Landscape of the Sea Floor

Herman A. Karl and William C. Schwab

Summary and Introduction

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 1 m (3 ft). 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.

Methods and Techniques

Profiling and Sidescanning

Subsea morphologic data are collected using two basic acoustic techniques—profiling and sidescanning (fig. 1). Acoustic narrow-beam profiling instruments towed behind a ship or mounted on the hull emit pulses of sound that travel through the water to the sea floor and bounce back to the sea surface. This reflected sound (echo) is recorded by instruments on the ship. The time that it takes for the echo to return from the sea floor is proportional to the water depth. In this way, continuous profiles of differences in elevation of the sea floor (water depth or bathymetry) are recorded as the ship travels along its course. Because the emitted sound is confined to a very narrow beam, these profiles provide a two-dimensional record of depth versus distance along a very narrow strip of sea floor directly under the ship's track (figs. 1*B*, 2). No information about the sea floor is acquired on either side of the track. However, by collecting many profiles side by side over an area, it is possible to construct a plan-view map of the ocean floor and thus estimate or interpret the landscape between profiles. Lines of equal water depth (isobaths) on these bathymetric maps define the undersea mountains, valleys, and plains (fig. 3). Bathymetric maps are the equivalent of topographic maps used by hikers, for example, to plan their routes. Training is required to interpret bathymetric maps and to recognize the various morphologic features. However, computers can be used to enhance and "shade" bathymetric maps to create a three-dimensional effect, and then no special skills are needed to recognize the undersea mountains, valleys, and plains (fig. 4). Recognition of morphologic features is simplified when color is added to the three-dimensional diagram (fig. 5).

The collection of bathymetric data has been greatly improved in recent years with the development of multibeam instruments that acquire information along a strip of sea floor on either side of the ship's track. Multibeam bathymetric data are commonly collected by using a method called swath mapping, described below, which provides accurate information about water depth over large contiguous areas. Computers onboard ship are programmed to construct bathymetric maps from the data acquired in this way. These bathymetric maps more accurately define the morphologic features of the sea floor than those constructed from profiles that are spaced wide apart and where no data have been collected between profiles (fig. 6).

Other types of information about the morphology of the sea floor are obtained by instruments called sidescan sonars that scan or "look" to either side of the ship's track (fig. 1*A*). Sidescan sonar provides an acoustic image or sonograph of the sea floor that is similar to a satellite image of the Earth's land surface or an aerial photograph (optical image). As the sidescan-sonar instrument is towed behind a ship along previously determined tracklines, the sonar continuously emits pulses of sound that insonify strips or swaths of sea floor. The sound bounces off, or "backscatters," from the sea floor. This backscattered sound is recorded as various shades of gray on paper and video displays onboard the research ship. The shades of gray that range from black to white define the features of the sea floor and represent varying energy levels of sound returned from the sea floor and, thus, the acoustic image. The difference in the energy of the backscattered sound is related to various physical properties, including sediment grain size, surface roughness and hardness, and the slope of the sea floor. These sea-floor characteristics reflect the host of geologic processes that have produced the sea-floor environment.

Scientists use various sidescan-sonar systems to map the ocean floor. Low-frequency systems that send sound pulses at about 6.5 kHz (kilohertz or cycles per second) are best suited for regional mapping of broad areas of the sea floor. Midrange (30 kHz) and high-resolution (greater than 100 kHz) sidescan-sonar systems are best suited for most environmental-monitoring purposes and for locating manmade objects on the sea floor. In the Gulf of the Farallones study area, a midrange sidescan sonar was used to map the Continental Slope, and high-resolution sidescan sonars were used to survey the Continental Shelf.

Low-frequency sidescan-sonar systems can be used at speeds as high as 10 knots (11.5 mph) and image swaths of sea floor as wide as 60 km (38 mi), but swaths of 45 km (28 mi) and speeds of 6 to 8 knots (7–9 mph) are more typical during routine surveys. These systems are not used in water depths shallower than about 200 m (660 ft) and cannot resolve features smaller than about 50 to 150 m (165–495 ft). The GLORIA (Geological Long Range Inclined ASDIC) sidescan sonar is a low frequency system that is ideal for imaging very large features, such as mountain ranges and submarine canyons (undersea valleys) (fig. 7). Midrange sidescan-sonar systems are able to resolve features as small as a few tens of yards and, under optimum conditions, smaller. These systems have swath widths that range from 500 m (1,650 ft) to 5 km (3 mi) and generally are towed at speeds of about 3 to 4 knots (4–5 mph). Midrange systems, such as the SeaMARC1A, are highly versatile and can be used efficiently to map and detect features as large as undersea mountains (fig. 8) and as small as 55-gal barrels (see chapter on Farallon Island Radioactive Waste Dump). The high-frequency sidescan-sonar systems used to survey the Gulf of the Farallones study area have swath widths that range from 100 to 750 m (330–2,475 ft) and can resolve objects as small as a few feet. Because of their ability to resolve and detect sunken objects, these systems are commonly used to locate pipelines or debris on the sea floor.

Reconnaissance Versus Swath Mapping

Two different surveying methods are used to collect sidescan-sonar data—reconnaissance mapping and swath mapping. The reconnaissance-mapping method is used when information on large areas is required and (or) limited survey time is available. Within the area being surveyed, data are collected along widely spaced tracklines (fig. 9). The sidescan-sonar data collected along these tracks do not overlap, and so only strips of the sea floor are observed, not a contiguous area. Swath mapping is the method used to produce a mosaic (contiguous image) of the survey area (fig. 10). Swath mapping can be compared to mowing the lawn. The lawnmower cuts a swath of grass as it moves across the lawn. To ensure that no grass is uncut, the next return swath overlaps the previous swath until the entire lawn is cut. The swath-mapping method contrasts with the reconnaissance method, in which strips of lawn are left uncut. As discussed above, the width of the swaths depends on the type of sidescan-sonar system being used. When a mosaic is being constructed, tracklines are spaced so that adjacent swaths overlap by 10 to 20 percent. The sidescan-sonar data are processed by computers, and a mosaic of a chosen area of sea floor is progressively built by overlapping and joining adjacent swaths. A striking three-dimensional view of the sea floor results when bathymetry is combined with sidescan-sonar data to produce a stereographic image.

Gulf of the Farallones Study Area

Continental Shelf

Reconnaissance surveys were conducted on the Continental Shelf between Cordell Bank and Half Moon Bay east of the Farallon Islands using high-resolution sidescan-sonar systems (fig. 9). High-resolution sidescan sonar was chosen to be able to resolve features as small as ripples that have crests spaced inches to tens of inches apart and heights of a few inches. Approximately 2,500 line-km (1,560 mi) of sidescan-sonar imagery was collected during these surveys (fig. 9). Regional reconnaissance tracks were spaced nominally 4 km (2.5 mi) apart in a rectilinear pattern. The sidescan-sonar data were collected at a total swath of 200 m (660 ft) at ship speeds of from 1 to 4 knots (2–5 mph). Although high-resolution sidescan-sonar systems can resolve very small objects, only small areas can be surveyed at these swaths and speeds within a given period of time. These reconnaissance data were used to select a site to mosaic by the swath-mapping method. The chosen survey area was an 800-km^2 (320 mi^2) area on the central part of the Continental Shelf east of the Farallon Islands between Point Reyes and the Golden Gate and a 200-km^2 (80 mi^2) area on the upper part of the Continental Slope west of the Farallon Islands (Fig. 10).

Data collected along the reconnaissance tracks revealed various features on the seabed, including outcropping rock and several types of ripples, dunes, lineations, and depressions (these features are collectively called bedforms) (figs. 11–13). The various features were plotted on a map to establish their spatial distribution. However, the absolute boundaries of fields of bedforms and the geometric relations of various features could not be determined because of the widely spaced and nonoverlapping sidescan-sonar records. The regional map of the various features did establish that at least four major discrete fields of bedforms occur on the Continental Shelf between Point Reyes and Half Moon Bay. These fields were separated by monotonous stretches of flat, featureless sea floor. Of particular interest were a series of depressions floored by ripples with wavelengths of about 1 m (3 ft). These depressions, which are common east of the Farallon Islands between Point Reyes and the Golden Gate, compose the largest of the four fields of bedforms.

The mosaic, supplemented and complemented by sediment samples, bathymetric profiles, and high-resolution seismic-reflection profiles, provides sufficient information to allow a more thorough description of the morphology of the sea floor. The sidescan-sonar data that compose the mosaic were computer processed so that the mosaic represents a true plan view of the sea floor; that is, features on the sea floor shown on the mosaic are in their true spatial position and geometric shape. In addition to defining the extent and geometry of the depressions discovered during the reconnaissance survey, the swath survey revealed a variety of unusual and complex bedforms.

Some scientists attribute the digitate depressions to a combination of tidal currents and storm-generated currents. The depressions are erosional features that reflect the intensity of waterflow over the area. Large (1-m wavelength) ripples occur in the depressions floored by medium and coarse sand. The ripples appear to be generated by waves. No ripples have been resolved with the sidescan-sonar systems on the intervening areas of fine sand. Although small ripples probably occur on these areas, these ripples are too small to be resolved by the sidescan-sonar systems. The depressions and ripples manifest a dynamic and complex sediment transport system that certainly varies with space and time.

Clearly, the Continental Shelf in the Gulf of the Farallones 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.

Continental Slope

Gravity-induced transport is common on the relatively steep, rugged Continental Slope. Submarine slumps and slides and debris flows are some of the products of gravity-induced mass sediment transport. Submarine slides range in size from a few square meters to tens of square meters or even hundreds of square meters. Because of the rugged slope morphology, depth of water, and broad range of sizes of features characteristic of the slope, a midrange (30 kHz) sidescan-sonar system was chosen to map the Continental Slope.

The mosaic, constructed by overlapping 5-km (3 mi) swaths, covered approximately 3,000 km^2 (1,200 mi^2) of the Continental Slope from the shelf break at about 200-m (660 ft) water depth to the basin floor at about 3,200-m (10,560 ft) water depth (fig. 8). Tracks were spaced about 4 km (2.5 mi) apart to obtain 20-percent overlap. These data, complemented by sediment and seismic-reflection data, show that the rugged northern part of the study area is scarred by numerous small canyons. Sediment cover is thin or absent. This northern part contrasts markedly with the southern part of the study area, which is much less rugged and draped by a thin blanket of sediment. Sediment in the southern part of the study area appears stable because no large underwater landslides were discerned on the sonographs. Conspicuous geomorphic features in the southern part of the study area include Pioneer Canyon and Pioneer Seamount (fig. 8). Pioneer Seamount is volcanic basement (dark areas) being covered by hemipelagic sediment (light areas). The expansive white to light-gray areas north and south of Pioneer Canyon are gently sloping, relatively flat and featureless plains of mud. Sediment is accumulating in Pioneer Canyon and on Pioneer Seamount, suggesting that is area is depositional, in contrast to the active shelf environment described in the previous section.

Two large nongeologic targets appear on the mosaic (fig. 14). One target is the remains of the SS *Puerto Rican*, an oil tanker that sank several years ago. The other target, which is about 250 m (825 ft) long, could be the aircraft carrier USS *Independence*, scuttled in 1951 after being contaminated during atomic tests at Bikini Atoll; or it could be a dry dock scuttled in 1985.

Implications and Conclusions

The acoustic-profiling systems and sidescan sonars allow, in effect, the water column to be stripped from the sea floor, thereby providing a clear, unobstructed view of the seabed. By selecting the appropriate sidescan-sonar system, images can be obtained of features as large as seamounts tens to hundreds of miles in diameter and as small as sand ripples with wavelengths of only a few inches.

The sidescan-sonar mosaic provides a map that can be used to design other surveys and sampling schemes. Baselines can be established so that surveys can be repeated to monitor morphologic and other changes of the seabed. Knowledge of the regional morphology of the sea floor is invaluable to oceanographers, biologists, and geologists. For example, currentmeter arrays can be placed to measure the effects of bathymetry on current systems, or bathymetric features can be avoided if that is the goal of the experiment. Without a sidescan-sonar mosaic, the effect of bathymetry on the current measurements would be unknown. Information from the mosaic has 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 the mosaic to locate the substrate preferred by bottom fishes and crabs. Sidescan-sonar mosaics are so valuable for efficiently planning other surveys and experiments, that swath mapping with sidescan sonar should be considered a basic, first-order environmental-monitoring tool.

Further Reading

Belderson, R.H., Kenyon, N.H., Stride, A.H., and Stubbs, A.R., 1972, Sonographs of the sea floor, a picture atlas: Amsterdam, Elsevier Publishing, 185 p.

Gardner, J.V., Field, M.E., and Twichell, D.C. (eds.), 1996, Geology of the United States' seafloor—the view from GLORIA: Cambridge, Cambridge University Press, 364 p.

Schlee, J.S., Karl, H.A., and Torresan, M.E., 1995, Imaging the sea floor: U.S. Geological Survey Bulletin 2079, 24 p.

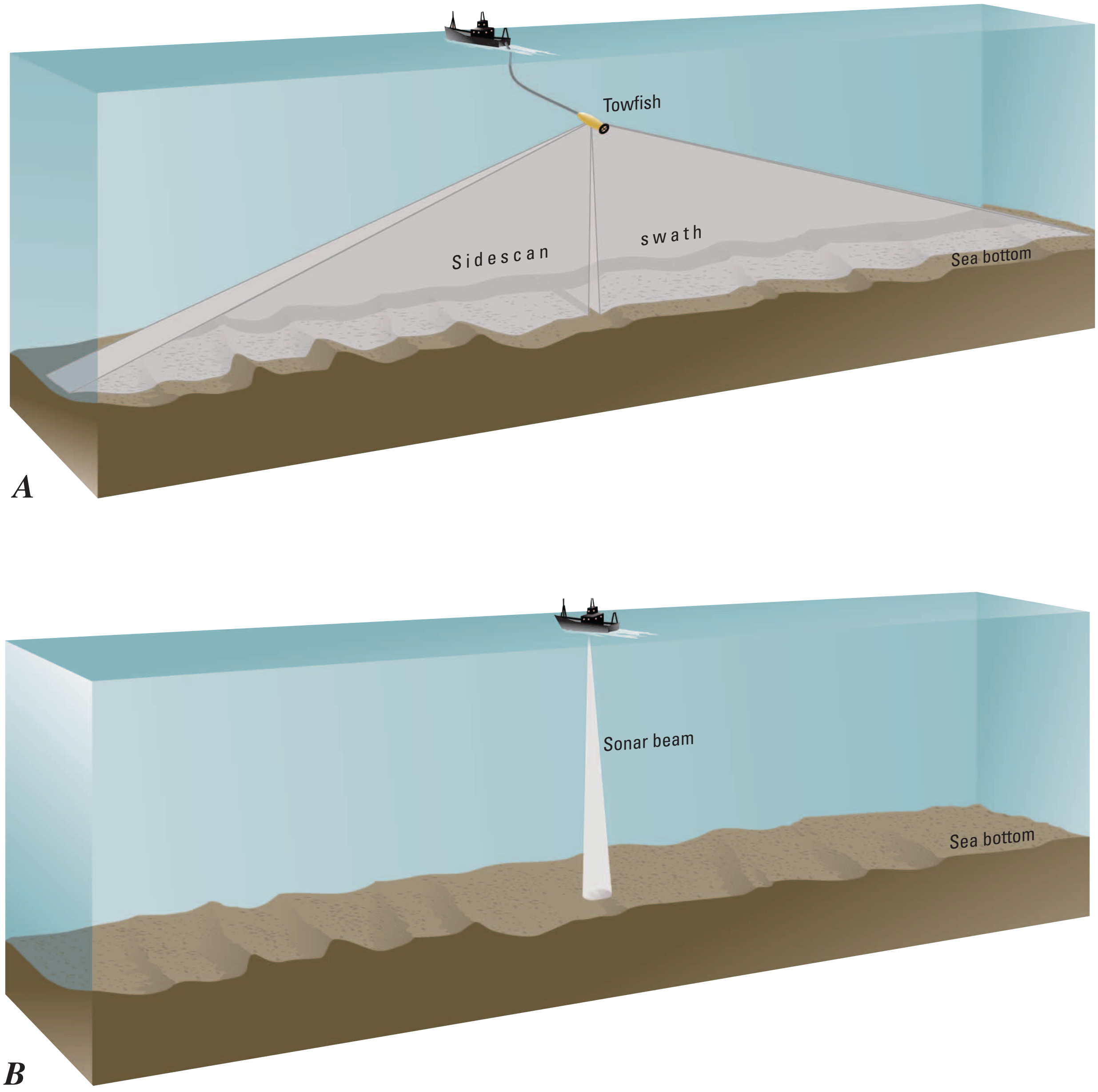

Figure 1. Comparison of swath coverage of two acoustic instruments. *A*, Swath coverage of a towed sonar instrument. *B*, Swath coverage of a hull-mounted narrow-beam profiling instrument.

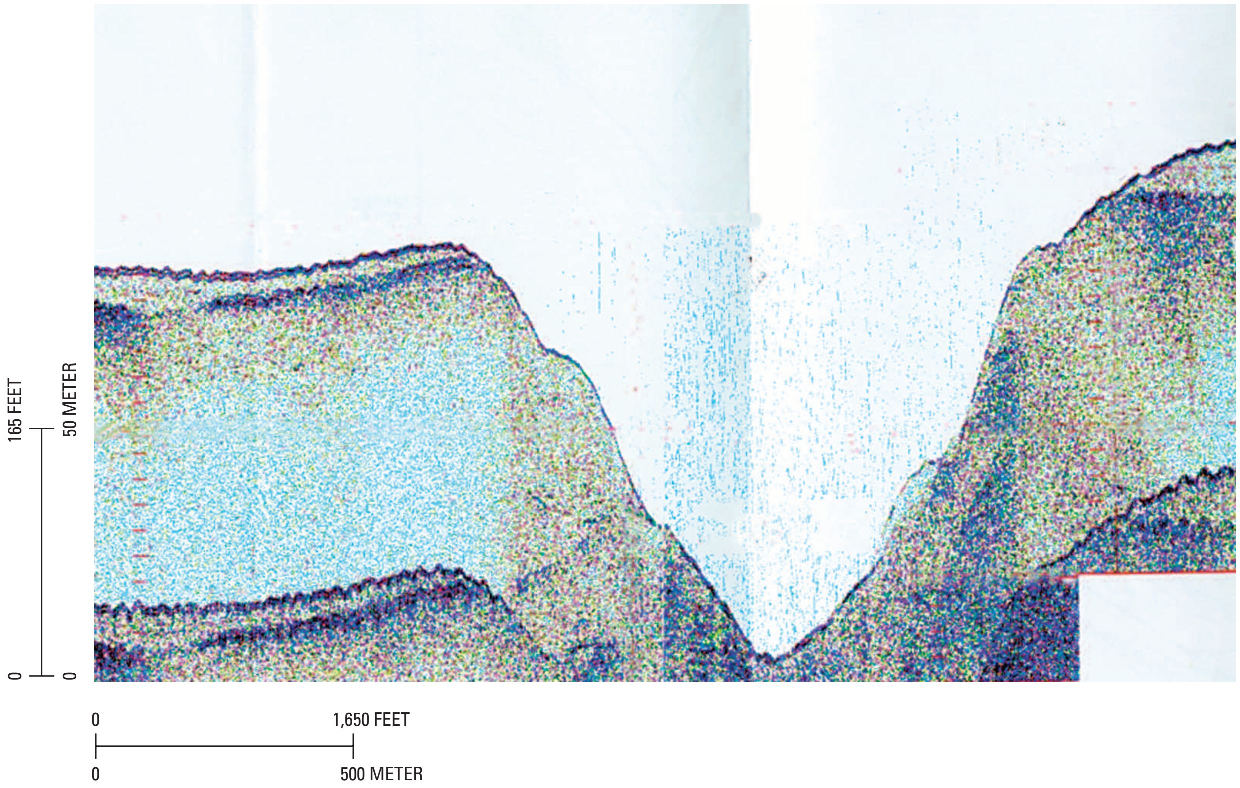

Figure 2. Profile from a narrow-beam acoustic profiling system, taken across a submarine canyon, shows the rugged sea bottom topography typical of the northern Gulf of the Farallones.

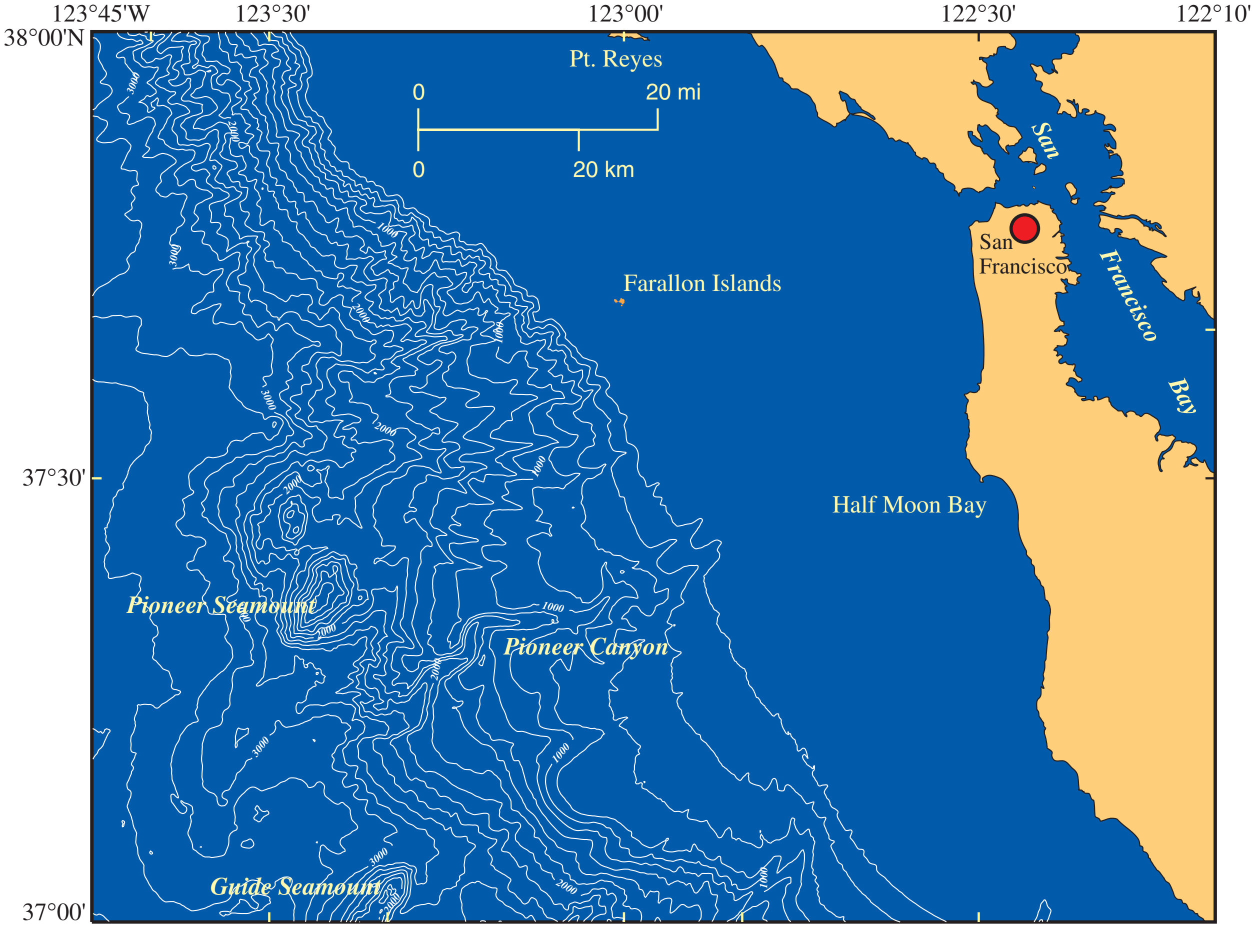

Figure 3. Bathymetric map of Gulf of the Farallones study area. Contour interval, 200 m (approx. 660 ft).

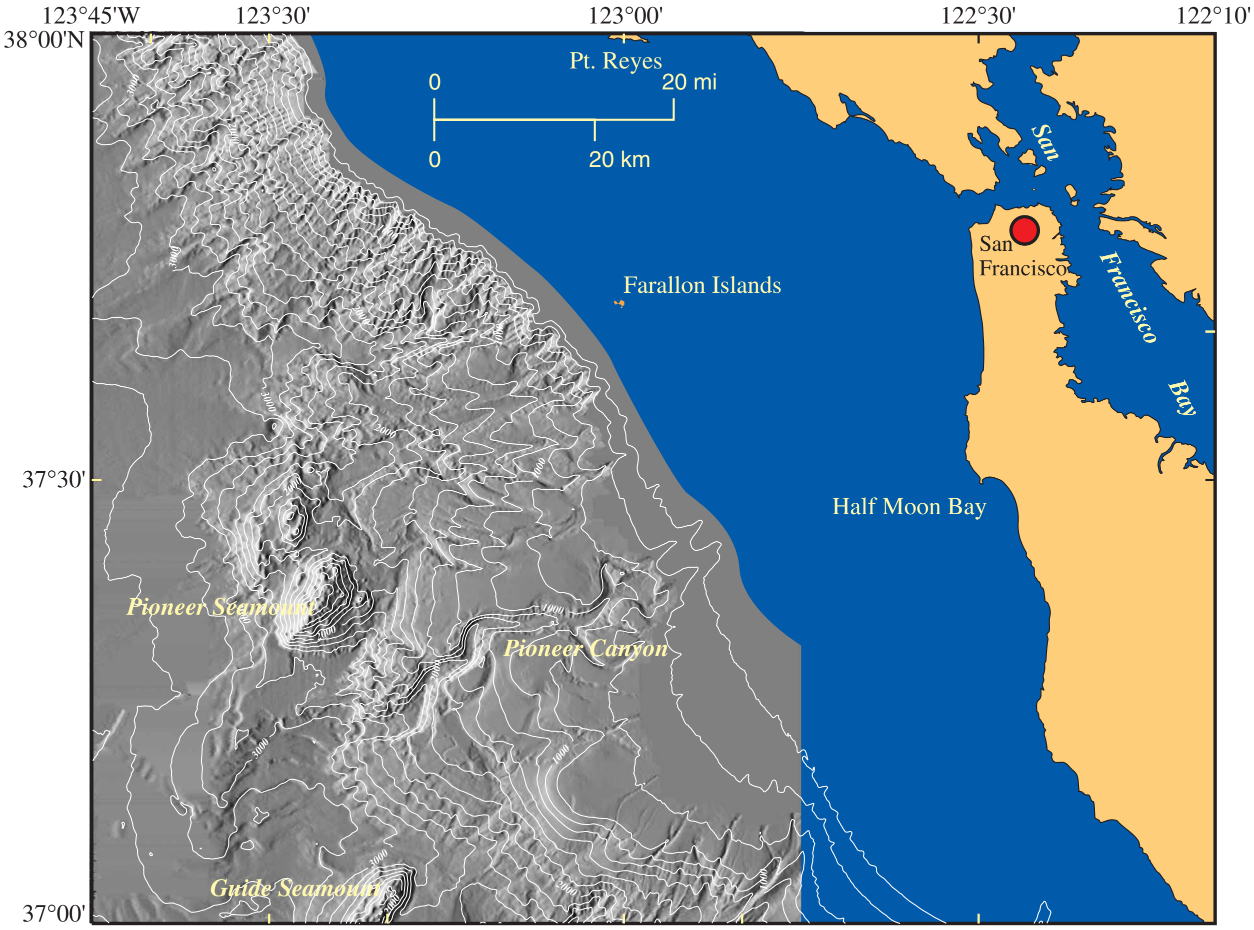

Figure 4. Three-dimensional bathymetric map of the Continental Slope in the Gulf of the Farallones created using sonar. Contour interval, 200 m (approx. 660 ft).

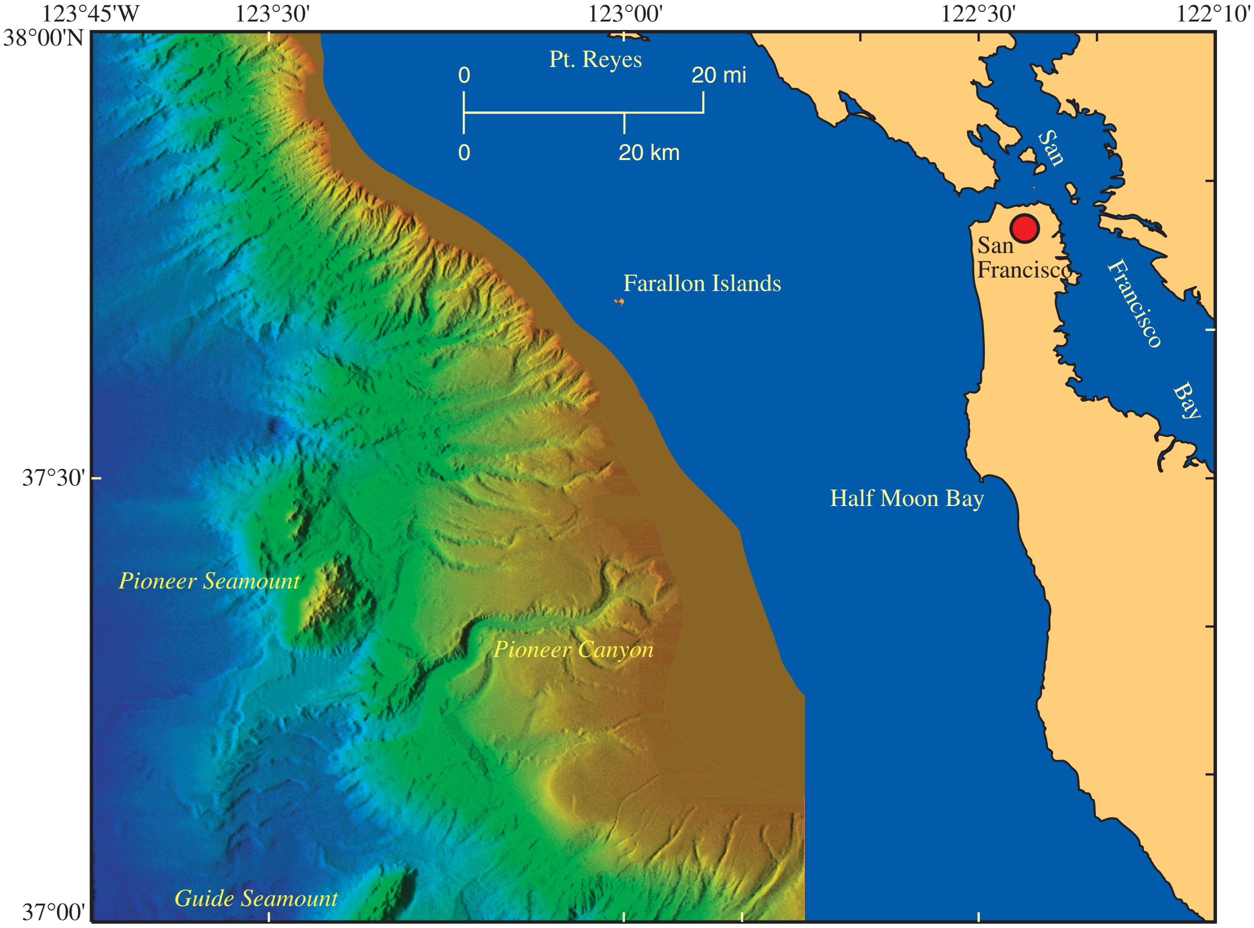

Figure 5. Color three-dimensional bathymetric map of Gulf of the Farallones study area. Contour interval, 200 m (approx. 660 ft).

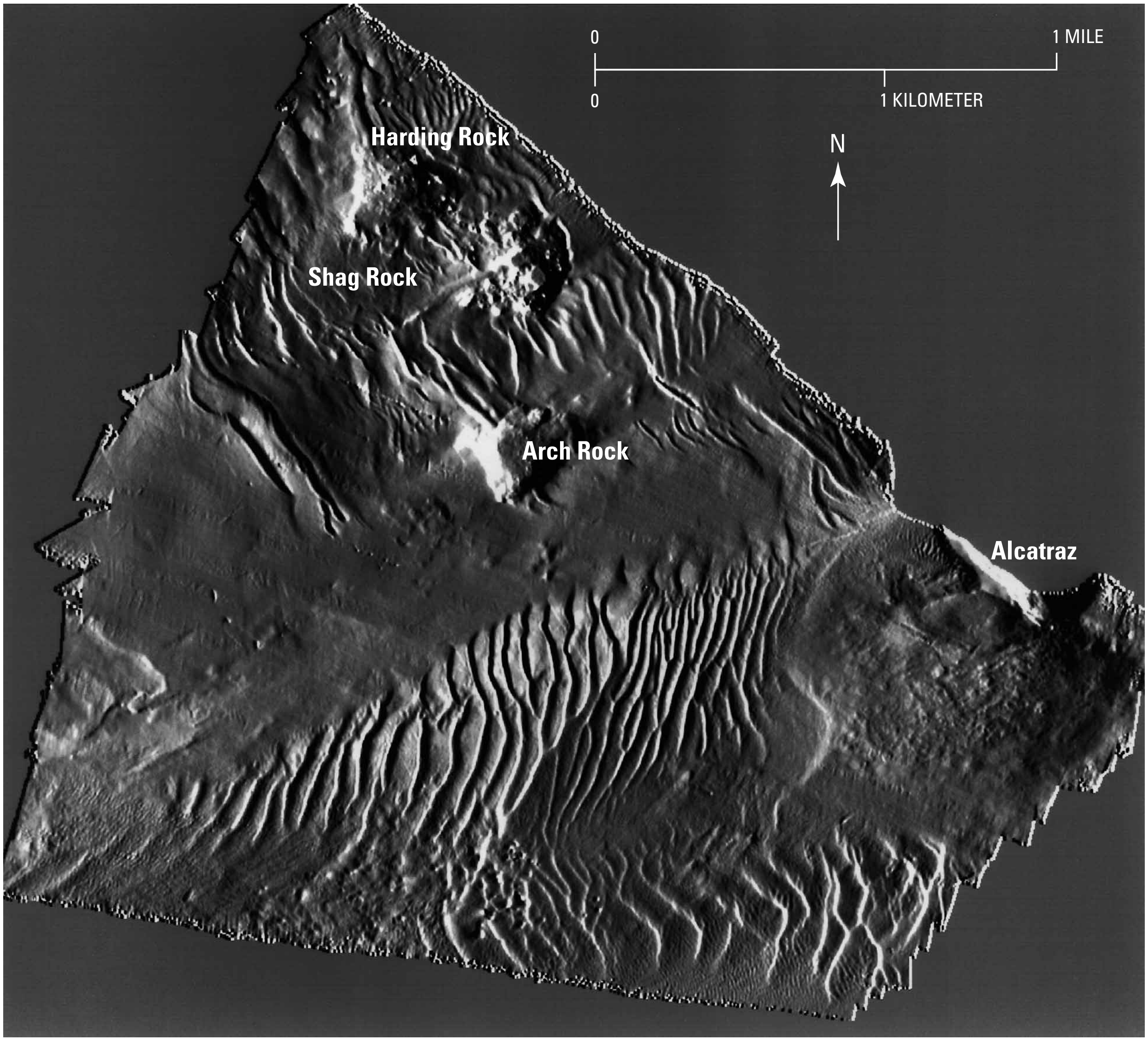

Figure 6. Typical shaded-relief image derived from multibeam data. Area of image is in San Francisco Bay and shows large sand dunes on the bay floor.

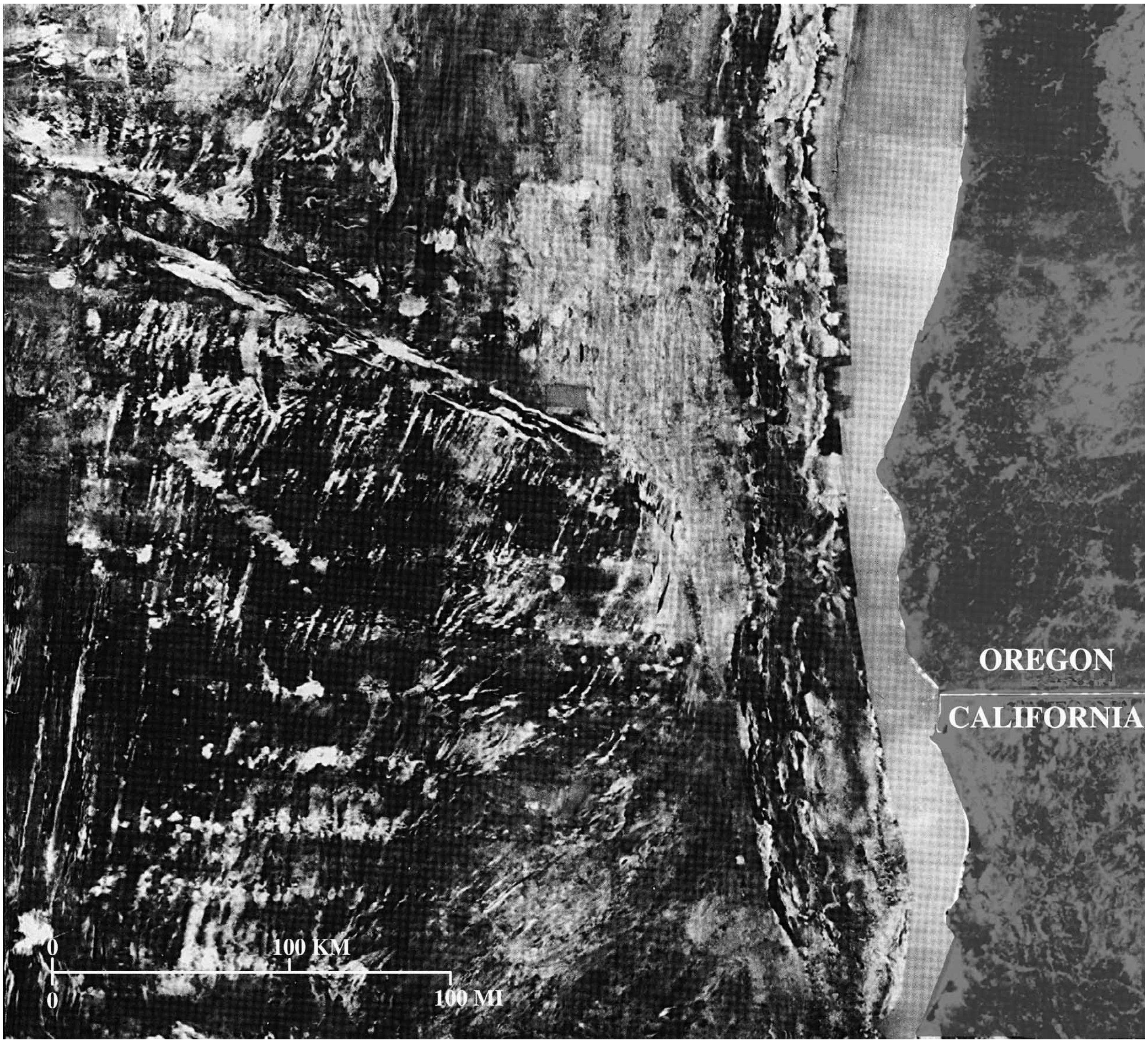

Figure 7. Mosaic image of sea floor off California-Oregon coast made using GLORIA sidescan-sonar system.

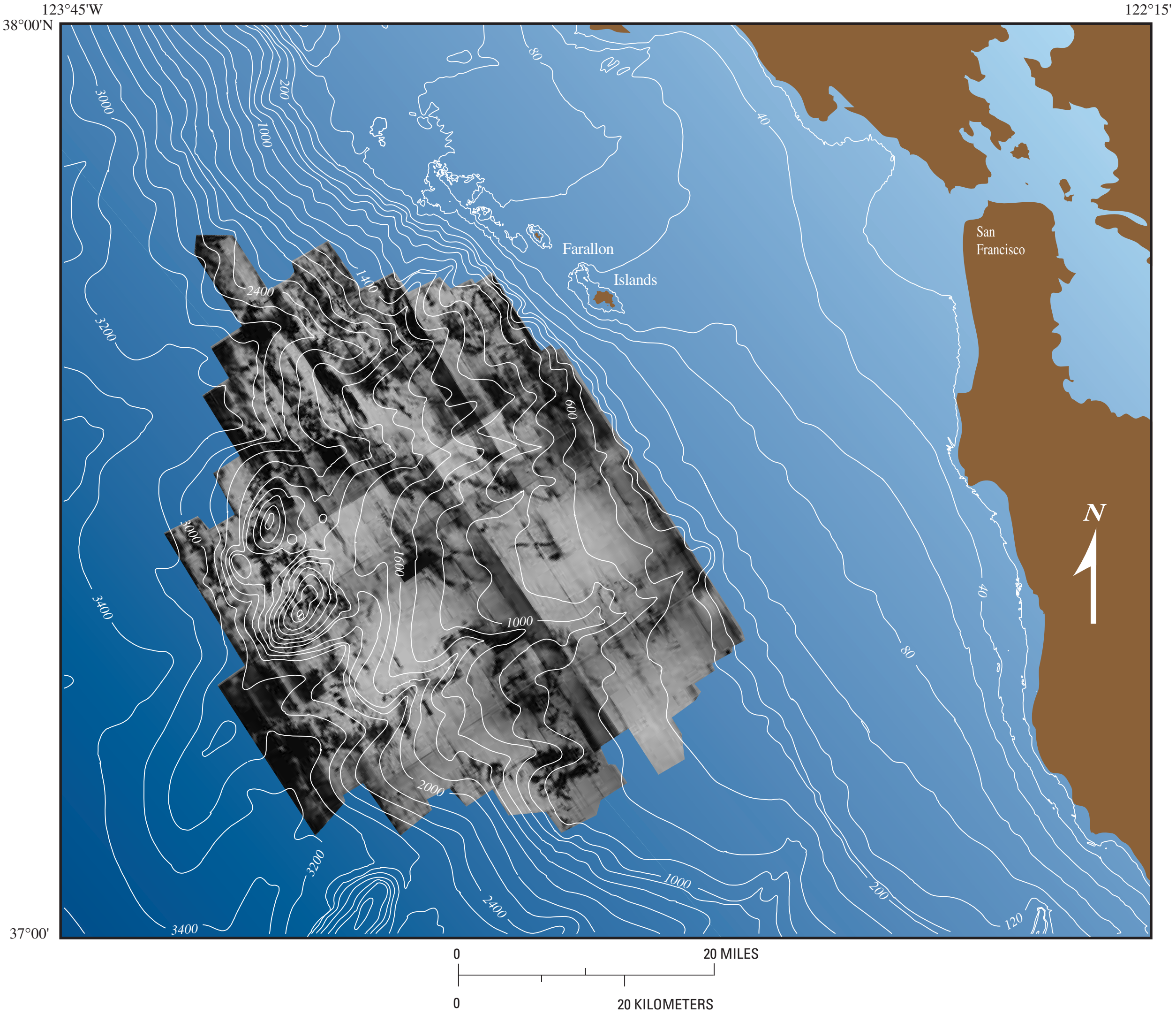

Figure 8. Sidescan-sonar mosaic of part of the Continental Slope in the Gulf of the Farallones. Contour interval, 20 m (approx. 66 ft) to 200-m (approx. 660 ft) depth; 200 m (approx. 660 ft) in deeper water.

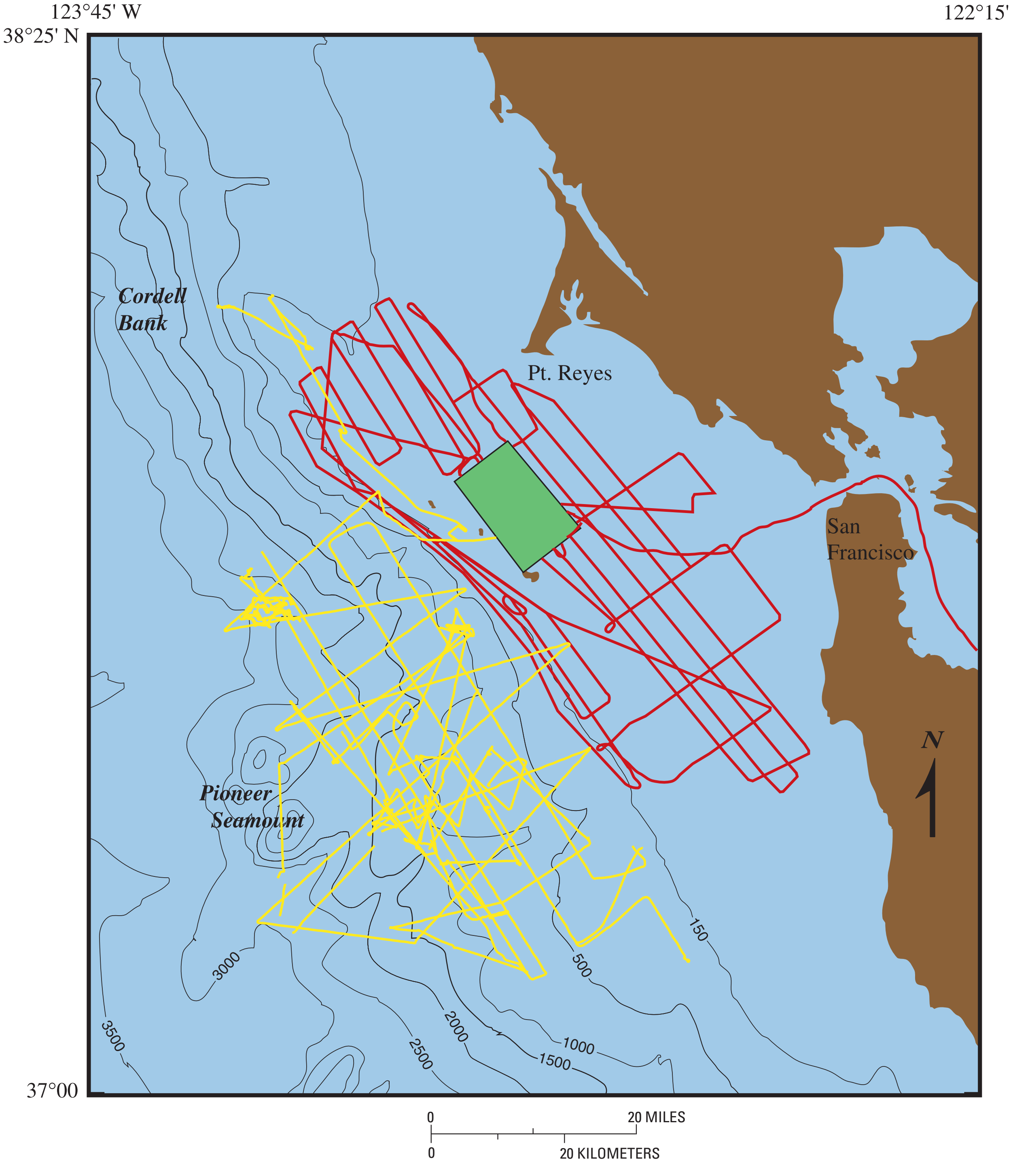

Figure 9. Gulf of the Farallones study area, showing reconnaissance coverage of ship tracklines on the Continental Shelf (red) and the Continental Slope (yellow). Green rectangle is area chosen for more detailed coverage. Contour interval, 500 m (1,650 ft), with supplementary contour at 150-m (500 ft) depth.

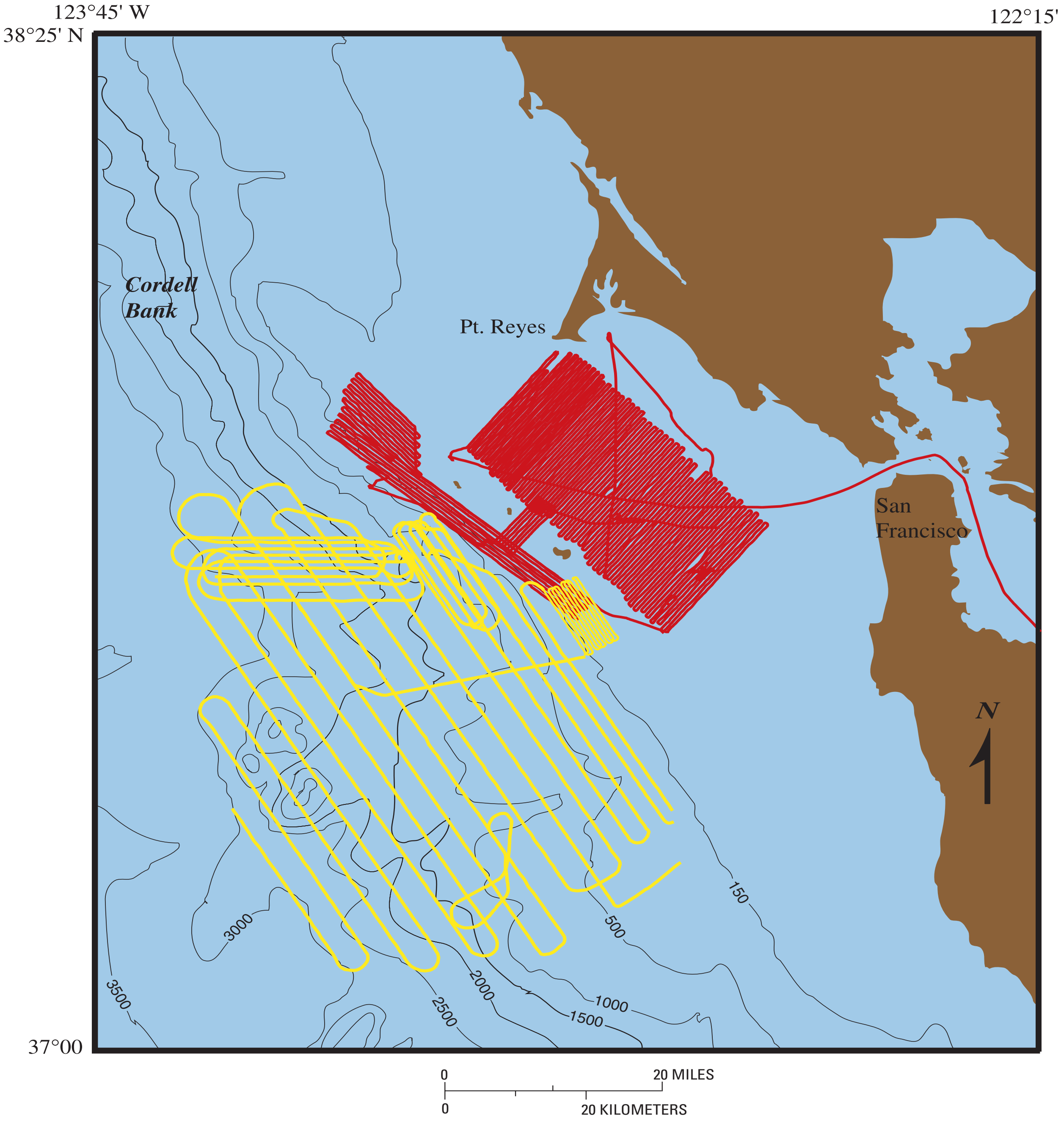

Figure 10. Gulf of the Farallones study area, showing ship tracklines from swath mapping on the Continental Shelf (red) (see figs. 12 and 13 for sample mosaics) and reconnaissance mapping on the Continental Slope (yellow). Mosaic in figure 8 was constructed from long, widely spaced tracks. Contour interval, 500 m (1,650 ft), with supplementary contour at 150-m (500 ft) depth.

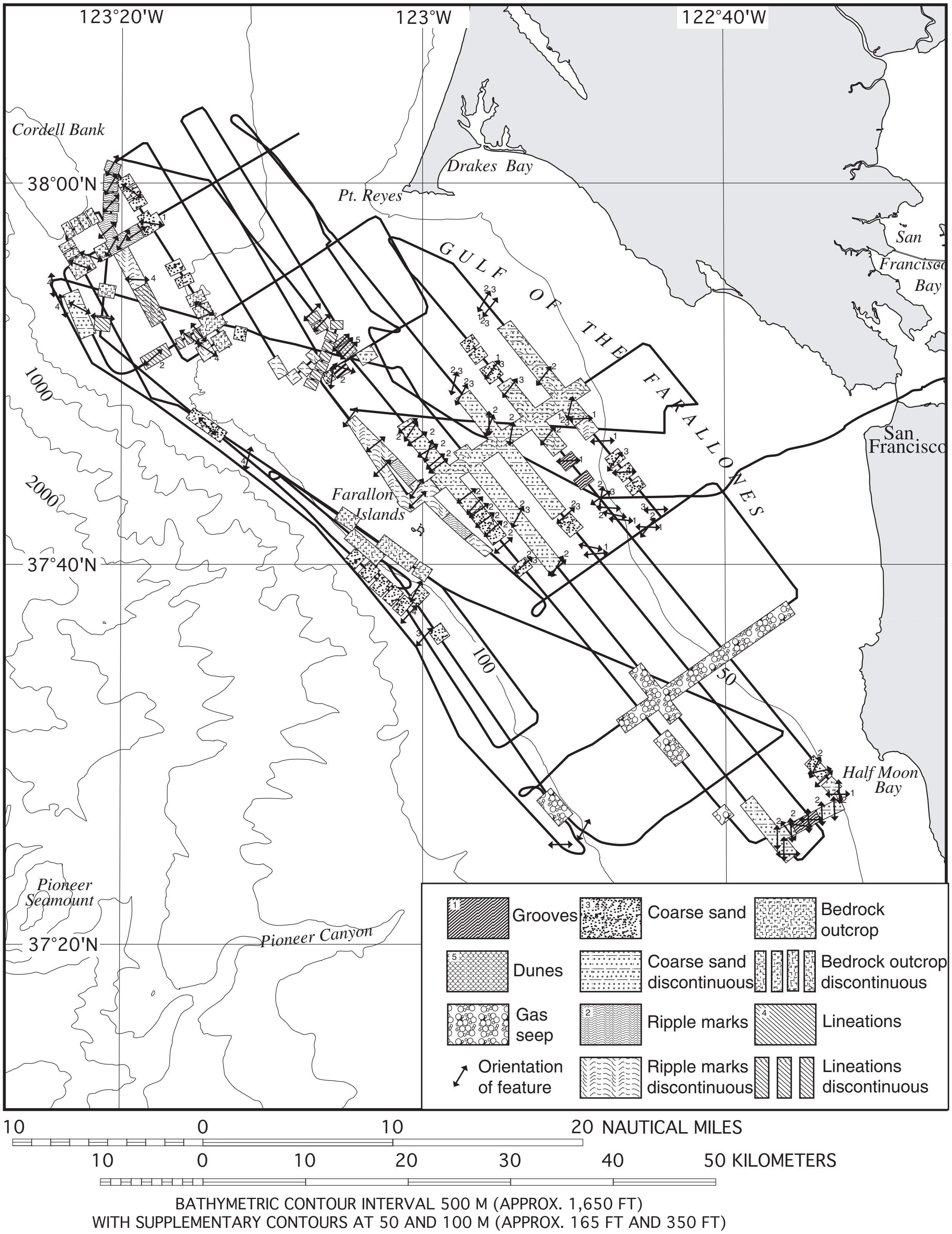

Figure 11. Interpretative map of Gulf of the Farallones based on sidescan sonar data, showing features of the sea floor.

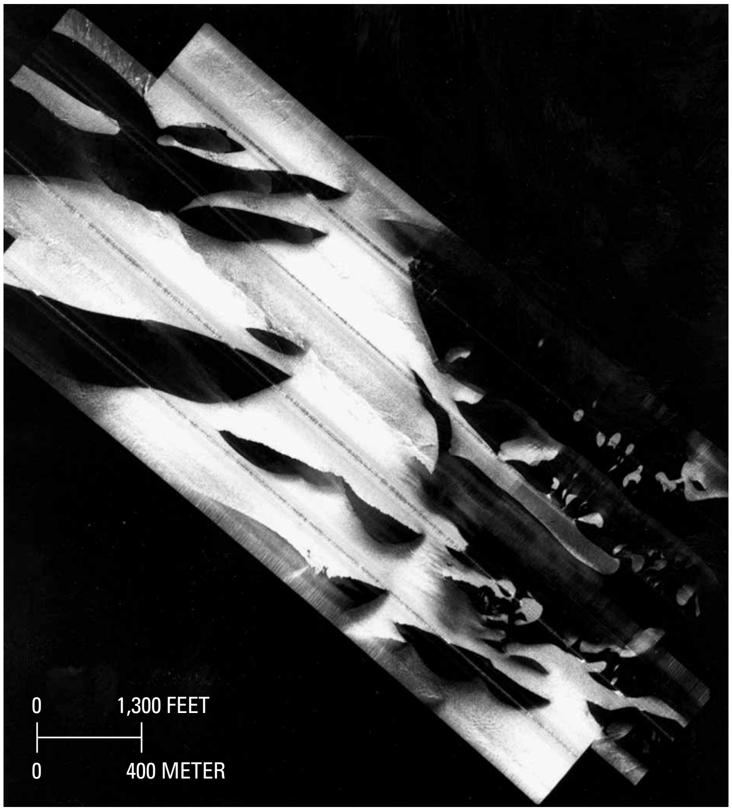

Figure 12. Sidescan-sonar mosaic, showing depressions floored by sand ripples east of the Farallon Islands between Point Reyes and the Golden Gate.

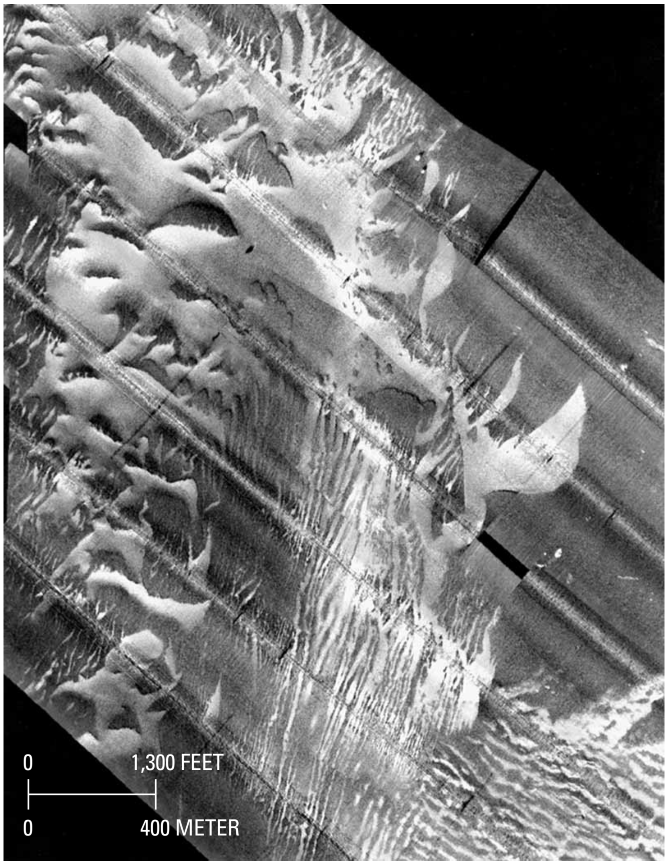

Figure 13. A sidescan-sonar mosaic from the Gulf of the Farallones showing unusual and complex bedforms, possibly ribbons of sand moving over sea floor.

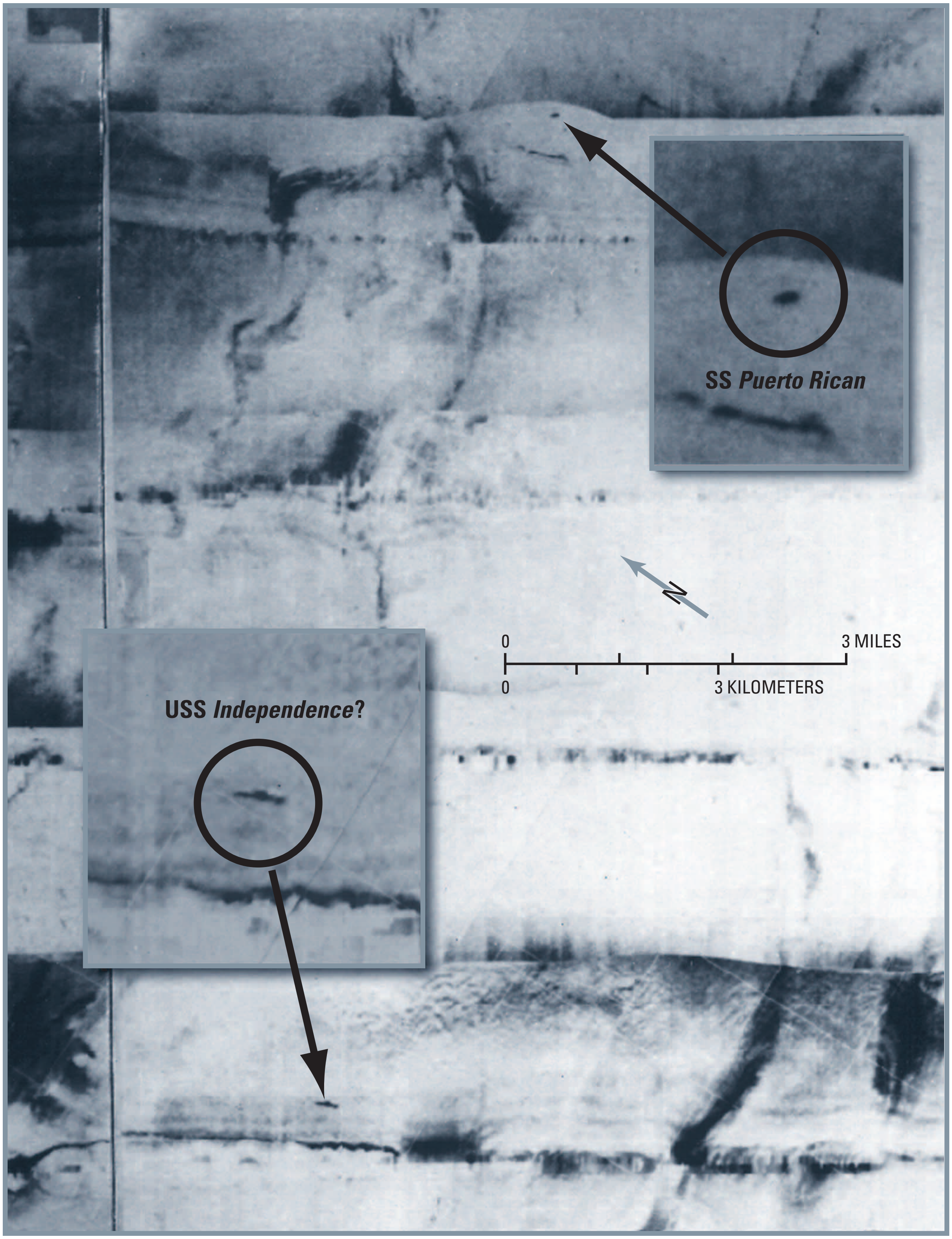

Figure 14. Detail of a U.S. Geological Survey sidescan-sonar mosaic from an area of the upper Continental Slope about 20 miles southwest of the Farallon Islands. On this image was discovered what is interpreted to be the USS *Independence* (CVL 22), a dangerously radioactive aircraft carrier scuttled in 1951. Also visible is the stern section of the SS *Puerto Rican*, an oil tanker that sunk in 1984.