Impacts of the Removal or Disturbance of Sediments, Shells or Bedrock in San Francisco Bay

A Report for the San Francisco Bay Subtidal Goals Project (July 2008)

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This paper discusses the direct impacts on organisms and habitats from the removal or disturbance of sediments by dredging, sand and shell mining, bottom trawling or ship movements and activities, and from the lowering of rock reefs or islands to eliminate navigational hazards. Impacts from these activities caused by the injection of sediments into the water column and their subsequent deposition, and from activities in the watershed that have altered sediment inputs to the Bay system (such as hydraulic mining, agriculture, grazing, road building, urban development), are treated under the Stressor "Change Sediment Inputs to the Water Column. Impacts caused by the injection of contaminants or nutrients associated with sediment are treated under the Stressors "Increase Contaminant Inputs" and "Change Nutrient Inputs."

Background Rate of Sediment Disturbance in the Bay

"Background" sources of bottom disturbance include the natural physical causes of sediment disturbance as well as activities by vertebrate and invertebrate animals (bioturbation).

Physical disturbance

Rubin and McCulloch (1979; see also Chin et al. 2004) used side-scan sonar to investigate changes in bedforms in the Central Bay. They found that over most of the Central Bay the principal physical process reworking the bottom is the migration of current ripples caused by tidal currents, which typically turned over only the upper 2-5 cm of sediment. However, in channels with sandy bottoms where current velocities were high the migration of sand waves resulted in turnover up to 1 m in depth. Hammond and Fuller (1979) found the surface of South Bay sediments to be fairly cohesive, and estimated that physical stirring affected only the upper 2 cm of the sediment or less. However, they found a high rate of radon flux through the sediment in the Central Bay, which if due to physical stirring of sandy sediments implies a turnover depth of about 40 cm.

Bioturbation

Several common gastropods In San Francisco Bay (e.g. *Ilyanassa obsoleta*, *Philine* spp., *Haminoea japonica*) and clams (juvenile *Venerupis philippinarum*) plow through the mud just under the surface, turning it over down to a few centimeters, while disturbance from the Bay's largest but much less common snail, the channeled whelk *Busycotypus canaliculatus*, might reach to around 10 cm. Lugworms (family Arenicolidae) belonging to at least two species are common in some areas, where they can rework the sediment down to around 20 cm. During the fall migration foraging water birds, especially scaup and scoter, can turn over substantial amounts of sediment in parts of the shallow subtidal and intertidal in the South Bay and San Pablo Bay (Poulton et al. 2002, 2004; Richman and Lovvorn 2004; Thompson et al. in press; Jan Thompson pers. comm.). Large wintering congregations of foraging shorebirds must also cause some significant disturbance of intertidal sediments (personal observations). A few common clams in the Bay (*Macoma nasuta*, *Mya arenaria*) typically burrow to depths of 10-25 cm (Haderlie and Abbott 1980), and the burrowing anemone *Flosmaris grandis* may possibly reach to 50 cm (Fautin 2007). Feeding pits up to 30 cm deep dug by California bat rays (*Myliobatis californica*) are very abundant in some intertidal areas (Nichols 1979; Thompson et al. in press; personal observations), while pits up to 50 cm deep recorded by side-scan sonar in a shoal area of the Central Bay have also been interpreted as bat ray feeding pits (Rubin and McCulloch 1979; Nichols 1979). These pits are so dense in some areas that they cover virtually the entire surface. Two abundant subtidal polychaetes (*Sabaco elongatus* and *Heteromastis filiformis*) may dig burrows that are up to 40-50 cm deep (Hammond and Fuller 1979; Hammond et al. 1985). The ghost shrimp *Neotrypaea* is common in parts of the Bay (probably *Neotrypaea gigas*—J. Chapman pers. comm.), where it lives in impermanent, branching burrows that reportedly can extend to depths of 75 cm (Haig and Abbott 1980). Note that of the above species, only *Macoma nasuta*, bat rays and ghost shrimp are clearly native, so the background rate of bioturbation may differ from the natural rate.

Effects of Sediment Removal

Sediment or shell is deliberately removed from parts of the Bay by channel dredging, sand mining and shell mining. This has several potential consequences: the removal or killing of organisms living in or on the sediments; the short-term or long-term alteration of bottom habitat; hydrodynamic changes; the release of buried organic matter, nutrients or contaminants; short-term increases in suspended sediment concentrations; and the subsequent settlement of suspended sediments (LTMS 1998]; ABP Research 1999). The first three of these—the removal or killing of organisms, the alteration of bottom habitat and hydrodynamic changes—are discussed here.

An immediate impact of dredging or bottom mining is the loss of organisms that cannot escape removal by mechanical or hydraulic (suction) dredges.[1] Benthic infauna are

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[1] Dredging results in at least a local depletion of these organisms. One study reported 99% mortality of fish entrained in pipeline dredges (Levine-Fricke 2004), while the mortality of Dungeness crab (*Cancer magister*) entrained by dredges ranged from 5%-100% depending on the type of dredging operation and the size of the crab (Wainwright et al. 1992; Nightingale and Simenstad 2001). Some invertebrate or algal

most vulnerable though epibenthic and demersal species may also be vulnerable (Nightingale and Simenstad 2001; Levine-Fricke 2004). Depending on the depth of dredging, some infaunal organisms may escape by deep burrowing, but probably most are removed (ABP Research 1999). Some fish species may move away from the area of disturbance and sediment suspension caused by active dredging and avoid entrainment (ABP Research 1999; Levine-Fricke 2004), though demersal species are less likely to avoid elevated concentrations of suspended sediments than are surface species (Hanson Environmental 2004). Larval and juvenile fish are more vulnerable than adults (LTMS 1998; Levine-Fricke 2004), and fish that dwell in burrows in the sediment or that flee into burrows in response to disturbance (such as the Arrow Goby *Clevelandia ios*) could be entrained in large numbers. In San Francisco Bay, Dungeness crab (*Cancer magister*), bay shrimp (*Crangon* spp.) and demersal fish are vulnerable due their residence in or on bottom substrates and behaviors of burrowing or hiding in bottom substrates, and white sturgeon (*Acipenser transmontanus*) are vulnerable due to their bottom-orienting behavior and limited swimming ability (Nightingale and Simenstad 2001; Levine-Fricke 2004; Hanson Environmental 2004). In the Columbia River mouth, at least 14, mostly demersal, fish species were observed in hopper dredges (Levine-Fricke 2004). Dredge entrainment rates have been determined for 36 Pacific Coast estuarine or marine fish species in studies in Gray's Harbor (Washington) and the Columbia River estuary (Larson and Moehl 1990; McGraw and Armstrong 1990; Nightingale and Simenstad 2001). Pacific sand lance (*Ammodytes hexapterus*) were by far the most frequently entrained species, followed by other demersal fish including flatfish species and Pacific staghorn sculpin (*Leptocottus armatus*). A few pelagic fish were also entrained, including herring and anchovies (Larson and Moehl 1990; McGraw and Armstrong 1990). Longfin smelt (*Spirinchus thaleichthys*) and salmonids have been entrained by dredging in rivers, and longfin smelt and American shad (*Alosa sapidissima*) in Gray's Harbor, but are unlikely to be entrained in large numbers in estuaries (Larson and Moehl 1990; Levine-Fricke 2004).

Sites defaunated by the removal of sediments are subsequently colonized primarily by the lateral movement of organisms and by settlement of planktonic (larval) forms. The initial colonizers are often opportunistic species (e.g. characterized by relatively short generation times, small size, and high frequency and abundance of larvae in the water) that differ from those that were present prior to sediment removal; however, over time, the new biotic community often comes to resemble the pre-removal community. Studies on different types of substrate in different parts of the world have estimated the recovery time to range from around a month up to 10 years, with the time typically being shorter and recovery being more complete on unstable substrates or in disturbed areas in estuaries, in shallow inshore waters, in harbors, etc. (including sites subjected to periodic maintenance dredging), where the pre-removal community typically includes

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species may fare better. If some organisms do survive the dredging, transport and disposal process, then the initial net impact of channel dredging on these organisms would be to remove them from the dredge site and transfer them to the disposal site, rather than to kill them. Whether they then survive and reproduce would depend on their condition and their response to their new environment. Note that the survival of these organisms is not necessarily a desirable outcome (depending in part on the distance between dredge and disposal sites), as it could faciliate the spread of non-native species or exotic genetic material between dredge and disposal areas.

opportunistic, colonizing species (Oliver et al. 1977; Hirsch et al. 1978; LTMS 1998; ABP Research 1999; Levine-Fricke 2004). Evidence from bottom disturbance studies suggest that the most vulnerable and least resilient sites would include biogenic substrates, such as mussel beds, seagrass beds and beds of structurally significant worm tubes (Collie et al. 2000).

Longer term changes may result from modifications to the habitat or topography. Natural sediment deposits may have a complex structure, including vertical variation in particle size; bacterial or algal mats stabilizing the surface; tubes, burrows or pits created by various organisms; and accumulations of fecal pellets (Dernie et al. 2003). It can take some time to rebuild this structural complexity after disturbance or removal of the surface sediment. A permanent change in habitat may result if the area refills with sediment of a different grain size and composition than was present before the dredging or mining activity; if significant biogenic structures do not re-establish; or if the area does not refill to its pre-existing elevation (Hirsch et al. 1978]; Chin et al. 2004). Once a depression is formed, it may be maintained by tidal currents that inhibit sedimentation or cause erosion (Chin et al. 2004). It is not known how long the depressions caused by dredging or bottom mining last (Chin et al. 2004). One study reported that intertidal pits 1 m x 4 m x 0.1 m deep filled in completely within about 100 days if dug in sand but had not filled in after more than 200 days if dug in muddy sand or mud; the rate at which the pits refilled with sediment declined linearly with the increase in silt and clay content (Dernie et al. 2003).

Chin et al. (2004, Fig. 12) provide a 1985 bathymetric profile of a borrow pit near the east shore of San Francisco Bay that was a source of construction fill for Bay Farm Island. The pit covers nearly 5 km^2, and its bottom lies 6-10 m below the pre-existing and surrounding surface, which is about 2-3 m below MLLW,[2] and is also much rougher (i.e. has much greater variation in depth) than the pre-existing surface. It seems likely that environmental conditions also differ, at least in the frequency and degree of disturbance by waves, currents or passing vessels and in the amount of available light, and possibly in sedimentation rate, sediment characteristics, etc. If the water over the pit ever stratifies (which because of eddy currents or other factors might be extremely rare—Jan Thompson pers. comm.), there could also be differences in salinity and temperature (for example, Conomos (1979) indicates a difference of about 5 ppt and 1°C over 10 m depth in this part of the Bay during wet winters).

The part of the Bay where this borrow pit is located is mapped as habitat for eelgrass (*Zostera marina*; Cosentino-Manning et al. 2007, Fig. 12), which grows down to around 3 m below MLLW in parts of the Bay (Cosentino-Manning et al. 2007). Marine algae have low light requirements and may grow to considerable depths in clear water, but can be restricted to depths of 2 m or less in turbid waters (Silva 1979). Thus eelgrass or algae (such as *Gracilaria*) might have occurred on the shallow, pre-existing surface (at 2-3 m below MLLW), but would not occur or would be very unlikely to occur on the deeper, dredged surface (at 9-13 m below MLLW). This borrow pit shows up on NOAA

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[2] Chin et al (2004, Fig. 12) show this as 3-4 m below Mean Sea Level (MSL). At the Alameda Tide Station (Station #9414750), MSL is 1.05 m above MLLW (NOS records).

navigation charts as an obvious hole in the bottom of the Bay, along with other holes off Emeryville, alongside Treasure Island and Hunters Point and at San Bruno Shoal, at least some of which are apparently also the result of bottom mining (Table 1). Other large borrow areas in the Bay include the Presidio Shoal Borrow Area and the Point Knox Shoal Borrow Area in the western part of the Central Bay, from which 15-22 million m^3 of sediment was dredged in 1936-38 to create Treasure Island. USGS multibeam sonar imagery shows a topographic depression still evident at the Point Knox Shoal site in 1997, with an estimated volume of missing sediment of at least 2.4 million m^3 in an area with sandy bottom (Chin et al. 2004, Fig. 10). Numerous smaller scale alterations of topography can also have a substantial cumulative effect. At the western end of Point Knox Shoal, the pits and channels caused by sand mining "are so numerous as to literally obliterate the fabric of the bay floor" (Chin et al. 2004).

Foxgrover et al. (2004) identified four large borrow pits in the South Bay, that showed up as anomalies in the patterns of erosion and deposition revealed by hydrographic surveys. Together these depressions cover approximately 31 km^2, and represent the removal of at least 39 million m^3 of sediment. Between 1956 and 1983, the sediment removed from two of these pits accounted for at least 37% of the net loss of sediment from the South Bay. These pits were apparently created either by dredging for fill material or by shell mining. However the history of these and the other large borrow pits in the bottom of the Bay is poorly known or unknown (Foxgrover et al. 2004).

Table 1. Some Large Borrow Pits in San Francisco Bay

Location	Approximate surface area (km^2)	Approximate sediment volume removed (10^6 m^3)	Period of Activity	Reference
West of Bay Farm Island	5	30-50		Chin et al. 2004
Presidio Shoal and Point Knox Shoal Borrow Areas		15-22	1936-38	Chin et al. 2004
South Bay Borrow Pit 1 (north of San Mateo Bridge)	2	≥3	1931-56	Foxgrover et al. 2004
South Bay Borrow Pit 2 (south of San Mateo Bridge)	11	≥10	1931-56	Foxgrover et al. 2004
South Bay Borrow Pit 3 (San Bruno Shoal)	9	≥9	1956-83	Foxgrover et al. 2004
South Bay Borrow Pit 4 (north of San Mateo Bridge)	9	≥17	1956-83	Foxgrover et al. 2004

Reductions in bottom elevation caused by dredging or mining can cause changes in the hydrodynamic regime which can in turn affect areas that are outside of the sediment removal zone. These hydrologic changes include the intrusion of salty bottom water further upstream; alterations in tidal ranges, tidal prisms or tidal currents; and changes in erosion patterns and consequent suspended sediment loads (ABP Research 1999). Such effects are likeliest when the size of the excavation is significant relative to the overall size of the system. Upstream salt intrusion has been noted as a potential or actual consequence of channel dredging in the Bay's northern reach and Delta.

Activities Removing Sediment from the Bay

Channel Dredging

Dredging removes sediments that are either in their natural condition (called "new work construction") or in a recently deposited condition ("maintenance dredging"), using either mechanical or hydraulic equipment, and then transports the sediments to a disposal site either on the dredge, on barges or scows, or in pipelines (LTMS 1998). Mechanical dredging can be used for either maintenance or new-work dredging. It removes either loose- or hard-compacted materials by applying direct mechanical force to the sediment, removing it in almost in situ densities with backhoe, bucket dredge (e.g. clamshell, orange-peel, dragline), bucket-ladder, bucket-wheel or dipper dredge. Hydraulic dredging is used mainly for maintenance projects. It removes loosely compacted sediment using cutterheads, dustpans, plain suction or sidecasters and transports the sediment in a liquid slurry through pipes (6-48 inches in diameter) either to the disposal site or to a hopper (LTMS 1998; Levine-Fricke 2004).Over the next 40 years an estimated average of 2.6 to 4.5 million m^3/yr of sediments will be dredged from the Bay, with 84-93% of this being maintenance dredging (LTMS 1998).

Sand Mining

Over 1-1.5 million m^3 of sand and gravel was dredged in 1912-1915 from Presidio Shoal to create San Francisco's Marina District (Chin et al. 2004). Sand mining with hydraulic suction pumps began in the Northern channels of the Bay in the 1930s, and in the Central Bay in the 1950s (Hanson et al. 2004). Currently, around 1.2 million m^3 of sand is mined from the Bay each year. About 90% is taken from the shoal areas of the West Central Bay at depths of 10-30 m, and about 10% from the main Suisun Bay channel between Benicia and Chipps Island at depths of 5-15 m (Hanson et al. 2004).

Shell Mining

Oyster shell has been mined commercially in South San Francisco Bay since 1924, primarily for use in the manufacture of cement, as a supplement in poultry feed, and as a soil amendment. The main mining sites were north and south of the San Mateo Bridge east of the shipping channel but in the western half of the Bay. Some shell was also mined off Bay Farm Island and south of the Dumbarton Bridge. The shell harvested is 2,300-2,500 year-old native oyster shell (*Ostrea conchaphila*) that occurs as lenses in the upper 10 m of sediment (within the "younger bay mud" deposit of Treasher 1963). The lenses are usually 1-5 m thick, and are typically overlaid by 0.6-2.5 m of fine mud. About 25-35 million tons of shell were removed between 1924 and the mid-1960s, with an estimated 75 million tons then remaining (Hanson Environmental 2004).

Shell is currently harvested at only one site in the Bay, on California State Lands Lease PRC 5534.1, a rectangular area covering 6 km^2 just north of the San Mateo Bridge on the east side of the channel, where the bottom is 2-4 m below MLLW. About 30,000 tons/year have been taken from this lease since 1999. The lease was recently renewed through December 2016 with a 10-year renewal option, and allows the removal of 40,000 tons of shell a year. Shell is harvested by burying the suction head of the dredge

0.3-1 m deep in the mud and then slowly trolling it; burying the suction head may reduce the entrainment of near-surface organisms. From the suction head a slurry consisting of approximately 50% shell, 45% water and 5% silt is carried through pipes into a barge. The shell is retained on the barge, with the water and most of the silt discharged back to the Bay (Hanson Environmental 2004). Averaged over the area of the lease, the removal of 40,000 tons of shell per year (≈60,000 cubic meters) corresponds to lowering the surface by about 1 cm per year.

Effects of Sediment Disturbance

Bottom trawling catches demersal fish or invertebrates for sale, research or educational purposes, and in the process churns up and turns over sediments. In addition to removing target species and by-catch, trawling crushes, buries or exposes organisms, which attracts predators and scavengers (Thrush et al. 1998; Watling and Norse 1998). As noted above, structural complexity in the sediment can be disrupted (Dernie et al. 2003; Watling and Norse 1988). While trawling can smooth ripples, mounds and other small-scale structures, plowing by trawl doors can create large furrows, potentially replacing "widespread, small-scale, low relief features...with a rather smoother landscape, interspersed with higher relief, but less frequent features" (Kaiser et al. 2002). The small-scale structural features destroyed by trawling can be of great importance to bottom biota and demersal fish (Watling and Norse 1998). The collapse of burrows and sediment voids, and damage to bioturbating infauna, could in turn affect biogeochemical exchange processes between sediments and the water column (Kaiser et al. 2002).

Different studies of the impacts of bottom fishing gear on biota often yield different results, in part because of the variety of gear, bottom types and environmental conditions. A common conclusion, however, is that bottom disturbance from fishing reduces large, long-lived epifauna and favors small organisms and juvenile stages (Thrush et al. 1998; Collie et al. 2000; Kaiser et al. 2002). An analysis of sites with varying degrees of fishing pressure found that greater bottom fishing reduces the density of echinoderms, large species and long-lived species; reduces the total number of species and individuals; reduces diversity as measured by the Shannon-Weiner diversity index; and increases the density of deposit feeders and small, opportunistic species (Thrush et al. 1998). A meta-analysis of 39 published studies found that all major taxonomic groups decline following bottom fishing, but concluded that anthozoa (anemones) and malacostraca (a type of crustacean including crabs, lobsters, shrimp, amphipods and isopods) are the hardest hit (Collie et al. 2000). This meta-analysis also found that otter and beam trawling has less impact than harvest methods that involve digging, raking or dredging that remove sediments as well as organisms from the seabed or that disturb sediments to a greater depth. Similarly, other studies have found that disturbance from otter trawls is largely restricted to the trawl boards (Kaiser et al. 2002). In general, mud or muddy-sand is affected more and takes longer to recover than sand (Collie et al. 2000; Kaiser et al. 2002; Dernie et al. 2003; but also see contrary results in Collie et al. 2000). One study found that otter trawl boards typically penetrate muddy sand 2-4 times deeper than fine or coarse sand, with the furrows remaining for at least a year (Churchill 1989; Kaiser et al. 2002). Collie et al. (2000) concluded that since sandy sites affected by bottom fishing gear recover in around 100 days, they can be fished 2-3 times per year without markedly changing their character, but that other types of bottom require longer recovery periods of up to 500 days. As with the impacts of dredging and bottom mining, shallow, turbid and naturally-disturbed sites are less likely to be significantly affected than deeper, undisturbed sites (Watling and Norse 1998; Kaiser et al. 2002).

Overall, these studies suggest that bottom fishing has not had a large impact on bottom habitat in San Francisco Bay, at least in recent decades when commercial trawling has been limited to a small bait shrimp fishery (see below). While most of the Bay bottom is mud, and thus more sensitive to the effects of trawling than sand bottom, the Bay is shallow and turbid with a high frequency of natural bottom disturbance from wind waves and tidal currents (e.g. Krone 1979; Conomos et al. 1979; Nichols 1979; but see Hammond and Fuller 1979, and Rubin and McCullough 1979, suggesting that natural disturbance affects only the upper 2 cm or 2-5 cm on mud bottom), and most of the commercial bottom fishing in the Bay has used gear types that have relatively smaller physical impacts on the bottom. Two caveats, however, should be borne in mind. First, there has been no quantification of the historic or current levels of fishing impacts on the bottom in terms of the distribution, acreage and frequency of trawling in the Bay. Second, impacts from trawling are believed to be substantially greater on biogenic substrates (Collie et al. 2000; Kaiser et al. 2002). In San Francisco Bay these include eelgrass, algae and oyster beds, and we have very little information on the initial extent and distribution of these beds or on their later historic or current distribution and extent relative to trawling activities.[3] Trawling also removes fauna and flora that are important sediment stabilizers, including tube-building amphipods (such as *Ampelisca abdita*) and polychaetes (such as *Sabaco elongatus*).[4] *Ampelisca* are removed in such numbers that the Department of Water Resources (research trawling) and Marine Science Institute (educational trawling) have moved transects to avoid beds of *Ampelisca*, which can completely clog nets (Jan Thompson pers. comm.).

Activities Disturbing Sediment in the Bay

Commercial Fisheries

Commercial fishing began in San Francisco Bay around 1848, initially with hand lines, beach seines and gill nets. By 1870 there were commercial fisheries for a few demersal species, including sole and flounder from the South Bay to southern San Pablo Bay, and sturgeon (*Acipenser* spp., caught on hook-and-line, or incidentally in nets deployed

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[3] One indication that there may have been some significant overlap between trawling sites and biogenic substrates comes from Ganssle (1966) who noted that in 1963-64 the tunicate *Molgula manhattensis* (reported as *M. verrucifera*) was "so abundant in San Pablo Bay bottom tows that it was impossible to haul the trawl aboard by hand." *Molgula* attaches to hard surfaces or vegetation and does not live on sediment, and the most likely substrate for the *Molgula* filling the trawl nets in San Pablo Bay was the seaweed *Gracilaria* (personal observations). Reserach trawling may thus have had some impact on *Gracilaria* beds.

[4] These are both exotic species, as are some of the other common sediment-stabilizing species in the Bay.

for other species) in northern San Pablo Bay. About this time Italian fishermen began seining for shrimp (*Crangon* spp.), but in 1871 the Chinese started catching shrimp with set or "bag" nets (nets held to the bottom by stakes or poles driven into the sediment which were emptied and then reset in the opposite direction with the change of tide) and the competition drove the Italian seine netters out of shrimping. In 1876 the paranzella or Mediterranean drag net was introduced to the Bay Area, and in 1885 the first steam tug for trawling (Skinner 1962; Smith and Kato 1979).

In 1895 the hook-and-line fishery for sturgeon in the Bay, practiced by Chinese fishermen, was prohibited. Commercial sturgeon fishing was prohibited in the Bay in most years between 1901 and 1916 and banned permanently in 1917 (Skinner 1962; Smith and Kato 1979). The Bay's shark fishery, which began in the South Bay in the 1890s, peaked in the late 1930s to the early 1940s with annual landings of around 900 tons. These had dropped to under 50 tons by the1950s, before the commercial fishery left the Bay (Skinner 1962; Smith and Kato 1979). A series of restrictions were placed on the Chinese shrimp fishery starting in 1901, and in 1911 set nets were prohibited only to be allowed again in the South Bay in 1915. Beam trawling for shrimp started in 1914-1921, mainly in San Pablo Bay, and steadily grew in volume while set net shrimping continued for a time in the South Bay. By the late 1920s, San Pablo Bay trawlers were catching nearly 800 tons of shrimp, compared to a South Bay set net catch of only 200 tons. Shrimp landings remained at around 1,000 tons/year through the 1930s, dropped to around 400 tons in the 1950s, and have been under 100 tons, sold mainly for bait for striped bass and sturgeon sport-fishing, since the mid-1960s. There were 19 boats trawling for shrimp in the Bay in 1930, and 15 boats in the late 1970s; by the mid-1990s, however, there were only seven licensed shrimp boats in San Pablo and Suisun bays and two in the South Bay (Clark 1930; Skinner 1962; Smith and Kato 1979; CDFG license data).

Research/Educational Trawling

Bottom trawling and beach seines are often used for research and education in the Bay. For example, the California Department of Fish and Game Bay-Delta Monitoring Program has used an otter trawl to conduct monthly sampling at 35-52 sites in the Bay and western Delta since 1980, and used beach seines at 27 shoreline sites in the Bay each month from mid-1980 through 1986 (CDFG 2007). The Marine Science Institute, an educational organization, has trawled in the South Bay for 35 years, conducting typically 200-400 otter trawls per year (MSI undated). Many other research, monitoring and education programs drag nets along the bottom of the Bay.

Shipping

Vessel movement, docking, anchoring and propeller wash can also cause some disturbance or alteration of bottom sediments and even of bedrock. Studies conducted at the Richmond Longwharf found that docking ships and barges stirred up large plumes of sediment (USACE 2005). During the geophysical investigation of Arch Rock conducted in 2000, deep gouges were noted that were thought to be possible anchor scars (Sea Surveyor 2001). Around 3,000-4,000 cargo vessels entered the Bay each year in 1977-1996 (Marine Exchange 1997). Although the cargo handled at San

Francisco Bay ports is projected to more than double between 2000 and 2020 from less than 20 to over 40 million tons (exclusive of oil and oil products, bulk sugar and Hawaiian molasses), the number of ship calls will decline as the average ship size increases (BCDC 2003). Other things being equal, bottom disturbance by ships may become less frequent (fewer ships) but produce greater disturbance per event (larger, deeper-draft ships).

Bedrock Removal

Four bedrock features in the western part of the Central Bay have repeatedly been lowered by blasting to reduce the navigational risk they pose to shipping (Chin et al. 2004). There are several records (not all of which may be accurate) of ships striking or grounding on these rocks in the 1800s, including the following: In 1832, the East Indiaman *Seringapatan* struck Blossom Rock without causing any harm to the vessel. In 1853 the pilot boat *Sea Witch* was wrecked on Arch Rock. In 1855 the *Lenore* grounded on Arch Rock. In 1856, the clipper ship *Goddess* grounded on Blossom Rock while heading out of the Bay. In 1862 the clipper ship *Flying Dragon* entered San Francisco Bay after a record-fast passage from Newcastle in Australia, was caught by a squall, wrecked on Arch Rock, and sank. In 1868 the *Autocrat* got stuck on Arch Rock and was wrecked. In 1877, a few years after the initial lowering of Blossom Rock, the *Highland Light* struck it and the *Blanchard* grounded on it while they were under tow.

Blossom Rock, which lies about 1 km north of the San Francisco wharves and 2 km southeast of Alcatraz Island, is a subsurface ledge that originally reached to within 2 m of Mean Lower Low Water (MLLW). It was reduced by mining and blasting to a depth of 7 m below MLLW in 1870, to 9 m in 1903 and to 12 m in 1932. Arch Rock, Shag Rocks and Harding Rock lie in an arc about 1 to 2 km west and northwest of Alcatraz Island. The southernmost, Arch Rock (also known at one time as Bird Rock), reportedly stood about 10 m above the water (above low water, presumably), and was about 15 m long and 3-6 m wide. There was an arched opening in its center, large enough to pull a boat through with difficulty. In 1900-1903 Arch Rock was lowered to 9 m below MLLW, and to 11 m in 1932. Shag Rocks (once also known as Barrel Rock) consisted of two rock knobs, the taller of which stood about a meter above the highest tides and was about 3 m long. The two rocks were lowered to a depth of 9 m below MLLW in 1900 and 1901 and to 11 m in 1931-32. Harding Rock, the northernmost of these rock features, was not discovered until 1917. It is a pinnacle that originally reached to about 9 m below MLLW, and was lowered to 11 m below MLLW in 1932 (Sea Surveyor 2001; Allan 2001; Chin et al. 2004). It has been proposed that these four rock features should now be further lowered to 17 m below MLLW, to reduce risks to modern deep-draft cargo vessels (Carlson et al. 2000; Chin et al. 2004). However, the U.S. Army Corps concluded that the benefits of lowering the rocks would not be worth the costs because "current navigational practices make an oil spill resulting from a tanker or other vessel grounding on one of the knobs very unlikely" (Chin et al. 2004).

Some of the names that have been used for the two rocks that originally projected above the water surface (Bird Rock, Shag Rock) suggest that they were heavily frequented by sea birds, though it's not known if they were used as breeding sites. All four rocks now have the form of submerged rock masses with flattened tops that rise 12-15 m above the surrounding sea floor and whose highest points are 11-12 m below MLLW (Sea Surveyor 2001). The upper surfaces of these rocks down to depths of 20-25 m below MLLW consist of rock reef strewn with blocky rubble that ranges from cobbles to boulders several meters long, apparently left from the blasting (USACE 2003; Chin et al. 2004). Below this depth the rock masses are separated from each other and isolated from other exposed bedrock features in the Bay by a cover of unconsolidated bottom sediment (coarse sand, gravel and shell hash) that is around 2 m to 8 m or more thick (Sea Surveyor 2001), and thus the rocks form small habitat "islands." They are generally similar to other hard-bottom habitats at similar depths along the Central California coast, but are uncommon habitat types within the San Francisco Bay region (Garcia and Associates 2001). A benthic video survey of the rocks conducted by ROV in 2001 found three species of sea stars, rock crabs (*Cancer* spp.) and turf organisms (hydroids, bryozoans, anemones, sponges, etc.) to be common on the rocks and tabulated a low species richness, though this result was influenced by the extremely poor visibility (due to high turbidity) and the limited taxonomic resolution of the survey (Garcia and Associates 2001). No reference was made to the presence or absence of macroalgae. Turf organisms covered 25% to nearly 100% of the bottom, and were more common above 18 m depth. On the three northernmost rocks there were abundant hard-bottom sea stars—species that are not capable of migrating across the intervening sediment-covered bottom and must have arrived on the rocks as planktonic larvae—consistent with the view that the rocks function as habitat islands (Garcia and Associates 2001).

In addition to the loss of sea bird resting habitat—and possibly the loss of sea bird breeding sites or pinniped haulout sites—the initial reduction of projecting rocks to depths below the surface is likely to have eliminated some supralittoral, intertidal and near-surface subtidal species. While further lowerings to progressively greater depths that have been done or are proposed are less likely to eliminate species, the decrease in cover by turf organisms with depth noted in the benthic survey suggests that there would be impacts on the abundance of some organisms and possibly on species composition. If species of algae are present, removal of the shallowest portions of the rocks would reduce and might eliminate them. Reductions in the total surface area of these habitat islands could also result in the loss of some species, and their isolation could hamper recolonization. Both from fishing reports (USACE 2003) and from observations (e.g. schools of fish obscuring side-scan images—Sea Survey 2001), it appears that fish are abundant and fishing is good around these rocks, and lowering them further could change that.

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Literature Cited

ABP Research. 1999. Good practice guidelines for ports and harbours operating within or near UK marine sites. Prepared for English Nature, UK Marine SACs Project. ABP Research & Consultancy Ltd,. Southampton, Hampshire, UK. http://www.ukmarinesac.org.uk/publications-launch-pdf.php?file=guidelines&filesize=6514

Allan, J.M. 2001. Marine Archaeological Investigation in Support of the San Francisco Bay Rocks Removal Project. Prepared for Sea Surveyor, Inc. under contract DACW07-98-D-0002 from the U.S. Army Corps of Engineers, San Francisco District. Sea *Su*rveyor, Inc., Benicia, CA.

BCDC. 2003. The San Francisco Bay Area Seaport Plan. San Francisco Bay Conservation and Development Commission, San Francisco, and the Metropolitan Transportation Commission, Oakland.

CDFG. 2007. San Francisco Bay Monitoring Program, California Department of Fish and Game, Sacramento. Website at http://www.delta.dfg.ca.gov/baydelta/monitoring/baystudy.asp.

Carlson, P.R., J.L. Chin and F.L. Wong. 2000, Bedrock knobs, San Francisco Bay—Do navigation hazards outweigh other environmental problems?: Environmental and Engineering Geosciences 6:41-55.

Chin, J.L., F.L. Wong and P.R. Carlton. 2004. Shifting Shoals and Shattered Rocks—How Man Has Transformed the Floor of West-Central San Francisco Bay. Circular 1259, U.S. Geological Survey, Menlo Park, CA.

Churchill, J. 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. Continental Shelf Research 9: 841-864.

Clark, G.H. 1930. Shrimps. Page 68 in: The Commercial Fish Catch of California for the Year 1928, Fish Bulletin No. 20, California Division of Fish and Game.

Collie, J.S., S.J. Hall, M.J. Kaiser and I.R. Poine. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. Journal of Animal Ecology 69: 785-798.

Conomos, T.J. 1979. Properties and circulation of San Francisco Bay waters. Pages 47-84 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Conomos, T.J., R.E. Smith, D.H. Peterson, S.W. Hager and L.E. Schemel. 1979. Processes affecting seasonal distributions of water properties in the San Francisco Bay estuarine system. Pages 115-142 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Cosentino-Manning, N., K. McGourty and S. Wainwright-De La Cruz. 2007. Plant beds. Pages 57-64 in: Schaeffer, K., K. McGourty and N. Cosentino-Manning (eds.). Report on the Subtidal Habitats and Associated Biological Taxa in San Francisco Bay. National Oceanic and Atmospheric Administration/National Marine Fisheries Service, Santa Rosa, CA.

Dernie, K.M., M.J. Kaiser and R.M. Warwick. 2003. Recovery rates of benthic communities following physical disturbance. Journal of Animal Ecology 72: 1043-1056.

Fautin, D.G. and C. Hand. 2007. Anthozoa. pages 173-184 in: Carlton, J.T. (ed.), The Light & Smith Manual: Intertidal Invertebrates of the California and Oregon Coasts, University of California Press, Berkeley, CA.

Foxgrover, A.C., Higgins, S.A., Ingraca, M.K., Jaffe, B.E. and R.E. Smith. 2004. Deposition, erosion, and bathymetric change in South San Francisco Bay: 1858–1983: U.S. Geological Survey Open-File Report

2004–1192. http://pubs.usgs.gov/of/2004/1192

Gannsle, D. 1966. Fishes and Decapods of San Pablo and Suisun Bays. Pages 64-94 in: Kelley, D.W. (ed.), Ecological Studies of the Sacramento-San Joaquin Estuary, Fish Bulletin 133, California Department of Fish and Game, Sacramento, CA.

Garcia and Associates. 2001. Final Survey Report: San Francisco Rock Removal Benthic Survey Off Alcatraz Island, CA. Prepared for San Francisco District, U.S. Army Corps of Engineers. Garcia and Associates, San Anselmo, CA.

Haderlie, E.C. and D.P. Abbott. 1980. Bivalvia: the clams and allies. Pages 355-411 in: Morris, R.H., Abbott, D.P. and E.C. Haderlie (eds.), Intertidal Invertebrates of California. Stanford University Press, Stanford, CA.

Haig, J. and D.P. Abbott. 1980. Macrura and Anomura: the ghost shrimps, hermit crabs and allies. Pages 577-593 in: Morris, R.H., Abbott, D.P. and E.C. Haderlie (eds.), Intertidal Invertebrates of California. Stanford University Press, Stanford, CA.

Hammond, D.E. and C. Fuller. 1979. The use of radon-22 to estimate benthic exchange and atmospheric exchange rates in San Francisco Bay. pages 213-230 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Hammond, D.E., C. Fuller, D. Harmon. B. Hartman. M. Korosec, L.G. Miller, R. Rea. S. Warren, W. Berelson and S.W. Hager. 1985. Benthic fluxes in San Francisco Bay. Hydrobiologia 129: 69-90.

Hanson Environmental. 2004. Oyster Shell Mining within South San Francisco Bay State Lands Comission Lease PRC 5534.1. Prepared for Morris Tug and Barge, Inc. Hanson Environmental, Inc., Walnut Creek, CA.

Hanson, C.H., J. Coil, B. Keller, J. Johnson, J. Taplin and J. Monroe. 2004. Assessment and Evaluation of the Effects of Sand Mining on Aquatic Habitat and Fishery Populations of Central San Francisco Bay and the Sacramento-San Joaquin Estuary. Prepared for Hanson Aggregates Mid-Pacific, Inc., RMC Pacific Materials, Inc. and Jerico Products, Inc./Morris Tug and Barge. Hanson Environmental, Inc., Walnut Creek, CA.

Hirsch, N.D., L.H. DiSalvo and R.K. Peddicord. 1978. Effects of dredging and disposal on aquatic animals. Technical Report DS-78-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Kaiser, M.J., J.S. Collie, S.J. Hall, S. Jennings and I.R. Poiner. 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish and Fisheries 3: 114-136.

Krone, R.B. 1979. Sedimentation in the San Francisco Bay system. Pages 85-96 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Larson, K., and C. Moehl. 1990. Fish entrainment by dredges in Grays Harbor, Washington. Pages 102-112 in: C.A. Simenstad (ed), Effects of Dredging on Anadromous Pacific Coast Fishes, Washington Sea Grant Program, University of Washington.

Levine-Fricke. 2004. Framework for Assessment of Potential Effects of Dredging on Sensitive Fish Species in San Francisco Bay. Final Report 001-09170-00 prepared for the U.S. Army Corps of Engineers. LFR Levine-Fricke, Emeryville, CA.

LTMS. 1998. Long-Term Management Strategy for Bay Area Dredged Material: Final Environmental

Impact Statement/Environmental Impact Report. http://www.spn.usace.army.mil/ltms/toc.html

Marine Exchange. 1997. Golden Gate Ship Traffic 1996. The Marine Exchange of the San Francisco Bay Region, San Francisco.

McGraw, K. and D. Armstrong. 1990. Fish entrainment by dredges in Grays Harbor, Washington. Pages 113-131 in: C.A. Simenstad (ed), Effects of Dredging on Anadromous Pacific Coast Fishes, Washington Sea Grant Program, University of Washington.

MSI. Undated. Trends in South San Francisco Bay Fish Populations from 1973 to 2002. Marine Science Institute, Redwood City, CA.

Nichols, F.H. 1979. Natural and anthropogenic influences on benthic community structure in San Francisco Bay. Pages 409-426 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Oliver, J.S., P.N. Slattery, L.W. Hulberg and J.W. Nybakken. 1977. Patterns of Succession in Benthic Infaunal Communities Following Dredging and Dredged Material Disposal in Monterey Bay. Technical Report D-77-27, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Poulton, V.K., J.R. Lovvorn and J.Y. Takekawa. 2002. Clam density and scaup feeding behavior in San Pablo Bay, California. Condor 104: 518-527.

Poulton, V.K., J.R. Lovvorn and J.Y. Takekawa. 2004. Spatial and overwinter changes in clam populations of San Pablo Bay, a semiarid estuary with highly variable freshwater inflow. Estuarine Coastal and Shelf Science 59(3): 459-473.

Richman, S.E. and J.R. Lovvorn. 2004. Relative foraging value to Lesser Scaup ducks of native and exotic clams from San Francisco Bay. Ecological Applications 14(4): 1217-1232.

Rubin, D.M. and D.S. McCulloch. 1979. The movement and equilibrium of bedforms in central San Francisco Bay. pages 97-113 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Sea Surveyor. 2001. Marine Geophysical Investigation in Support of the San Francisco Bay Rocks Removal Project. Prepared under contract DACW07-98-D-0002 for the U.S. Army Corps of Engineers, San Francisco District. Sea *Su*rveyor, Inc., Benicia, CA.

Silva, P.C. 1979. The benthic algal flora of Central San Francisco Bay. Pages 287-345 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Skinner, J.F. 1962. An Historical review of the Fish and Wildlife Resources of the San Francisco Bay Area. Water Projects Branch Report No. 1, California Department of Fish and Game< sacarmento, CA.

Smith, S.E. and S. Kato. 1979. The fisheries of San Francisco Bay: past, present, and future. Pages 445-468 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Thompson, J.K., J.R. Koseff, S.G. Monismith and L.V. Lucas. In press. Shallow water processes govern system-wide phytoplankton bloom dynamics: a field study. Journal of Marine Systems.

Thrush, S.F., J.E. Hewitt, V.J. Cummings, P.K. Dayton, M. Cryer, S.J. Turner, G.A. Funnell, R.G. Budd, C J. Milburn and M.R. Wilkinson. 1998. Disturbance of the Marine Benthic Habitat By Commercial Fishing: Impacts at the Scale of the Fishery. Ecological Applications, 8: 866–879.

Treasher, R.C. 1963. Geology of the sedimentary deposits in San Francisco Bay, California. Special Report 82, California Division of Mines and Geology.

USACE. 2003. San Francisco Bay Rocks Removal Project, San Francisco, California: Feasibility Study Reference Report. U.S. Army Corps of Engineers, San Francisco District, San Francisco and California State Lands Commission, Sacramento.

USACE. 2005. Assessment of Sediment Resuspension by Vessel Traffic at Richmond Longwharf. U.S. Army Corps of Engineers, San Francisco, and MEC-Weston Solutions, Tiburon, CA.

Wainwright, T., D. Armstrong, P. Dinnel, J. Orensanz and K. McGraw. 1992. Predicting effects of dredging on a crab population: an equivalent adult loss approach. Fish. Bulletin 90: 171-82.

Watling, L. and E.A. Norse. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conservation Biology 12:1180-1197.