Bedrock Knobs, San Francisco Bay: Do Navigation Hazards Outweigh Other Environmental Problems?

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ABSTRACT

Three bedrock knobs (Arch, Harding, and Shag rocks) rise above the unconsolidated sediment of central San Francisco Bay to a water depth of less than –12 m (<–39.4 ft MLLW). These rocks are within the westbound vessel traffic area, and the northernmost, Harding Rock, is ~300 m (984 ft) from the two-way deep water traffic lane. The rocks pose a hazard to deep-draft vessels. Large ships with drafts deeper than –17 m (–55.8 ft) cross central San Francisco Bay bound for and returning from major port cities of the Bay estuary. Acoustic profiling data show that bedrock extends at a gentle to moderate slope away from the knobs. These data also show that two of the knobs, Harding and Shag, may be part of a bedrock ridge that extends to Alcatraz Island and perhaps southeast to Blossom Rock. The tops of these rocks should be lowered to a depth of –17 m (–55.8 ft), with a total volume of as much as 245,000 m^3 (320,460 yd^3), at an estimated cost of nearly 27 million dollars, to eliminate the possibility that a tanker would strike one and rupture. A resulting large oil spill would likely cost many times more than the 10 million dollars needed to clean up a small 1996 spill. If the rocks were removed, local habitat for striped bass and other game fish would be altered, with potential negative impact on sport fishing. Currently, public officials are studying the benefits to the Bay environment of lowering the rock knobs.

INTRODUCTION

The Problem

Three rock knobs in central San Francisco Bay (Figure 1) are potential navigational hazards to the deep-draft vessels that transit the area. The bedrock knobs rise to within 11–12 m (36.1–39.4 ft) MLLW (mean lower low water) of the water surface of the central bay. Increased hull displacement to as great as 16.8 m (55 ft) is planned or realized for some of the modern tankers and freighters that transit the central part of San Francisco Bay to the ports of Oakland, Richmond, Sacramento, San Francisco, and Stockton. In 1995, more than 200 vessels with a draft greater than 11.6 m (38 ft) used the deep water traffic lanes (Harbor Safety Committee, 1996). The rock knobs (Figure 2) could cause a shipping accident if a ship were to stray from the narrow shipping lanes due to emergency maneuvering to avoid collision with another ship, loss of steering, unusually strong tides and winds, and errors in judgment or navigation. Such an accident might be compared to the massive and expensive oil spill that befell Prince William Sound (PWS) nearly 10 years ago. For example, in 1996 an 8,000-gallon spill occurred in San Francisco Bay, and was about 0.07 percent of the volume of the 1989 PWS spill (11 million gallons). In San Francisco Bay, the relatively small spill cost 10 million dollars to clean up (San Francisco Chronicle, 1996); which was only about 0.5 percent of the 2 billion dollars cost for the PWS spill cleanup (Alaska D. E. C., 1993). Currently, a sub-committee of the San Francisco Bay Harbor Safety Committee is studying what to do about the rock knobs, to minimize the potential for shipping accidents. Initial estimates of the cost to remove the tops of the rocks to –55 ft (–16.8 m) is 26,722,000 dollars (Harbor Safety Committee, 1996).

Removal of the tops of these knobs would obviate the hazard they pose. Some questions relevant to removal include the following:

1. What are the configurations and volumes of these bedrock outcrops that protrude above the bottom sediment and volumes of the subcrop buried beneath the sediment?
2. What is the composition of these knobs?
3. How much sediment has accumulated on the sides of these knobs?
4. What is the seafloor morphology surrounding these knobs?

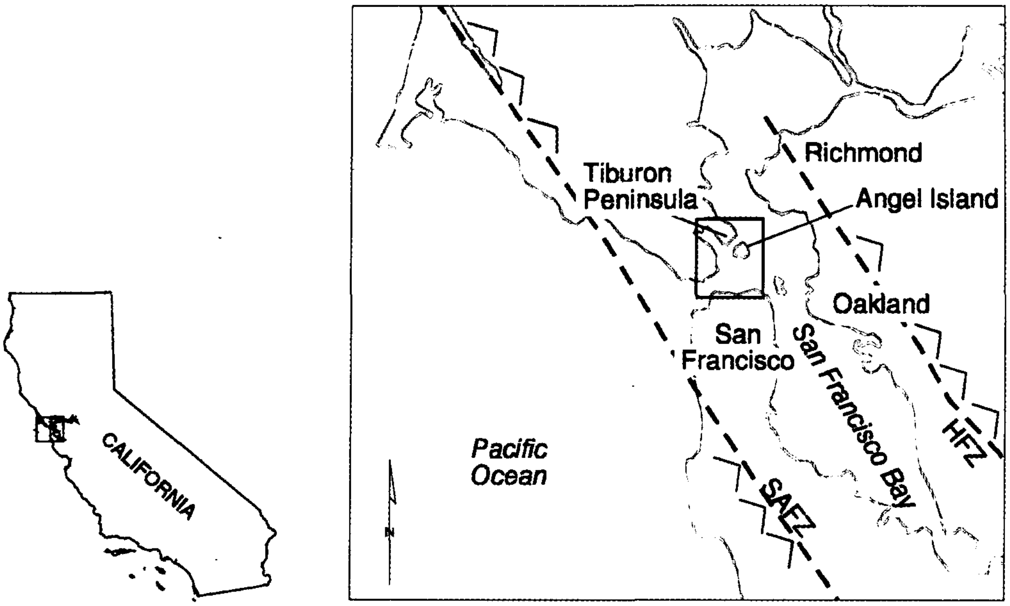


Figure 1. Location map of San Francisco Bay including major bounding faults (SAFZ = San Andreas Fault Zone; HFZ = Hayward Fault Zone), mountain ranges (^ ^ ^ ^ ^), and ports. Box delineates approximate area of multibeam imagery shown in Figure 2.

5) Can the bedrock material removed from the tops of the knobs be placed in adjacent depressions without deleterious effects on the surrounding seafloor?
6) What effects do the bedrock knobs and ridges have on the water circulation patterns in the central bay, and will the removal of the uppermost 6–7 m (19.7–23 ft) from these knobs modify significantly the water circulation in the central bay?
7) What effect would removal of the upper portions of the bedrock knobs have on fish behavior in the central bay? Are there specific types of fish that inhabit these features?

Setting

San Francisco Bay is a large complex estuary system (568 sq km), that is bounded both east and west by branches of the northwest-trending Coast Range mountains and by major fault systems: the San Andreas to the west and Hayward to the east (Figure 1). The Bay depression resulted from faulting and folding of Jurassic/Cretaceous Franciscan Complex rocks associated with tectonic activity in the last few tens of millions of years between the North American and Pacific plates (Page, 1992). The Bay is geologically young, and began to form about one million years ago during the first of several episodes of rising sea level (Atwater et al., 1977). The sediment filling the bay depression (Figure 3) ranges from late Pleistocene to Holocene in age (Rogers and Figuers, 1992). A very large volume of sediment flowed into the bay between 1850 and 1900 from extensive hydraulic gold mining in the foothills of the Sierra Nevada Range (Gilbert, 1917).

In this paper, we will concentrate primarily on a 6.5 km^2 (2.5 mi^2) area northwest of Alcatraz Island (Figures 2, 4, and 5).

Approaches

In order to provide scientific information pertinent to policy decisions regarding removal of the tops of the rocks, the USGS has recently collected multibeam swath bathymetric data of the floor of central San Francisco Bay that effectively portrays the seafloor in shaded relief (Figure 2). (For stereo format see USGS web site: http://TerraWeb.wr.usgs.gov/TRS/projects/SFBaySonar/Alcatraz_3dsr/index.html).

Using the multibeam data as a guide to seafloor features in the central bay, we have since collected additional seafloor data, including high-resolution seismic-reflection profiles, side-scan-sonar imagery, and samples of unconsolidated bottom sediment to supplement older, deeper penetration, seismic-reflection profile data over the area of the knobs. These various data sets are used to define the physical characteristics of the seafloor areas adjacent to the bedrock knobs.

Data Collection Techniques

High-resolution seismic-reflection profiles of central San Francisco Bay were obtained in the mid 1960s by the California Division of Bay Toll Crossings, San Francisco. Additional acoustic data were collected by the USGS in the late 1960s using 400 J (Joule) boomer and 2000 J sparker systems (Carlson et al., 1970). From all available

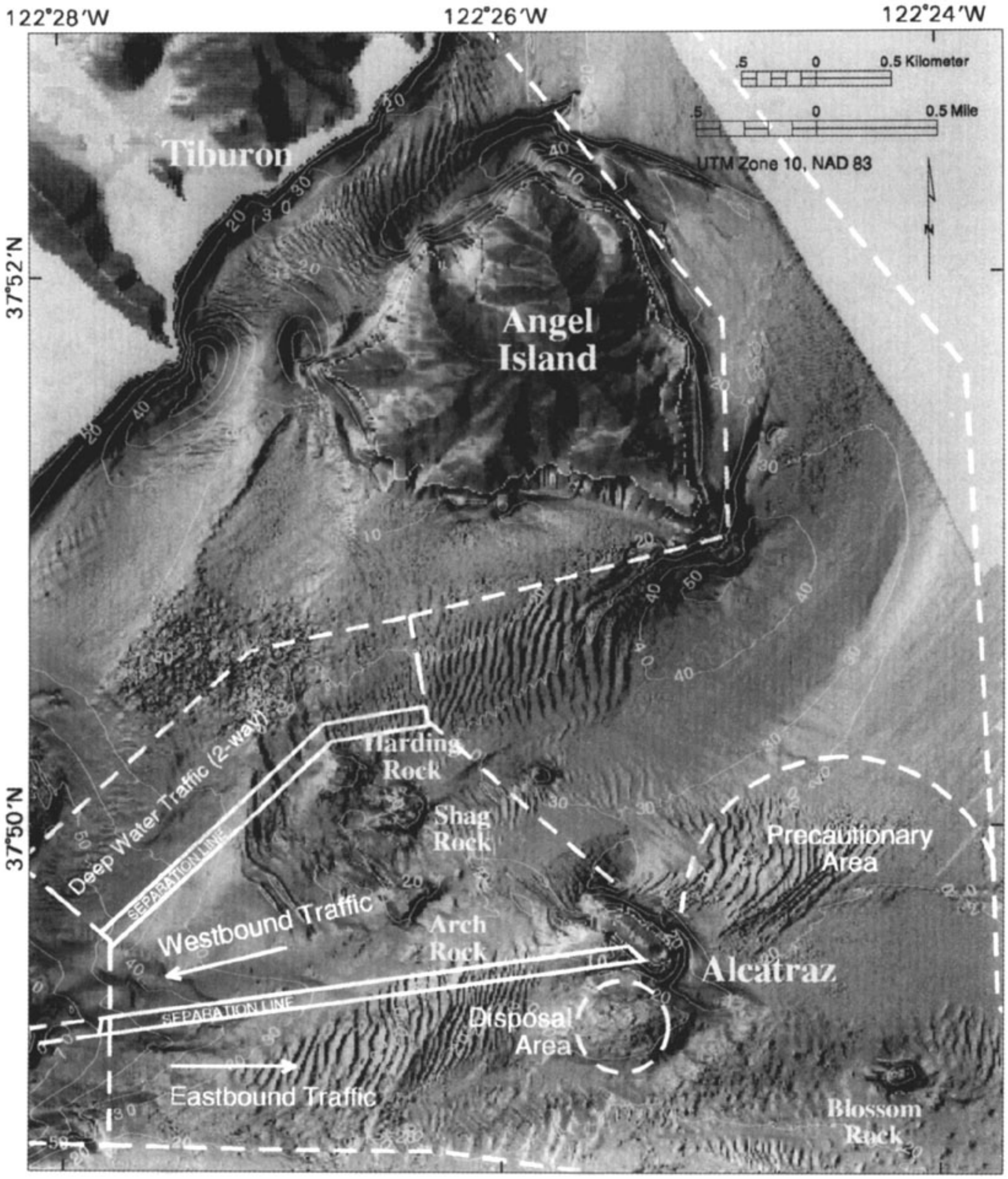


Figure 2. Shaded relief map of central San Francisco Bay based on multibeam bathymetric data, showing morphology of bay floor and navigational control zones.

data, Carlson and McCulloch (1970) produced a contour map showing the depth to the irregular bedrock surface that underlies the central bay sediment fill and in some places crops out at the bay floor. Navigation was by radar with location accuracy of about 400 m (437 yd). These seismic-reflection data were recorded as analog profiles on paper that has deteriorated, and become essentially unreadable. Fortunately, interpretive line drawings made on acetate overlays were saved and two of these overlays appear in this report.

A multibeam swath bathymetry survey conducted in 1997 has provided an accurate picture of the floor of central San Francisco Bay (Figure 2; Cacchione et al., 1997; Chin et al., 1998a). These newly acquired data, using Differential Global Positioning System (DGPS) navigation, have one meter (3.3 ft) horizontal accuracy and 0.1–0.2 m (0.33–0.66 ft) depth accuracy (after tidal corrections to MLLW). The system used in 1997 included a Simrad A/S EM-950 multibeam bathymetry and imagery system and peripheral integrated components for navigation, water property measurements, and data collection (see Kleiner et al., 1998, for details).

After the multibeam imagery of the central bay was collected, GIS technology was employed to digitally

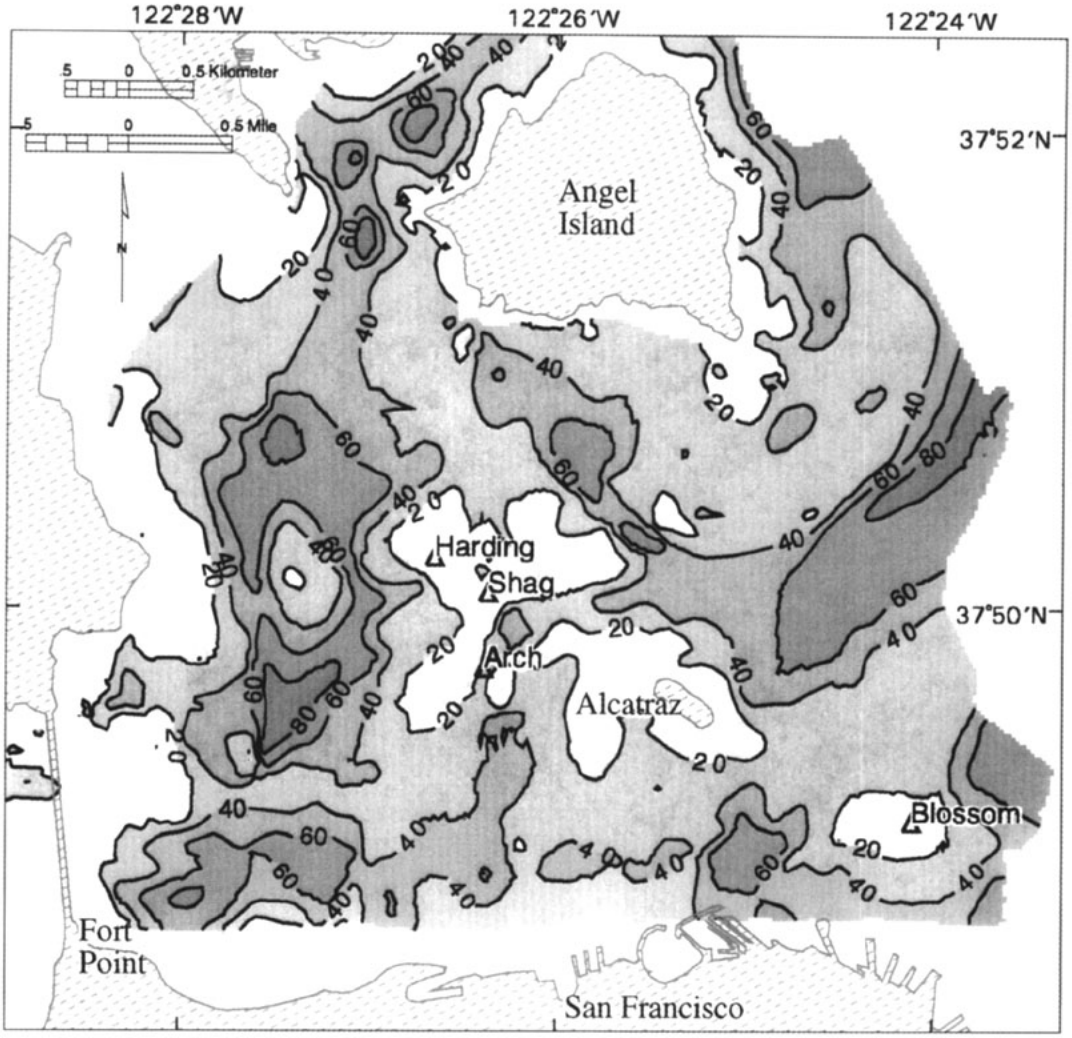


Figure 3. Sediment thickness map of central San Francisco Bay. Twenty-meter contour interval (modified from Carlson and McCulloch, 1970).

subtract the older (1960s) bedrock data from the multibeam bathymetric data of the present day seafloor. The result was a sediment thickness map of the west-central bay (Figure 3). We used these data to plan track lines for a 1998 high-resolution seismic-reflection, side-scan sonar, and bottom sampling cruise that makes up part of the data set used in this paper. Equipment for the January 1998 cruise included a Klein 100 kHz side-scan-sonar (sss), a 175 J single-plate and a 375 J double-plate Geopulse, and a 300 J minisparker. For sampling we used a 0.68 ft^3 (0.019 m^3) van Veen grab sampler.

RESULTS

Bathymetry

The new bathymetric map generated from the multibeam data (Figure 4), clearly shows some of the bay floor features that pose potential hazards to navigation and may require remediation in the central bay. The principal hazards to deep-draft vessels are bedrock knobs, the shallowest of which, Arch, Shag, and Harding rocks are about −11 m (−36.1 ft) (MLLW) below the bay water surface. We have calculated volumes of rock that will need to be removed to lower the summits of the three rocks to a depth of −17 m (−55.8 ft; Table 1).

The multibeam imagery (Figures 2, 4, 5, and 6) shows that Arch and Shag rocks are fairly flat on top as they have been altered by human activity. In 1900 the tops of Shag Rock (rocks 1 and 2) were blasted off in stages using several surface charges of nitrogelatin (90 percent nitroglycerin), followed by the removal of the rock debris with clam shell dredges (Hagwood, 1982). Using similar techniques, the top of Arch Rock was blown off in 1901 (ibid.). An old U. S. Coast Survey chart, sheet No. 2, Register No. 462, titled "Bay of San Francisco,"

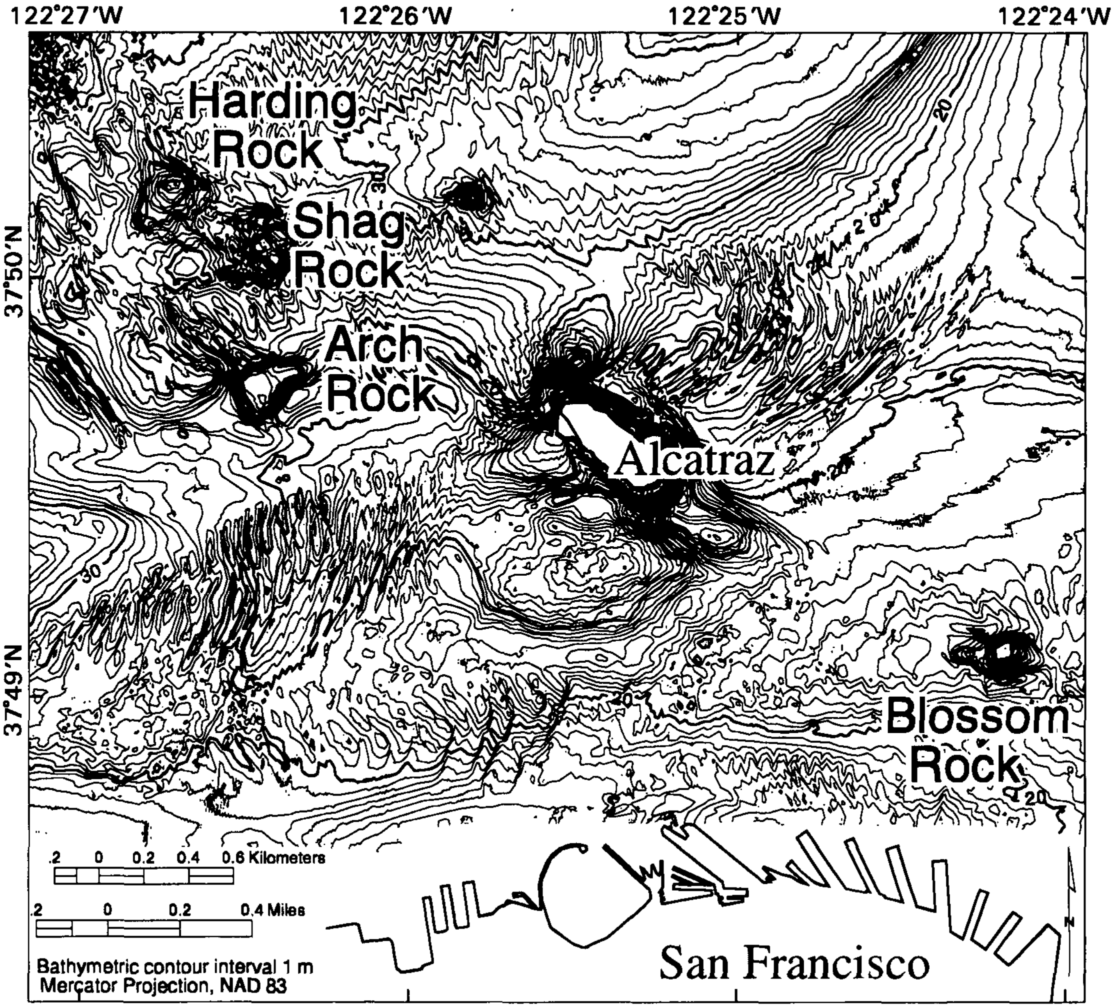


Figure 4. Detailed bathymetric map of study area. One-meter contour interval.

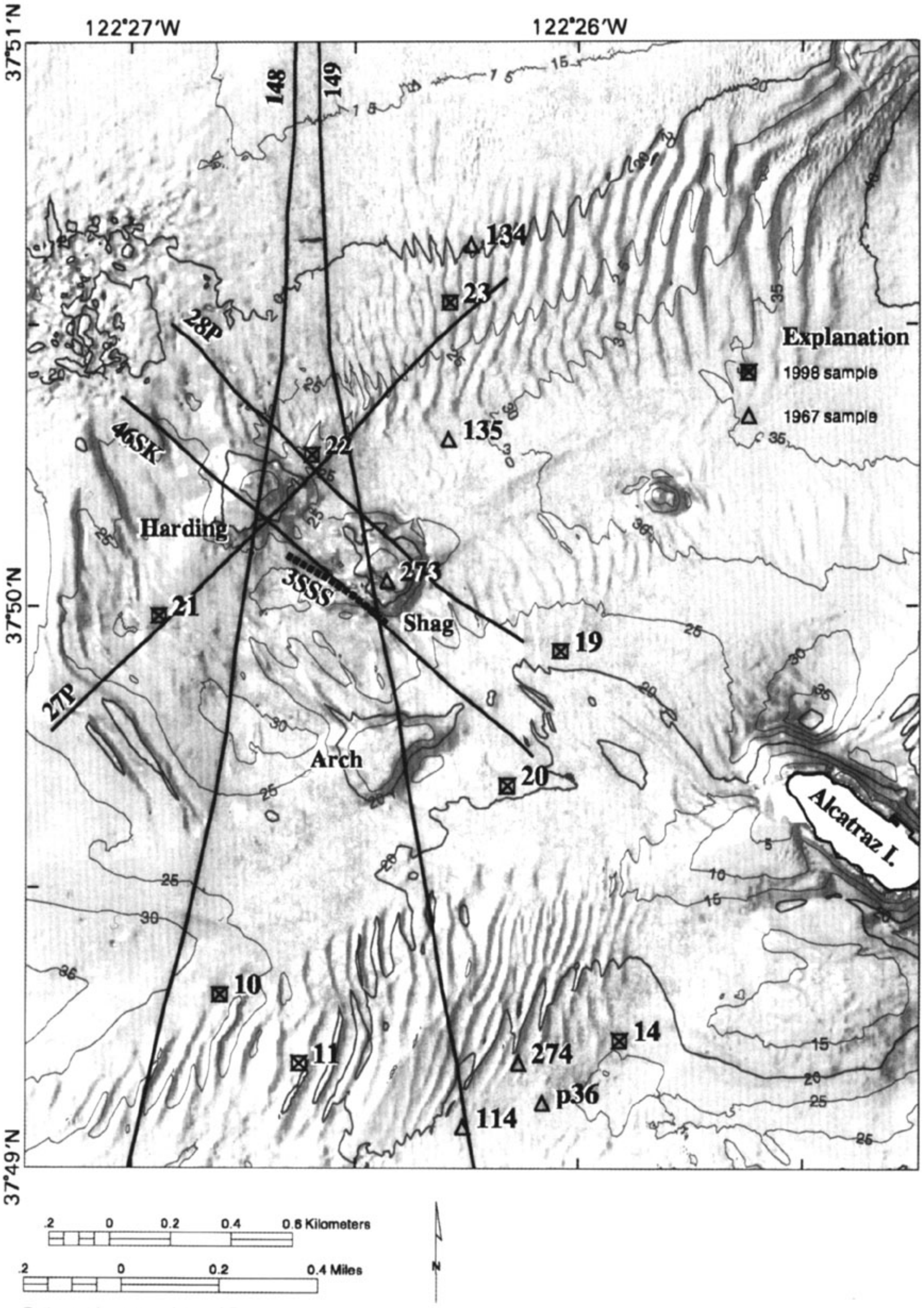
published in 1854, shows numerous shallow soundings around Shag Rock, the shoalest of which was –24 ft (–7.3 m). An 1859, U. S. Coast Survey chart shows soundings over Arch Rock, as shallow as –9 ft (–2.7 m). This site is labeled Bird Rock and is marked as the site of the wreck of the "Flying Dragon." Both the 1854 and 1859 charts show a sounding line near, but not directly over the top of Harding Rock; the shoalest depths on the 1854 chart line were –52.5 and –54.1 ft (–16 and –16.5 m) and on the 1859 chart about –68.9 ft (–21 m). We have not found any information that suggests the top of Harding Rock has been altered.

Arch Rock, presently the shallowest of the three, is slightly deeper than –11 m (–36.1 ft) at its shoalest part. This rock mass is somewhat triangular in shape, with a maximum length of 310 m (1,017 ft) along a west-southwest-east-northeast axis and 170 m (557.8 ft) wide in the northwest-southeast direction (Figures 2, 4, and 5). The area of this knob at –17 m (–55.8 ft) is ~45,000 m^2 (53,800 yd^2; Table 1). Arch Rock has the largest amount of rock at 156,100 m^3 (204,200 yd^3) that must be removed to lower the top of the rock to –17 m (–55.8 ft, MLLW).

Shag Rock whose top is somewhat oval to rectangular in shape has two flat spots at the top, both at ~–12 m (–39.4 ft) water depth (Figures 2, 4 and 5). The area at –17 m (–55.8 ft) is ~17,300 m^2 (20,700 yd^2). The volume of Shag Rock above –17 m (–55.8 ft) is ~51,100 m^3 (66,800 yd^3).

Harding Rock shoals to less than –12 m (–39.4 ft), has three small [<25 m (82 ft) diameter] protuberances on top, and is relatively round above the –17 m (–55.8 ft) contour (Figures 2, 4, and 5). The area at –17 m (–55.8 ft) is ~18,300 m^2 (21,900 yd^2). The volume of material to be removed to lower the top of Harding Rock to a MLLW depth of –17 m (–55.8 ft) is ~37,800 m^3 (49,400 yd^3; Figure 6).

To ensure the safe passage for deep-draft vessels, the total volume of rock to be removed from the tops of the three bedrock knobs is ~245,000 m^3 (320,460 yd^3). An estimate of the cost for cutting the rocks to that depth



Bathymetric contour interval 5 m
Mercator, 122°25'W, 37°51'N, NAD 83

Figure 5. Detailed shaded relief map of study area showing track lines of acoustic profiles and samples from 1998 and 1960s cruises.

Table 1. *Dimensions and water depths of the three bedrock knobs above –17 m, compared to dimensions of Alcatraz Island.*

Rock Name	Shoalest Depth m	Length at –17 m	Width at –17 m	Area at –17 m	Volume above –17m
Arch	>11 m	310 m	170 m	45,000 m^2	156,100 m^3
Harding	<12 m	160 m	150 m	18,300 m^2	37,800 m^3
Shag	~12 m	200 m	120 m	17,300 m^2	51,100 m^3
Alcatraz	emergent	550 m	200 m	181,600 m^2	n.a.

and then removing the material would likely exceed 14.2 million dollars (Gulf Engineers and Consultants, 1994)

In comparison to the areas of the three bedrock knob outcrops just listed, the area of Alcatraz above –17 m (–55.8 ft) water depth is about 181,600 m^2 (217,200 yd^2). (See Table 1).

The bay-floor sediment cover adjacent to these bedrock knobs varies from fairly flat beds that may be quite smooth or may contain small ripples, to surfaces dominated by different sizes of larger bedforms (Figures 2 and 5). On the shaded relief image of the study area (Figures 2 and 5), there are three fairly large bedform areas adjacent to the knobs. The largest field, about 1 x 2.5 km (0.62 x 1.55 mi), begins north of Harding Rock and trends northeast to the southeast corner of Angel Island. The bedform field terminates just before the large scour depression associated with that point of the island (Figure 2). A second bedform field, 0.6 x 1.2 km (0.4 x 0.75 mi), begins southwest of Shag Rock and extends east-northeast between Shag and Arch rocks for 1.2 km (0.75 mi) to a smaller unnamed bedrock knob. South of Arch Rock there is an apparently smooth area about 0.35 km (0.22 mi) wide that trends southwest-northeast. Further south of Arch Rock off the San Francisco waterfront, is a third large bedform field (Figure 2 and 4). This rather complex field is more than 1 km (0.62 mi) wide and about 2 km (1.24 mi) long.

According to Rubin and McCulloch (1980), bedforms smaller than 10 cm (4 in.) high, which may include small sand waves and current ripples, may be indistinguishable on sss imagery. This description may be applicable to the relatively smooth area immediately south of Arch Rock (Figure 5). The bedforms that can be seen on the side-scan and seismic-reflection data (Figure 7 and 8) range from small sand waves 10–20 cm (4–8 in.) high to large sand waves and dunes that, according to Rubin and McCulloch (1980) may attain heights of more than 8 m (26 ft). They explain that the heights and types of bedforms are dependent upon depth and velocity of the water and size of the sediment grains. They further conclude that in many areas where small bedforms (e.g., ripple marks) are superimposed on larger bedforms, vertical variations exist in the flow velocities (ibid.).

High-Resolution Seismic-Reflection Profiles

Two seismic-reflection profiles from the 1960s cruise and four from the 1998 cruise provide examples of the subbottom bedrock configuration and the overlying sedimentary units that lap onto these bedrock knobs. The track lines of the illustrated portions of these profiles are shown on Figure 5.

Line 27P, a single-plate Geopulse profile (Figure 8) crosses Harding Rock from southwest to northeast, somewhat southeast of its shoalest peak (Figure 5). The shallowest water depth along the 280 m (919 ft) segment of exposed bedrock on this transect is ~–22 m (–72.2 ft); thus, the trackline is offset from the <–12 m (–39.4 ft) shoal point on the bedrock knob. The bedrock reflector can be traced on each side of Harding Rock to a depth of ~–75 m (–246 ft) below the water surface (Figure 8). The water depth to the sand-wave surface on each side of this large bedrock knob is about –25 to –30 m (–80.3 to –98.4 ft), thus as much as 50 m (164.1 ft) of sediment has accumulated on each side of the outcropping knob. The apparent maximum slope of the bedrock surface buried beneath the onlapping sediment is about 7.5 degrees to 9.5 degrees on each side of this profile. The sediment surface morphology along the profile shows bedforms (sand waves) that range in wavelength from 50 to 150 m (164.1 to 492.2 ft). The bedforms vary in height from one to three m (3.3 to 9.6 ft). Trough cross bedding appears at depth on the northeast side of Harding Rock (Figure 8), suggesting that similar sedimentary structures are preserved in the subsurface. These subbottom characteristics indicate that tidal currents also influenced this immediate environment at the time the trough cross-beds formed.

Another Geopulse profile, Line 28P (Figure 9), was collected at approximately right angles to Line 27P (Figure 8) and crosses Shag Rock from northwest to southeast (Figure 5). The shallowest point on the profile, about –18 m (–59.1 ft), is part of a very irregular rocky outcrop offset from the ~–12 m (–39.4 ft) peak of Shag Rock (Figures 5 and 9). The portion of Shag Rock crossed by this profile has an average apparent slope of ~4.7 degrees to the southeast compared to an average apparent slope of about 3 degrees to the northwest. This profile crosses just to the northeast of Harding Rock. The gently sloping

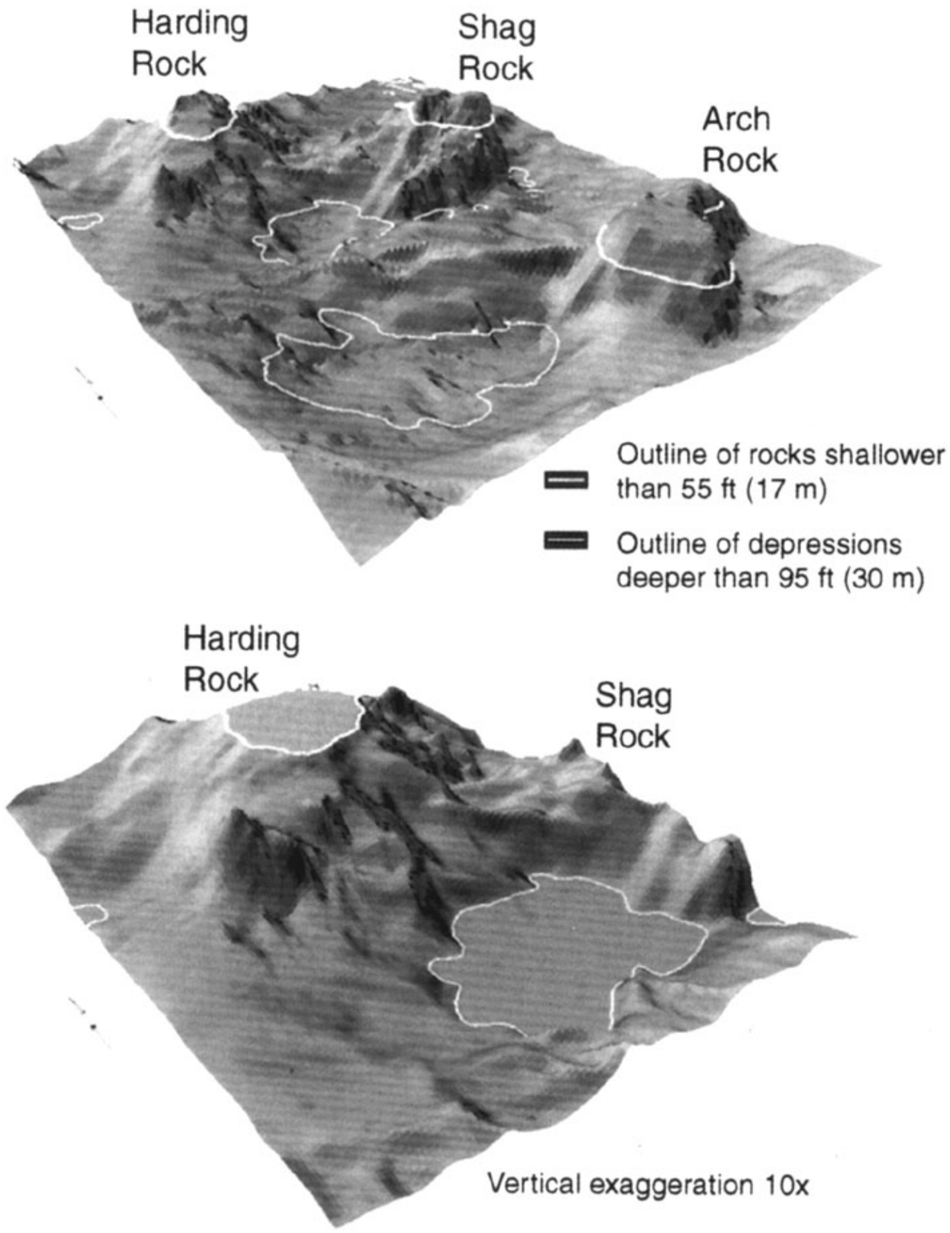


Figure 6. Perspective view of the three rocks (top). Bottom figure (enlarged view) shows a decapitated Harding Rock and the level to which the adjacent deep hole would be filled with the excavated rock.

bare bedrock surface that extends ~450 m (1,476 ft) to the northwest from the crest of Shag Rock, may also be continuous with Harding Rock.

Minisparker line 46SK (Figure 10), collected in 1998, crosses the southwest flank of both Harding and Shag rocks from northwest to southeast (Figure 5). The shoal point over Harding is ~–19 m (–62.3 ft) and over Shag, crossed at the southwest part of the outcrop, is ~–25 m (–82 ft). Along this track the two knobs project through the sediment and bound a small pond of sediment that is as much as 8 m (26.2 ft) thick (Figure 10). To the northwest the reflecting bedrock surface of Harding Rock slopes away at an apparent angle of ~5.7 degrees for a distance of 0.7 km (0.4 mi), at which point the onlapping sediment reaches a thickness of >55 m (180.5 ft). Here the bedrock reflection appears to continue its downward trend, but can no longer be traced with any certainty on the minisparker record collected in 1998. To the southeast, the bedrock surface has an average apparent gradient of ~5.7 degrees for a distance of ~0.4 km (0.25 mi) from the highest point on Shag Rock.

The deeper-penetration (2000 J) minisparker lines that were collected in 1967–68 included lines 148 and 149 (Figure 11). These lines extend northward across the central

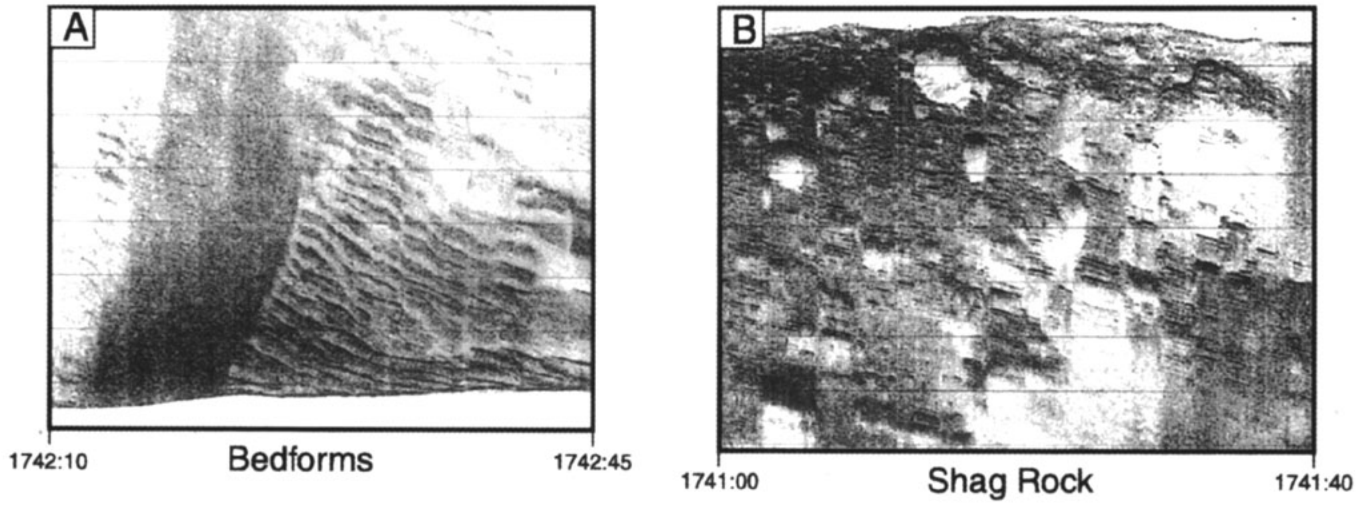


Figure 7. Images from 1998 side-scan-sonar line 3. A) Port channel: Example of bedforms (3–4 m wave lengths) west of Shag Rock. B) Starboard channel: Rocky outcrop of a part of Shag Rock. (See Figure 5 for location of sss line 3).

bay between the San Francisco waterfront and Angel Island (Figure 5). Line 148 (Figure 11) passes about 0.5 km (0.3 mi) west of Arch Rock and directly over Harding Rock. The higher energy of this system provided a relatively consistent bedrock reflection along the track line. This reflection reached a maximum depth of more than –60 m (–196.9 ft) below the water surface and revealed a sedimentary section that was more than 40 m (131.2 ft) thick on the north side of Harding Rock. South of Harding Rock there is another sedimentary section, possibly as thick as 40 m (131.2 ft), but the interpreted bedrock reflection is more tenuous. The bedrock reflections of each side of Harding Rock, as shown on profile 148 (Figure 11), have steep slopes, with parts of each slope exceeding 12 degrees. About 1.2 km (0.75 mi) south of Harding Rock, a sharp, apparent bedrock peak with deep holes to either side illustrates the very irregular surface of the Franciscan bedrock that forms the basement rock of central San Francisco Bay. .

The eastern line, 149, crosses somewhat east of Arch and west of Shag Rock, but near the centers of each outcrop area (Figure 5). This profile shows the bedrock reflection south of Arch Rock at more than –60 m (–196.9 ft) below the present bay water surface (Figure 11). North of Shag Rock the deepest bedrock hole visible on this profile is more than –50 m (–164.1 ft) below sea level. The maximum sediment thicknesses are more than 40 m (131.2 ft) south of Arch Rock, and in a much shallower bedrock depression, more than 20 m (65.6 ft) north of Shag Rock. Between the two peaks there is a 0.5 km (0.3 mi) wide basin or saddle with sediment that is more than 25 m (82 ft) thick. On profile 149 (Figure 11) the bedrock reflection is well-defined for all but the southernmost portion. The slopes of the bedrock reflections of these two knobs are more variable than those of Harding Rock. The south flank of Arch Rock has an apparent slope of ~4 degrees and the north flank of ~11 degrees, but contains a segment with a slope of more than 30 degrees. Shag Rock shows less variance for the two sides: ~8 degrees on the south and ~4.7 degrees on the north. The interpreted profile 149 (Figure 11) shows the bay floor north of Shag Rock to consist of a field of large bedforms that extend for nearly 1 km (0.62 mi). Similarly, the multibeam bathymetry (Figures 2 and 5) shows some well-developed bedforms north of Shag Rock.

Both the seismic-reflection profile data and multibeam imagery suggest the presence of an extensive bedrock ridge that includes the bedrock knobs. The ridge extends northwest of Harding Rock and southeast at least to Alcatraz and possibly further southeast to Blossom Rock (Figure 2). This ridge approximately parallels the regional structure exhibited by the major faults and coastal mountains (Figures 1 and 2).

Sediment Size Characteristics

From the bedrock knobs area, we collected eight van Veen grab samples in 1998. We also have data from five samples collected in the late 1960s (Figure 5). Except for one muddy sample, the grab samples range from fine to coarse sand to pea gravel, and are from well-defined bedforms according to the multibeam map (Figure 5). The only muddy sample, 20, (Figure 5) is a very poorly sorted, muddy, gravelly sand obtained from an area east of Arch Rock that is devoid of any clearly defined bedforms on the multibeam imagery. Sample 19 (Figure 5), collected from a field of large bedforms northeast of Arch Rock, consists of coarse sand to pea-gravel-size sediment. Sample 21 (Figure 5), taken from a less well-developed bedform area southwest of Harding Rock, consists of a gravelly

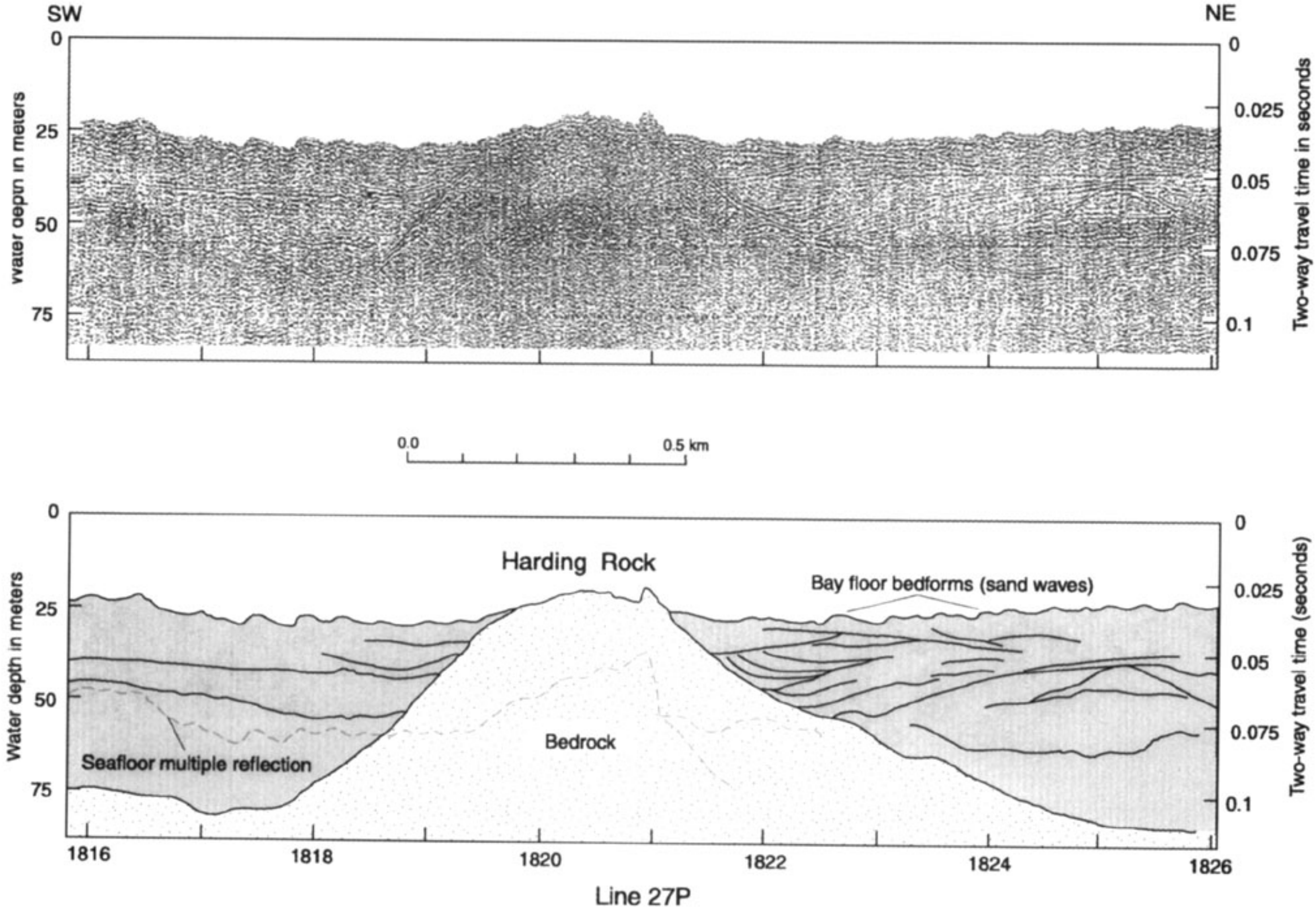


Figure 8. Single-plate Geopulse profile and interpretive sketch from line 27P (1998 cruise) crosses the shoulder of Harding Rock. [Vertical exaggeration (V.E.) ~6.7X; see Figure 5 for location].

sand. The surficial sediment from the bedform field northeast of Harding Rock varies from well-sorted fine sand (22 and 135) at the edge of the bedform field, to well-sorted medium sand (23 and 134) in the middle portion of the field (Figure 5). In the field of bedforms south of the rock knobs (Figure 5), the six grab samples showed more variability. Sample 11 from within the bedform field, and samples 114 and 274 collected from the southern edge of the bedforms, consisted of well-sorted coarse sand. Sample 10, from the northern edge, as well as samples 14 and p36 collected along the southern edge of the well-defined bedform field, fall in the fine to medium sand range.

In addition to sampling the sediment that surrounds the rocky knobs, attempts have been made through the years, with limited success, to sample the tops of the bedrock knobs. Traditional bottom grabs and corers are not very successful sampling devices on these substrates. Figure 7B shows the irregular rocky surface on the flank of Shag Rock that is typical of the side-scan-sonar imagery of the rocks above the sediment blanket that laps onto the lower slopes of these bedrock knobs.

A short gravity core of bedrock, fresh graywacke, was obtained from the top of Shag Rock in the early 1960s by the U. S. Bureau of Mines (Schlocker, 1966). Additional evidence suggesting the lack of unconsolidated sediment on these bedrock knobs was reported by Carlson and others (1970) who had no success in several casts of a grab sampler and dented a gravity core cutting head (273, Figure 5) while trying to sample the tops of these knobs. On our 1998 cruise we failed to collect any sediment in one grab-sample attempt on the top of Shag Rock.

DISCUSSION

Bedrock Trends

From the bathymetry (Figures 2 and 4), Harding, Shag, Alcatraz, and Blossom rocks appear to form a ridge along a northwest-southeast structural trend. This trend is roughly parallel to the regional alignment of the Coast Range and major faults, as well as south San Francisco Bay and the Tiburon Peninsula (Figure 1). Acoustic profiles normal to the regional structural trend suggest that the

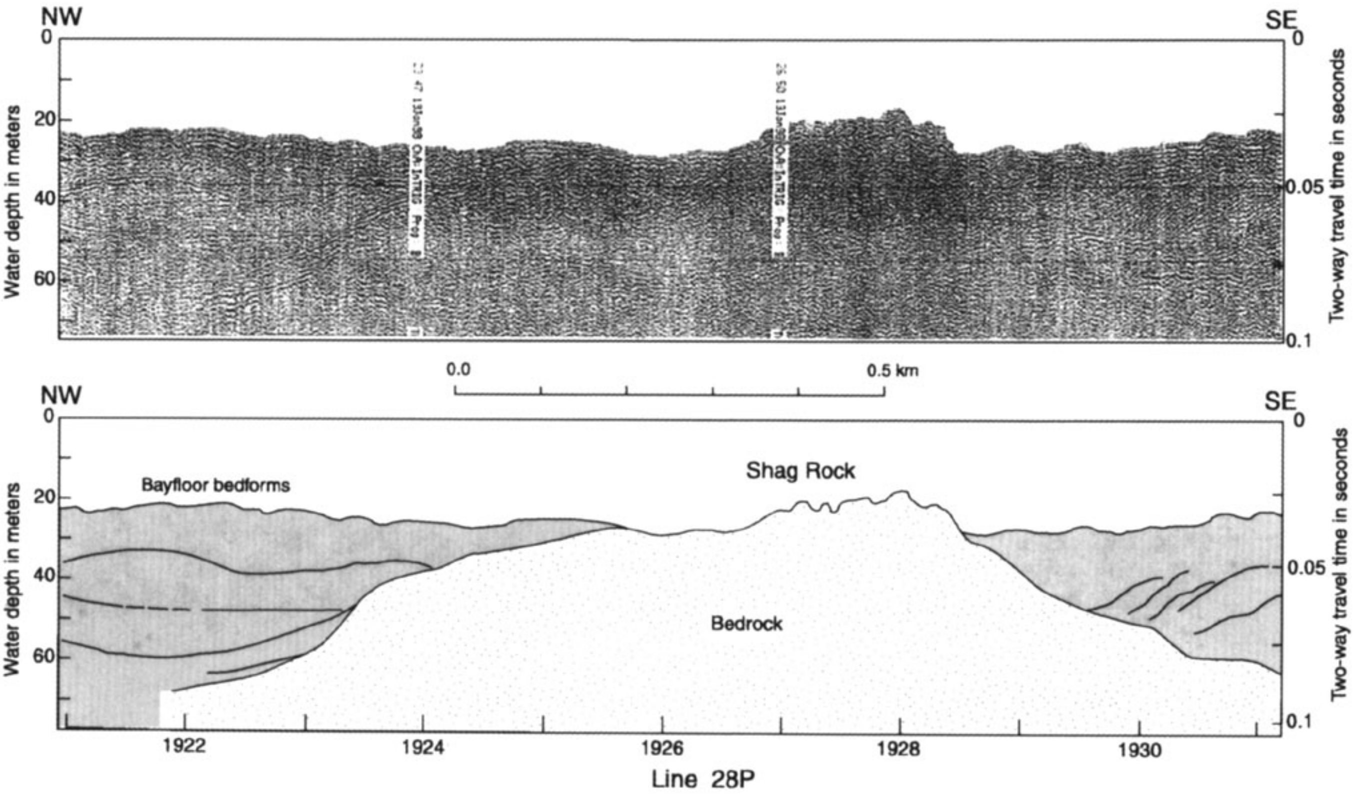


Figure 9. Single-plate Geopulse profile and interpretive sketch from line 28P (1998 cruise). (V.E. ~5.5X; see Figure 5 for location).

bedrock ridge continues at least a short distance northwest of Harding Rock. Lack of penetration through the substrate to the northwest does not allow mapping of the bedrock ridge further than about 1 km (0.62 mi) northwest of Harding Rock. Arch Rock is offset to the southwest of the trend and appears to be elongated at nearly right angles to the regional trend. However, the map of depth to bedrock that was originally published by Carlson and McCulloch (1970) suggests that the bedrock ridge bends to the southwest to incorporate Arch Rock. Additional deep-penetration seismic-reflection profiles are needed to more accurately determine the extent of the bedrock ridge and its relation to the bedrock knobs and islands in the west-central bay.

Sediments

The combination of multibeam imagery, bathymetric data, seismic-reflection profiles, side-scan-sonar imagery, and bottom samples provides a picture of the character and thickness of the sediment that is lapping up on the rock knobs. This sediment varies from the extremes of sandy mud to coarse sand with small pebbles and some shell hash. However, the most common surficial sediment in this area consists of medium to fine sand, often swept into various sizes of bedforms by prevailing currents. The muddy sediment sample (20) from the east side of Arch Rock (Figure 5) was probably sheltered from the most intense bottom current action by the rocky outcrop. If Arch Rock is lowered to ~–17 m (–55 ft) MLLW, the tidal currents may winnow the fine sediment from the resulting less-protected bay floor. In contrast, samples 23 and 134, well-sorted medium sand, from about 1 km (0.6 mi) northeast of Harding Rock (Figure 5), were exposed to the full brunt of the strong tidal currents, both ebb and flood, that sweep unimpeded around the south side of Angel Island. The intensity of these tidal exchanges on the bottom sediment is evidenced by the field of large sand waves (bedforms) and the pronounced scour pit at the southeast corner of Angel Island (Figure 2). According to Rubin and McCulloch (1980), the depth-averaged, peak-flow velocities of tidal currents in the area around the bedrock knobs range from 125 to 175 cm/sec (2.8–3.9 mph). Two other bedform fields are present in the study area: a smaller one that extends between Shag and Arch rocks and a large bedform field south of Arch Rock (Figures 2, 4 and 5).

If the tops of the rock knobs (Figure 6) are lowered to a depth of –17 m (–55.8 ft), the circulation patterns resulting from the diurnal ebb and flood of the tidal currents will certainly change. This in turn will affect the sediment erosion and distribution patterns and bedform

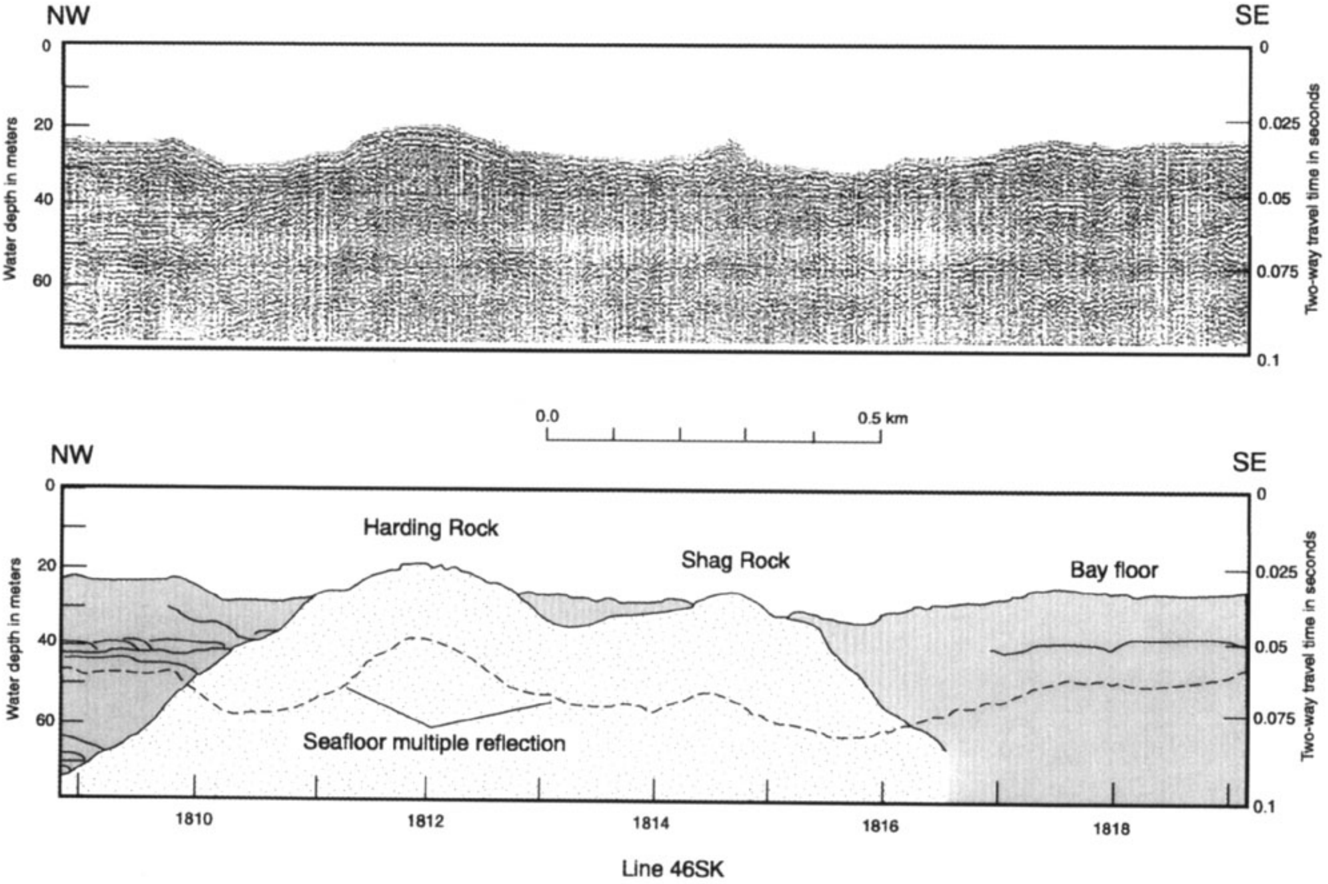


Figure 10. Minisparker profile and interpretive sketch from line 46SK (1998 cruise). (V.E. ~ 7.5X; see Figure 5 for location).

configurations, especially in proximity to the bedrock knobs. Redistribution of the various sediment types may in turn influence where the construction industry may find dredgable sand to meet their future needs. Currently the California State Lands Commission permits dredging of sand in central San Francisco Bay primarily from Presidio-Alcatraz Shoal and Pt. Knox Shoal (Chin et al., 1998b). In the past, these areas were used as borrow sites, from Presidio Shoal for development of the 1915 Panama-Pacific Exposition, and from all three shoals for construction of Treasure Island developed for the 1938 Golden Gate International Exposition (Scheffaeur, 1954). Detailed modeling incorporating additional tidal current, bottom morphology, and bay-floor sediment data, may be required to quantitatively estimate the magnitude and significance of these changes in sedimentation in order to meet future needs.

Rock Removal

The three bedrock knobs are all within the general westbound traffic lane, and the summit of Harding Rock is 300 m (984 ft) south of the prescribed traffic lane for deep-water vessels (Figure 2). With the increasing number of deep-draft vessels entering San Francisco Bay, the likelihood of a shipping accident also increases. Hence, the question is no longer whether or not to remove the tops of these rocks to prevent an accident, but rather when it should be done and how best to do it to minimize the impacts on the local ecosystem.

The volume of material to be removed from the three main rock knobs (Table 1) to reach the depth of –17 m (>–55.8 ft) below MLLW is about 245,000 m^3 (320,200 yd^3). The rock constituting these knobs probably belongs to the Franciscan Complex of Mesozoic age. Graywacke (a dirty unsorted sandstone and the most prevalent rock type, of the highly variable types of rocks of the Franciscan, according to Bailey et al., 1964), was cored from the top of Shag Rock (Schlocker, 1966) and thus seems likely to be present in the other bedrock knobs. Other possible rock types that may be present include shale and siltstone, greenstone, bedded chert and associated shale; these types are all quite common in the San Francisco Bay area (Bailey et al., 1964). Nearby subaerial outcrops provide clues as to rock types making up the basement rock of the central bay (Figure 2). Angel Island consists of a complex association of graywacke, argillite, conglomerate, chert, greenstone, serpentine, and

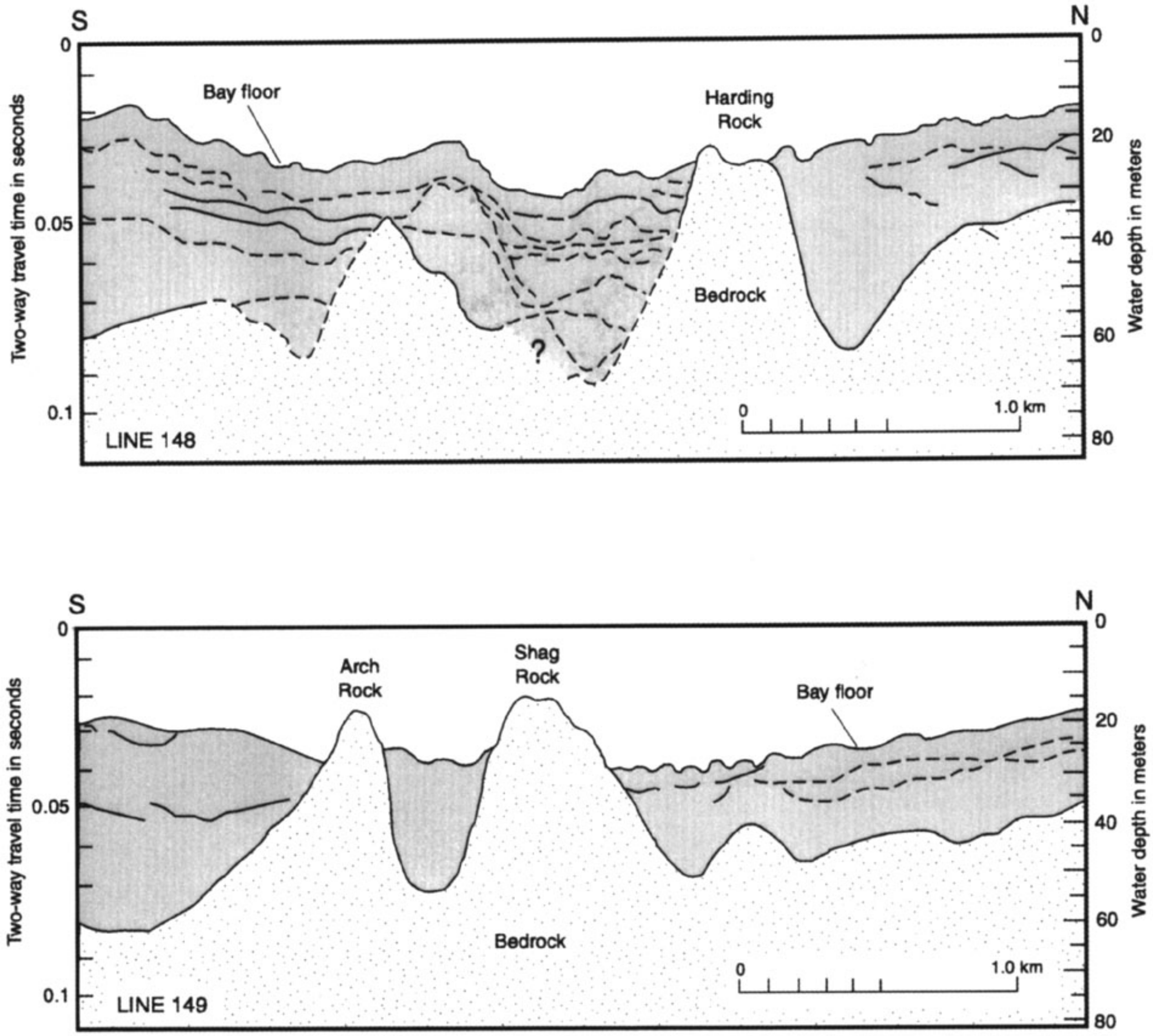


Figure 11. Interpretive sketches from 1960s cruise of high-energy (2000 J) minisparker lines 148 and 149 (V.E. ~18X; see Figure 5 for locations).

schist (Wahrhaftig, 1984). Alcatraz Island contains abundant graywacke in the form of turbidites (Blake et al., 1984). On the mainland at the north side of the Golden Gate, an accretionary complex is exposed that includes radiolarian chert and pillow basalt of Mesozoic age (Wahrhaftig, 1984).

Habitats

The bedrock knobs are not only a threat to deep-draft vessels transiting through the bay, they are also the site of a local ecosystem that is regularly visited by sport fisherman. For example, as many as 40 drift-fishing boats may at times vie for space over the rock knobs (Jim Cox, Sport Fishing Charters, oral communication, 7/21/98). Thus, issues have been raised by oversight groups [(e.g., Harbor Safety Committee), whose meetings we have attended] about the effects on fish habitat of lowering the tops of the knobs. The rock knobs create leeward turbulence during times of strong flood and ebb of the diurnal tidal flow, and are areas where drift fishing from charter boats is common. Striped bass are the principal game fish, but other species fished include shark, rockfish, salmon, Pacific herring, and bottom feeders, such as halibut (Jim Cox, Sport Fishing Charters, oral communication, 7/21/98). If the tops of the rocks (Figure 6) are lowered about 5 m (16.4 ft), the tidal flow patterns and the leeward turbulence will change, and may significantly affect fish habitats and possibly the number of fish present. Because the bedrock knobs are important habitats to game fish, the California Department of Fish and Game suggested to the Harbor Safety Committee that if the tops of the knobs are lowered, perhaps the excavated bedrock could either be left nearby as rubble fill, or, piled on the adjacent, deeper bay floor (Figure 6). These resulting artificial reefs could serve as auxiliary fish habitats (R. N. Tasto, California Fish and Game, oral communication, 7/20/98).

Removal of the tops of the knobs will clearly affect the fish habitats around the bedrock highs by removing fish hiding places and modifying leeward water turbulence. The resulting effects on sport fishing are unknown, but could be positive, especially if new habitats are created at the base of the knobs with the excavated debris.

However, the potential damage to wildlife in the bay (e.g., fish, birds, mammals, and lower life forms) due to an oil spill from a tanker that hits the bedrock knobs would damage the San Francisco Bay ecosystem, as happened with the Prince William Sound (PWS) spill. In PWS the estimated death toll was more than 250,000 birds and 3,500 sea otters, significant reductions in intertidal and subtidal organisms, and increased mortality of herring, salmon and other fish (Spies et al., 1996). The long-term effects in San Francisco Bay, like Alaska, would also likely be large. After nearly a decade, spilled oil from the 1989 PWS catastrophe can be found buried in some of the beach sediment and in some mussel beds (Bruce Wright, National Marine Fisheries, Auke Bay, Alaska, oral communication, 7/21/98). Thus, the assessment of possible damage due to an oil spill resulting from a ship hitting a rock knob in San Francisco Bay must consider both the immediate and decades-long impact on the marine environment and ecosystems.

CONCLUSIONS

1. Bedrock knobs as shallow as about –11 m (–36.1 ft) are potential obstacles to safe vessel transport through central San Francisco Bay. Acoustic profiling shows the extent of these knobs: a) in outcrop on the bay floor and b) with their slopes buried by encroaching sediment. Detailed multibeam imagery provides more accurate bathymetry than the old single-beam profiles and also gives a morphologic perspective view of these knobs. These acoustic data plus bottom sediment samples form a database that can be used in evaluating how best to lower the rocks and remove the hazard. If the bay planners choose to remove the tops of the knobs below deep-draft vessel depth, the volumes of Franciscan bedrock to be removed totals ~245,000 m^3 (320,460 yd^3) [Harding ~37,800 m^3 (49,400 yd^3), Shag ~51,100 m^3 (66,800 yd^3), Arch ~156,100 m^3 (204,200 yd^3)]. Removal of the rock knobs would change the water current patterns. However, the resulting debris could be placed in adjacent depressions (Figure 6) that would still remain below the average depth of the bay floor surrounding the rocky knobs, and thus, would not be likely to have a large influence on the tidal currents.
2. Increasing deep-draft vessel traffic increases the chances that a vessel may strike the top of one of these rocks. If a large oil spill should occur in San Francisco Bay, then the cost of remediation would likely be in the tens to hundreds of millions of dollars, based on the two billion dollar cost to clean up the 11-million gallon PWS Exxon Valdez oil spill in 1989.
3. Lowering the tops of the rock knobs in central San Francisco Bay will affect fish habitats associated with the bedrock highs. It is unknown if the habitat impacts will be positive or negative, but, if they are negative, these impacts should be relatively minor compared to the damage wildlife in the bay would experience following an oil spill on the order of the PWS spill. The impacts from the PWS spill caused the death of birds in the hundreds of thousands, sea otters in the thousands, plus increased mortality of many commercial and sport fish, and significant reductions in intertidal and subtidal organisms. A cost analysis of any spill scenario must consider damages from time zero to perhaps a decade or more.
4. Additional oceanographic and sedimentologic data are needed to permit pertinent modeling in order to help quantify the effects of rock removal, to generate an accurate feasibility/cost study, and to prepare the required Environmental Impact Statement.

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