Nevada. At least 17 such fault-bounded structural blocks (terranes) of different sizes and rock types have been identified in the bay region.

To help reduce injuries and property damage from future earthquakes in the San Francisco Bay region, it is necessary to have a good understanding of the geology of this region. This must encompass both the onshore and offshore geology, including that of the Gulf of the Farallones.

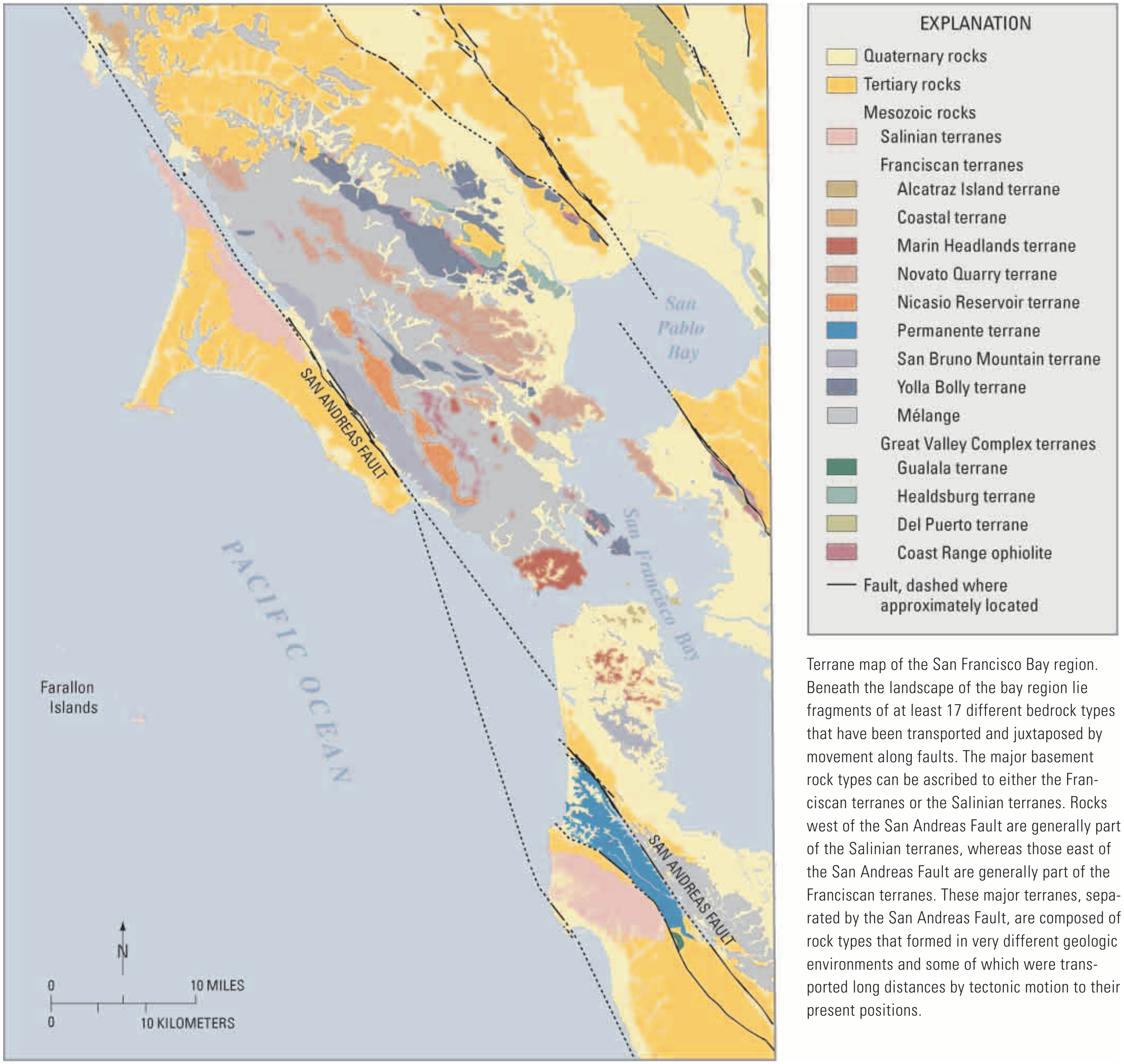


Seismogram from 1989 Loma Prieta earthquake

The photograph above, taken from a "captive airship" 5 weeks after the great earthquake of April 18, 1906, shows the devastation wrought on the city of San Francisco by the quake and subsequent fire. In the city and surrounding region, the official death toll was about 700, but it is now believed that the actual loss of life was three to four times greater. At the time, property losses were estimated to be more than $400 million. If a similar earthquake occurred in northern California today, after many decades of rapid urban growth, many thousands of people might be killed, and economic losses could be in the hundreds of billions of dollars. The photograph at left shows a fence near Bolinas, about 20 miles southeast of Point Reyes, that was offset by ground movement along the San Andreas Fault in the 1906 quake.



The San Francisco Bay region lies on the boundary zone between two of the major tectonic plates that make up the Earth's outer shell. The continuous motion between the Pacific and North American Plates, distributed across this zone, is monitored by geophysicists using the satellite-based Global Positioning System (GPS). Arrows on this map depict recent (mid to late 1990's) rates of movement, relative to the interior of the North American Plate, of reference markers anchored in rock or deep in solid ground. This relentless motion of the plates strains the crustal rocks of the bay region, storing energy that eventually will be released in earthquakes. During the time represented in this diagram, most of the faults in the bay region have been "locked," not producing earthquakes.



Terrane map of the San Francisco Bay region. Beneath the landscape of the bay region lie fragments of at least 17 different bedrock types that have been transported and juxtaposed by movement along faults. The major basement rock types can be ascribed to either the Franciscan terranes or the Salinian terranes. Rocks west of the San Andreas Fault are generally part of the Salinian terranes, whereas those east of the San Andreas Fault are generally part of the Franciscan terranes. These major terranes, separated by the San Andreas Fault, are composed of rock types that formed in very different geologic environments and some of which were transported long distances by tectonic motion to their present positions.

SAN FRANCISCO BAY REGION EARTHQUAKE PROBABILITY

70%

odds (±10%) for one or more magnitude 6.7 or greater earthquakes from 2000 to 2030.

This result incorporates 9% odds of quakes not on shown faults.

EXPLANATION

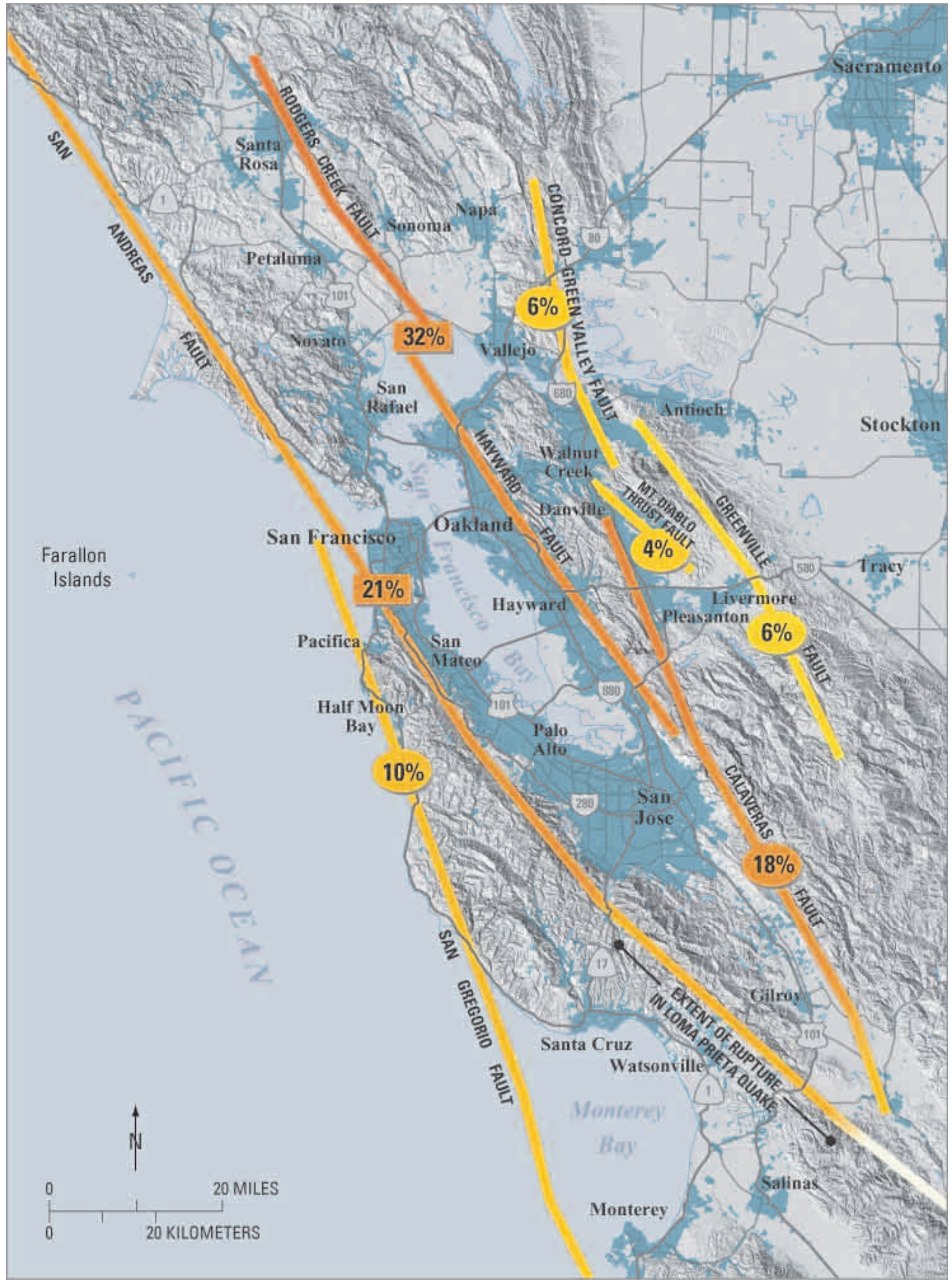
21% Odds of magnitude 6.7 or greater quakes before 2030 on the indicated fault

18% Odds for faults that were not previously included in probability studies

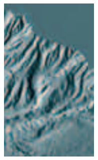
Increasing quake odds ⟶ along fault segments

Individual fault probabilities are uncertain by 5 to 10%

Expanding urban areas



In 1999, the U.S. Geological Survey and cooperators released this earthquake probability map for the San Francisco Bay region. The threat of earthquakes extends across the entire region, and a major quake is likely before 2030. As continuing research reveals new information about earthquakes in the bay region, these probabilities are revised.



Landscape of the Sea Floor

Herman A. Karl and William C. Schwab

Various forces sculpt the surface of the Earth into shapes large and small that range from mountains tens of thousands of feet high to ripples less than an inch high in the sand. We can easily see these morphologic features on dry land, and most are accessible to be explored and appreciated by us as we walk and drive across or fly over them. In contrast, people can travel at sea without ever being aware of the existence of large mountains and deep valleys hidden by tens of feet to tens of thousands of feet of water. At one time, it was impossible to see the landscape beneath the sea except by direct observation, and so the bottom of the deep oceans remained as mysterious as the other side of the Moon. Methods of using sound to map the features of the sea floor were developed in the decades after World War I, and we now know that mountains larger than any on land and canyons deeper and wider than the Grand Canyon exist beneath our oceans.

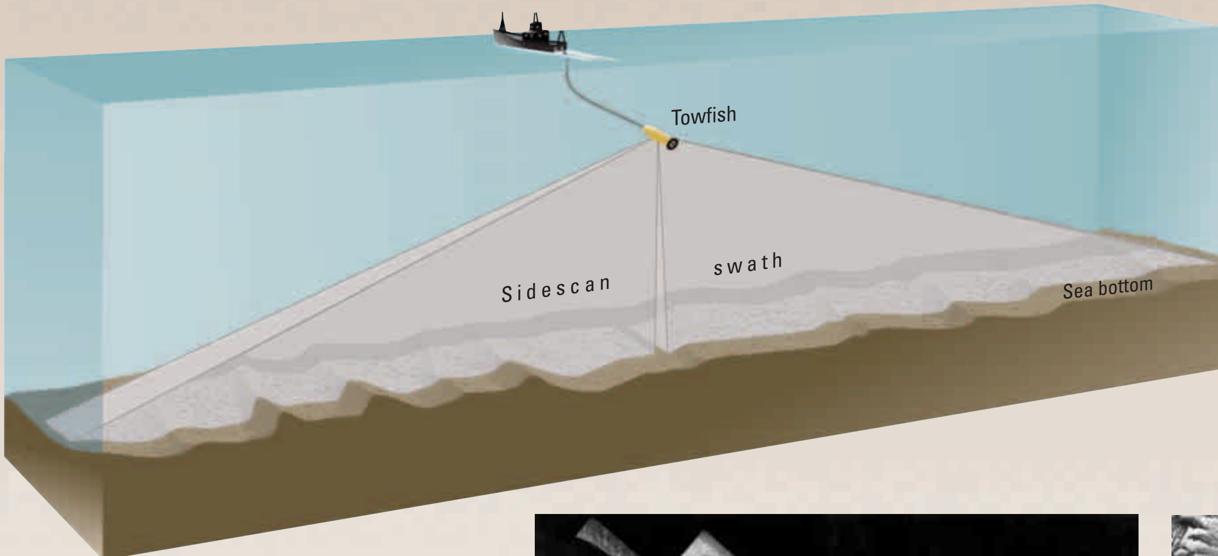
Images of large areas of the land surface are taken by cameras in aircraft and acquired by sensors in satellites. Optical instruments (cameras) record reflected light to produce images (photographs) of mountains, plains, rivers, and valleys. However, light does not penetrate far in water, and so photographs cannot be produced that show entire mountains and valleys beneath the sea. Just as underwater cameras can take photographs of only very small areas and objects not far distant, divers and submersibles can observe only very small areas of the ocean bottom. Such methods of observation are analogous to walking around at night with a flashlight and trying to see a mountain or a forest. It is possible in this way to see rocks, pebbles, leaves, and trees along your path, but not the entire mountain and forest. To observe and make images of the mountains and valleys under the sea, scientists have developed instruments that use sound (acoustic energy) as a way to "insonify" (flood with sound waves) rather than illuminate (flood with light) those features. Computers are used to process the acoustic data so that the resulting sound images (sonographs) resemble aerial photographs (light images).

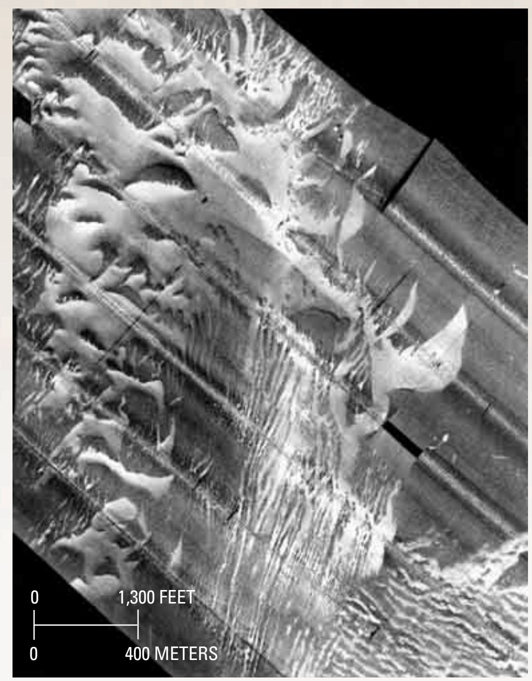
Data collected from the Continental Shelf in the Gulf of the Farallones by the U.S. Geological Survey (USGS) reveal various features on the seabed, including outcropping rock and several types of ripples, dunes, lineations, and depressions (these features are collectively called bedforms). A regional map compiled from these data established that at least four major discrete fields of bedforms occur on the Continental Shelf between Point Reyes and Half Moon Bay. These fields are separated by monotonous stretches of flat, featureless sea floor. Of particular interest is a series of depressions floored by ripples with wavelengths of about 3 feet. These depressions, which are common east of the Farallon Islands between Point Reyes and the Golden Gate, form the largest of the four fields of bedforms. The shelf in the study area is morphologically complex. This complexity reflects an intricate geologic history and a wide variety of geologic and oceanographic processes that operate on the shelf to transport, erode, and deposit sediment.

Data collected from the Continental Slope by the USGS show that the rugged northern part of the Gulf of the Farallones is scarred by numerous small canyons. Sediment cover is thin or absent. This northern part contrasts markedly with the southern part of the gulf, which is much less rugged and draped by a thin blanket of sediment. Sediment in the southern part appears stable because no large underwater landslides were discerned on the sonographs. Conspicuous geomorphic features in the southern part include Pioneer Canyon and Pioneer Seamount. Sediment is accumulating in Pioneer Canyon and on Pioneer Seamount, suggesting that this area is depositional, in contrast to the active transport environment found on the shelf.

USGS sonographs made of the Gulf of the Farallones have several practical applications. For example, the evidence of strong currents, as indicated by large ripples in coarse sand, suggests that dredge material and pollutants disposed of at sites on the Continental Shelf could be redistributed over large areas. Also, commercial fisherman can use these images to locate the substrates preferred by bottom fishes and crabs.

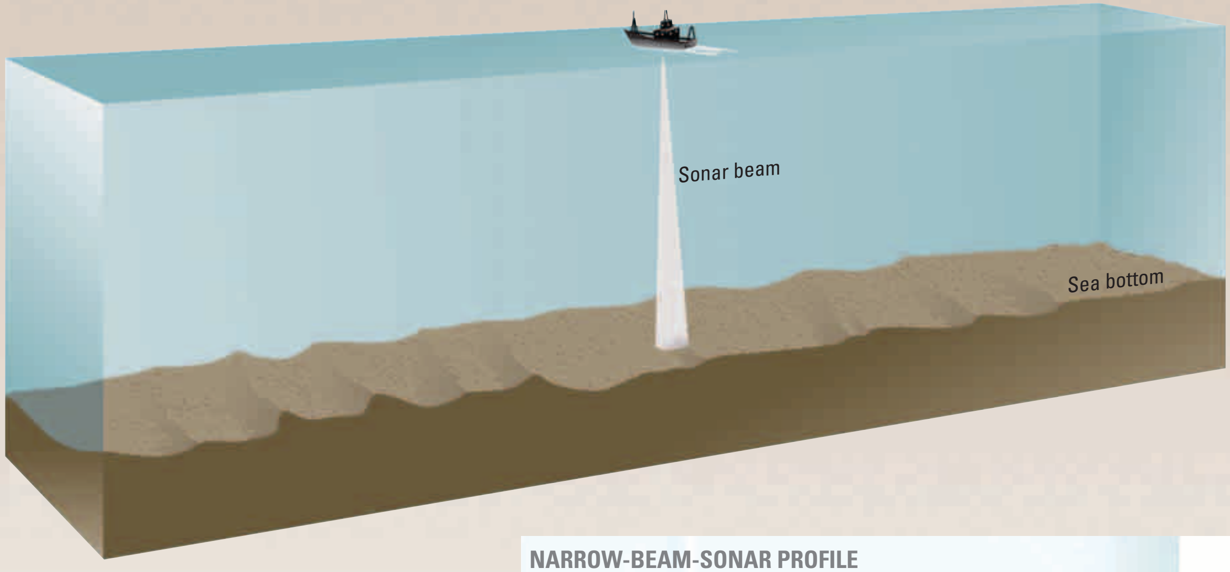
MAPPING THE SEA FLOOR USING SIDESCAN SONAR



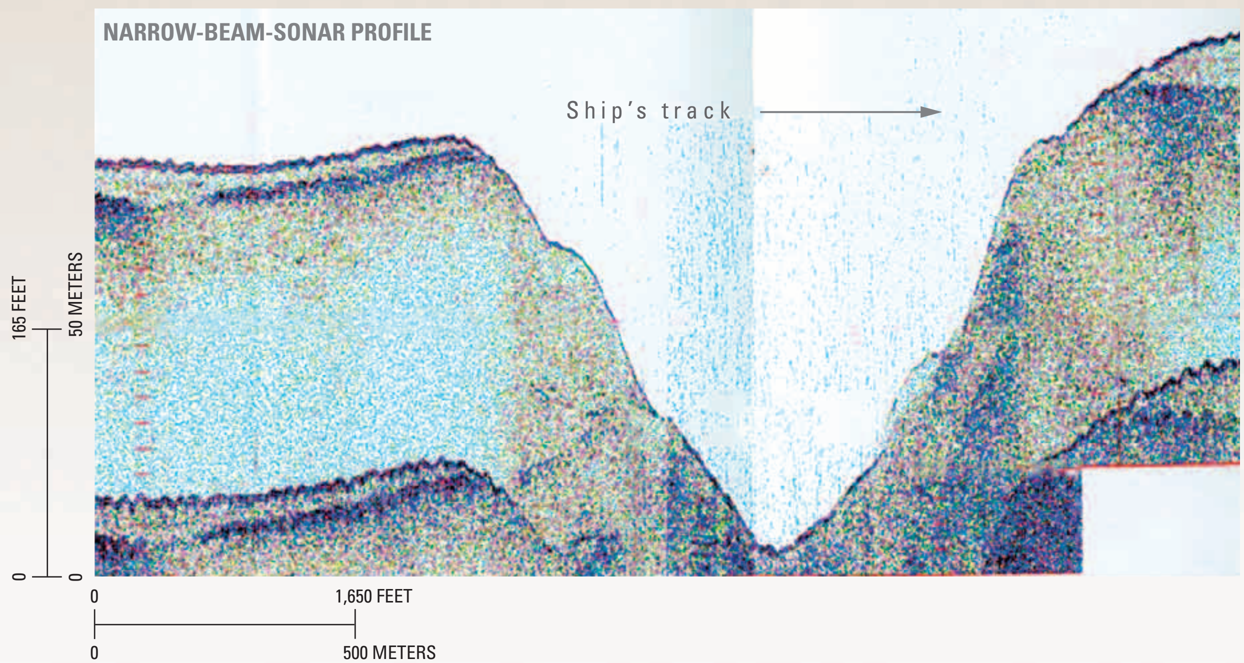


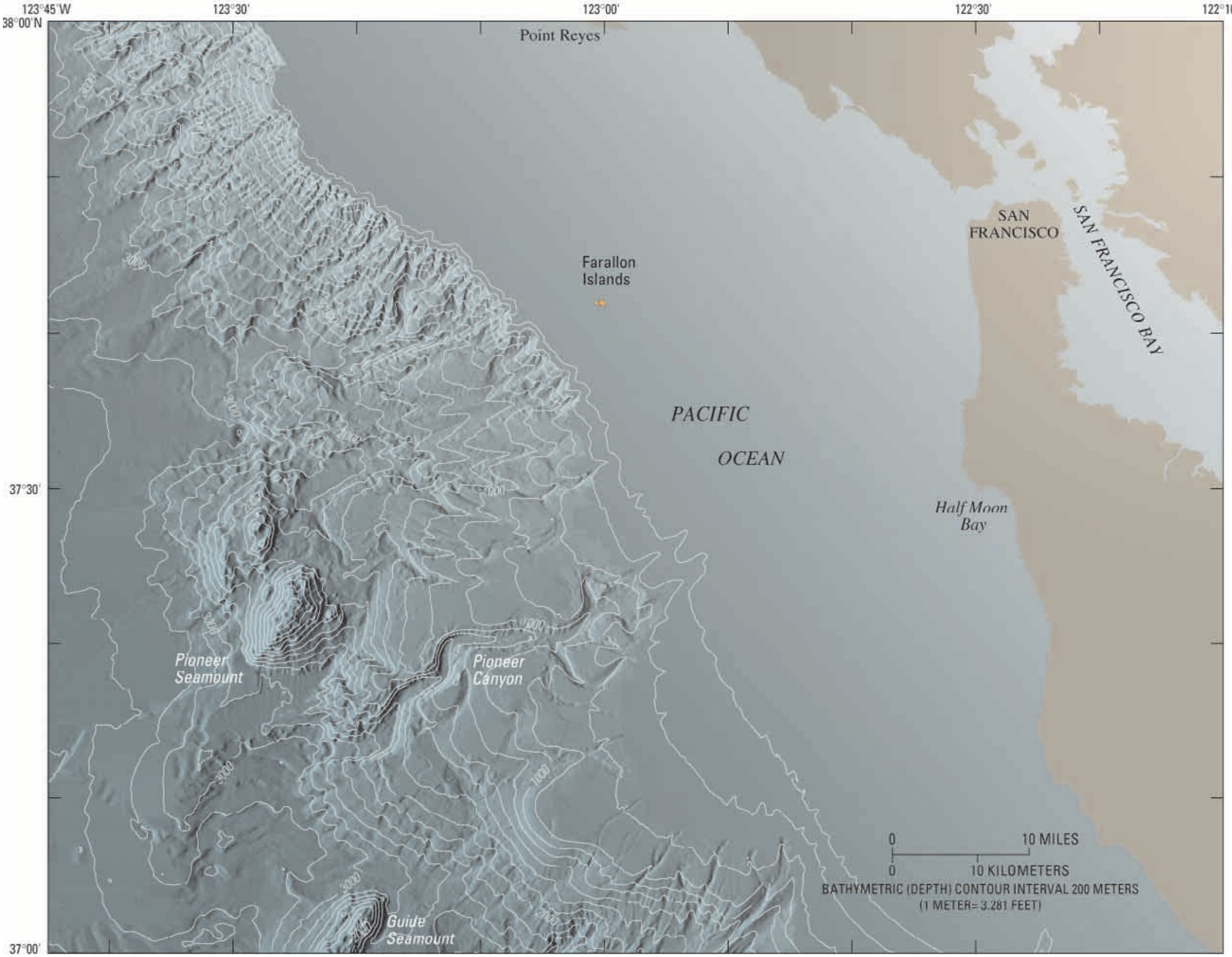
In the diagram above, a sidescan-sonar "towfish" is pulled behind a ship, imaging a broad swath of the sea floor. When combined, such swaths form sidescan-sonar "mosaics" or maps of large areas of the sea bottom. The mosaic at left shows depressions (dark areas) floored by sand ripples east of the Farallon Islands between Point Reyes and the Golden Gate, and the mosaic at right shows unusual and complex bedforms, possibly ribbons of sand moving over the sea floor.

MAPPING THE SEA FLOOR USING NARROW-BEAM SONAR



In the diagram above, a hull-mounted, narrow-beam sonar system is producing a continuous profile of the sea floor as the ship moves. The sample profile at right, taken across a submarine canyon, shows the rugged sea-bottom topography typical of the northern Gulf of the Farallones.





Three-dimensional bathymetric map of the Continental Slope in the Gulf of the Farallones. This image was created using sonar.

Current Patterns Over the Continental Shelf and Slope

Marlene A. Noble

The waters of the Gulf of the Farallones extend along the central California coast from Point Reyes southeastward to Año Nuevo. 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 7 miles per hour. 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.

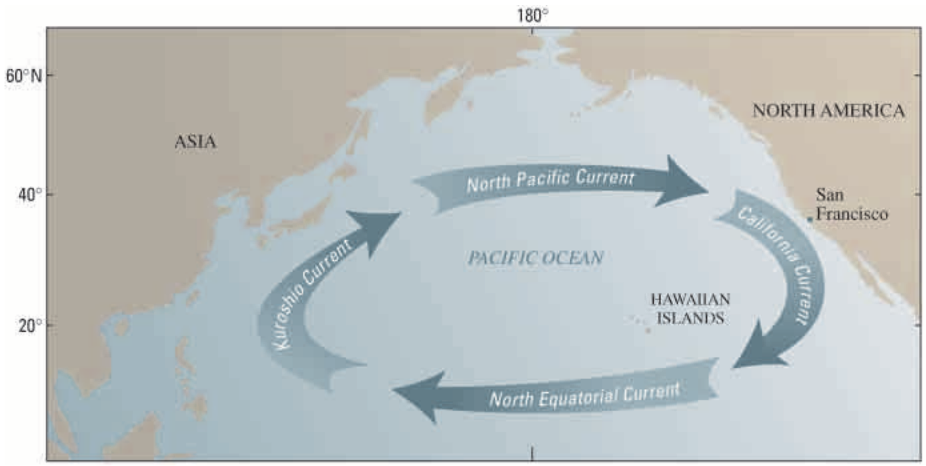
During the 1990's, several programs were undertaken by the U.S. Geological Survey and other organizations to gather information about how currents, nutrients, and suspended material move through the Gulf of the Farallones. The area studied by the USGS covers about 1,000 square nautical miles of the gulf and ranges in water depth from 660 to 10,500 feet. 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.

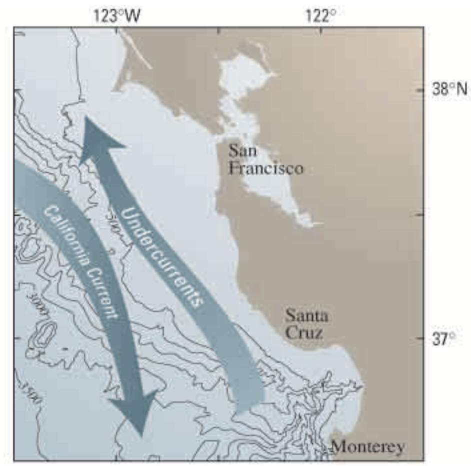
Currents over the Continental Shelf tend to flow southeastward and slightly offshore in summer, causing nutrient-rich cool waters to upwell onto the shelf. Shelf currents flow mostly northwestward in winter. Tidal currents are strong over the shelf and tend to be the dominant features in flow patterns 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.

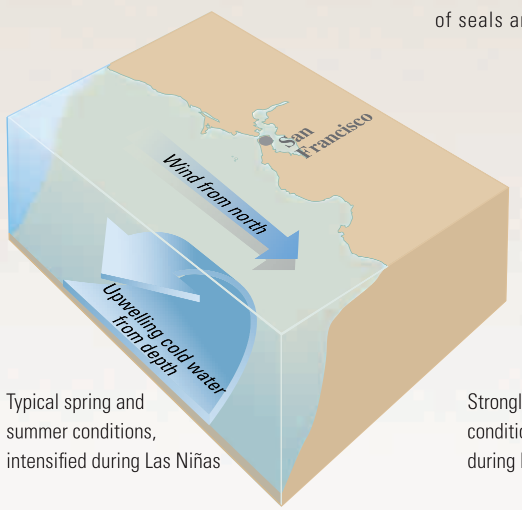




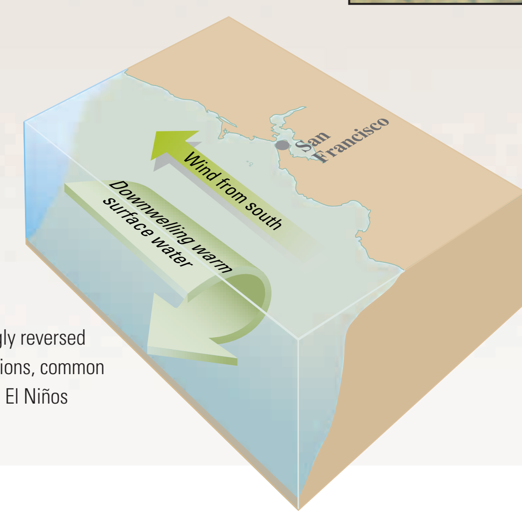
The California Current is part of a permanent, ocean-wide gyre in the surface waters of the North Pacific. It forms the east part of this gyre, which is defined in the west by the Kuroshio Current (Pacific Gulf Stream), in the north by the North Pacific Current, and in the south by the North Equatorial Current. In the Gulf of the Farallones, currents over the Continental Slope are quite distinct from the southeastward-flowing water of the California Current farther offshore. These slope currents are confined to a relatively narrow band seaward of the Continental Shelf and flow northwestward, parallel to the topography, as the California Undercurrent. In the gulf, the undercurrent is generally found over the slope in water depths less than 2,600 feet. Bathymetry in meters (1 m = 3.281 ft).

WATER MOVEMENTS AND WINDS OFF THE NORTHERN CALIFORNIA COAST

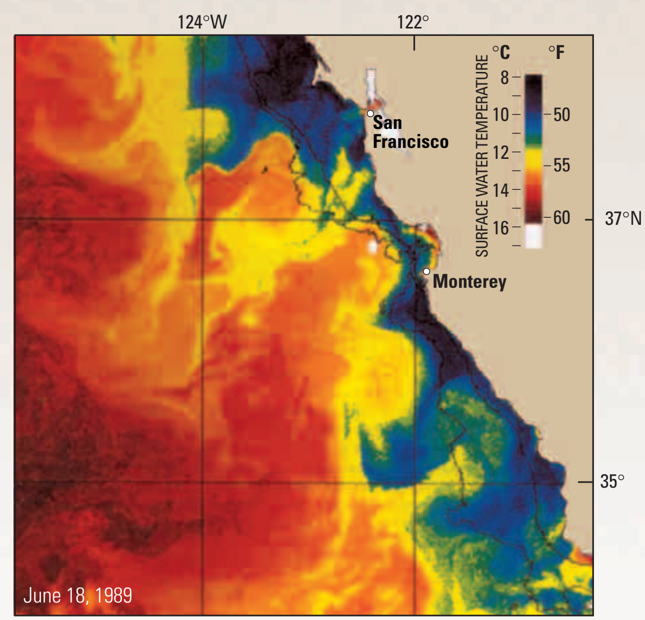
In spring and summer, strong winds blowing toward the equator, together with the Coriolis effect (the tendency of winds and currents to veer to the right in the Northern Hemisphere and to the left in the Southern Hemisphere), push surface water away from the California coast. To fill its place, nutrient-rich colder water rises to the surface in the yearly upwelling that makes the ocean off northern California so cold in spring and summer and the Gulf of the Farallones so biologically productive. When El Niño atmospheric phenomena occur, they disrupt this pattern and cause 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. Areas of cold, upwelled water (blue) along the central California coast are shown in the satellite image below (NOAA AVHRR satellite data, processed at Naval Postgraduate School).



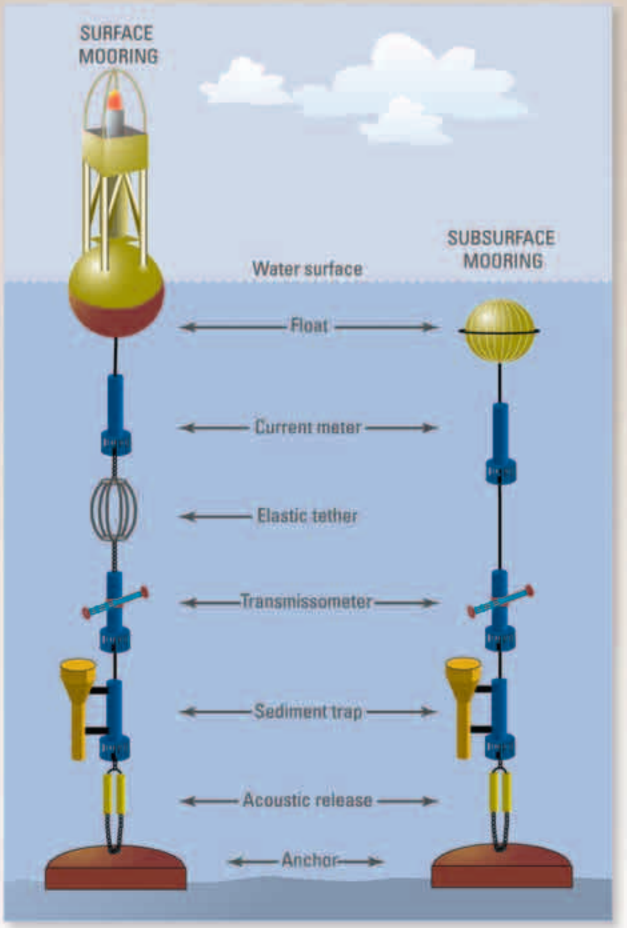
Typical spring and summer conditions, intensified during Las Niñas

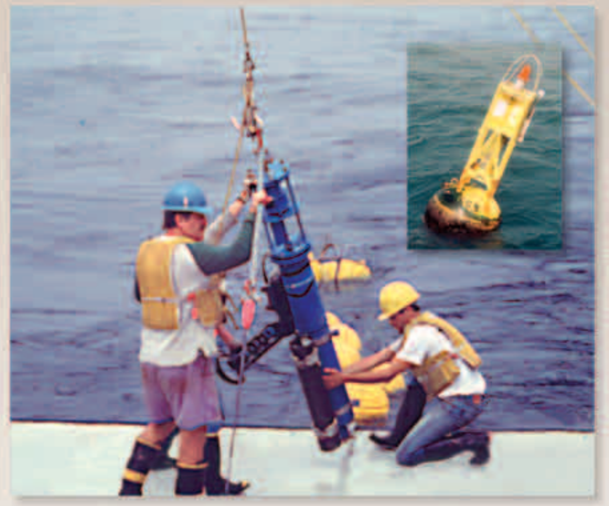


Strongly reversed conditions, common during El Niños



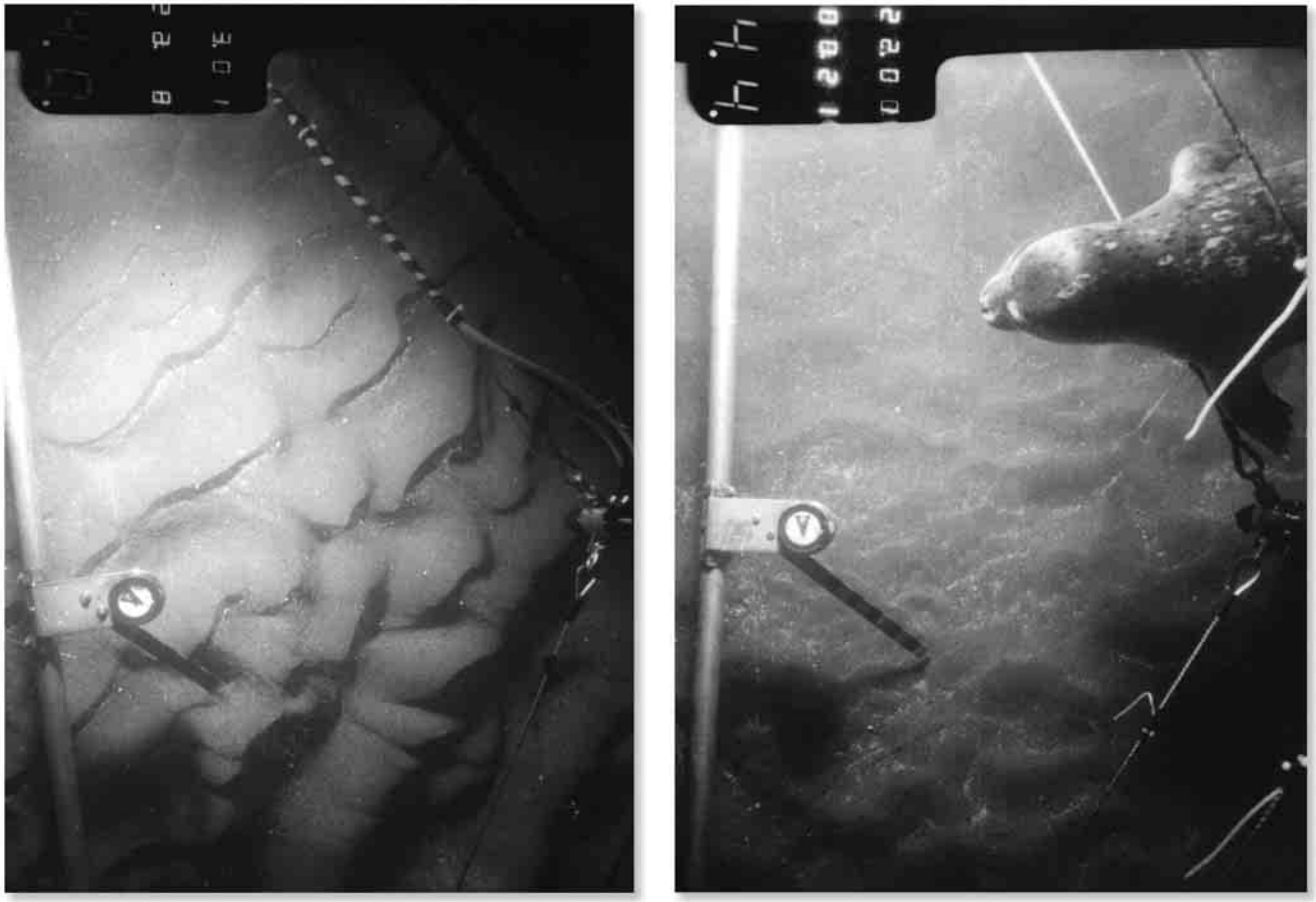
STRINGS OF INSTRUMENT PACKAGES ARE USED TO MEASURE OCEAN CURRENTS





One method the U.S. Geological Survey has used to measure ocean currents in the Gulf of the Farallones is strings of instrument packages attached to mooring lines anchored on the sea bottom. Surface moorings are mainly used in shallower water. Photograph below shows a current meter with an attached transmissometer (instrument to measure water clarity) being lowered into the waters of the gulf. Inset shows surface mooring (float) used for a bottom-anchored string of intrument packages.

These photographs were taken from a U.S. Geological Survey instrument station lowered to the sea floor in the Gulf of the Farallones. Strong bottom currents can create sand ripples (left), and weaker currents can leave a smooth sea bottom (right, with a curious seal).



Oceanography and Geology of the Gulf of the Farallones

Sediment of the Sea Floor

Herman A. Karl

Many people perceive the sea floor to be a smooth blanket of sand similar to a sandy beach. For some areas of the sea floor this is true, but just as the sandy beach is flanked by rocky headland and muddy wetland, so are the smooth sandy plains of the sea floor flanked by various different substrates. This is the case for much of the sea floor in the Gulf of the Farallones.

The earliest general model of sediment distribution across the sea floor was that the size of sediment particles gradually decreased with increasing water depth. According to this model, the nearshore consisted of a blanket of sand—an extension of the sandy shore—that was gradually replaced by silt and then by clay in deeper water. This model was based on the concept that the energy of ocean currents and waves decreased from shallow water to deeper water and that, therefore, smaller particles could only settle to the bottom in less energetic, deeper water.

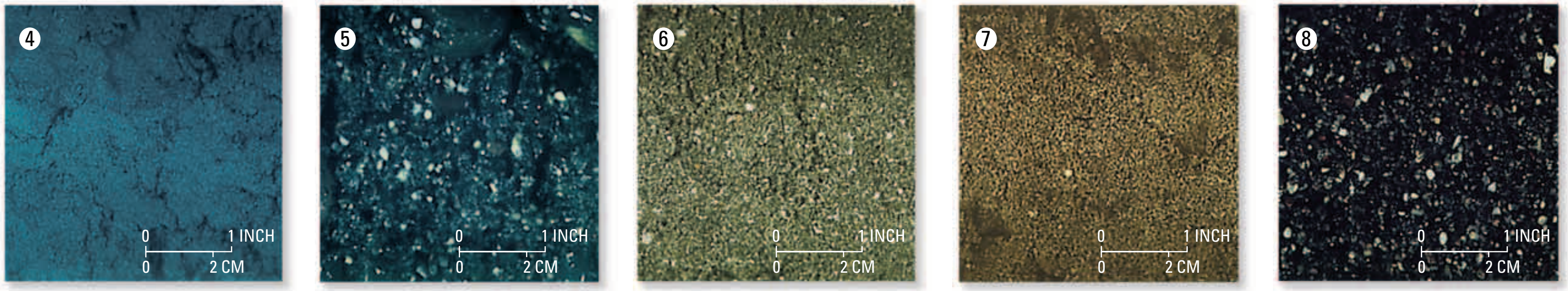
This early model was based on very limited data. These limited data led scientists to believe that the deep ocean floor, from which very few samples had been collected and of which no direct observations were possible, consisted of a uniform and monotonous layer of fine-grained sediment. As sampling techniques improved and more information was collected, scientists learned that the ocean bottom is as texturally varied and morphologically complex as the land surface. The physical characteristics (for example, size, shape, composition) and the distribution of sediment are the result of a complex interaction among geologic, oceanographic, and biologic processes. Moreover, scientists know that the distribution of sediment on the Continental Shelf is made more complex by deposits of relict sediment. Relict sediment is that material, generally coarse sand and gravel, left on the shelf when it was exposed during times of lower sea level.

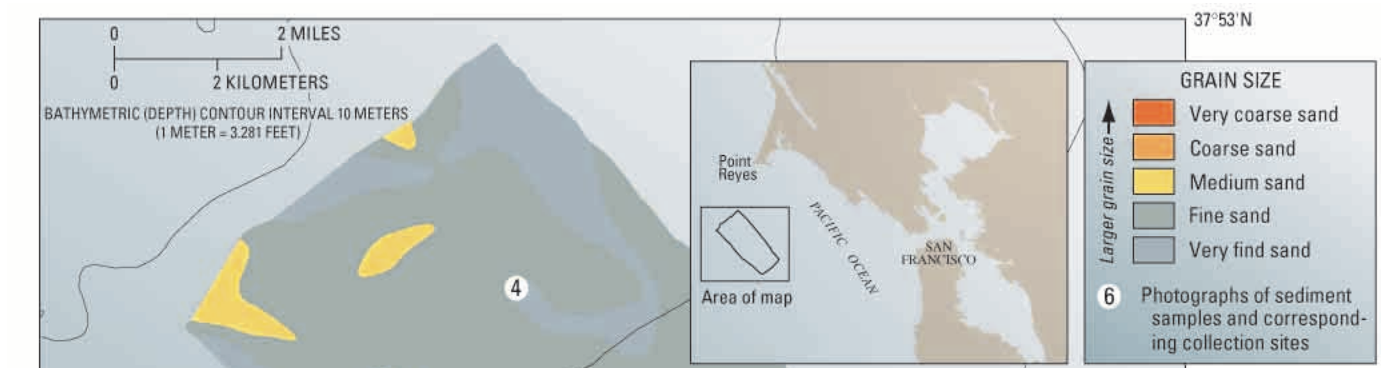
Evidently, then, the distribution of different types and grain sizes of sediment and rocks provides clues about the geologic history of an area and the types of ocean currents that deposited or reworked the sediment. Moreover, the different substrates provide habitats for the various organisms that live on, in, and near the sea floor. Information about substrates in Gulf of the Farallones National Marine Sanctuary is used by scientists investigating biodiversity and ecologic systems to help understand and manage the variety of animals and plants that live in the sanctuary. Such information is also used by commercial fishermen as an aid for locating fishes and crabs that prefer a particular substrate.

The sea floor in the Gulf of the Farallones consists of many different types of substrate, including rock outcrops, gravel, sand, clay, and deposits of broken shells. Some of these different types of substrate are found very close to each other and have abrupt boundaries between them. On the Continental Shelf a wide corridor of sand extends westerly from the Golden Gate to the Farallon Islands. Silty sand and sandy silt bound the corridor to the northwest and southeast, and a band of silt extends around Point Reyes.

In general, the sediment on the surface of the Continental Slope is finer and more uniform than that on the Continental Shelf in the Gulf of the Farallones. Nonetheless, most of the surficial sediment on the Continental Slope in the area of the Gulf of the Farallones studied is very sandy, a condition that is unusual (continental slopes are generally characterized by silt and clay). The reason for this abundance of sand is not fully understood. In general, exceptionally strong currents are required to transport large amounts of sand from the shelf to the slope, but such situations are extremely uncommon.

It is not yet known whether the textural patterns and bedforms on the Continental Shelf in the Gulf of the Farallones reflect entirely present-day processes or whether some of these features are remnants of processes that operated during lower stands of sea level in the past. During the glacial cycles of the past several million years, sea levels were lowered to as much as 445 feet below present-day sea level. Therefore, ancient relict features created during lower stands of sea level are common on Continental Shelves worldwide. Such lowstands of sea level would have exposed virtually all of the shelf in the Gulf of the Farallones.





Samples and photographs of the sea floor in the Gulf of the Farallones collected by the U.S. Geological Survey reveal a variety of substrates, including rock outcrops, gravel, sand, clay, and deposits of broken shells. Some of these different types of substrate are found very close to each other, and the boundaries between them are abrupt. In general, surficial sediment on the Continental Slope in the gulf is finer and less varied in composition and texture than that on the Continental Shelf. This map shows sediment size distribution on an area of the shelf to the northeast of the Farallon Islands.

Chemical Composition of Surface Sediments on the Sea Floor

Walter E. Dean and James V. Gardner

Sediments cover most of the sea floor in the Gulf of the Farallones, with a few areas of exposed bedrock. To help determine the origin and distribution of these sediments, 112 core samples were taken by the U.S. Geological Survey at sites on the sea floor from the shallow shelf down to a water depth of about 10,000 feet. These samples were analyzed for 28 major and trace elements, organic carbon, and calcium carbonate.

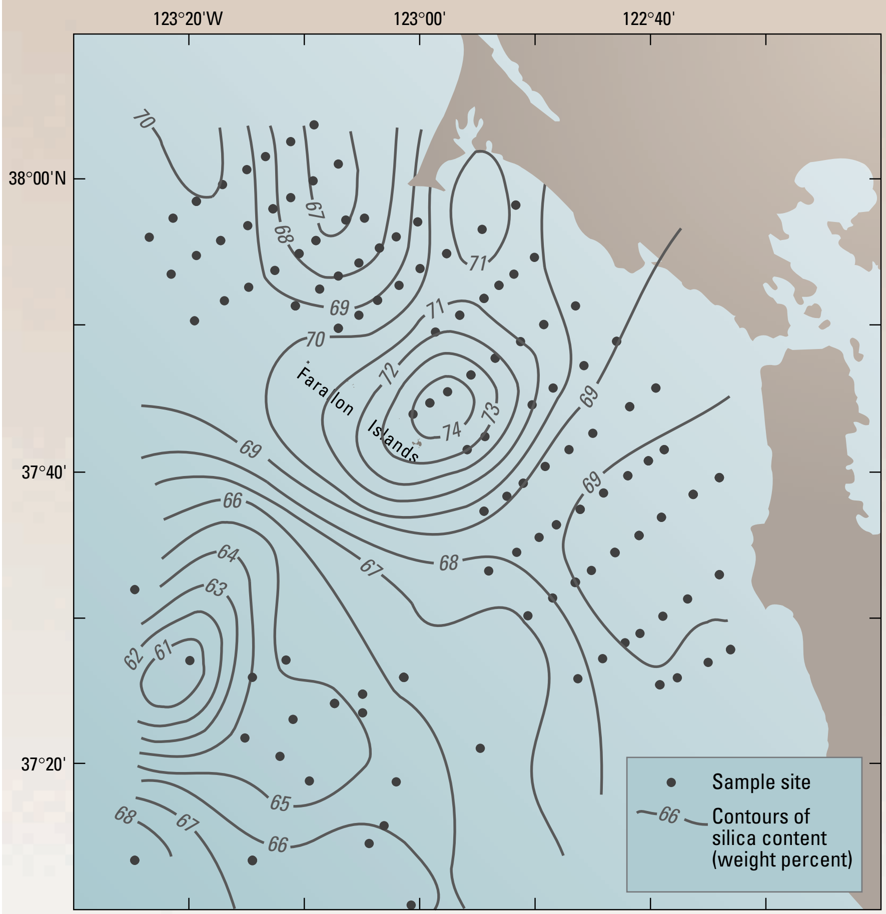
Many factors have affected the history, transport, and distribution of sediments in the Gulf of the Farallones, including the shape of the sea floor, sea-level fluctuations, and current patterns. The Continental Shelf in much of the gulf has a low gradient of about 0.1 degree, and water depth ranges from less than 160 feet to about 400 feet. The Continental Slope in much of the gulf has a steeper gradient of about 3 degrees, and water depth reaches about 11,500 feet at its base. Although the shelf is uncut by channels and canyons, the upper slope is incised with numerous gullies and submarine canyons, including Pioneer Canyon.

Before 500,000 years ago, the main sources of sediment to the Gulf of the Farallones were the nearby onshore areas with their variety of sedimentary, metamorphic, and igneous rocks. About 500,000 years ago, drainage from interior California broke through to the Pacific Ocean at the Golden Gate, providing additional sources of sediment from as far away as the Sierra Nevada. The Continental Shelf between the Golden Gate and the Farallon Islands is covered with sandy sediment, which has been repeatedly reworked by fluctuations in sea level and great (100-year) storms. Major lowerings of sea level during global glaciations have exposed the shelf in the gulf as dry land several times, most recently from about 20,000 to 15,000 years ago. In these glacial periods, sea level was lowered by hundreds of feet, because of the large amount of water tied up in ice sheets on land. During these lowstands, a river probably coursed across all of what is now the Continental Shelf in the gulf, although no channel has yet been identified. About 15,000 years ago, rising sea level caused by the melting of the ice sheets once again drowned the Continental Shelf.

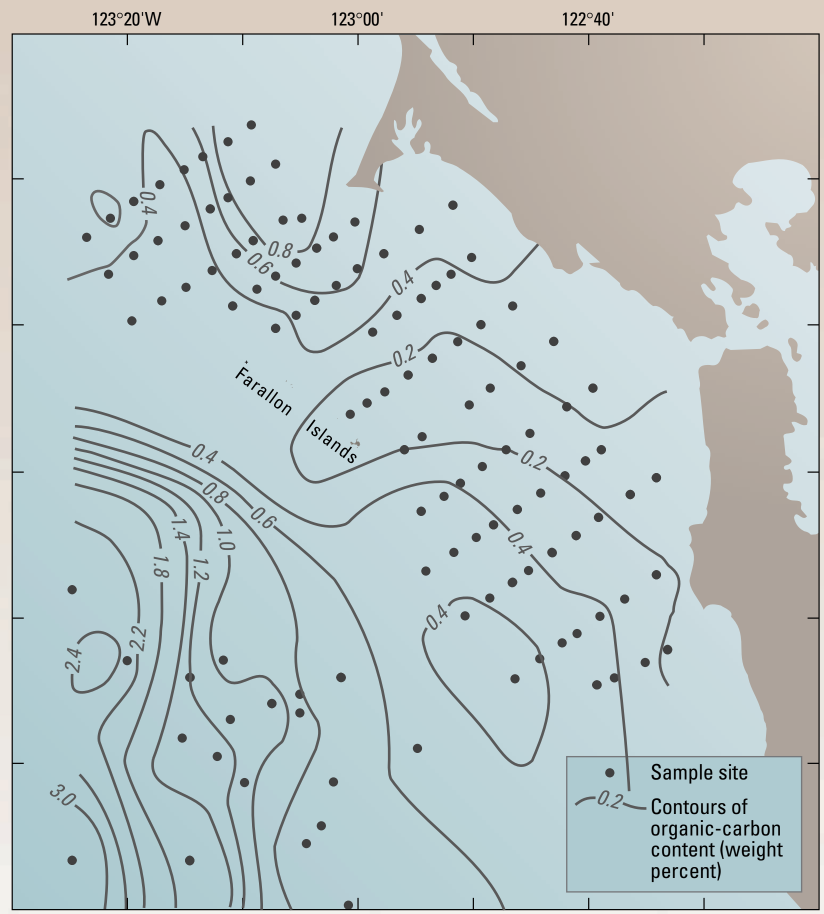
Water movement in the Gulf of the Farallones affects the distribution of sediment on the sea floor and the movement of sediment across the Continental Shelf to the deep sea (see chapter on Current Patterns over the Continental Shelf and Slope). The main oceanographic influences on circulation in the gulf include the southward-flowing California Current during the winter and the northward-flowing California Undercurrent during the summer. Strong offshore currents can also be caused by summer northwesterly winds, leading to coastal upwelling of cold water. Currents generated by tides also help account for the seaward transport of sediment in the gulf.

The results of chemical analysis of the core samples collected from the sea floor in the Gulf of the Farallones can be used as “fingerprints” to identify sources and transport patterns of sediment (see chapter on Heavy-Mineral Provinces on the Continental Shelf). The sandy sediments on the Continental Shelf between the Golden Gate and the Farallon Islands contain abundant heavy minerals that are rich in iron, magnesium, titanium, phosphorus, and many trace elements. The sediments immediately adjacent to the Farallon Islands contain low concentrations of heavy minerals and the chemical elements associated with them; instead, these sediments are rich in silica (SiO_2). Sediments deposited on the Continental Slope have higher contents of organic matter and clay and, consequently, have higher concentrations of elements associated with clay minerals, such as aluminum, lithium, potassium, and sodium. Calcium carbonate ($CaCO_3$), mainly from the shells of pelecypods (oysters, clams, and mussels), is a very minor constituent of surface sediments in the gulf.

CONTENT OF SILICA AND ORGANIC CARBON IN SEA-FLOOR SEDIMENTS



Sea-floor sediments on the Continental Shelf in the Gulf of the Farallones have high contents of silica (SiO_2), especially adjacent to the Farallon Islands, where granitic sand has been shed from the islands. The silica content of sediments is lower on the Continental Slope, because the clay minerals making up much of the sea-bottom mud there are lower in silica. The higher silica content in sediments on the slope at the south end of the map probably reflects sand moving down Pioneer Canyon.



The content of organic carbon (carbon from the remains of organisms) in sea-floor sediments from the Gulf of the Farallones is relatively high for an area of ocean adjacent to a continent, reflecting the high biologic productivity supported by the nutrient-rich seasonal upwelling of the California Current system. The finer-grained sediments on the Continental Slope in the gulf have higher contents of organic carbon than the mostly sandy sediments on the Continental Shelf.

Heavy-Mineral Provinces on the Continental Shelf

Florence L. Wong

Minerals are integral to every aspect of our lives—from esthetically pleasing gem stones to more mundane but essential components of concrete. In geology, minerals are useful in unraveling certain questions, such as where do large bodies of sediment come from (source), how do they move around (transport processes), and where do they settle (distribution). This chapter looks at these geologic issues in the Gulf of the Farallones by examining small (sand-size) mineral grains of high specific gravity (“heavy minerals”— in this study, minerals at least 2.96 times as dense as water). Small grains are apt to be transported great distances by natural processes. In contrast, large mineral grains are not transported far before coming to rest in a depositional basin and thus are not as diagnostic as smaller grains. Therefore, small particles of heavy minerals are good clues to sediment source, transport, and distribution.

The Gulf of the Farallones extends from Point Reyes on the north to Año Nuevo on the south and from the Golden Gate westward across the Continental Shelf to the Continental Slope beyond the Farallon Islands-Cordell Bank ridge. Water depths on the shelf are generally less than 330 feet. Most of the gulf lies west of the major tectonic feature known as the San Andreas Fault Zone, which separates two different types of basement rock: granitic rocks of the Salinian block on the west, and various sedimentary, volcanic, and metamorphic rocks of the Franciscan terranes to the east (see chapter on Earthquakes, Faults, and Tectonics).

The surficial sediment in the Gulf of the Farallones was initially eroded from rocks onshore and then transported and deposited in the present offshore basin. The agents of this process included faulting and folding of the Earth’s crust and changes in global climate, including glaciation. The sediment of the sea floor in the gulf (see chapter on Sediment of the Sea Floor) is composed of sand, mud, some gravel, and biologic debris, such as shells and bone fragments.

Sediment on the Continental Shelf in the Gulf of the Farallones west of San Francisco Bay was systematically sampled by the U.S. Geological Survey in 1989 to study its characteristics, distribution, and origin. Various properties of the samples were analyzed, including grain size and mineralogic and chemical composition (see chapter on Chemical Composition of Surface Sediments on the Sea Floor). The minerals present in the samples reflect two major sources in the central California region: (1) the large variety of rock types of the Franciscan terranes and (2) granitic materials shed from the Sierra Nevada and similar rocks in the central California region. The two mineralogical assemblages are distributed in different areas of the shelf; how this distribution developed is less clear.

The mineral and chemical composition of sediments from the Gulf of the Farallones define four depositional provinces—two that are composed of granitic debris and two that reflect sources in the Franciscan terranes of northern California. The granitic sediment comes from two sources. The dominant source is the Sierra Nevada. The sediment from this source was transported down the Sacramento-San Joaquin drainage and through San Francisco Bay and the Golden Gate. The lesser source is the granitic basement rocks of the Salinian block west of the San Andreas Fault system. Sediment from a Sierran source is spread over the Gulf of the Farallones to a limited extent north of the Golden Gate and to at least the shelf edge south of the Gate. A small contribution of sediment from Salinian rocks of the Farallon Islands-Cordell Bank ridge, along the west edge of the shelf, is also found on the shelf near the ridge.

Minerals derived from the Franciscan terranes characterize surface sediment on the Continental Shelf in the northern Gulf of the Farallones. These minerals represent reworked shelf deposits, erosion of dune deposits accumulated during the last low stand of sea level, and coastal erosion of Franciscan bedrock exposures.

A

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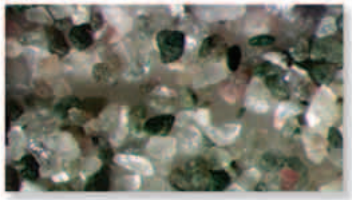

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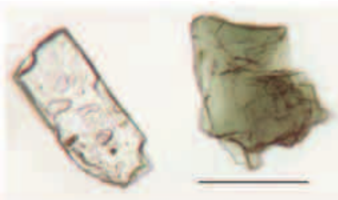

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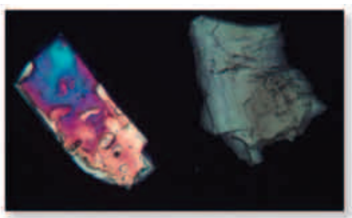
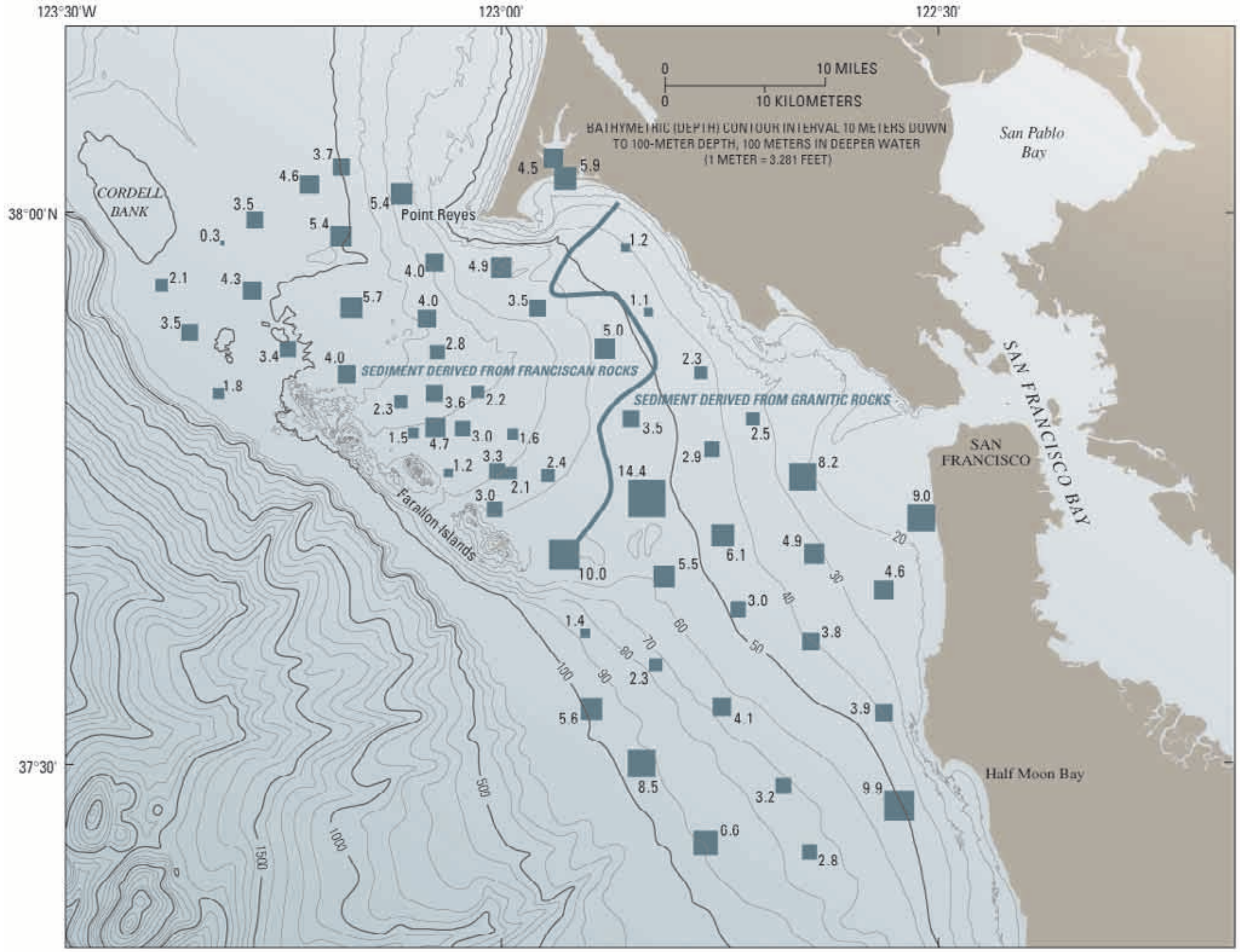


D

Photographs taken through microscopes of samples of bottom sediments collected from the Gulf of the Farallones (1 millimeter equals 0.04 inch). *A*, Sample consisting mostly of medium-grained shell material. *B*, Sample consisting of "light" (less than 2.96 times as heavy as water) mineral grains; most light-colored grains are of the minerals quartz or feldspar; dark grains are glauconite, a clay mineral. *C*, Grains of two "heavy" minerals—hypersthene (left) and hornblende (right)—mounted on a glass slide for examination under a microscope in polarized light. *D*, The same grains photographed in cross-polarized light. The characteristics of the grains under each type of illumination were used to identify the minerals.



Map of the Gulf of the Farallones, showing sites where the U.S. Geological Survey collected bottom-sediment samples for mineralogical analysis. Grains of fine and very fine sand (about 0.002 to 0.010 inch in diameter) were separated and then divided into "light" minerals (less than 2.96 times as heavy as water) and "heavy" minerals (more than 2.96 times as heavy as water). Numbers on the map show the abundance of heavy minerals as a percent of sample weight, and the sizes of the shaded boxes are proportional to this abundance. The thick blue line marks the approximate boundary between areas covered by different heavy-mineral assemblages. The mineralogy and geochemistry of sediments from the Gulf of the Farallones define two main depositional provinces—one composed of granitic debris and one that indicates a source in the Franciscan terranes of northern California. The granitic sediment comes from two sources. The dominant source of granitic sediment is the Sierra Nevada. The sediment from this source was transported down the Sacramento-San Joaquin drainage and through San Francisco Bay and the Golden Gate. The lesser source of granitic sediment is the basement rocks of the Salinian terranes west of the San Andreas Fault system, including the Farallon Islands. Minerals derived from the Franciscan terranes characterize surface sediment on the Continental Shelf in the northern Gulf of the Farallones. These minerals represent reworked Continental Shelf deposits, erosion of dune deposits accumulated during the last lowstand of sea level, and coastal erosion of Franciscan bedrock.

Biology and Ecological Niches in the Gulf of the Farallones

Year round, thousands of people are attracted to the cold waters of the Gulf of the Farallones for its whale and bird watching, beautiful coastal tide pools, and commercial and sport fishing. Few realize that the organisms that they see and catch are only a small part of a rich and complex marine ecosystem.

Scientists have found that the distribution and abundance of marine flora and fauna in the gulf are directly related to the physical and chemical conditions of its waters. Upwelling of deep nutrient-rich waters along the coast during the spring and summer months of most years feeds microscopic plankton that support a complex but fragile web of organisms, from Dungeness crabs, chinook salmon, and brown pelicans to elephant seals, great white sharks, and giant blue whales. The Cordell Bank, Gulf of the Farallones, and Monterey Bay National Marine Sanctuaries help to protect and preserve this marine abundance.

Phytoplankton

Gregg W. Langlois and Patricia Smith

Phytoplankton play a key role in the marine ecology of the Gulf of the Farallones. These microscopic, single-celled plants are found in greatest abundance in nearshore coastal areas, typically within the upper 160 feet of the water column. The name "phytoplankton" consists of two Greek words meaning "plant" (phyto) and "wanderer" (plankton). There are two major groups of phytoplankton—(1) fast-growing diatoms, which have no means to propel themselves through the water, and (2) flagellates and dinoflagellates, which can migrate vertically in the water column in response to light. Each group exhibits a tremendous variety of cell shapes, many with intricate designs and ornamentations.

All species of phytoplankton are at the mercy of oceanic currents for transport to areas that are suitable for their survival and growth. Thus, physical processes can play a significant role in determining the distribution of phytoplankton species. Rapid cell division and population growth in phytoplankton can produce millions of cells per liter of seawater, resulting in visible blooms or "red tides."

With the potential for such high productivity, it is not surprising that phytoplankton are the first link in nearly all marine food chains. Without phytoplankton, the diversity and abundance of marine life in the Gulf of the Farallones would be impossible. Phytoplankton provide food for a tremendous variety of organisms, including zooplankton (microscopic animals), bivalve molluscan shellfish (mussels, oysters, scallops, and clams), and small fish (such as anchovies and sardines). These animals, in turn, provide food for other animals, including crabs, starfish, fish, marine birds, marine mammals, and humans.

The coastal area of the Gulf of the Farallones undergoes periods of strong upwelling during the spring and summer months (see chapter on Current Patterns over the Continental Shelf and Slope). In addition to delivering colder, nutrient-rich waters from depth, coastal upwelling concentrates phytoplankton near the surface. This concentration of cells in sunlit surface waters, together with increased nutrients, may provide a competitive edge for the faster growing diatoms during upwelling events. Conversely, a stratified water mass consisting of a layer of warmer surface water and a deeper layer of colder, nutrient-rich water can form following upwelling. These conditions favor the development of dinoflagellate blooms, such as toxic "red tides," because these types of phytoplankton can actively swim to the surface to photosynthesize during the day and migrate to deeper areas at night to absorb nutrients. Such conditions can also be associated with downwelling, in which warmer offshore waters move shoreward, pushing coastal surface waters down and along the sea floor to deeper areas. Research in other parts of the world has shown that dinoflagellates are commonly associated with such nearshore downwelling.

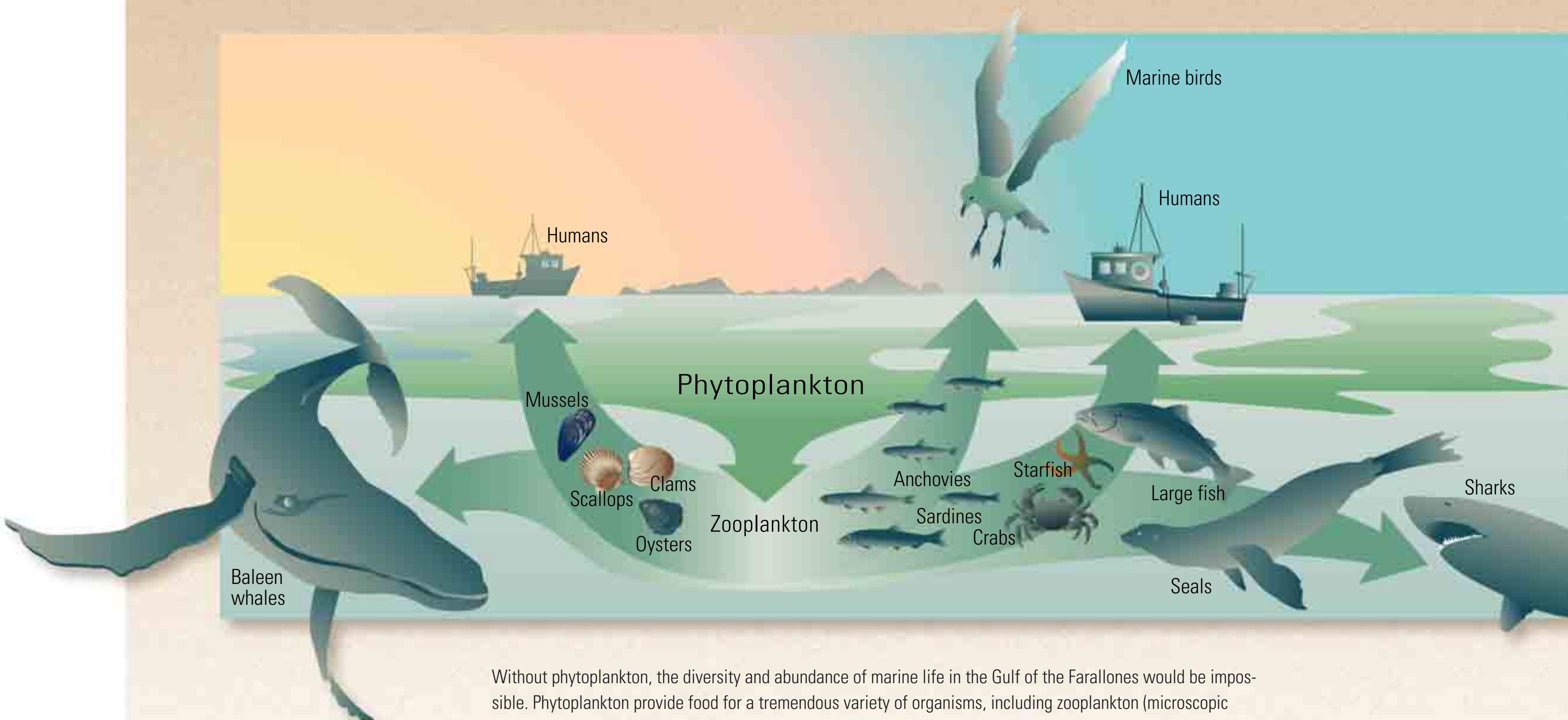
Of the more than 5,000 known species of marine phytoplankton, approximately 40 species worldwide have been linked with production of toxins. These marine biotoxins can have subtle to lethal effects on various forms of marine life. Human consumers of certain seafood items (especially clams, oysters, and mussels) are also at risk. It remains difficult to avoid the harmful effects associated with blooms of these toxic species because phytoplankton ecology is not fully understood.

Within the Gulf of the Farallones, red tides are a common natural phenomenon, usually occurring from August through October, when a relaxation of coastal upwelling results in a warmer, more stable water mass nearshore that appears to favor dinoflagellate populations. The commonly used term "red tide" is misleading, because phytoplankton blooms frequently are other colors, such as brown, green, and yellow, and are in any case not a tidal phenomenon.

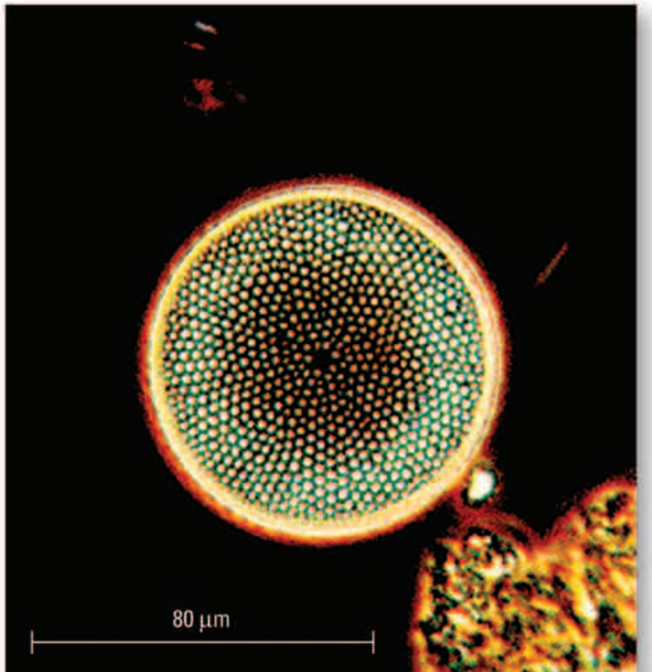
Nearly all phytoplankton blooms along the California coast and within the Gulf of the Farallones involve nontoxigenic species. Conversely, most incidents of paralytic shellfish poisoning (PSP) in humans caused by eating shellfish caught in California waters have occurred in the absence of visible blooms of toxin-producing phytoplankton. Because the coastal area encompassed by the marine sanctuary has been the focal point for PSP toxicity in California, and because of the continued increase in commercial bivalve shellfish aquaculture within this area, the California Department of Health Services has intensified its biotoxin-monitoring efforts in the area.

The key to understanding the combination of physical, chemical, and biological factors that result in blooms of the phytoplankton species that produce PSP toxins may lie within the Gulf of the Farallones. Such understanding would greatly assist in the protection of public health.

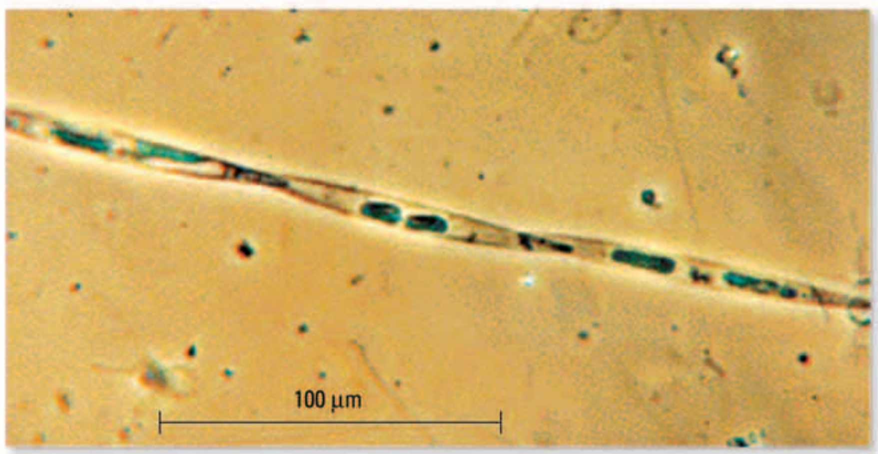
SIMPLIFIED DIAGRAM OF THE FOOD WEB IN THE GULF OF THE FARALLONES

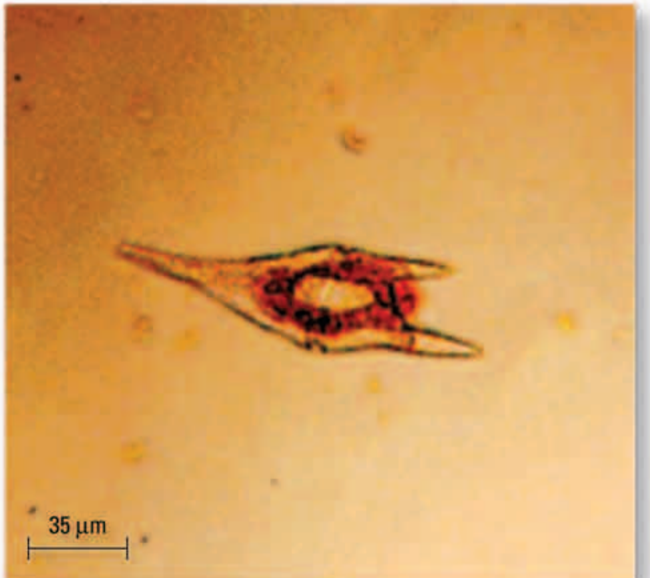


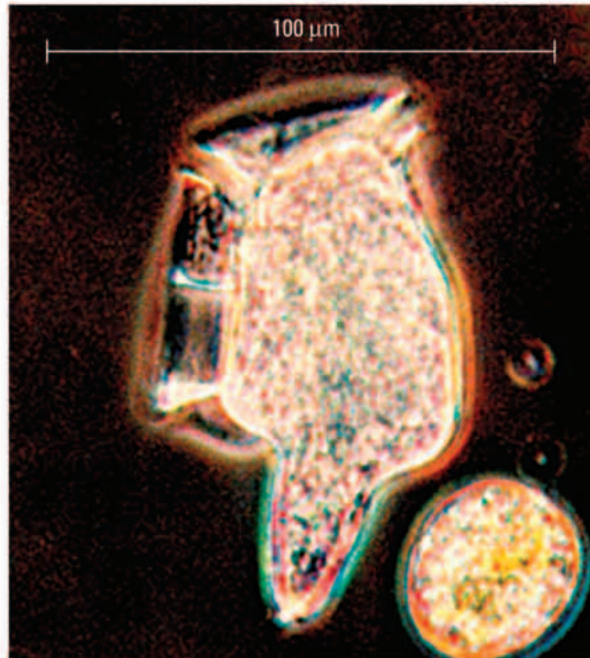
Without phytoplankton, the diversity and abundance of marine life in the Gulf of the Farallones would be impossible. Phytoplankton provide food for a tremendous variety of organisms, including zooplankton (microscopic animals), bivalve molluscan shellfish (mussels, oysters, scallops, and clams), and small fish (such as anchovies and sardines). These animals, in turn, provide food for other animals, including crabs, starfish, fish, marine birds, marine mammals, and humans.



Photographs of diatoms taken through a microscope. *Coscinodiscus* (left) and the chain of *Chaetoceros* (right) are centric diatoms. *Pseudonitzschia* (bottom) produces domoic acid, which can contaminate shellfish and cause "amnesic shellfish poisoning" in humans who eat the shellfish. Symptoms include abdominal cramps, vomiting, disorientation, memory loss, and even death. Scale bars are in micrometers (µm); 1 micrometer is one-millionth of a meter or about 1/25,000 of an inch.







Photographs taken through a microscope of the armored dinoflagellates *Ceratium* (left), *Dinophysis* (right) and *Alexandrium catenella* (bottom). Some species of Dinophysis produce toxins that can cause severe diarrhea (diarrhetic shellfish poisoning) in humans who eat contaminated shellfish. *Alexandrium catenella* produces toxins that can cause "paralytic shellfish poisoning" in humans who eat contaminated shellfish. Symptoms include nausea, vomiting, diarrhea, abdominal pain, and tingling or burning lips, gums, tongue, face, neck, arms, legs, and toes and later shortness of breath, dry mouth, a choking feeling, confused or slurred speech, lack of coordination, and even death. Scale bars are in micrometers (μm); 1 micrometer is one-millionth of a meter or about 1/25,000 of an inch.

Krill

Dan Howard

Just as there are growing seasons on land, so there are growing seasons in the ocean as well. In the Gulf of the Farallones, the growing season begins in early spring, when the first phytoplankton blooms (large increase of microscopic plants) of the year fuel growth at higher levels of the marine food web. In California, as in many parts of the world, euphausiid shrimp, commonly called "krill," are one of the beneficiaries of this early-season production and are a critical link in the marine food web. Feeding on phytoplankton (microscopic plants) and small zooplankton (animals), krill populations expand and by being eaten by other marine animals, transfer energy from the lowest (primary producer) level into the upper levels of the marine food web. They are often referred to as "keystone" species because they play such an important role in the functioning of many marine ecosystems.

Krill hatch from free-floating eggs and pass through larval and juvenile stages before maturing into adults. This development process involves a series of molts (casting off the rigid outside skeleton that restricts growth), during which segments and appendages are gradually added. While the new outside skeleton is still soft, the individual can increase its size. Adult euphausiids have the unique ability to actually shrink in size after a molt if food resources are scarce. Because krill can increase and decrease their size, it can be difficult to determine their age or the age distribution of a population of animals from their sizes.

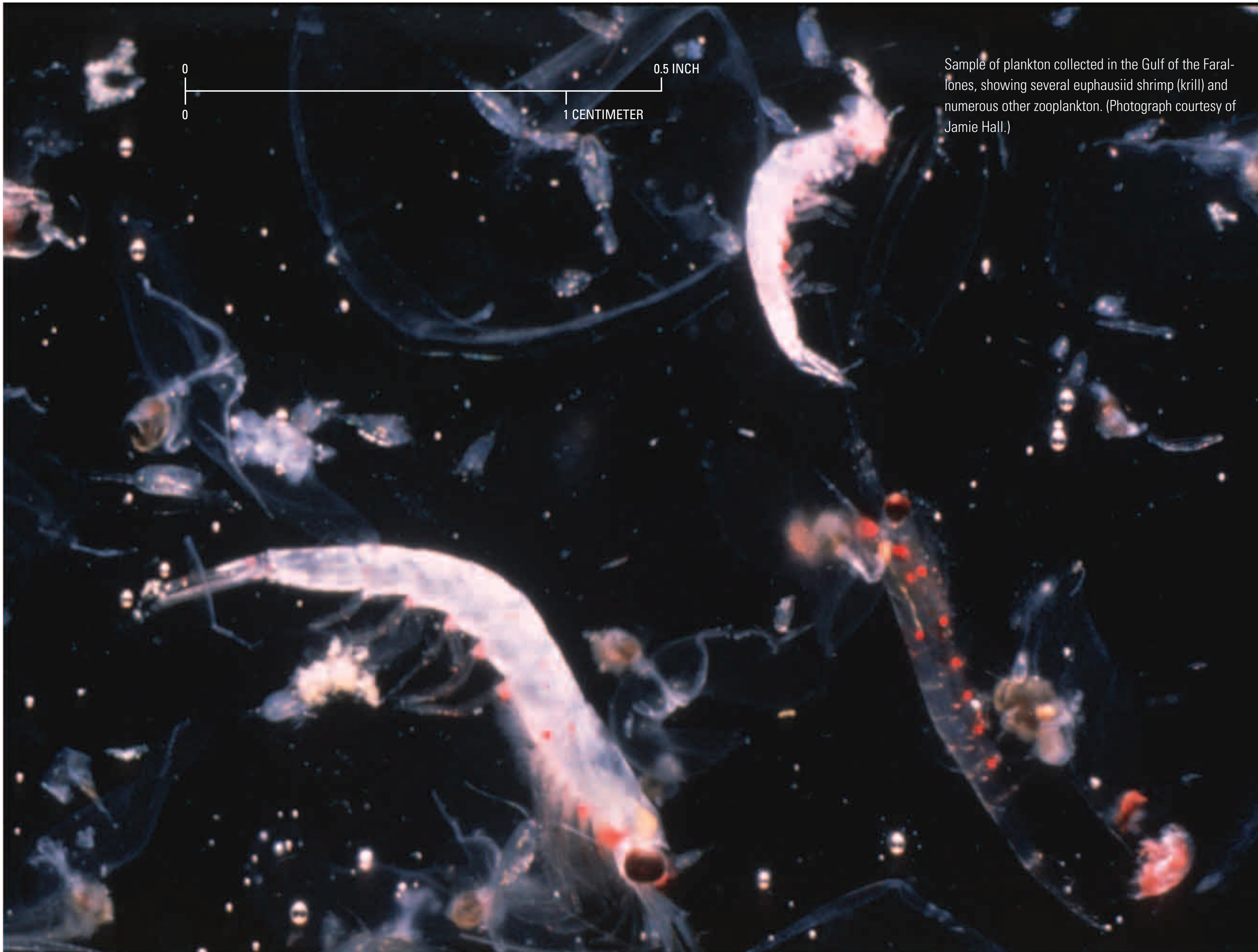
Krill have legs called "swimmerets" that have evolved to look like small feathers and function like fins, giving them great mobility and agility for life in the water column. They feed while swimming, using their modified front legs to form a food basket that strains food from the water while they swim.

Krill are typically very gregarious, which means they are often found in large, concentrated groups, including dense swarms with as many as 100,000 krill per cubic yard of ocean water. This swarming behavior makes krill especially vulnerable to predators. Swarming activity starts sometime in spring and continues through the fall. These aggregations can commonly be located in the Gulf of the Farallones by finding flocks of diving seabirds or clusters of birds picking at the surface. Fishermen use these feeding flocks to help them locate salmon feeding on the undersides of the krill swarms. Lunging humpback whales that break the surface of the water are also a good indication that krill are swarming at or near the surface. Surface swarms provide ideal feeding conditions for these large filter feeders. With its huge mouth, a gaping humpback (and other baleen whales) is capable of engulfing a large volume of krill in a single gulp. These dense aggregations of prey provide the several tons of food per day required by these whales during the summer feeding season.

In the Gulf of the Farallones, the two most abundant species of krill are *Thysanoessa spinifera* and *Euphausia pacifica*. They are typically about 3/4 inch long and live for about 2 years. *Thysanoessa spinifera* is found mostly in shallower water over the continental shelf, whereas *Euphausia pacifica* is usually found in deeper water towards the margin of the shelf and beyond. Between them they are a major food source for salmon (krill pigments give salmon flesh its characteristic pink to orange color), rockfish, seabirds, and whales. Krill are the main reason hungry humpback and blue whales visit the gulf in the summer—to fatten up for the rigors of the coming year. Both of these krill species demonstrate special adaptations that enable them to succeed despite constant predation pressure. From spring through fall, *Thysanoessa spinifera* swarm at the surface during the day. Though it is unclear what is driving this behavior, the benefits must outweigh the cost, which is increased predation.

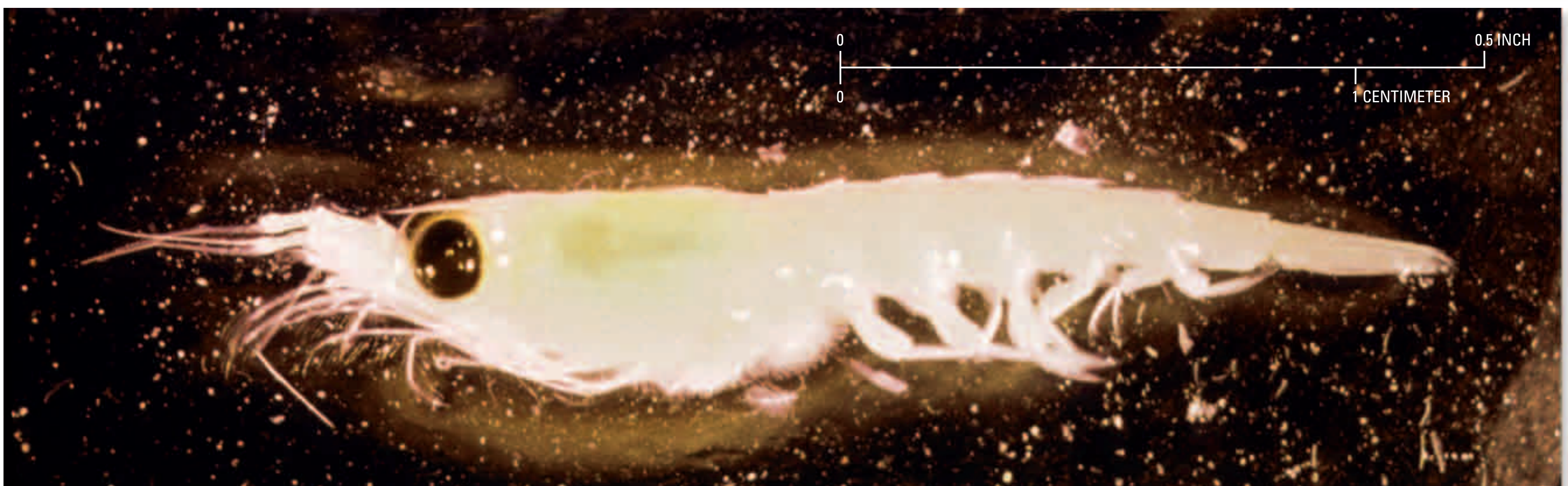
Euphausia pacifica, controlled by light intensity, migrate out of ocean depths and into surface waters each night. As dawn approaches, they return to deep water for the day. This migration pattern is shared with many other organisms in the ocean, and during the day krill form part of the so-called "deep scattering layer" that fishermen see on their depth sounders. The timing of this daily event in response to changing light intensities provides *Euphausia pacifica* with several advantages. By moving upward at night, *Euphausia pacifica* minimizes exposure to daytime predators, while grazing in surface waters where food is abundant. They also realize an energy gain by returning during the day to the colder deep water, where metabolism slows. Releasing eggs in warmer surface waters speeds development times, thus reducing the time exposed to predators; it also ensures that hatching larvae are in productive waters when they start feeding, increasing their chances of survival.

Krill are a critical link in the Gulf of the Farallones marine food web and in marine food webs around the world. They directly or indirectly support the survival and well-being of many animals living in different oceans. Knowing the key position filled by krill in many marine ecosystems, we need to ensure that their populations remain healthy—for the well-being of all.



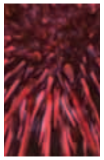
Sample of plankton collected in the Gulf of the Faral-lones, showing several euphausiid shrimp (krill) and numerous other zooplankton. (Photograph courtesy of Jamie Hall.)

The two species of krill common in the Gulf of the Farallones are *Euphausia pacifica* (right, photograph courtesy of Steven Haddock) and *Thysanoessa spinifera* (below, photograph from Gulf of the Farallones National Marine Sanctuary.)



Seabirds feeding on swarming krill in the Gulf of the Farallones. (Photograph from Gulf of the Farallones National Marine Sanctuary.)

Lunging humpback whales feeding on surface swarms of krill are a common sight in the Gulf of the Farallones in the summer. (Photograph courtesy of Thomas R. Kieckhefer, Pacific Cetacean Group.)



Free-Floating Larvae of Crabs, Sea Urchins, and Rockfishes

Stephen R. Wing

Free-floating larvae of bottom-dwelling marine organisms play an important role in the ecology of the Gulf of the Farallones and are a major food source for many species, including salmon and seabirds. Free-floating larvae are also the primary means by which several important species are dispersed along the northern California coast. Most commercially harvested invertebrates (for example, sea urchins and crabs) and some fish populations are made up of a network of adult subpopulations spread along the coastline, connected almost solely by larval dispersal.

In the Gulf of the Farallones many commercially important coastal species, such as Dungeness crab (*Cancer magister*), red sea urchin (*Strongylocentrotus franciscanus*), and rockfish (*Sebastes* spp.), have swimming larval forms that drift as plankton during the spring. These larvae are subject to the strong offshore and southward flow present in the California Current system during the spring upwelling season (see chapter on Current Patterns Over the Continental Shelf and Slope). Understanding how larvae of these species maintain themselves at latitude and are transported inshore into suitable juvenile habitat is important in ensuring the long-term viability of these fisheries.

In 1992, a study was begun to understand how coastal oceanographic processes influence the distribution of crab and sea-urchin larvae around Bodega Head, a coastal headland at the northern margin of the gulf. This required the cooperative efforts of many organizations, including Gulf of the Farallones and Cordell Bank National Marine Sanctuaries, U.S. National Marine Fisheries Service, Scripps Institution of Oceanography, Point Reyes Bird Observatory, Oregon State University, California Department of Fish and Game, and Pacific Fisheries Environmental Group.

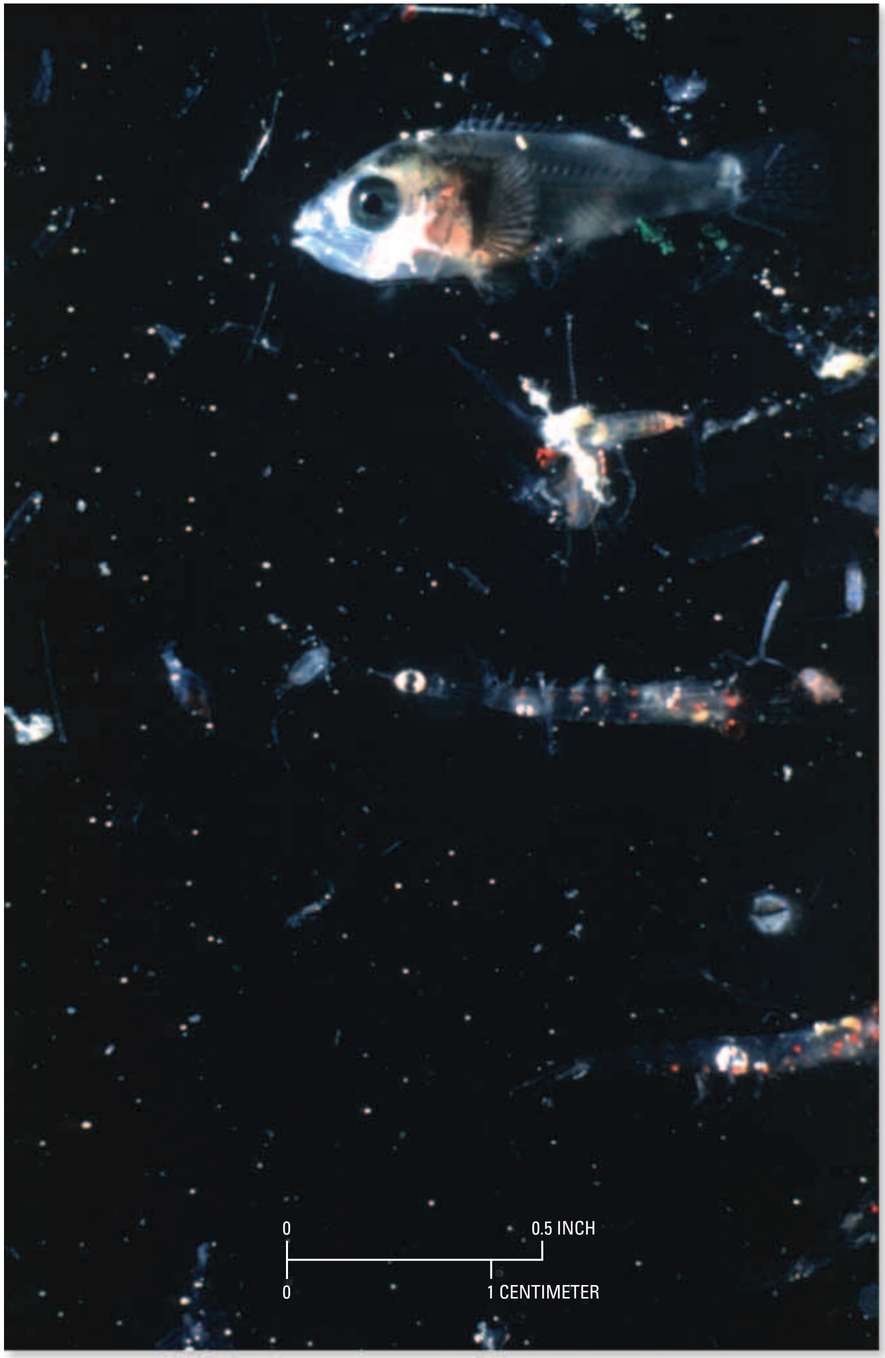
Sampling extended over several years and was done both from aboard ships and at shore stations. Results indicate that during periods of upwelling, larvae accumulate in the warm water that collects between the Farallon Islands and Point Reyes in the northern gulf. Larval accumulation was also observed in the upwelling shadows, or eddies, that form behind other capes and headlands when the wind is blowing from the north and surface water is moving in a southerly offshore direction. When the northerly winds that cause upwelling relax, this larvae-rich water moves north in buoyancy-driven currents that remain coastally trapped. During this time many larvae that have been retained in the gulf are transported to the north, and some settle out of the water column and onto the sea floor for their next life stage.

In both 1994 and 1995, an upwelling jet seaward of Point Reyes and an upwelling shadow downwind (south) of the point were evident from the currents, temperature, and salinity of the surface waters. Information was collected at the boundaries between four distinct water masses: (1) newly upwelled water, (2) oceanic water from offshore, (3) San Francisco Bay outflow, and (4) a mixture of these water types that was called "gulf water." The different water masses contained different types of larvae. In general, all stages of larval development for crabs of several species could be found within, but not outside, the gulf water. This water mass is found in the wind shadow south of Point Reyes. In contrast, rockfish larvae were found in high concentrations offshore in oceanic water and at the boundary between newly upwelled water and gulf water. The Gulf of the Farallones provides a pathway along which distinct masses of water containing both crab and rockfish larvae are likely to be transported to suitable juvenile habitats within the gulf and to the north.

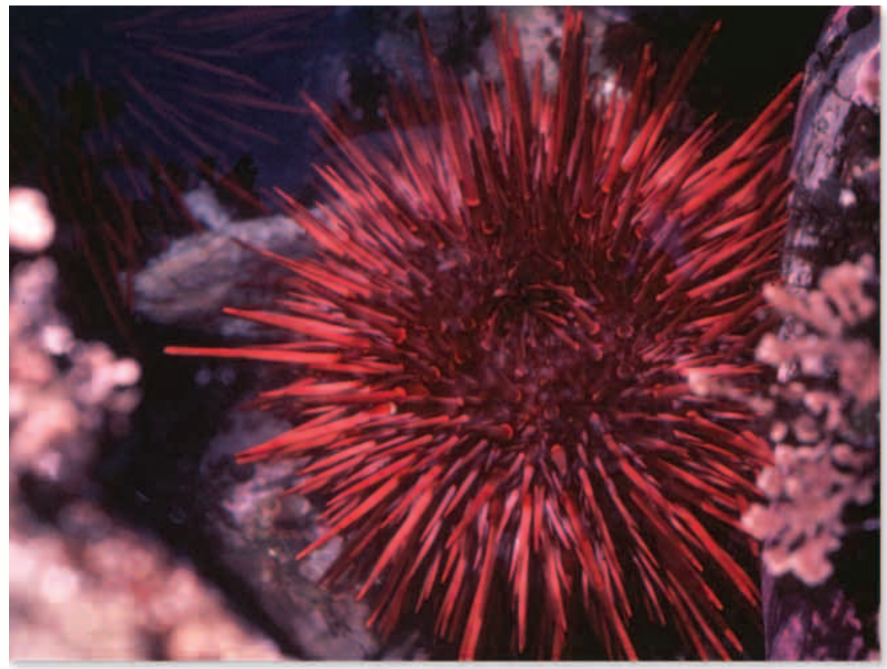
Larval settlement becomes more episodic and less frequent with increasing northward movement away from the area of larval retention/accumulation south of Point Reyes. Nearly twice as many crab larvae settle at Point Reyes and to the south, where warmer gulf water is constantly present, than to the north, where settlement occurs only when the northerly winds that cause upwelling subside and relaxation currents move northward. Sea urchin larvae also settle during specific oceanic conditions, but less predictably than crabs.

Consistent larval dispersal from any subpopulation of adult animals may be limited to the length of an embayment. For example, two such embayments on the northern California coast are from Point Reyes to Point Arena and from Point Arena to Cape Mendocino. Because strong seaward currents form at each end of these embayments during upwelling, larvae caught in these currents would be swept out to sea and have no chance of developing and becoming a part of the adult population.

The data collected in this study on the distribution of free-floating larvae in the Gulf of the Farallones provide critical information on the lifecycles of commercially important bottom-dwelling species. Because these larvae are a food source for many marine species, this information is crucial to the effective management and conservation of coastal marine ecosystems in the gulf.



Larval crab from the Gulf of the Farallones, greatly magnified.



◄ Sample of plankton collected in the Gulf of the Farallones, showing a larval rockfish, euphausiid shrimp (krill), and other zooplankton. (Photograph from Gulf of the Farallones National Marine Sanctuary.)

▲ Red sea urchins, harvested for sushi, are one of many commercially important coastal species in the Gulf of the Farallones with swimming larval forms that drift as plankton during the spring. (Photograph from Gulf of the Farallones National Marine Sanctuary.)

Salmon

Peter Adams

Two species of salmon—chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*)—are commonly found in the Gulf of the Farallones. Chinook salmon fishing is the activity that brings the most people out on the waters of the gulf. In 1995, the chinook fishery in the gulf was valued at more than $24 million.

Chinook (or king) salmon are key predators in the gulf, and their distribution and occurrence are related to their seasonal diet cycle. Most chinook salmon found in the gulf are 3-year-old fish returning from the open ocean that are preparing to enter the Sacramento River system, where they will spawn and then die. After the eggs hatch the following spring, the juvenile salmon will grow for 7 months in freshwater. They then migrate to the ocean, where they will live for 2 years before returning to the gulf. Coho (or silver) salmon along the California coast are listed as a threatened species under the Endangered Species Act, and their capture has been prohibited since 1993. Native-run (versus hatchery) chinook salmon are also a candidate for a threatened-species listing.

Chinook salmon returning from the open ocean move into the Gulf of the Farallones in February and March, when they are found off the Golden Gate from Bolinas Point in the north to Point San Pedro in the south. While in this area they feed almost equally on Pacific herring and anchovies. The herring have just migrated back to their feeding grounds outside of the Golden Gate from San Francisco Bay, where they spawned from November through February, and anchovies are gathering in nearshore waters before moving into the bay beginning in April.

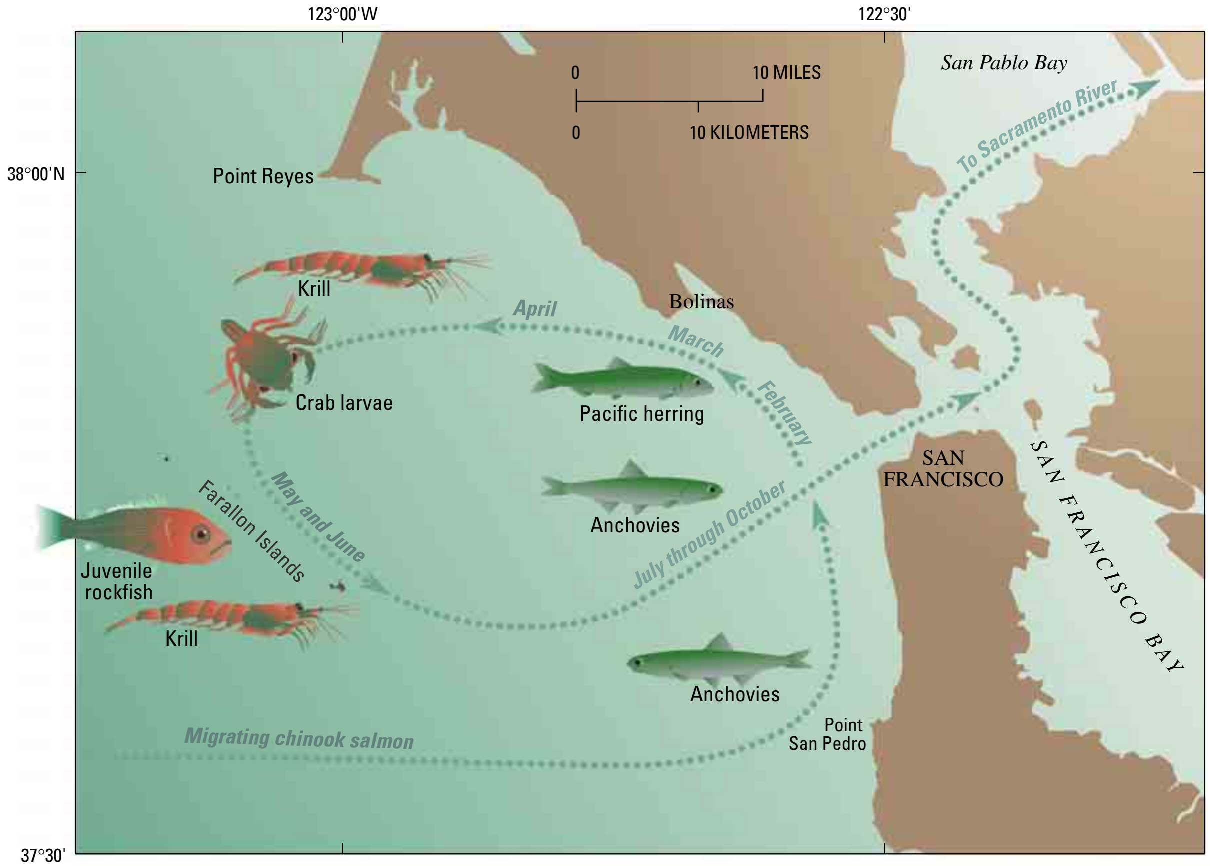
In April, chinook salmon are found from north of the Golden Gate to Point Reyes and offshore to the Farallon Islands. There they feed on invertebrates, largely the euphausiid shrimp (krill) *Thysanoessa spinifera*. Krill are taken as prey from surface and subsurface swarms that occur over a wide area of the gulf during April and May. The pink to orange color of salmon flesh during this period is due to a carotenoid pigment in the exoskeleton of the krill (for more information, see chapter on Krill). This flesh color has become so popular that now there are fisheries for krill, which are freeze-dried and fed to pen-reared salmon as a finishing product to produce this color.

For a brief 2- or 3-week period in April, the chinook's diet is dominated by the megalopa larvae of the Dungeness crab (*Cancer magister*) (see chapter on Free-Floating Larvae of Crabs, Sea Urchins, and Rockfishes). These larvae are the last pelagic (free-floating or swimming) stage before the crabs sink to the bottom and take on their adult shape. More than 7,000 Dungeness megalopa have been found in a single chinook-salmon stomach.

In May and June, chinook start feeding on krill and juvenile rockfish offshore near the Farallon Islands. These rockfish are late pelagic-stage fish that as adults will migrate to bottom habitats. In years when juvenile rockfish are abundant, they are the preferred prey and dominate the chinook diet during these months, whereas in low-abundance years, chinook salmon feed mainly on krill.

Sometime between mid-June and mid-July, the chinook salmon abruptly move from near the Farallon Islands to directly in front of the Golden Gate, the so-called "middle grounds." Here, chinook salmon feed exclusively on anchovies, which had moved into San Francisco Bay in May and June to begin spawning in the warmer water. After June, when the water in the gulf warms up because of the absence of cold upwelled water, anchovies move out of the bay and into the gulf where they continue spawning into October. Chinook Salmon remain in front of the Golden Gate until October, but in lower and lower concentrations as they move up the Sacramento River system to spawn. The following February, the next year's 3-year-old chinook salmon begin to enter into the gulf, and the cycle begins again.

During strong El Niño years, the normal sequences of chinook salmon prey do not develop because the large increase in ocean temperature disrupts the prey's normal behavior. As a result, the aggregations of salmon that feed on these prey do not form, and chinook salmon of a given length weigh much less than normal. California's commercial salmon catch also drops severely, and the recreational catch is far below average.



As shown in this simplified diagram, 3-year-old chinook salmon returning from the open ocean move into the Gulf of the Farallones in February and March and feed on Pacific herring and anchovies off the Golden Gate from Bolinas Point in the north to Point San Pedro in the south. In April, they feed on invertebrates, largely the euphausiid shrimp (krill) *Thysanoessa spinifera*. For a brief 2- or 3-week period in April, the chinook salmon's diet is dominated by larvae of the Dungeness crab (*Cancer magister*). In May and June, chinook salmon start feeding on krill and juvenile rockfish near the Farallon Islands. Sometime between mid-June and mid-July, chinook salmon abruptly move from near the Farallon Islands to directly in front of the Golden Gate, the so-called "middle grounds." Here, chinook salmon feed exclusively on anchovies. Chinook salmon remain in front of the Golden Gate until October, but in lower and lower concentrations as they move up the Sacramento River system to spawn. The following February, the next year's 3-year-old chinook salmon begin to enter into the gulf, and the cycle begins again.

A chinook salmon (*Oncorhynchus tshawytcha*). Most chinook salmon found in the Gulf of the Farallones are 3-year-old fish that are returning from the open ocean and preparing to enter the Sacramento River system, where they will spawn and then die. (Photograph from U.S. Food and Drug Administration.)

Chinook salmon fishing is the activity that brings the most people out on the waters of the Gulf of the Farallones. This large salmon was caught in the gulf. (Photograph from National Marine Fisheries Service.)

Biology and Ecological Niches in the Gulf of the Farallones

Seabirds

Peter Pyle

Among the animals of the Gulf of the Farallones, seabirds are the easiest to study. Residing above the water surface (for the most part), seabirds are readily observed by land- or boat-bound humans. They generally nest in huge colonies on islands, facilitating research on their breeding-population sizes and nesting requirements. For these reasons, seabirds are commonly used as barometers of the health of marine ecosystems. This observation is true in the gulf, where a widely varying marine environment supplies an interesting extra dimension for study.

"Seabirds" is not a technical term but refers to individuals among a hodgepodge of different bird families that share in common their ability to make a living on the ocean. In the Gulf of the Farallones there are 11 or 12 species of breeding seabirds, including common murres, Cassin's and rhinoceros auklets, western gulls, Brant's and pelagic cormorants, storm petrels, pigeon guillemots, and tufted puffins. Another 35 species of migrant seabirds are regular visitors to the gulf but do not breed there; examples of these species include Pacific and red-throated loons, red-necked and western grebes, black-footed albatross, pink-footed, Buller's, and black-vented shearwaters, herring and glaucous-winged gulls, and black and surf scoters. About 25 additional species of nonbreeding seabirds have been recorded rarely or as vagrants in the gulf, including the manx shearwater, an Atlantic species that has recently been seen sporadically and could even begin to breed in the gulf.

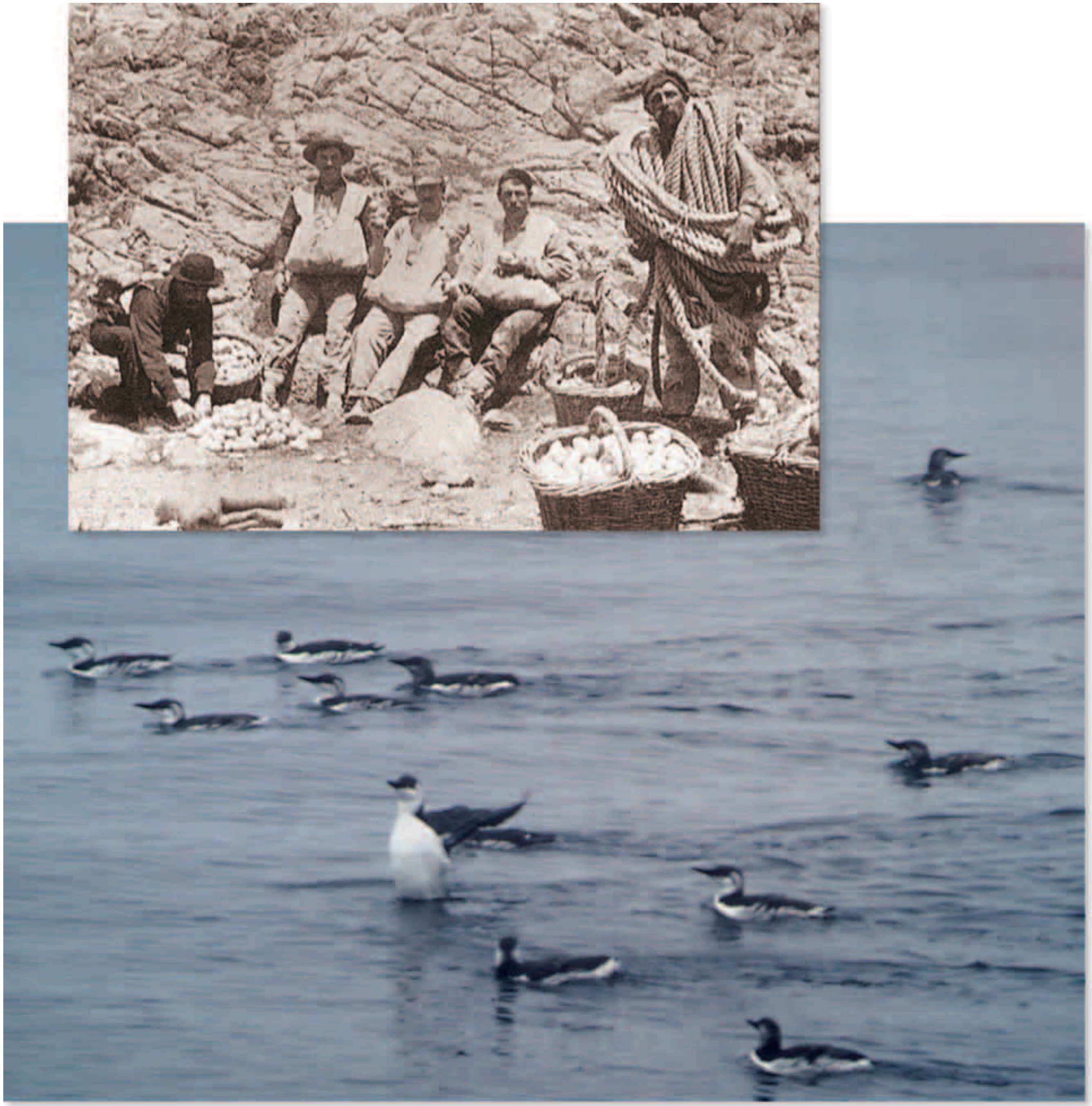
All of the breeding species in the Gulf of the Farallones nest on the Farallon Islands, which are in the center of the gulf. Since 1968, biologists from the Point Reyes Bird Observatory have monitored the size and productivity of these populations. Only through such long-term research can a full understanding of the population dynamics of these species and of their relation to the marine environment be achieved. Some of these species also nest on cliffs and small islets along the Marin County coast, north of the Golden Gate.

The common murre typifies breeding seabirds in the Gulf of the Farallones. Before the 1850's, an estimated 400,000 to 600,000 murres bred on Southeast Farallon Island, but this population was decimated by egg collecting in the wake of the California Gold Rush, before chickens had arrived in sufficient numbers to provide eggs for the burgeoning San Francisco populace. Other threats, such as oilspills, human disturbance on the islands, and the depletion of Pacific sardine stocks, reduced populations further until they reached a low of about 6,000 birds during the 1950's. Southeast Farallon Island became a National Wildlife Refuge in 1969, and through protection and increased environmental awareness, populations in the Gulf of the Farallones gradually climbed to about 100,000 individuals by the year 2000.

Common murres, along with the other seabirds breeding at the Farallones, have "good years" in which 90 percent or more of the pairs successfully fledge a chick, and "bad years" in which failure rates reach 50 percent or more. These good and bad years generally reflect the strength of the California Current, the intensity of coastal upwelling, the presence and absence of "El Niño" events (see chapter on Current Patterns Over the Continental Shelf and Slope), and the effects that these processes have on juvenile rockfish, anchovies, sardines, and other food resources.

Because of the high levels of marine productivity found in the Gulf of the Farallones, many species that nest far away also come to the region during their non-breeding seasons. The most common of these species is the sooty shearwater, which visit the Gulf of the Farallones in late summer by the hundreds of thousands, if not a million or more at a time. Every autumn there is also a great northward dispersal of organisms into the Gulf of the Farallones from the south, following the northward migration of the northern anchovy. Among the birds that follow this migration are brown pelicans, Heermann's gulls, and elegant terns. Many species of loons, grebes, ducks, gulls, and alcids (a family of diving seabirds having a stocky body, short tail and wings, and webbed feet—they include the horned puffin, the ancient murrelet, Xantu's murrelet, and the threatened marbled murrelet) take up winter residence in the Gulf of the Farallones, escaping the harsher winters of their Alaskan breeding grounds. Finally, a few species of seabirds breed to the north and winter primarily or entirely to the south of the gulf. These long-distance migrants, including phalaropes, jaegers, and Sabine's gull, can be seen passing through the Gulf of the Farallones from July to October and in April and May.

Current threats to seabird populations in the Gulf of the Farallones region include effects of contaminants from San Francisco Bay, overfishing, low-level or "chronic" oil pollution, and mortality associated with gill-netting in Monterey Bay. Declines in some seabird populations in the gulf are occurring because of these and other effects. Data on the reproductive success and survival of these seabirds, integrated with knowledge of food resources and the marine environment, can be used to assess the status and health of the Gulf of the Farallones marine ecosystem.



The common murre typifies breeding seabirds in the Gulf of the Farallones. Before the 1850's, an estimated 400,000 to 600,000 murres bred on Southeast Farallon Island, but this population was decimated by egg collecting in the wake of the California Gold Rush (see inset, courtesy of the California State Library), before chickens had been brought in sufficient numbers to provide fresh eggs for the burgeoning San Francisco populace.

▲ A South Polar skua, the avian "king of the sea" with a 4-foot wingspan, in search of victims in the Gulf of the Farallones. Breeding deep in the Southern Hemisphere, skuas disperse over the oceans during the nonbreeding seasons (summer and fall in the Northern Hemisphere), as far north as the Gulf of Alaska. Skuas are piratic and forcibly extract food from their victims—shearwaters, petrels, gulls, and even albatrosses. They are solitary marauders, nowhere common, but in the gulf they are always a menace to visiting seabirds.

A tufted puffin eating a small fish. Only 50 or 60 of these birds breed on the Farallon Islands each year, in deep rocky crevices within the cliffs. Where these striking birds go in the winter is unknown, evidently somewhere far out at sea. Populations of tufted puffins numbered in the thousands during the 1800's; recent declines are attributed to a degradation in the marine environment and, possibly, to the disappearance of Pacific sardines in the 1940's. (Photograph from Gulf of the Farallones National Marine Sanctuary.) ►

Western gulls (chick shown below) nesting on Southeast Farallon Island. Populations of western gulls in the Gulf of the Farallones since 1950 have benefited from feeding at land-based dumpsites and fish-processing plants, expanding from about 6,000 breeding birds historically to more than 25,000 birds during the early 1990's. (Photographs from Gulf of the Farallones National Marine Sanctuary.)

Biology and Ecological Niches in the Gulf of the Farallones

Marine Mammals

Jan Roletto

Many people are attracted to the Gulf of the Farallones by the variety and abundance of marine mammals that can be seen there. In the gulf, they reign as both apex predators and high-profile or “heroic” species. Some marine mammals migrate through the gulf, whereas others come there to “haul out” on land, rest, and (or) rear their young. They are attracted to the gulf because of the high biological productivity of its waters and the variety of prey species that are distributed and retained there by oceanic circulatory patterns and intense upwelling of nutrient-rich water.

The gulf attracts at least 33 species of marine mammals. Of the 11 species that dominate the coastal and pelagic (open ocean) zones, the humpback whale and blue whale are Federally listed as endangered species and the Steller sea lion is listed as a threatened species. The other dominant species are the gray whale, Pacific white-sided dolphin, harbor porpoise, Dall’s porpoise, California sea lion, northern fur seal, northern elephant seal, and harbor seal.

From the shore, the gray whale is the most commonly seen of the cetaceans (whales, dolphins, and porpoises) in the gulf. Gray whales annually migrate from their feeding grounds in the Arctic Ocean and Bering Sea to the warm lagoons of Baja California (Mexico), where they give birth to their young. They can be seen migrating southward through the gulf beginning in November, and peak sightings are during January and March. A few juveniles may be seen year round. Gray whales are “baleen” whales—instead of teeth, they have numerous long overlapping strips of elastic fingernail-like material (baleen) hanging from their upper jaws that they use to filter out food. Gray whales feed primarily on the shallow bottom (less than about 400 feet deep), where they swim on their sides while shoveling up mouthfuls of mud and water to strain out small crustaceans, such as amphipods, and other animals living in the sediment. They also feed in the water column on euphausiid shrimp (krill) and a few fish species, such as herring.

Humpback whales are the most acrobatic of the baleen whales seen in the gulf. They use the gulf and Cordell Bank to the north as feeding grounds during the summer and fall months. Their prey consist primarily of the krill species *Thysanoessa spinifera* and *Euphausia pacifica*, and they also feed on schooling fish, such as herring, juvenile rockfish, and anchovy.

Blue whales migrate to the Gulf of the Farallones during the late summer and are found there throughout the fall. As adults, these giant whales generally weigh more than 100 tons and may be the largest animals that ever lived on Earth, possibly exceeded only by the dinosaur Ultrasaurus. These baleen whales feed primarily on krill and, infrequently, red pelagic crabs. Red pelagic crabs are found in the gulf only during warmer-water conditions, such as occur when El Niño events affect the gulf (see chapter on Current Patterns Over the Continental Shelf and Slope).

The most familiar of the pinnipeds (seals and sea lions) in the gulf is the California sea lion. During its nonbreeding season from August through May, males, juveniles, and some females of this species are abundant in the gulf. During that period, 10 to 40 percent of the total local population are females. The sea lions are seen locally on docks, on nearshore rocks, and in large numbers on the Farallon and Año Nuevo Islands, along the Point Reyes headlands, and at Bodega Rock. They feed on anchovy, herring, hake, mackerel, crabs, and squid. In times of low productivity, they have been known to feed on red pelagic crabs, sharks, eels, birds, and algae.

Also common in the Gulf of the Farallones is the northern elephant seal, one of the deepest-diving marine mammals. Adult female elephant seals can dive to depths of 4,000 feet and males to 5,700 feet. While at sea, these seals are submerged 80 to 90 percent of the time. Hunting, feeding, and sleeping all take place underwater. They come on land only to breed and molt. Their breeding season begins during December and ends in mid-March. Deep-water fish and invertebrates—squid, octopus, hagfish, ratfish, hake, and rockfish—are their primary foods.

Other marine mammals observed in the gulf include four species Federally listed as endangered—fin whale, sei whale, right whale, and sperm whale. Two other species are listed as threatened—Guadalupe fur seal and southern sea otter. Many additional species of marine mammals have been observed in the gulf. Apart from the minke whale, which is a baleen whale, these species are all members of the group known as “toothed whales.” They include the northern right-whale dolphin, short-beaked common dolphin, long-beaked common dolphin, bottlenose dolphin, striped dolphin, spotted dolphin, Risso’s dolphin, killer whale, short-finned pilot whale, pygmy sperm whale, dwarf sperm whale, Cuvier’s beaked whale, Baird’s beaked whale, Hubb’s beaked whale, and Blainville’s beaked whale.

Gray whale straining water from its mouth (photograph courtesy of Jim Cubbage). Gray whales are "baleen" whales—instead of teeth, they have numerous long overlapping strips of elastic fingernail-like material, called baleen (inset), hanging from their upper jaws that they use to filter out food (photograph from Gulf of the Farallones National Marine Sanctuary). "Whale watching" is a popular activity in the Gulf of the Farallones and helps to highlight the important ecological roles played by marine mammals.

Adult females and immature northern elephant seals at Southeast Farallon Island. Inset shows the characteristic nose of an adult male. (Photographs from Gulf of the Farallones National Marine Sanctuary.)

Humpback whale swimming underwater. (Photograph from Gulf of the Farallones National Marine Sanctuary.)

Pacific white-sided dolphin (above) and northern right-whale dolphin (below) swimming underwater. (Photograph courtesy of Ken Balcomb.)

◄ Immature California sea lions at play in the surf. (Photograph by Jan Roletto, Gulf of the Farallones National Marine Sanctuary.)

▼ Adult male and female Steller sea lions at a breeding colony. This species is Federally listed as threatened under the Endangered Species Act. (Photograph courtesy of Robert Wilson.)

▲ Harbor seals resting on shore. (Photograph from Gulf of the Farallones National Marine Sanctuary.)

Biology and Ecological Niches in the Gulf of the Farallones

White Sharks

Scot Anderson

Each fall, white sharks (*Carcharodon carcharias*) are observed around the Farallon Islands, preying on seals and sea lions (pinnipeds) (see chapter on Marine Mammals). The shark's dark back and light underbelly blend with the surrounding environment, hiding the shark from unsuspecting pinnipeds. White sharks spend a great deal of time searching for food; it may be weeks or a month between feeding opportunities.

The peak in predation, in the fall months, is related to the number of young (1- and 2-year-old) northern elephant seals arriving at the islands at this time. These immature seals are the preferred prey of the white shark at the Farallon Islands. Observations there indicate that the white sharks eat young elephant seals seven times more frequently than they eat other pinnipeds, such as California sea lions and harbor seals.

Immature elephant seals arrive at the Farallon Islands to come ashore beginning in September and continuing through November. The small pocket beaches and surge channels around the islands offer undisturbed "haul out" sites and resting areas. Unlike California sea lions, which are the most numerous pinnipeds on the islands, elephant seals cannot climb high up on the islands' rocky shores. Therefore, they are restricted to the pocket beaches and surge channels. The fall haul out of elephant seals is commonly their first visit to the islands. Many of these seals are from other colonies, such as those at the Channel Islands or Point Año Nuevo to the south, and they may be unaware of white sharks patrolling the waters around the Farallon Islands.

Studies of white sharks in the Gulf of the Farallones begun in 1987 have revealed the remarkable way in which these predators are able to locate and catch pinnipeds. Using photographs of dorsal and tail fins, and underwater videotapes of entire sharks, it has been possible to identify individual white sharks and follow their movements in the gulf over many years. Several of the larger sharks have been seen in the same areas for more than 5 years. When individual sharks are identified, they are always seen in the same area. However, some of the sharks are regular visitors, whereas others are only intermittently seen in the gulf.

By 1995, monitoring of individual white sharks around the Farallon Islands, using small transmitters swallowed by the animals, had documented their movement patterns and internal temperatures. The movement patterns indicate that each shark has an area that it covers by zigzagging back and forth. These sharks are not swimming aimlessly; they increase their odds of finding pinnipeds by looking in familiar areas where they have previously been successful. The largest sharks covered the smallest home ranges and the smallest shark tracked covered the largest home range. The larger, older sharks seem to be more experienced and therefore know where to search.

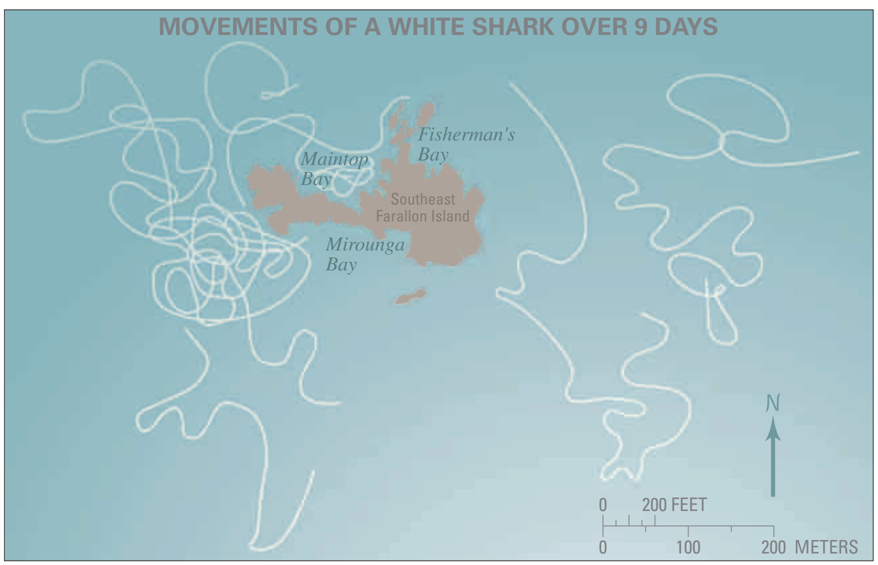
Monitoring found that white sharks in the Gulf of the Farallones maintain a constant body temperature of nearly 80°F in the cold (54 to 57°F) water of the gulf. This allows them to move quickly and to capture warm-blooded marine mammals, such as pinnipeds. Most of the world's predatory sharks cannot increase their body temperature above the ambient water temperature, and so their range is limited to warmer tropical waters.

High tides and large swells affect the rate of white shark predation on pinnipeds in the waters around the Farallon Islands. Such conditions force many of the seals to move from their haul-out space. This displacement may explain why significantly more attacks on elephant seals—sometimes two or three in one day—are observed when large swells are combined with high tides.

Despite the white shark's fearsome reputation and Hollywood image, attacks on humans are relatively rare. In northern and central California, there is on average one or two white shark attacks on humans per year and about one fatality per decade (chances of drowning in the State's coastal waters are at least 100 times greater). In most of these instances, the shark has bitten only once and then released the person immediately. Those bitten usually survive if they can make it to shore, so swimming alone is not advised. Some evidence suggests that white sharks do not like the "taste" of people but sometimes mistake them for there favorite prey, pinnipeds. Therefore, it is not advisable to swim or surf near colonies of pinnipeds, where white sharks may be actively feeding. Areas where there has been a history of shark attacks should also be avoided. For these reasons, sport divers avoid the waters around the Farallon Islands.

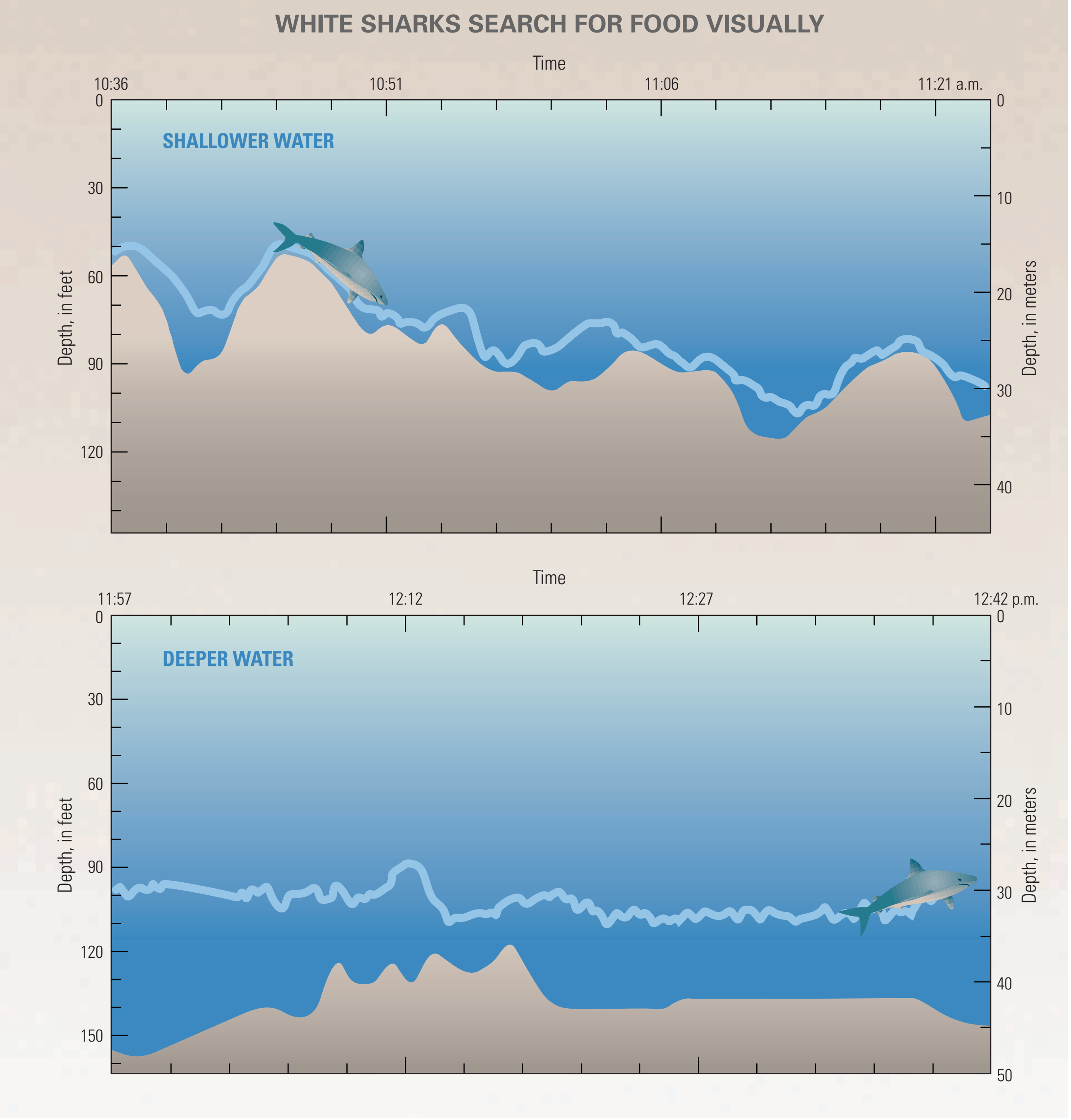
The population of white sharks off California's coast is probably small, having perhaps a few hundred to a few thousand adults. White sharks are important predators in the State's marine ecosystems. In 1994, with the support of scientists, fishermen, surfers, divers, and others, the State of California placed the white shark on the list of species protected in its waters.

The white shark is a fearsome predator, well adapted to live in cold water, where food is more abundant. It is far from a "primitive" cold-blooded fish but is actually a highly evolved warm-blooded animal.



White sharks do not swim aimlessly; they increase their odds of finding seals by looking in familiar areas where they have previously been successful. The map shows the movements of a white shark tracked during October 21–29, 1993, around Southeast Farallon Island, using a transmitter swallowed by the animal.

The white shark searches for food visually, staying near the sea bottom in water less than 90 feet deep (top) and paralleling the ocean's surface in deeper water (bottom). In both situations, the shark's dark back and light underbelly blend with the surrounding environment, hiding the shark from seals and sea lions, its usual prey.



Gulls hover over a predatory attack by a white shark on a northern elephant seal. Southeast Farallon Island is in the background.

Attack by white sharks is violent and quick; the sharks can strike quickly because they are warm blooded.

Continental Slope Communities

Tom Laidig

In the shallow coastal areas of the Gulf of the Farallones, as in other regions of the world, fishing pressure has increased and numbers of fish have decreased over the past few decades. As many fish stocks have declined, some fishermen have been forced to look elsewhere to fill their nets.

Traditional fishing grounds in the gulf have been located on the Continental Shelf, a rather flat, relatively shallow area of the sea floor adjacent to the coast. At a depth of about 600 feet, the bottom starts to drop off more rapidly on what is called the Continental Slope. It is on upper and middle parts of this steeper slope that the new fishing grounds have been established. Because the fish inhabiting these deeper waters are less understood than those in shallower water, there is a danger of overharvesting, which could threaten the long-term viability of these newer fisheries.

The deep waters of the Continental Slope are characterized by nearly freezing temperatures, extremely low light conditions, and very high pressures. Because of the cold, organisms that live at these depths have slower metabolisms—they eat less frequently, are slower in digesting their food, and move and grow more slowly. They also attain greater ages than their counterparts that live in shallower waters—some deep-sea rockfish live more than 70 years.

Many of the animals living in the perpetual darkness of the Continental Slope have developed light-producing organs. These serve various functions, such as communicating with members of their own kind (as in courtship), attracting food (like attracting moths to a flame), and avoiding being eaten (flashing a light in a predator's eyes can give an animal a chance to get away).

Another adaptation to the darkness is an absence of color diversity. With no light, colors have little function. Therefore, animals living on the Continental Slope are generally a dark color, like black, brown, or red. Among the fishes, rockfish and thornyheads are dominantly red. Red objects appear black at depth, allowing red organisms to blend in with their dark surroundings.

The water pressure on the sea floor at the top of the Continental Slope is more than 10 times higher than at the surface, and at the bottom of the slope the pressure can be more than 100 times higher than at the surface. To compensate for this high pressure, organisms have a large percentage of water in their tissues, bones, and shells that replaces other substances, such as gases and calcium. Owing to the high water content of their tissues, many larger, older fish caught from deeper waters are limp and soft when brought to the surface.

Fishes living at different depths on the Continental Slope have different life histories. Species living near the top of the slope produce pelagic (open-ocean) young that spend the first few months to years of life swimming in the upper water column and then settle out in relatively shallow water and migrate downslope as they grow and mature. Dover sole, sablefish, and rockfish have this type of life history; however, most species living deeper, such as rattails, deep-sea soles, and slickheads, have young that live in the same depths as the adults.

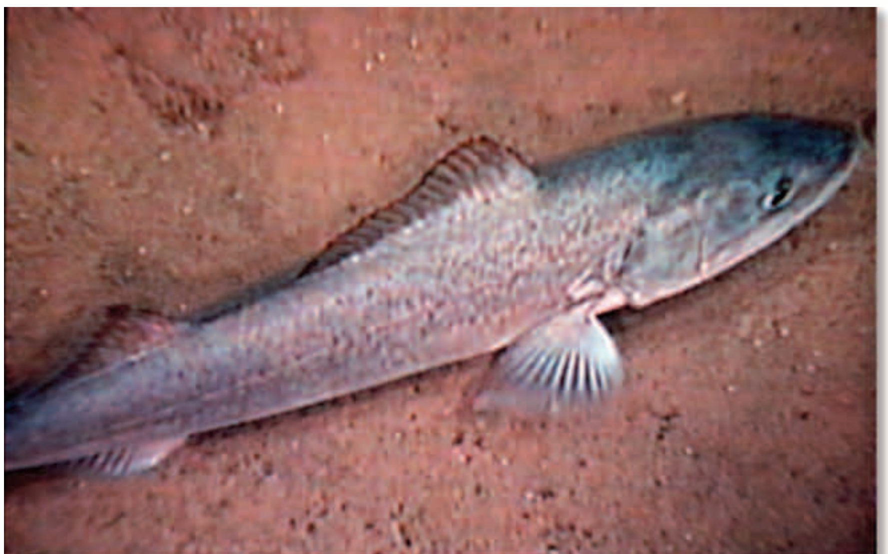
Relatively few species occur at all or most depths on the Continental Slope. Species occupying one depth commonly are replaced by similar species at other depths. An exception is the eel-like hagfish, which is found at all depths on the slope.

Productive commercial fisheries operating today on the Continental Slope off California's coast catch Dover sole, sablefish, deep-living rockfishes, and thornyheads. Many of these fishes occupy similar habitats and generally are caught together. One increasingly active fishery is for rattails, a deep-living fish with a large head and a long tail that tapers to a point.

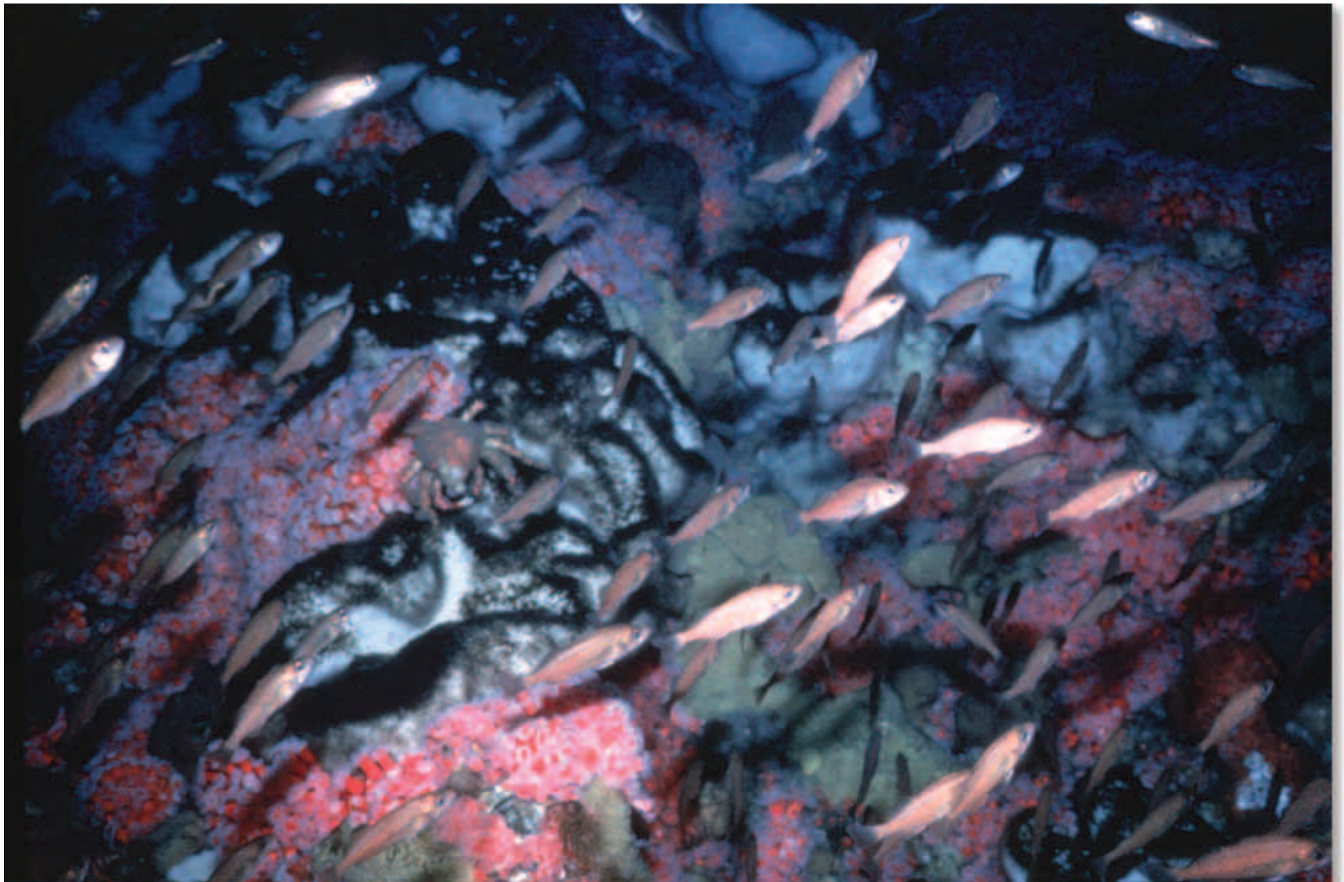
One major fishery of note is for hagfish, the skin of which is used to make what are sold as "eel skin" wallets. Hagfish are not true eels but are a primitive group of fish that have no bones or jaws. Instead of bones, they have cartilage, and instead of jaws, they have a large sucker-like mouth similar to that of a lamprey or a leech. Once attached, hagfish use a tongue with many tiny teeth to dig into their prey. Once inside, the prey is eaten from the inside out. Besides its unique method of eating, the hagfish has another interesting trait—it produces copious amounts of slime, probably used to discourage predators, which gives the fish its nickname, the "slime eel."

Except for fishing activities, the Continental Slope and its communities of fish and invertebrates are still virtually untouched by humans, offering scientists the opportunity to study a generally undisturbed natural system. New methods, such as viewing animals and their habitat by underwater video cameras in submarines and in remotely operated vehicles, have been particularly productive in providing a new understanding of fish and invertebrates living on the slope. In the Gulf of the Farallones, scientists are using these methods to collect data at increasingly greater depths, providing critical information needed to better protect these areas from overuse.

Northern lampfish with light organs (small white circles) along its underside. This small fish, only about 2.5 inches long, also displays the dark coloration typical of many animals on deeper parts of the Continental Slope. (Photograph courtesy of K. Sakuma and D. Roberts.)

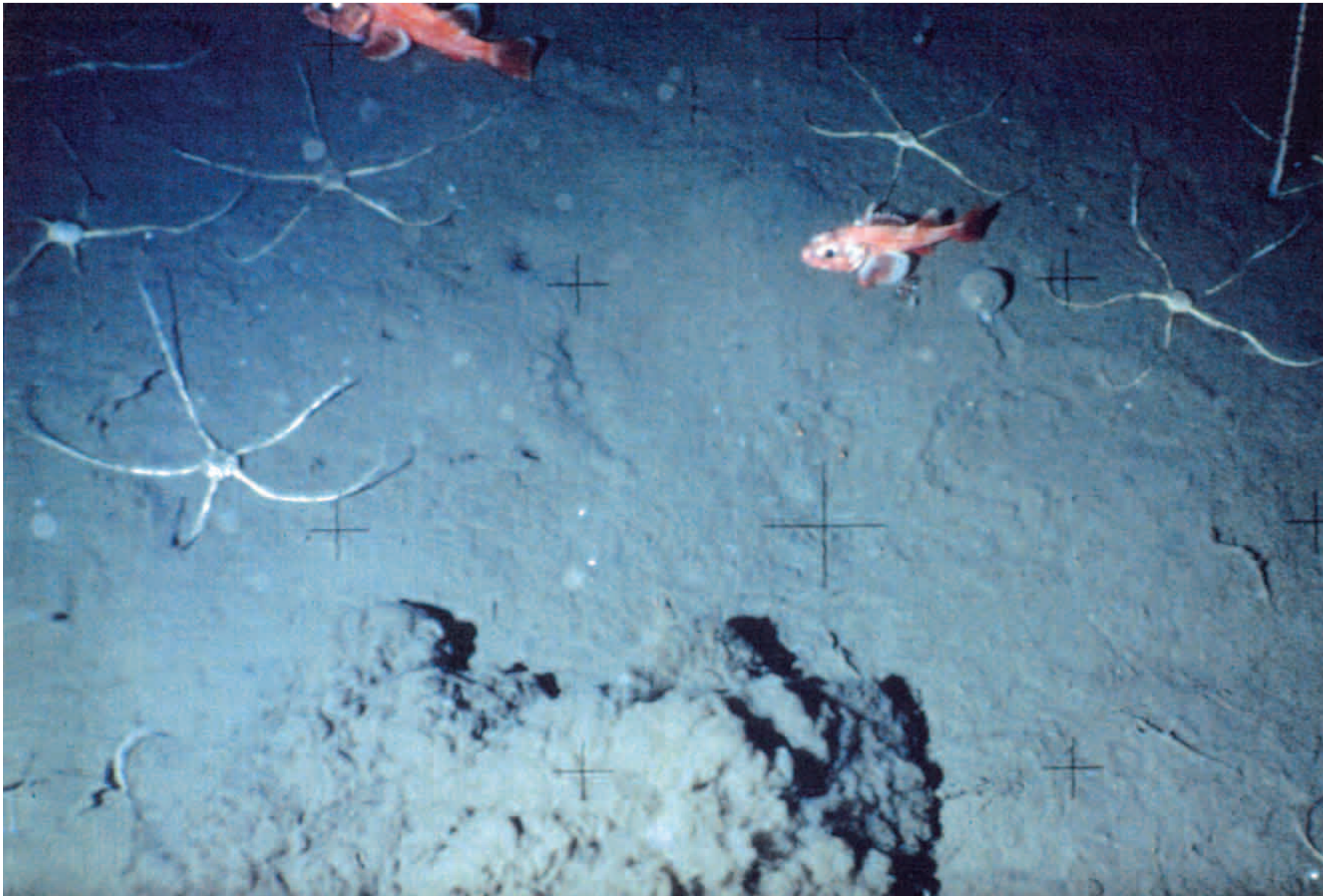


Because of the absence of light on the Continental Slope, animals living there are generally either a dark color, such as the sablefish (left), or red, such as the shortspine thornyhead (right).



Juvenile rockfish swimming over Cordell Bank in the northern Gulf of the Farallones. Species of fish living near the top of the Continental Slope in the gulf produce pelagic (open-ocean) young that spend the first few months to years of life swimming in the upper water column and then settle out in relatively shallow water and migrate downslope as they grow and mature. (Photograph courtesy of Robert Schmieder, Cordell Expeditions.)

A red-banded rockfish on the Continental Slope in the Gulf of the Farallones. Relatively few species of fish occur at all or most depths on the slope. Those occupying one depth commonly are replaced by similar species at other depths. For example, greenstriped and stripetail rockfishes live on muddy bottoms on the upper part of the slope, whereas at greater depth they are replaced by species of thornyheads.



Thornyheads, giant brittle stars, and other animals on the deeper Continental Slope in the Gulf of the Farallones. (Photograph from Gulf of the Farallones National Marine Sanctuary.)

Issues of Environmental Management in the Gulf of the Farallones

Since the mid-1800's, when the California Gold Rush first brought frantic development to the San Francisco Bay region, the waters of the bay and of the Gulf of the Farallones, beyond the Golden Gate, have been used to dispose of manmade waste. Perhaps of greatest concern are thousands of barrels of low-level radioactive waste dumped in the gulf during several decades following the Second World War. To evaluate the hazard from radioactivity to the marine environment, including increasingly important fisheries, scientists have begun the search for containers of radioactive waste on the sea floor of the gulf.

Another issue is the need to find suitable places in the gulf to dump material dredged from shipping channels in San Francisco Bay. Studies of the sea floor in the gulf have already enabled the Environmental Protection Agency to designate the Nation's first deep-ocean disposal site for dredge spoils.

Disposal of Dredged Material and Other Waste on the Continental Shelf and Slope

John L. Chin and Allan Ota

The history of waste disposal in the Gulf of the Farallones is directly linked with the history of human settlement in the San Francisco Bay region. The California Gold Rush of 1849 triggered a massive influx of people and rapid, chaotic development in the bay region. Vast quantities of contaminated sediment and water from mining in the Sierra Nevada were carried by rivers into San Francisco Bay, and some was carried by currents through the Golden Gate and into the gulf. The burgeoning region's inhabitants also contributed to the waste that flowed or was dumped into the bay. Eventually, waste began to be dumped directly into the gulf.

Hundreds of millions of tons of waste has been dumped into the Gulf of the Farallones. Since the 1940's, this has included sediment (sand and mud) dredged from shipping channels, waste from oil refineries and fruit canneries, acids from steel production, surplus munitions and ships from World War II, other unwanted vessels, and barrels of low-level radioactive waste.

Because of navigational errors and inadequate record keeping, the location of most waste dumped in the gulf is poorly known. Between 1946 and 1970 approximately 47,800 containers of low-level radioactive waste were dumped into the gulf south and west of the Farallon Islands. From 1958 to 1969, the U.S. military disposed of chemical and conventional munitions at several sites in the gulf, mostly by scuttling World War II era cargo vessels.

The hulks of ships, possibly dating as far back as the 17th century, litter the sea floor in the gulf. From 1951 to 1987, many vessels were deliberately sunk there. Most of these probably pose little environmental hazard because they were carefully prepared before sinking. One exception may be the highly radioactive World War II aircraft carrier USS *Independence*, exposed in atomic tests at Bikini Atoll in 1946 and sunk by the U.S. Navy in 1951 at an unspecified location off the California coast, possibly in the gulf.

Since at least 1959, some sediment dredged from San Francisco Bay and from the sandbar outside the entrance to the bay (the Golden Gate Bar) has been dumped onto the Continental Shelf in the gulf. Much of this material is from dredging to maintain shipping channels into and within the bay, but some is from other engineering projects.

Until 1970, ocean disposal of both radioactive and nonradioactive waste was acceptable under government policy. That year, the United States terminated all ocean disposal of radioactive waste materials. In 1972, Congress passed the Ocean Dumping Act, which regulates the dumping of wastes into ocean waters. A global ban on the dumping of radioactive waste in the oceans took effect in 1983.

The Environmental Protection Agency (EPA) is currently responsible for designating ocean disposal sites for the United States. The U.S. Army Corps of Engineers (USACE), with EPA's concurrence, issues permits for ocean disposal of dredged material at designated sites. Only sediments evaluated as "clean" (non-toxic) by EPA standards may be disposed of in the marine environment.

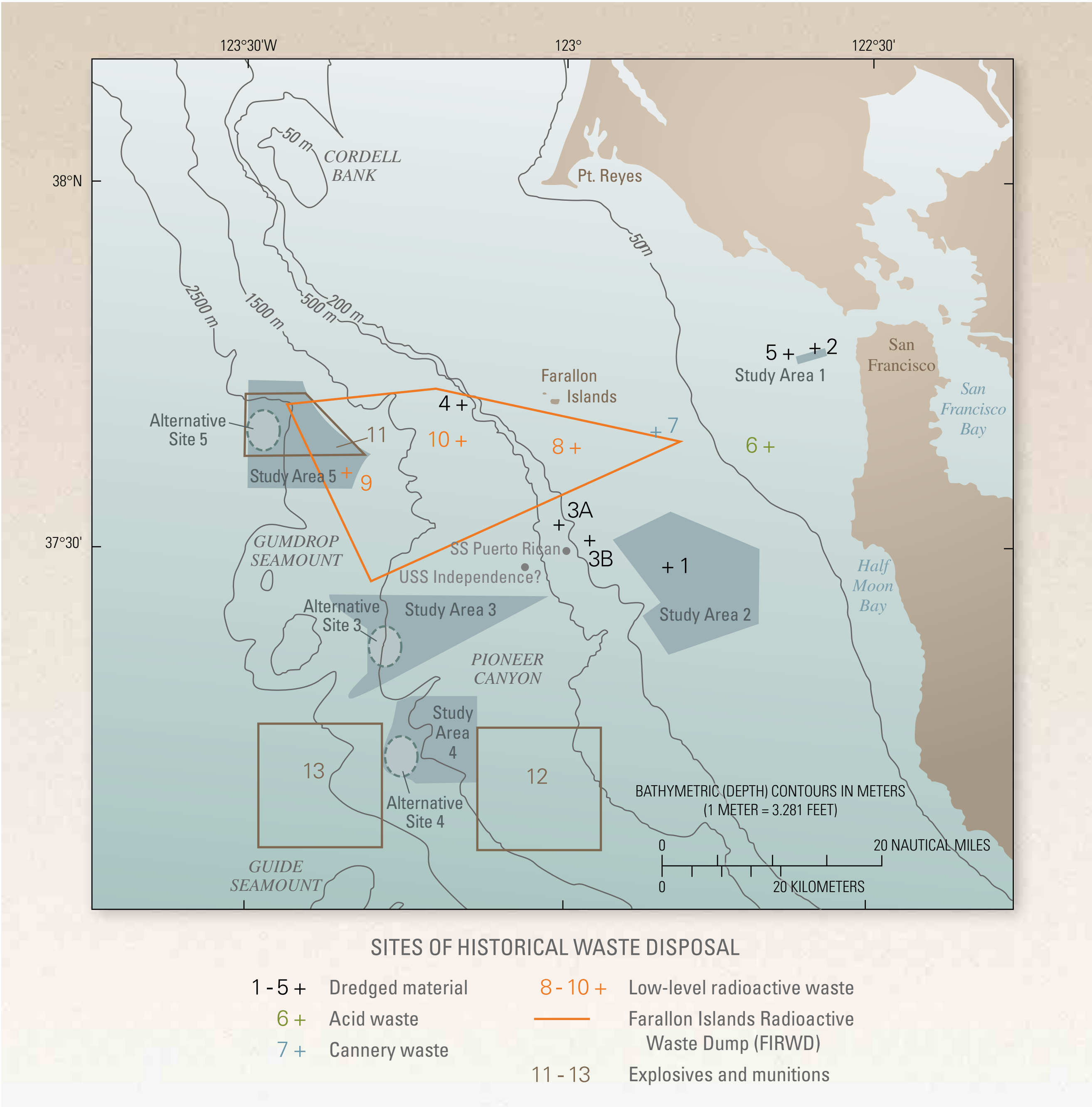
San Francisco Bay's 85 miles of navigable waterways require annual maintenance dredging. The bay's average depth is about 19 feet, but oil tankers and container vessels need from 40 to 60 feet of water for safe transit. Environmental concerns and limited disposal capacity for dredged material in the bay have made it necessary to find suitable dumping sites in the ocean beyond the Golden Gate.

A new approach for the management of dredging and disposal of dredged material for San Francisco Bay was coordinated under a regional effort begun in 1990 as a Federal-State partnership of four agencies and later joined by about 30 other public and private organizations. This effort was formally called the Long Term Management Strategy (LTMS) for the San Francisco Bay region. The primary task of the LTMS was to develop a long-range plan for meeting the bay region's need to dispose of an estimated 300 million cubic yards of dredged material over the next 50 years. The EPA, a leading Federal agency in this effort, had the responsibility for selecting a location for an ocean disposal site for dredged material.

In 1990, the U.S. Geological Survey (USGS) was asked by EPA, USACE, and the Navy to investigate four study areas for locating potential disposal sites for dredged material in the Gulf of the Farallones. This survey also tested the feasibility of using sidescan sonar to locate the radioactive-waste containers in the gulf (see chapter on Search for Containers of Radioactive Waste on the Sea Floor).

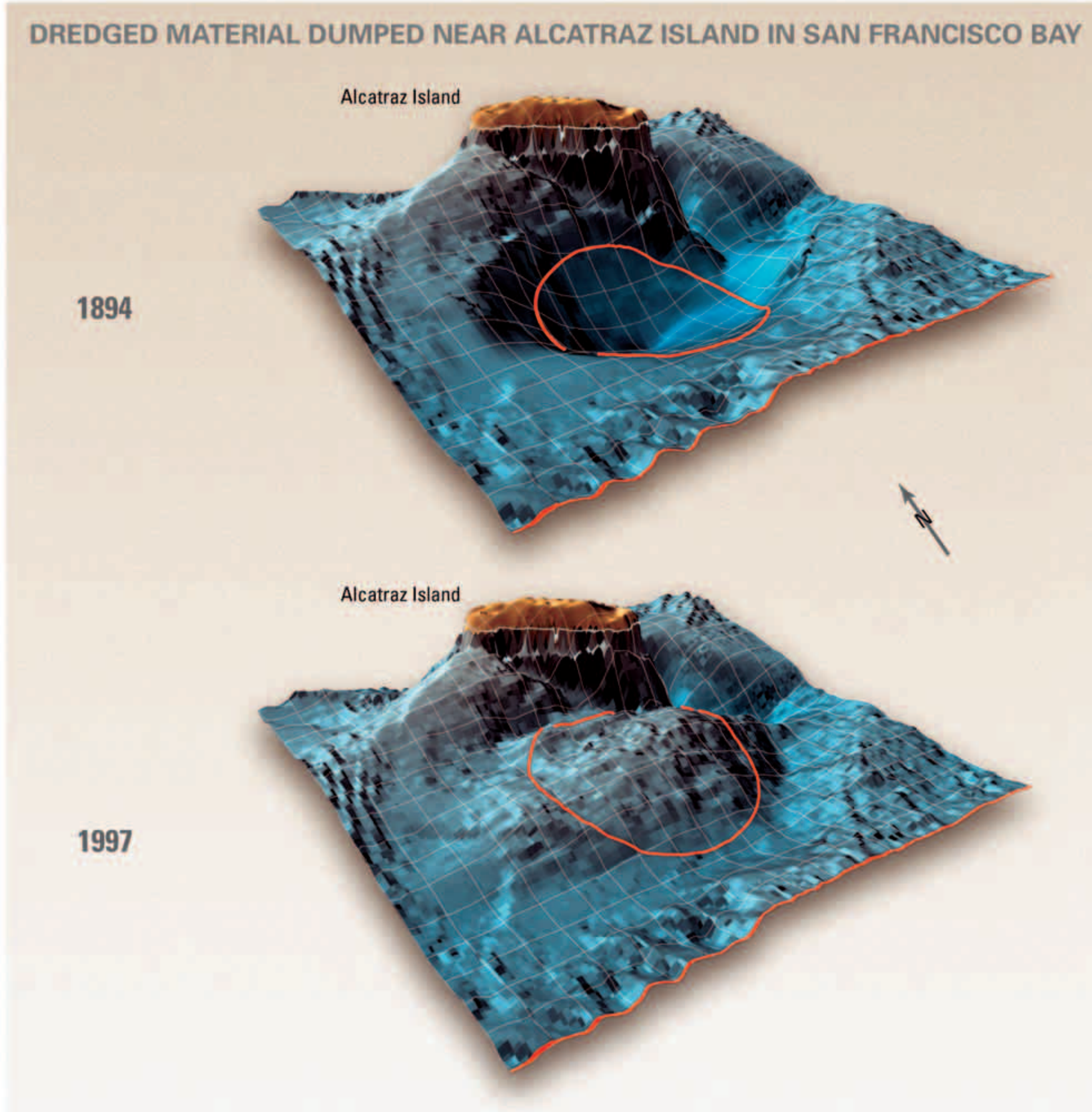
Each of the four study areas was evaluated by the USGS for the presence of deposition and erosion, sediment transport pathways, and the likely effect deposited dredged material might have on the stability of the sea floor (see earlier chapters).

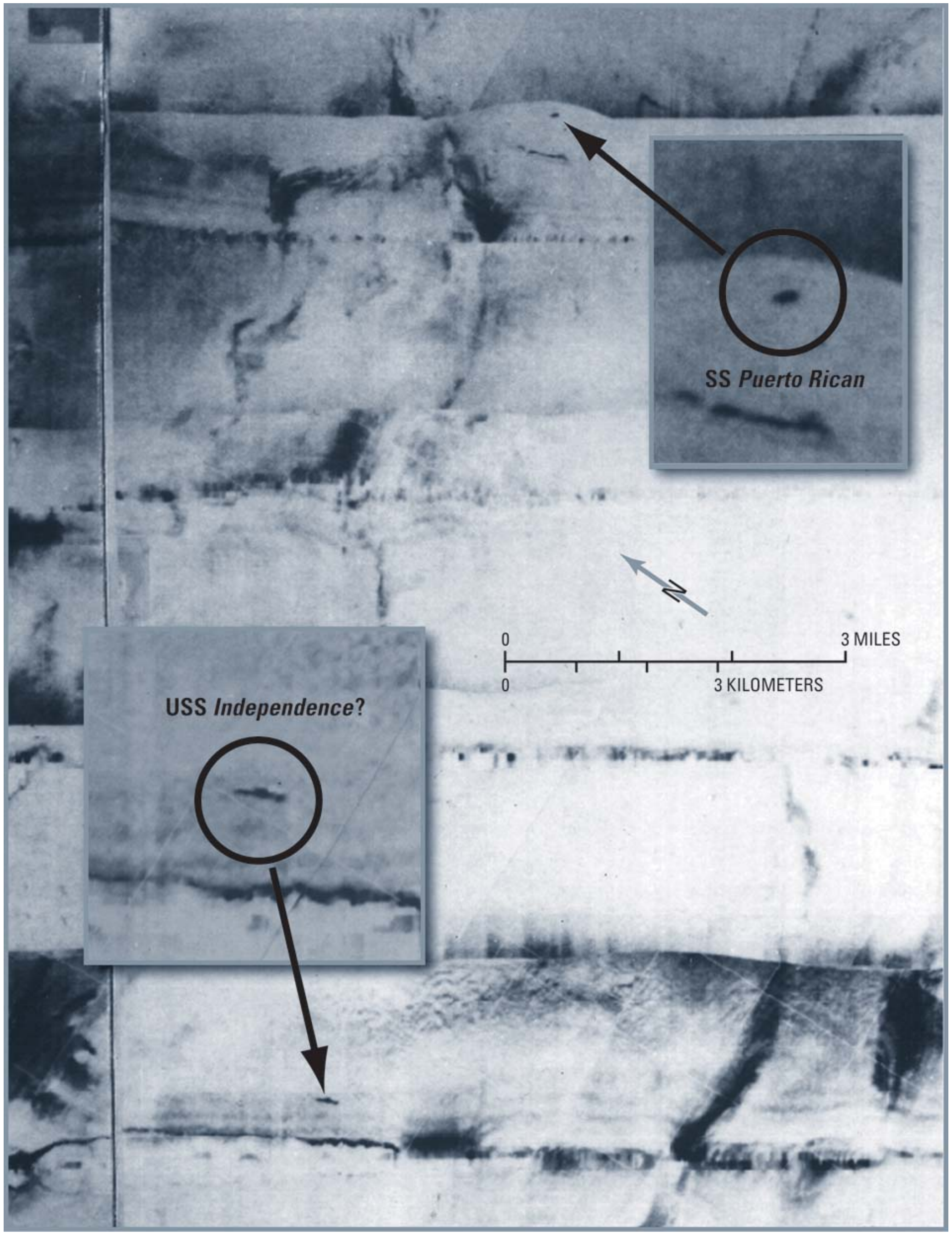
Using the results of the USGS studies, EPA in 1994 designated the San Francisco Deep-Ocean Disposal Site. This site is 55 miles beyond the Golden Gate and 5 miles outside of the Gulf of the Farallones National Marine Sanctuary in 8,200 to 9,800 feet of water.



Map of the Gulf of the Farallones, showing sites of historical waste disposal, as well as locations of U.S. Environmental Protection Agency (EPA) Study Areas (shaded) and Alternative Sites (dotted outlines). Study Areas 2 through 5 and Alternative Sites 3 through 5 were investigated by the U.S. Geological Survey (USGS) for possible designation by the EPA as disposal sites for dredged material. After the USGS reconnaissance survey, Study Areas 3, 4, and 5 on the Continental Slope were retained, and Study Areas 1 and 2 on the Continental Shelf were eliminated from further consideration. In 1994, the EPA designated Alternative Site 5 as the San Francisco Deep-Ocean Disposal Site.

Historically, much of the sediment dredged from the San Francisco Bay to maintain shipping channels has been disposed of in the bay itself, particularly in its deeper parts, such as near Alcatraz Island. These computer-generated oblique images of the bay floor south of Alcatraz Island show the effects of dumping millions of cubic yards of dredged material between 1894 and the mid-1980's in the area outlined by the red circles. The images were created by the U.S. Geological Survey using historical bathymetric data and recent multibeam (acoustic) mapping. (Grid squares are 100 yards on a side, and submarine vertical exaggeration is x10.)





Detail of a U.S. Geological Survey sidescan-sonar mosaic from an area of the upper Continental Slope about 20 miles southwest of the Farallon Islands. On this image was discovered what is interpreted to be the USS *Independence* (CVL 22), a dangerously radioactive aircraft carrier scuttled in 1951. Also visible is the stern section of the SS *Puerto Rican*, an oil tanker that sank in 1984.

The USS *Independence* during active service as a U.S. Navy aircraft carrier (left). The ship is shown below as it appeared after being exposed to atomic tests at Bikini Atoll in 1946. (U.S. Navy photographs.)

Issues of Environmental Management in the Gulf of the Farallones

Search for Containers of Radioactive Waste on the Sea Floor

Herman A. Karl

Between 1946 and 1970, approximately 47,800 large containers of low-level radioactive waste were dumped in the Pacific Ocean west of San Francisco. These containers, mostly 55-gallon drums, were to be dumped at three designated sites in the Gulf of the Farallones, but many were not dropped on target, probably because of inclement weather and navigational uncertainties. The drums actually litter a 540-square-mile area of sea floor, much of it in what is now the Gulf of the Farallones National Marine Sanctuary, which was established by Congress in 1981.

The area of the sea floor where the drums lie is commonly referred to as the "Farallon Islands Radioactive Waste Dump." Because the actual distribution of the drums on the sea floor was unknown, assessing any potential environmental hazard from radiation or contamination has been nearly impossible. Such assessment requires retrieving individual drums for study, sampling sediment and living things around the drums, and directly measuring radiation levels.

In 1974, an unmanned submersible was used to explore a small area in the Farallon Islands Radioactive Waste Dump, but only three small clusters of drums were located. Two years later, a single drum was retrieved from this site by a manned submersible. However, use of submersibles in this type of operation is highly inefficient and very expensive without a reliable map to direct them.

In 1990, the U.S. Geological Survey (USGS) and the Gulf of the Farallones National Marine Sanctuary began a cooperative survey of part of the waste dump using sidescan sonar—a technique that uses sound waves to create images of large areas of the ocean floor. Because of limited time and funding, the survey only covered about 80 square miles, or 15 percent of the waste dump area.

Expert skills are required to distinguish waste drums and other manmade objects from natural geologic features or acoustic noise on ordinary sidescan-sonar images produced onboard ship. USGS scientists developed new techniques for enhancing the sidescan-sonar data from the Farallon Islands Radioactive Waste Dump to detect waste drums more easily and to distinguish them from other targets with a high level of confidence. Using these techniques, it was also possible to differentiate real targets (drums) from acoustic noise.

The enhanced images from the survey showed the locations of many objects that the scientists interpreted to be radioactive waste containers. In 1994, the USGS, the Marine Sanctuary, and the U.S. Navy used the Navy's DSV (Deep Submergence Vehicle) *Sea Cliff* and unmanned Advanced Tethered Vehicle (ATV) to verify these interpretations by direct observation of the sea bottom. The previous attempts in the mid-1970's to locate waste drums in the Gulf of the Farallones using submersibles had been like trying to find a needle in a haystack and had little success.

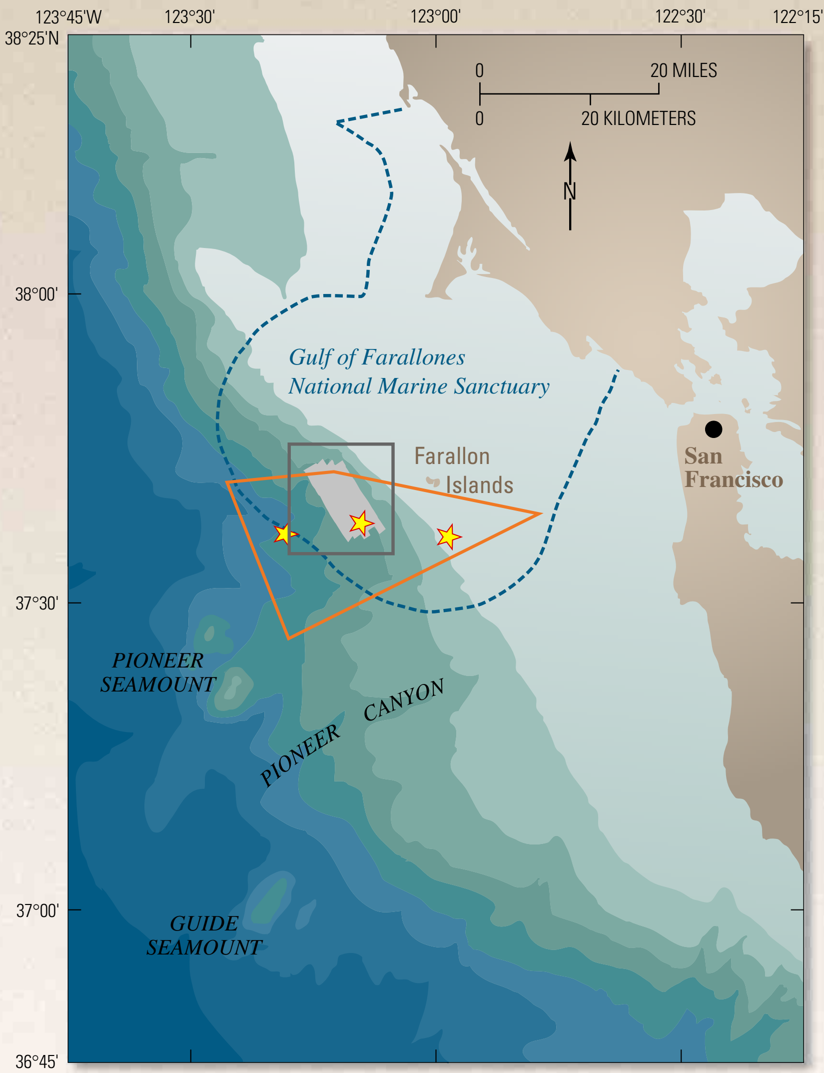
Using the enhanced sidescan-sonar images as guides, *Sea Cliff* and ATV were able to "drive" directly from one suspected drum site to the next. In every instance, waste containers and other physical features were found where the enhanced images showed them to be, and no containers were found where they were not indicated.

This was the first successful test of locating barrels by regional mapping and, in that regard, represents a breakthrough. By using the new USGS maps to detect suspected barrel sites and U.S. Navy technology to directly view the sea floor, many barrels and other containers were found during just a single 24-hour ATV deployment, and each DSV *Sea Cliff* and ATV dive verified the predicted absence or presence of barrels. Visual observations revealed that the condition of the barrels ranged from completely intact to completely deteriorated.

This work proved that enhanced sidescan-sonar images are a cost-effective and time-efficient method for locating relatively small objects on the sea floor and could be used to locate containers of hazardous waste in other ocean areas, such as Boston Harbor in Massachusetts and the Kara Sea in the Arctic Ocean north of Russia.

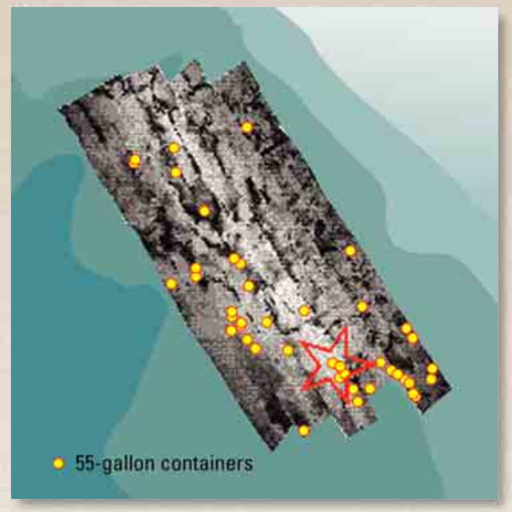
Besides being the site of a marine sanctuary, the Gulf of the Farallones supports a major commercial fishery. In the past, fear of radiation contamination from leaking drums in the "Farallon Island Radioactive Waste Dump" has adversely affected the market for fish caught in the gulf. In 1998, the actual impact of the drums on the marine ecosystem began to be evaluated. Preliminary results suggest that it is much less than feared (see chapter on Measuring Radioactivity from Waste Drums on the Sea Floor).

RADIOACTIVE-WASTE DRUMS IN THE GULF OF THE FARALLONES

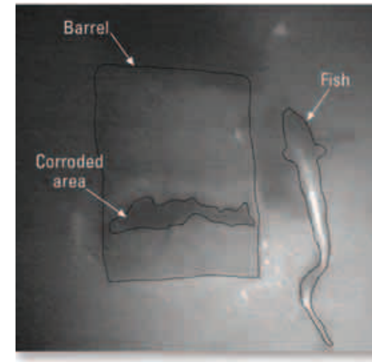


EXPLANATION

- Gulf of the Farallones National Marine Sanctuary
- Farallon Islands Radioactive Waste Dump (FIRWD)
- Designated sites for dumping of radioactive waste used from 1946 to 1970
- Area enlarged in image at upper right



About 47,800 containers of low-level radioactive waste, mostly 55-gallon drums, were dumped in the Gulf of the Farallones from 1946 to 1970. These containers were to be dumped at the three designated sites (small stars) shown on the map at left. However, many containers were not dropped on target, probably because of inclement weather and navigational uncertainties, and lie scattered over an area of the sea floor commonly called the "Farallon Islands Radioactive Waste Dump." An enlargement (above) of the area around one of the designated sites (large star) shows locations of probable radioactive-waste drums detected by the U.S. Geological Survey, superimposed on a sidescan-sonar mosaic.



These images show 55-gallon drums thought to contain low-level radioactive waste on the Continental Slope in the Gulf of the Farallones. A corroded drum (top), with a large fish resting next to it, was photographed in the early 1990's using a U.S. Geological Survey underwater-camera/video sled. An intact drum (bottom) was photographed in 1974 on a submersible dive sponsored by the Environmental Protection Agency.

Measuring Radioactivity from Waste Drums on the Sea Floor

David G. Jones, Philip D. Roberts, and Johannes Limburg

South and west of the Farallon Islands, offshore from the Golden Gate and the San Francisco Bay region, is an area of sea floor commonly referred to as the "Farallon Islands Radioactive Waste Dump." This area was where approximately 47,800 large containers, mostly 55-gallon drums, of low-level radioactive waste were dumped between 1946 and 1970. The containers were to be dumped at three designated sites, but they actually litter an area of sea floor of at least 540 square miles in water depths ranging from about 300 feet to more than 6,000 feet.

The Gulf of the Farallones and adjacent areas support a major commercial fishery and are also used extensively for sport fishing and other forms of recreation. Fears of radioactive contamination from leaking containers have in the past had an adverse impact on the fishery. However, the actual locations of the drums on the sea floor was unknown, and therefore evaluating potential hazards from radiation or contamination was nearly impossible.

In the early 1990's, the U.S. Geological Survey (USGS) and the Gulf of the Farallones National Marine Sanctuary surveyed part of the waste dump using sidescan sonar—a technique that uses sound waves to create images of large areas of the ocean floor (see chapter on Search for Containers of Radioactive Waste on the Sea Floor). By using new techniques to enhance the sonar images, USGS scientists were able to identify many objects that they believed to be radioactive-waste containers. These identifications were confirmed in 1994 using U.S. Navy submersibles.

In late 1994, discussions between the USGS and the British Geological Survey (BGS) led to a proposal to carry out a radioactivity survey of parts of the area where the drums had been mapped, using the BGS's proven towed seabed gamma-ray spectrometer system. This system, called "EEL" because of its eel-like appearance, is towed along the sea floor and had to be modified to operate in the deeper waters found in the survey area. Previous attempts to measure radioactivity on the sea floor in the Farallon Islands Radioactive Waste Dump had been restricted to the analyses of samples of water, sediments, and marine animals and plants. Sediments from only a relatively small number of sites had been sampled, although in the mid-1970's some samples were collected from areas near drums found by chance using submersibles.

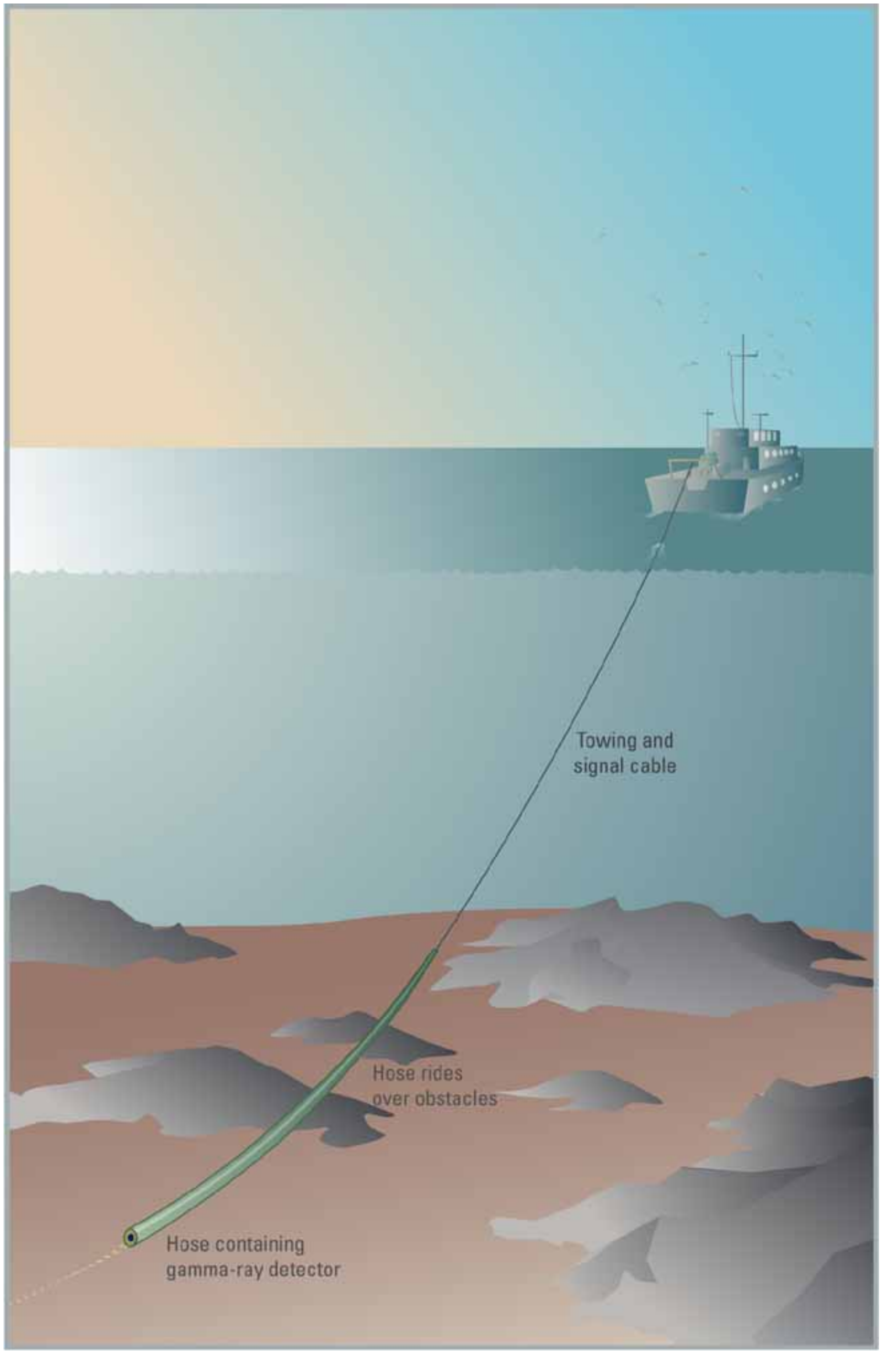
Using drum locations indicated on the USGS sidescan-sonar images, a survey was designed to investigate regional-scale levels of radioactivity in the sea floor sediments of the gulf. In 1998, the BGS EEL was used to make continuous measurements of sea-floor radioactivity in the gulf along several tracklines. These were mostly at depths between 300 and 3,000 feet, but some extended down to a maximum depth of about 4,900 feet. Samples of sea-floor sediment were collected on the basis of the EEL results and also were collected in areas where clusters of drums had been previously identified but where the seabed topography was too rugged for safe bottom towing of the EEL.

Both measurements made by the EEL on the sea floor and laboratory analyses of sediment samples indicate only very low levels of artificial radionuclides (radioactive atoms, such as Cesium-137, that do not occur naturally but are produced by nuclear reactions) in the surveyed areas of the Farallon Islands Radioactive Waste Dump. These results are similar to those that had been reported in the limited previous studies.

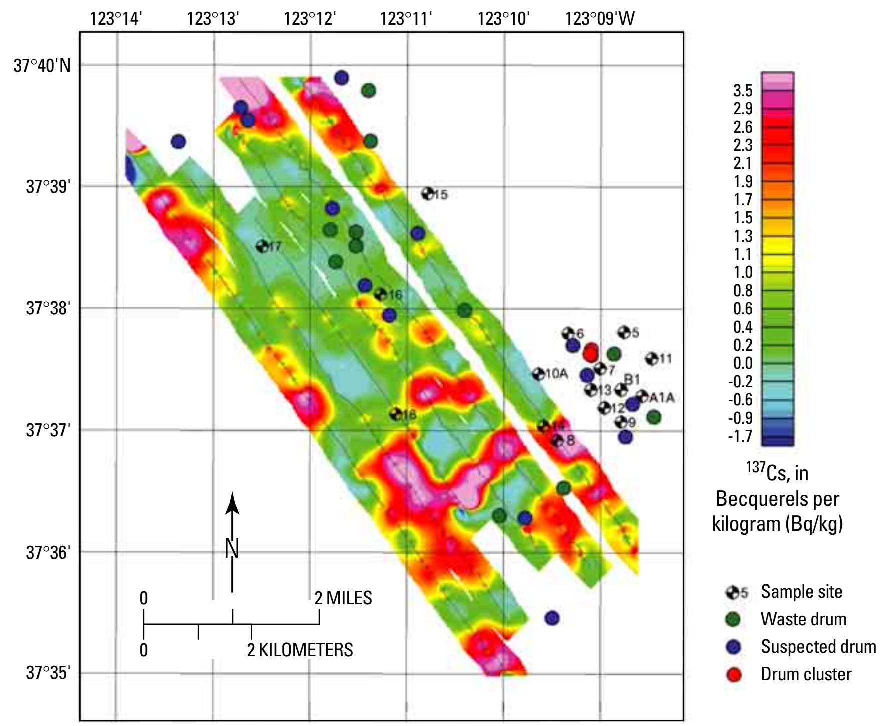
The results of the EEL survey suggest some leakage from drums in the Farallon Islands Radioactive Waste Dump, but it appears that this has caused only a localized increase in radionuclides on the sea floor in the gulf. The data do not suggest any significant elevation of radionuclide levels on a regional scale. Most of the observed variations in sea-floor radioactivity are due to changes in natural radioactivity and show a good correlation to geological features, and some of the very low levels of artificial radionuclides detected in the area surveyed may simply be from fallout from atmospheric nuclear testing done during the Cold War.

It should be borne in mind that no data have yet been obtained for large areas of the Farallon Islands Radioactive Waste Dump. In particular, the deeper water areas where the majority of containers are believed to have been dumped remain virtually unstudied, both in terms of the radionuclide content of the sediments and the actual locations of the containers.

To date, container locations have only been mapped in 15 percent of the Farallon Islands Radioactive Waste Dump and radionuclide concentrations examined in only about 10 percent of the dump area. Although the areas studied are the shallower parts of the site most accessible to people and where contamination would be of most concern, further studies must be done to fully evaluate the possible hazards from radioactivity in the Farallon Islands Radioactive Waste Dump. This could be important because, as many fish stocks have declined in the shallow coastal areas of the Gulf of the Farallones, some fishermen have been forced to fish in the deeper waters of the Continental Slope to fill their nets (see chapter on Continental Slope Communities).

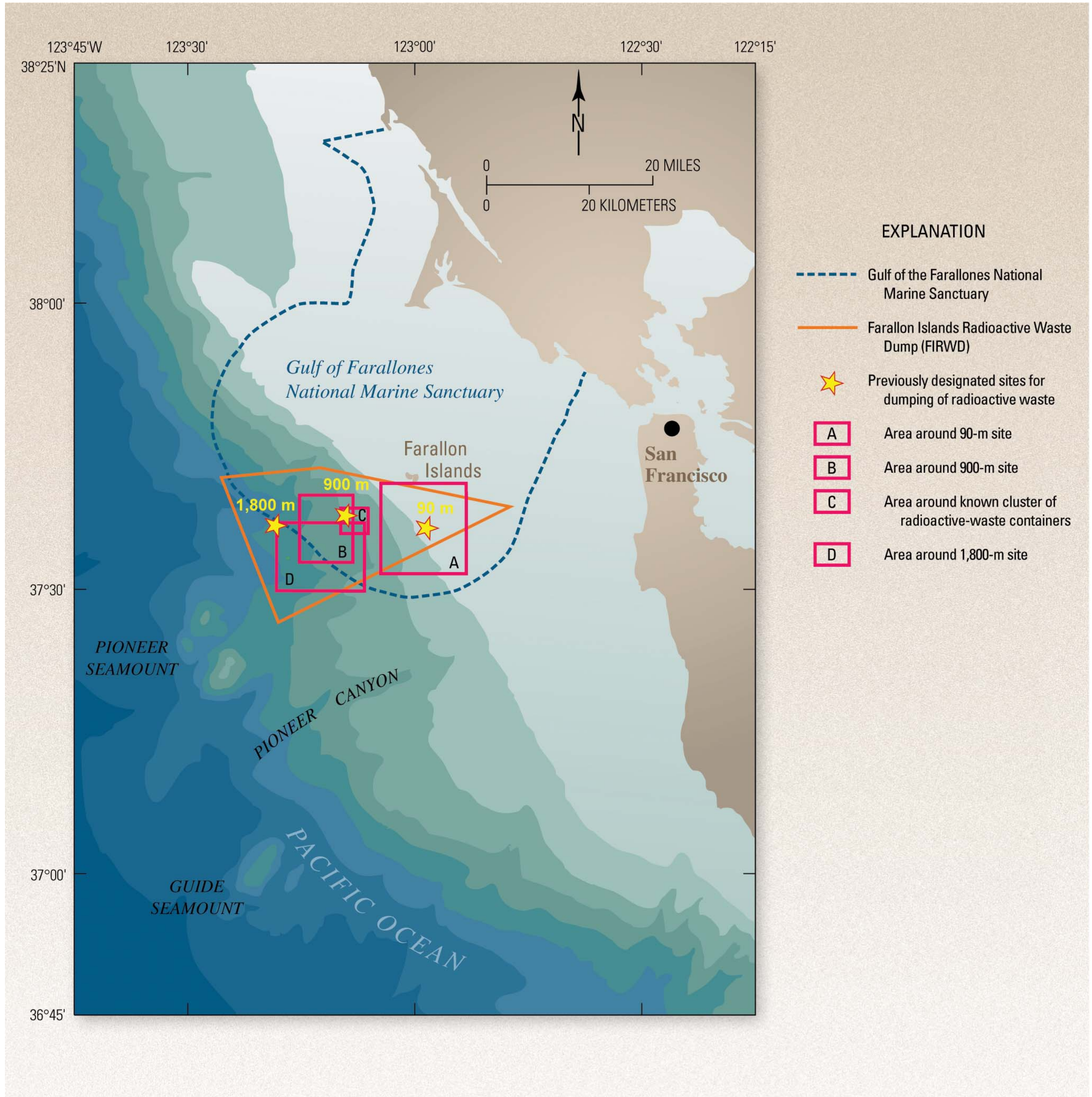


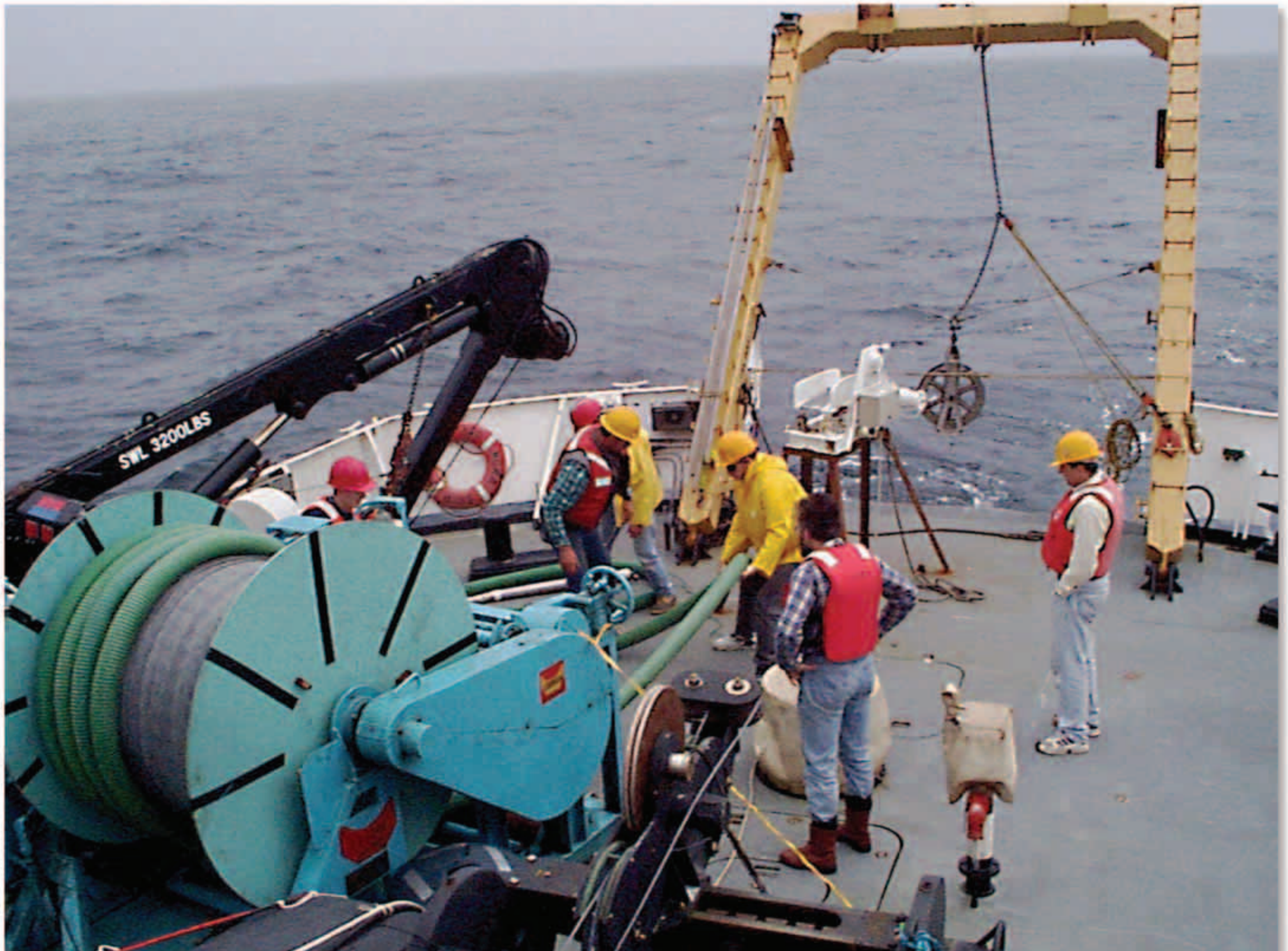
◄ A seabed gamma-ray spectrometer belonging to and operated by the British Geological Survey, called the EEL because of its eel-like appearance, was used to measure the radioactivity of the sea floor in the Gulf of the Farallones. As shown in this diagram, the probe, housed in a protective hose (green), is towed along the sea floor. Data are sent up the towing cable to a shipboard computer and recorded continuously. The gamma-ray detector can measure both natural and artificial radioactivity in the top foot or so of sea-floor surface material.



▲ Distribution of measured cesium-137 (^{137}Cs) radioactivity for the survey of the 900-meter dump (see area B on map, next page). This is an example of a plot produced from gamma-ray radioactivity data collected by the EEL in the Gulf of the Farallones. The EEL data from the gulf do not suggest any significant elevation of radionuclide levels on a regional scale. Most of the observed variations in sea-floor radioactivity are due to changes in natural radioactivity and show a good correlation to geological features but almost no correlation to the distribution of low-level radioactive-waste drums. Apparent negative radioactivity values are an artifact of data-processing calculations, combined with the statistical uncertainty inherent in measuring extremely low radioactivity levels.

Map showing areas of the Gulf of the Farallones where levels of sea-floor radioactivity were measured using the British Geological Survey EEL. Also shown is the approximate extent of the Farallon Islands Radioactive Waste Dump. This area was where approximately 47,800 large containers, mostly 55-gallon drums, of low-level radioactive waste were dumped between 1946 and 1970. The containers were to be dumped at three designated sites (informally referred to as the 90-meter, 900-meter, and 1,800-meter sites), but they actually litter an area of sea floor of at least 540 square miles in water depths ranging from about 300 feet to more than 6,000 feet.





This photograph shows the British Geological Survey's EEL being prepared for deployment in the Gulf of the Farallones. Housed within the green hose of the EEL are several instruments, including a gamma-ray detector that measures radioactivity on the sea floor.

Further Reading

Oceanography and Geology

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http://walrus.wr.usgs.gov/
http://quake.usgs.gov/
http://www.abag.ca.gov/bayarea/eqmaps/
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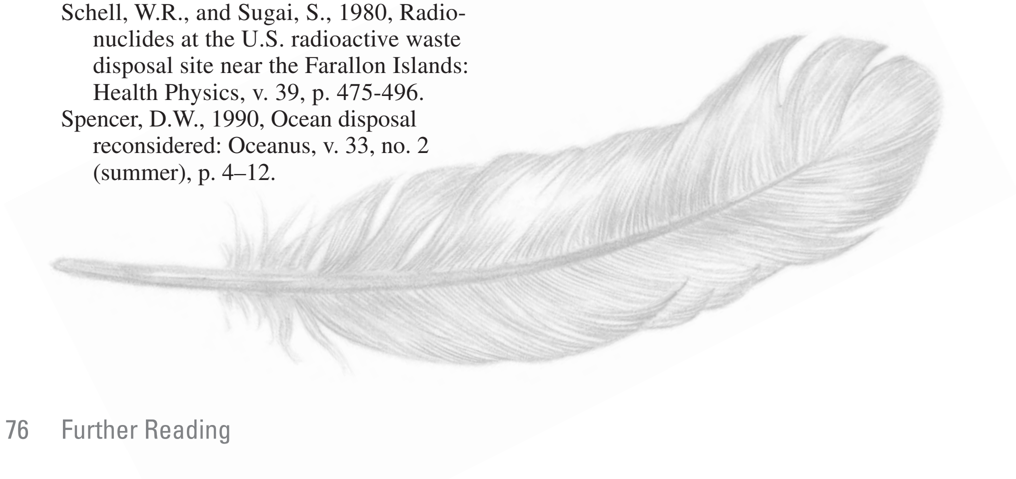

Glossary

Acoustic release package. A device that upon command releases current meters or other instruments from the weight that holds them to the sea floor.

Acoustic system. Pertaining to a package of devices that puts sound energy into the water column, receives signals reflected from the sea floor and layers of rock and sediment below the sea floor, and displays and records the reflected signals.

Advection [oceanography]. The horizontal or vertical flow of water as an ocean current.

Amphipod. Any small crustacean of the order Amphipoda with vertically thin bodies and sets of legs used for both swimming and hopping; one common variety is the "sand flea."

Arc volcanism. The processes associated with the extrusion of lava on and adjacent to a chain of islands (for example, the Aleutians) rising from the deep sea floor.

Asthenosphere. The zone of the Earth's upper mantle, below the lithosphere, where rock is weak and capable of flowing.

Basalt. A dark, fine-grained extrusive igneous rock.

Bathymetric contour. A line on a map showing equal depth below sea level on the sea floor.

Bathymetry. The measurement of ocean depths and the charting of the topography of the sea floor.

Bioturbated. Said of sediments disturbed by organisms.

Blueschist. A metamorphic rock with a blue color due to the presence of certain minerals produced at high pressures in the Earth.

Camera transect. A track across the sea floor along which a camera takes a series of photographs.

Chert. An extremely fine-grained (microcrystalline) sedimentary rock composed of silica (SiO_2), often from the tiny skeletons of aquatic microorganisms.

Continental margin. The ocean floor that is between the shoreline and the deep (abyssal) ocean floor.

Continental shelf. That part of the continental margin from the shoreline to the continental slope or, where there is no noticeable break in slope, to a depth of about 660 feet (200 meters).

Continental slope. That part of the continental margin that is between the continental shelf and the deep (abyssal) ocean floor.

Convergent boundary [currents]. An area or zone where ocean currents come together.

Convergent boundary [plate tectonics]. A boundary between two tectonic plates that are moving toward each other.

Coring device. An apparatus used to take vertical, cylindrical or rectangular sections of sediment from the sea floor.

Core sample. A vertical, cylindrical or rectangular sample of sediment from which the nature or stratification of the sea-floor deposits may be determined.

Crust [Earth's]. The outermost layer or shell of the Earth.

Current meter. A device that measures the speed and direction of ocean currents.

Deep submergence vehicle. A submarine that is capable of submerging to very great depths, usually used for research.

Diabase. An dark intrusive igneous rock.

Diatom. A microscopic single-celled plant that secretes a silica (SiO_2) skeleton; diatoms are abundant in both marine and fresh water.

Dike. A tabular igneous intrusion that cuts across the bedding or foliation of the host rock.

Dinoflagellate. A single-celled microscopic organism with resemblances to both plants and animals; most species are marine, and some are the cause of toxic "red tides."

Divergent boundary [currents]. The area or zone where different currents or water bodies move apart from each other.

Divergent boundary [plate tectonics]. A boundary between two plates that are moving apart from each other.

Eclogite. A granular rock composed essentially of garnet and sodic pyroxene.

Ekman transport. The current generated from wind blowing over the surface of the water, where the surface current moves at 45 degrees to the right of the wind direction (northern hemisphere) and successively deeper layers of water move increasingly to the right until at some depth the water is moving opposite the wind direction; the net transport is 90 degrees to the right of the wind direction.

El Niño. An anomalous warming of the surface waters of the eastern tropical Pacific Ocean, which can have worldwide and significant effects on weather, ocean currents, and sea life and can cause droughts, floods, and other natural disasters.

Entrenched valley. A deepened, incised valley that suggests rapid vertical uplift or lowering of base level.

Epicenter. The point on the Earth's surface that is directly above the focus of an earthquake.

Euphausiid. A group of small planktonic marine shrimp, commonly called krill, that are an important food source for many marine animals, including some whales.

Eustatic [sea level]. Said of worldwide changes in sea level that affect all the world's oceans.

Exotic terrane. A geologic terrane that has moved far from its place of origin and is unrelated to those adjacent to it.

Factor analysis. A mathematical technique used to discover simple patterns in relations among variables.

Farallon Escarpment. The steep submarine slope in the region of the Farallon Islands; part of the Continental Slope.

Farallon Shelf. The gently sloping part of the sea floor in the vicinity of the Farallon Islands from the shore to the Farallon Escarpment; part of the Continental Shelf.

Fault. A fracture or zone of fractures in the Earth along which there has been displacement of the sides relative to one another.

Flagellates. Microorganisms possessing whip-like flagella, which they use for propulsion.

Franciscan Complex/Assemblage. A disorderly assemblage of rocks of various characteristics in the Coast Ranges of California that have undergone unsystematic disturbance; typical rocks of this assemblage crop out in the vicinity of San Francisco.

Franciscan mélange. A variation of Franciscan Assemblage; a mélange is characterized by fragments and blocks of various rock types of all sizes.

Gabbro. A dark, granular intrusive rock; the intrusive equivalent of basalt.

Geomorphological. Pertaining to the general configuration of the Earth's surface; the nature and origin of landforms.

Geophysics. The study of the Earth by quantitative physical means.

Glacier. A large mass of ice formed by the accumulation, compaction, and recrystallization of snow.

Global Positioning System (GPS). A network of satellites used for navigation.

Granite. A light-colored plutonic rock rich in quartz and feldspar.

Granitic. Of or pertaining to granite.

Gravity corer. A device with a long cylindrical pipe topped by a heavy weight used to take samples of sea-floor sediments.

Graywacke. A dark-gray, hard, coarse-grained sandstone that consists of poorly sorted, angular to subangular mineral grains embedded in a clay matrix.

Great Valley of California. Also called the Central Valley, it is a nearly flat alluvial plain in the central part of California about 450 miles long and on average 50 miles wide. Geologically, the Great

Valley is a large, elongate northwest-trending structural trough filled with a thick sequence of sediments that range in age from Jurassic to present.

Heavy minerals. Detrital minerals that have a specific gravity higher than a standard, usually 2.85.

Highstand. Generally referring to the highest eustatic sea levels during any period of geologic time.

Ice Age. A time of extensive glacial activity; most recently the Pleistocene, which began about 1.6 million years ago and lasted until about 10,000 years ago.

Igneous. Said of rocks or minerals that solidified from molten or partly molten material.

Intervalometer. A timing device on a submarine camera that automatically operates the shutter at predetermined intervals.

Intrusion. The process of emplacement of magma in preexisting rock, leading to the formation of igneous rocks in the form of dikes, plutons, and batholiths.

Lava. Molten material erupted (extruded) at the surface of the Earth; also, the rock that solidifies from such material.

Limestone. A sedimentary rock composed chiefly of calcium carbonate ($CaCO_3$), often from the shells of marine organisms.

Lithosphere. The solid outer portion of the Earth; it includes the crust and uppermost mantle, above the asthenosphere.

Lithostratigraphic unit. A layer of rock defined on the basis of lithologic characteristics and stratigraphic position.

Loran-C. A high-precision navigation system.

Lowstand. Generally referring to the lowest eustatic sea levels during any period of geologic time.

Magma. Molten rock below the Earth's surface.

Magnitude (M). A measure of the strength (energy released) of an earthquake.

Mantle [Earth's]. The zone of the Earth below the crust and above the core.

Megalopa (megalops). An advanced larval stage of crabs, just preceding the adult stage.

Mesozoic. An era of geologic time from about 225 to about 65 million years ago, best known as the time of the dinosaurs.

Metamorphic. Pertaining to rocks and minerals that have been changed by heat and pressure.

Oceanic plate. A tectonic plate of the Earth's lithosphere that is characterized by thin basaltic crust; moves horizontally and adjoins other plates along seismically active zones.

Pelagic. Said of marine organisms whose environment is the open ocean, rather than the bottom or shore areas.

Photic (euphotic) zone. The upper zone of ocean waters in which sunlight penetrates sufficiently to support photosynthesis; generally the upper 150 to 450 feet of the water column.

Photosynthesis. The process by which plants make organic compounds from carbon dioxide and water using the energy of sunlight, a byproduct of which is the production of free oxygen; photosynthesis is the primary basis for food production on Earth.

Phytoplankton. Aquatic plants, mostly microscopic, that have a planktonic lifestyle.

Pillow basalt. A type of basalt that is characterized by pillow-shaped structures, generally interpreted to indicate that it was erupted under water.

Plankton. Aquatic plants and animals, chiefly microscopic, that drift or float in the water and are the main basis of marine food webs.

Plate tectonics. A theory of global tectonics in which the lithosphere is divided into a series of plates that move horizontally relative to one another.

Primary producers. Green plants, including most phytoplankton; so called because they produce, through photosynthesis, the organic compounds that form the beginning link in food webs.

Radiolarian chert. A layered (well bedded) microcrystalline rock consisting of the remains of one-celled marine animals called radiolarians.

Ranging navigation system [Del Norte/Benthos]. A system used relatively close to shore to determine a precise position at sea.

Red tide. A reddish discoloration of seawater caused by a bloom of toxic dinoflagellates.

Salinian terrane/block (Salinia). A 300-mile-long slice of rock that forms most of the basement in the central coastal part of California, west of the San Andreas Fault; this terrane has been interpreted to be displaced northward from a southward extension of the Sierra Nevada or possibly from even farther south.

Sea-floor spreading. The process in which new ocean crust is created by upwelling of magma at midoceanic-ridge spreading centers; as new crust is created, it moves horizontally away from the ridge.

Seismic-reflection profile. A profile produced from the return of acoustic energy reflected off the sea floor and off density discontinuities at layers below the sea floor.

Seismometer. An instrument that detects Earth motions.

Serpentine. A group of common minerals, commonly a mottled shade of green, that form by alteration of olivine and other magnesium-rich minerals found in igneous and metamorphic rocks.

Serpentinite. A characteristically green rock consisting almost wholly of serpentine-group minerals; it is a common rock type in coastal central California.

Shelf break. An abrupt change in slope that marks the boundary between the Continental Shelf and Slope.

Sidescan sonar. An acoustic device that emits sound signals to the side of a ship's track; these signals are reflected back from the sea floor, revealing its character.

Souter Van Veen grab sampler/corer. A jawed or clam-like device that grabs or scoops up samples of sediment from the sea floor.

Stream valley. An elongate depression in the Earth's surface carved by a stream.

Structural fold. A fold in rock or strata produced by deformation.

Subaerial. Processes or conditions, such as erosion, that exist or operate in the open air at the Earth's surface.

Subduction. The process of one lithospheric plate descending beneath another along a convergent boundary.

Subduction zone. A zone along which subduction occurs.

Tectonic plate. One of the large plates of lithosphere constituting the surface of the Earth that move horizontally relative to one another.

Terrane. A fault-bounded body of rock of regional extent, characterized by a geologic history different from that of adjacent terranes.

Terrestrial lowland. An area or place of low-lying land, especially near the coast.

Towfish. A device towed on a cable behind a ship; commonly applied to a sidescan-sonar transceiver.

Transform boundary. In plate tectonics, a plate boundary that ideally shows pure strike-slip displacement (two plates sliding horizontally past each other).

Transmissometer. A device that measures levels of light in the water, providing an estimate of the amount of suspended particulate matter.

Tsunami. A gravitational seawave initiated by a short-duration, large-scale disturbance of the sea floor, usually by strong earthquake.

Unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

Water column. A vertical section of water from the surface to the bottom of a body of water.

Zooplankton. Aquatic animals, mostly microscopic, that have a planktonic lifestyle.

Oceanography and Geology of the Gulf of the Farallones

The San Francisco Bay region of California is famous for its stunning landscapes and complex geology. Adjacent to this region, in the watery world of the Pacific Ocean beyond the Golden Gate, lies the Gulf of the Farallones, a physical environment equally complex and fascinating, but less obvious, less visible, and therefore more mysterious.

Scientific studies are revealing that the sea floor of the gulf, like the region onshore, was crafted by geologic forces that include movements of the San Andreas Fault system, major changes in sea level, and the action of rivers. The ceaseless work of oceanic currents has further sculpted the sea bottom in the gulf into landscapes that today range from flat plains and giant sand ripples to deep canyons and rugged mountains, some of whose highest summits poke above the water to form the Farallon Islands.

Biology and Ecological Niches in the Gulf of the Farallones

Year round, thousands of people are attracted to the cold waters of the Gulf of the Farallones for its whale and bird watching, beautiful coastal tide pools, and commercial and sport fishing. Few realize that the organisms that they see and catch are only a small part of a rich and complex marine ecosystem.

Scientists have found that the distribution and abundance of marine flora and fauna in the gulf are directly related to the physical and chemical conditions of its waters. Upwelling of deep nutrient-rich waters along the coast during the spring and summer months of most years feeds microscopic plankton that support a complex but fragile web of organisms, from Dungeness crabs, chinook salmon, and brown pelicans to elephant seals, great white sharks, and giant blue whales. The Cordell Bank, Gulf of the Farallones, and Monterey Bay National Marine Sanctuaries help to protect and manage this marine abundance.

Issues of Environmental Management in the Gulf of the Farallones

Since the mid-1800's, when the California Gold Rush first brought frantic development to the San Francisco Bay region, the waters of the bay and of the Gulf of the Farallones, beyond the Golden Gate, have been used to dispose of manmade waste. Perhaps of greatest concern are thousands of barrels of low-level radioactive waste dumped in the gulf during several decades following the Second World War. Another issue is the need to find suitable places in the gulf to dump material dredged from shipping channels in San Francisco Bay.

To evaluate the hazard from radioactivity to the marine environment, including increasingly important fisheries, scientists have begun the search for containers of radioactive waste on the sea floor of the gulf. Studies of the sea floor in the gulf have already enabled the Environmental Protection Agency to designate the Nation's first deep-ocean disposal site for dredge spoils.

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