

THE MARINA DISTRICT, SAN FRANCISCO, CALIFORNIA: GEOLOGY, HISTORY, AND EARTHQUAKE EFFECTS

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ABSTRACT

A northwest-trending valley in the bedrock surface is buried by firm Pleistocene bay clay, a dense Pleistocene sand layer, soft Holocene bay sediments, loose to dense Holocene beach and dune sands, and artificial fill that have an aggregate maximum thickness of about 90 m (300 ft). Artificial filling of a cove at the site of the Marina District proceeded gradually from the late 1860s to 1912, when major hydraulic filling was done for the Panama-Pacific International Exposition. The remains of thousands of piles driven for the Exposition very probably still exist and have had unknown effects on long-term ground settlement and earthquake-related ground displacements. Intensity maps of the 1906 earthquake, and seismic recordings and severe building damage in 1989, reported by others, indicate that ground motion was amplified on both natural and artificial ground. This suggests that the configuration of the bedrock surface and the location and thickness of various clay and sand deposits underlying the fill had an important effect on the shaking. However, most of the settlement and liquefaction and the damage to pipelines, building foundations, streets, sidewalks, and curbs occurred in areas of artificial fill consisting mainly of loose sand.

INTRODUCTION

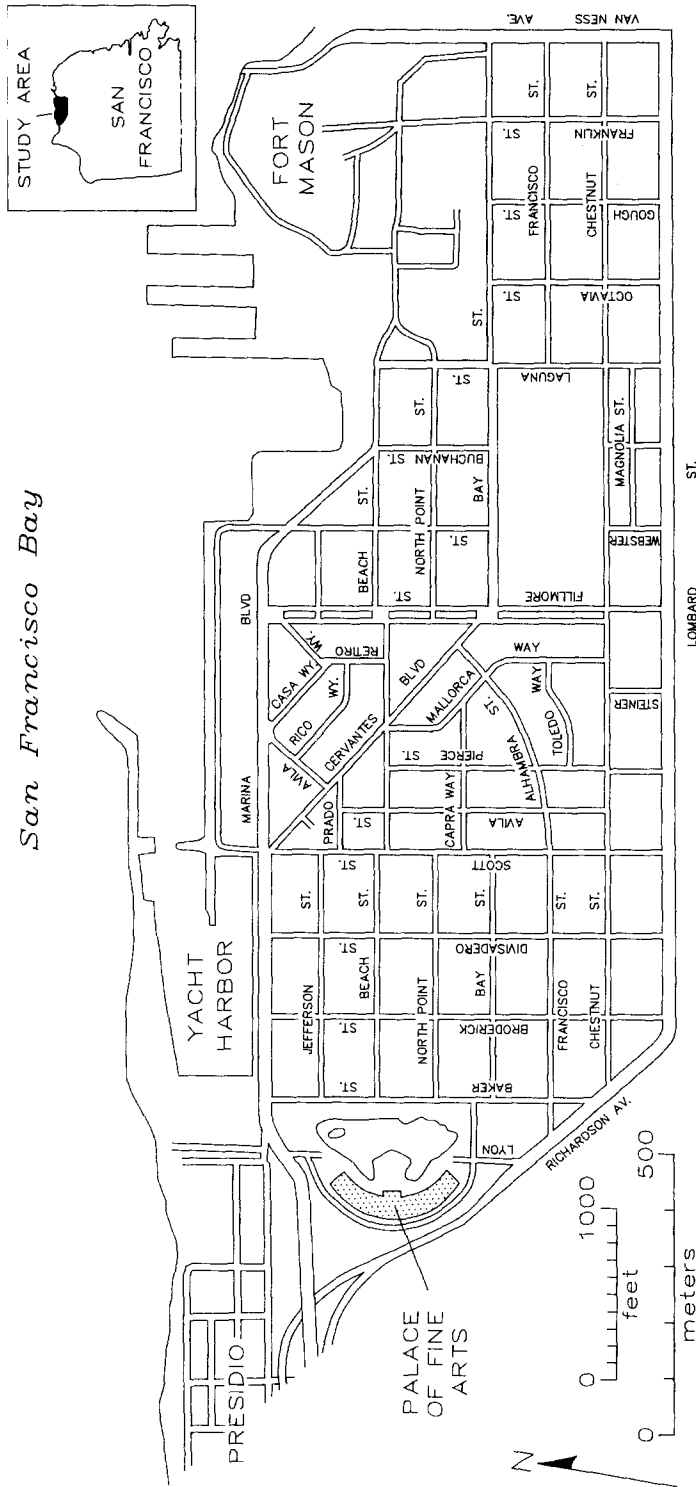
During the Loma Prieta earthquake of 18 October 1989, substantial damage occurred in the Marina District of San Francisco, even though it was 100 km (60 miles) from the epicenter. Factors that influenced the damage included liquefaction, differential settlement, amplification of ground motion, and the types and conditions of the buildings. To understand the reasons for the damage and to anticipate the effects of future earthquakes, various studies were made, among them a preliminary report on the geology and the artificial fills that underlie the Marina District (Bonilla, 1990). The present article is a revision and expansion of the earlier report and includes a map showing approximate contours on the buried bedrock surface. The purpose of the article is to provide a summary of recent studies of the geology, including artificial fills, and to provide background information for current and future scientific and geotechnical investigations of the Marina.

Streets and localities referred in the text are shown on Figure 1. For brevity, the Marina District is referred to as the Marina in the following text.

GEOLOGY

Bedrock

The bedrock underlying the Marina consists of the Franciscan assemblage and serpentine. Nearby outcrops consist of sandstone and shale, except to the west where serpentine is also exposed (Schlocker, 1974). A boring near the south end of the Palace of Fine Arts (Fig. 1) penetrated shale, but a USGS



Base from U.S. Geological Survey San Francisco North 7.5' quadrangle, photorevised in 1973

Fig. 1. Location map of the Marina District.

boring southeast of the intersection of Divisadero and Beach Streets penetrated serpentine. The location of outcrops of Franciscan sandstone and shale in Fort Mason are shown on Figure 2.

Several maps show the configuration of the bedrock surface beneath the Marina. The map of Whitworth (1932, pl. XXXII) shows the surface at an elevation of 75 m (250 ft) below sea level in the southern and southeastern part of the Marina. The maps of Schlocker (1962, 1974) and Schlocker *et al.* (1954) show similar depths except in the western part of the Marina where they show elevations of zero to -15 m (-50 ft). The map of Schlocker *et al.* (1954) relied on the borings given in Whitworth (1932), but included a precautionary note: "Bedrock may be considerably deeper than shown; contours drawn on top of "yellow Hardpan" of drillers log." This note was omitted from the later bedrock surface maps of Schlocker (1962; 1974, pl. 3). Various post-1932 borings show that the bedrock is indeed deeper than the yellow hardpan. A map showing the bedrock surface under part of the Marina and San Francisco Bay (Carlson and McCulloch, 1970) is based on the 1962 map of Schlocker and interpretation of offshore continuous subbottom acoustic profiling.

My interpretation of the configuration of the bedrock surface is shown on Figure 3. Although more than 200 borings have been made in the Marina, few reach the bedrock surface. Preparing a map of the bedrock surface therefore requires many inferences and interpretations. In preparing Figure 3, I assumed that the bedrock surface was shaped by steam erosion, rather than tectonic deformation, and that the stream had its outlet through the Golden Gate, where bedrock is about 120 m (400 ft) below sea level (Carlson and McCulloch, 1970). The maps by Carlson and McCulloch (1970) and Schlocker (1974) show a bedrock basin in the Marina that opens northward just west of Fort Mason. However, two borings considerably farther west penetrated bedrock at elevations of -77 m (-252 ft) and -23 m (-75 ft) and indicate that the bedrock basin may open to the northwest rather than to the north. A stream flowing northwest would have a shorter path to the Golden Gate than one flowing northward and then westward, and a northwest-flowing drainage was assumed. With this basic model, the surface drainage shown on the old topo maps was extrapolated, and contours were inferred using boring data, outcrops, and the offshore geophysical survey of Carlson and McCulloch for controls.

The bedrock surface shown in the northwest corner of Figure 3 is deeper than the onshore and near-offshore contours shown by Carlson and McCulloch (1970). Their interpretations onshore in the western part of the Marina were influenced by the erroneous contours on the yellow hardpan (Schlocker, 1962) and are discounted. Offshore, Carlson and McCulloch show a -75 m (-250 ft) bedrock elevation where Figure 3 shows -90 m (-300 ft) elevation. Straight-line extrapolations of the bedrock surface between borings or between outcrops and borings indicate bedrock elevations of at least -90 m (-300 ft) well inland under the Marina and, if the stream-erosion model is correct, bedrock elevation must be less than that in the northwest corner of Figure 3. Owing to difficulty in identifying bedrock in the reflection profiles and unknown velocities in firm materials above bedrock, the bedrock surface may well be lower than shown on the Carlson and McCulloch map (P. R. Carlson, personal comm., 1990). Van Reenan (1966) also states that identification of the bedrock surface by reflection methods is difficult in some places, and notes on his profiles indicate that refraction data locally show greater depths than reflection data.

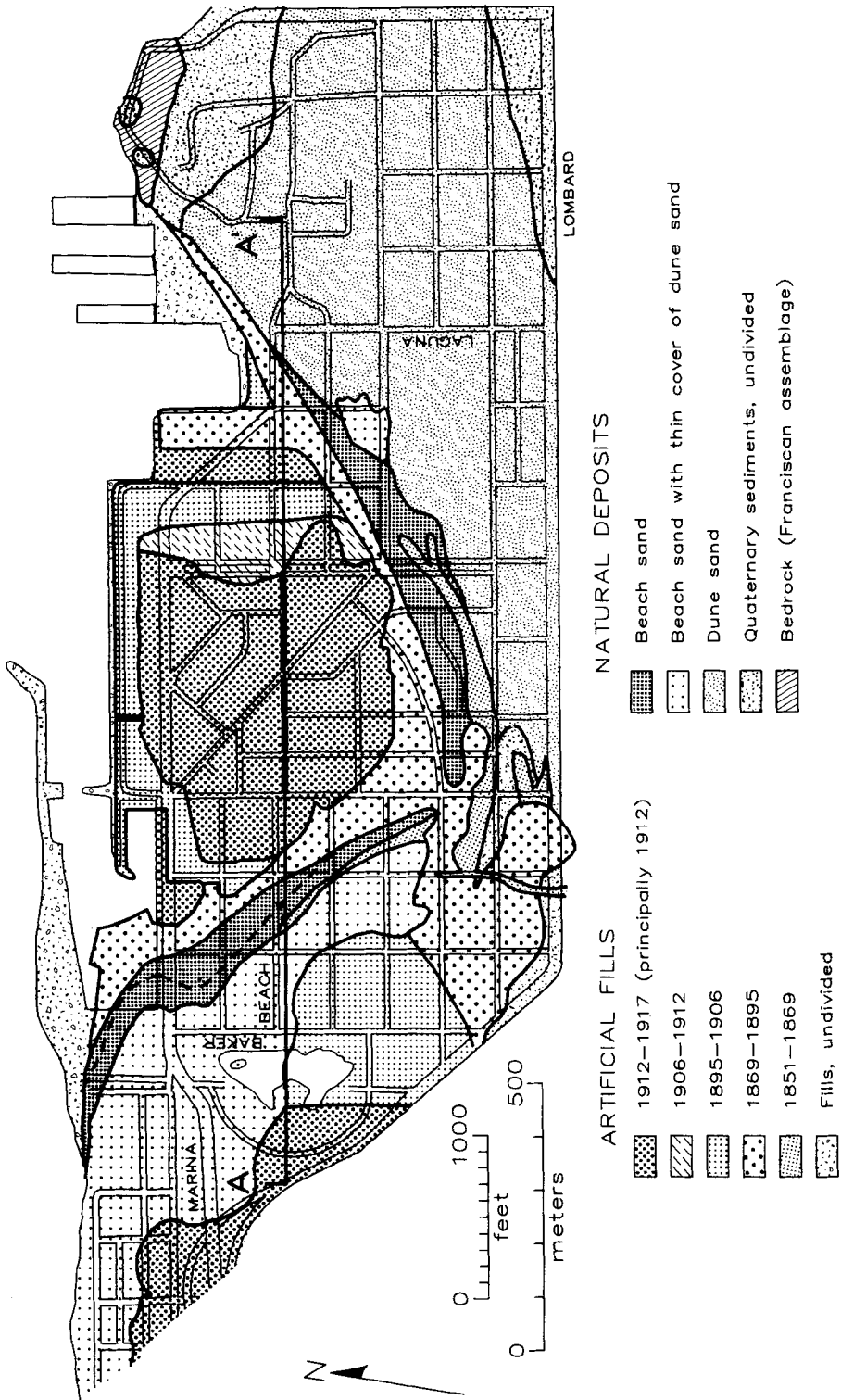


FIG. 2. Map showing geology and ages of artificial fills. Curved northwest-trending dashed line in left part of map represents part of the 1851 shoreline. The undated fill near the Fort Mason docks was placed between 1895 and 1909, and the fills north of the yacht harbor are post-1914.

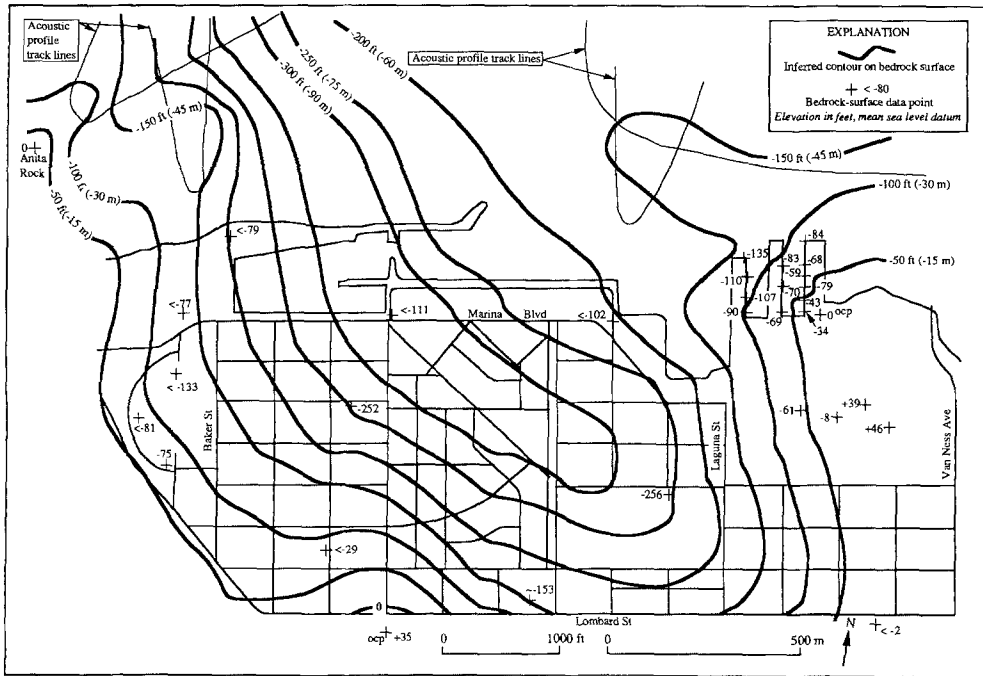


FIG. 3. Map showing inferred contours on surface of bedrock. Data points at rock outcrops are designated ocp. Acoustic profile track lines from Carlson and McCulloch (1970).

O'Rourke *et al.* (1991a, Fig. 12) independently prepared a map showing contours on the bedrock surface beneath the Marina. They used bedrock outcrops at a greater distance to southwest, south, and east than I did, but not Anita Rock or the offshore geophysical surveys. Their map, generated by computer software that uses a method called kriging, is similar to Figure 3 in showing a northwest-trending valley in the bedrock surface, but it differs in that the valley is about 15 m shallower and does not extend as far to the southeast.

Unconsolidated Natural Sediments

The bedrock in the Marina is buried by a sequence of unconsolidated sediments. The term "unconsolidated" is used here in the geologic sense (i.e., not hard rock) rather than the geotechnical sense. The complexity of these sediments can be partially understood by reviewing the recent geologic history of the San Francisco Bay estuary system. During the last million years at least four periods of deposition occurred in San Francisco Bay, separated by periods in which the level of the ocean was lowered because ocean water was incorporated in glaciers (Atwater, 1979). The lower sea levels during glacial periods resulted in erosion of valleys in the then-existing sediments. Exposure of the sediments resulted in near-surface dessication and oxidation, which made the sediments more firm and produced the brown colors commonly reported in borings. This geologic history produced a variety of geologic units in the Marina and surrounding area, including bay, marsh, beach, and dune sediments.

Pleistocene Bay Sediments

Several borings in the Marina penetrated silty to sandy clay at considerable depth. In USGS boring WSS, south of Beach Street and east of Divisadero Street (Kayen *et al.*, 1990), the clay is 58 m (189 ft) thick and extends from elevation -19 m (-63 ft) to the bedrock surface at elevation -77 m (-252 ft). The clay is probably correlative with one or more of the three pre-Holocene bay deposits that formed in San Francisco Bay in the last million years (Atwater, 1979). During the last interglacial sea-level highstand about 100,000 years ago, an extensive bay deposit formed in San Francisco Bay (Atwater *et al.*, 1977; Atwater, 1979, Fig. 3). The upper part of the thick clay encountered in USGS boring WSS is probably the approximately 100,000-year-old bay deposit, but the deeper parts may be part of the still older bay sediments. The Pleistocene bay sediments are not exposed at the surface in the Marina, but their inferred east-west extent in the area of Figure 2 is shown on cross section A-A' (Fig. 4). When a plan-view sketch was made of the upper surface of the Pleistocene bay sediments, using the few data from borings, it became apparent that the surface has a broad depression, represented on Figure 4, that probably extends northeast. Treasher (1963) reports that valleys eroded into the older bay sediments are common in various parts of San Francisco Bay, and Atwater *et al.* (1977) also recognize a major unconformity at that stratigraphic level. Whether the depression in the surface of the Pleistocene bay sediments in the Marina is the result of erosion is unclear. The interfingering of the Pleistocene clay and Pleistocene sand shown in the eastern part of Figure 4 is schematic and is meant to indicate that the clay does not everywhere rest directly on bedrock.

Pleistocene Sand Layer

Many borings penetrated a sand layer overlying the Pleistocene bay silty clay. In section A-A' (Fig. 4), it has an estimated minimum thickness of about 9 m (30 ft). Two samples of the sand from boring USGS WSS contain only 1 to 6% silt and clay (Kayen *et al.*, 1990), which suggests dune or beach origin. A third sample had 26% silt and clay and could be of stream or estuarine origin. In borings in other parts of the Marina, the sand layer is described as sand, silty sand, or clayey sand. A sand layer in the southeast part of San Francisco has a similar stratigraphic position—under the Holocene bay clay and above the older bay clay—and in that area the lower part of the sand is interbedded with the older clay (Radbruch and Schlocker, 1958). Because few borings penetrate it, local interbedding of the lower part of the Marina sand layer with the older bay clay cannot be ruled out. The sand layer is probably less than 100,000 years old, because it overlies the Pleistocene bay sediments thought to be about 100,000 years old. As discussed in the following section, the upper part of the sand layer was apparently eroded by streams near the end of the last glaciation and is thus interpreted to be of Pleistocene age.

The sand layer resembles the Colma Formation and possibly is correlative with that formation. The Colma Formation, commonly a weathered sand, is thought to have originated primarily as a beach deposit (Schlocker, 1974). This formation was estimated to be 500,000 or more years old by Helley and Lajoie (1979), but new information on the age of an ash bed in marine deposits beneath the Colma in the southwest part of San Francisco indicates that it must be considerably less than 400,000 years old and perhaps correlates with one of the

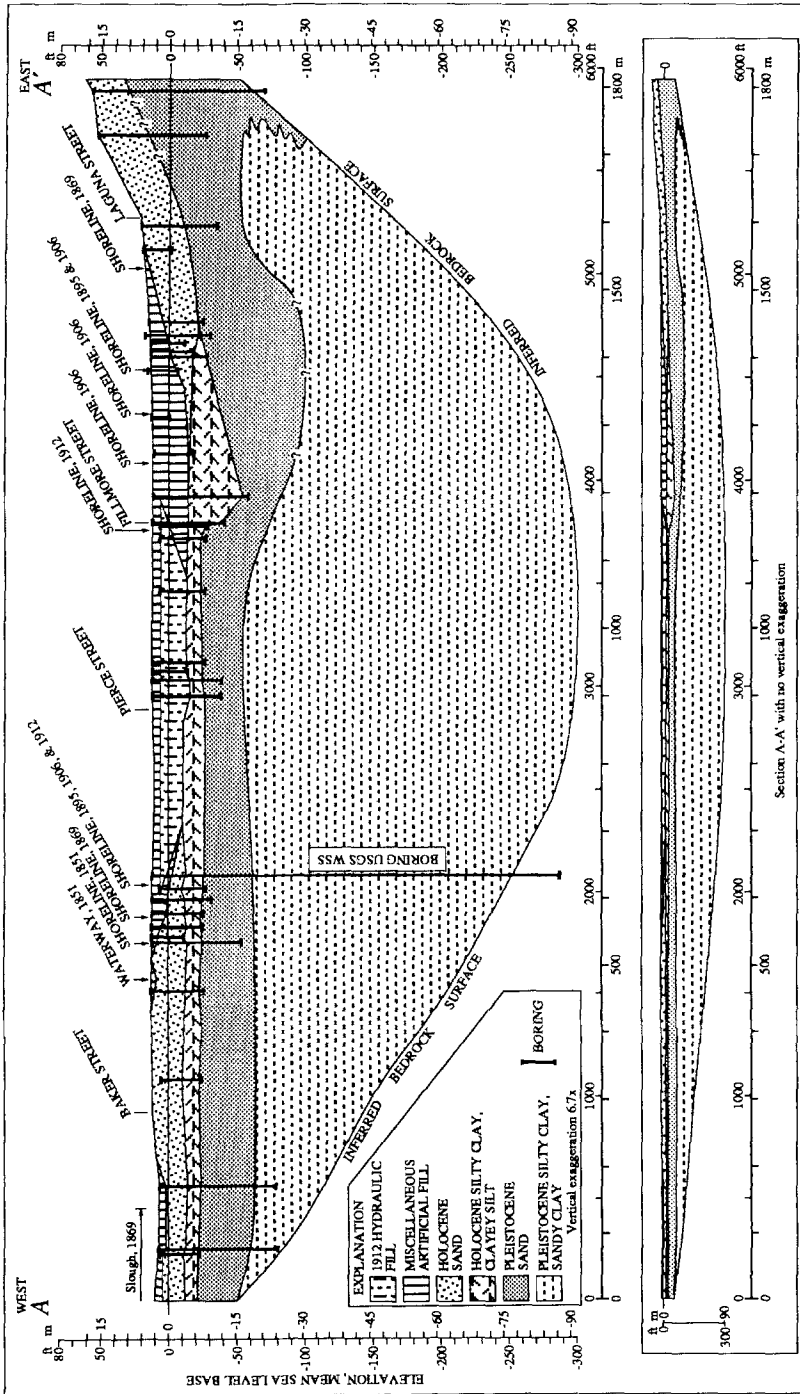


FIG. 4. East-west cross section of the Marina along Beach Street. The location of the cross section is shown on Figure 2 by the line labeled A-A'. Marsh deposits below the artificial fill in the western part of the section are too thin to be delineated. Querries indicate uncertainty in location. The interfingering of Pleistocene clay and Pleistocene sand in the eastern part of the section is schematic.

last sea-level highstands between about 70,000 and 130,000 years ago (Meyer *et al.*, 1980; Sarna-Wojcicki *et al.*, 1985; Clifton *et al.*, 1988).

Holocene Bay Sediments

Sea level during the last (Wisconsin) glaciation was 90 to 120 m (300 to 400 ft) lower than it is now, and the ocean shoreline was probably seaward of the Farallon Islands, about 50 km west of San Francisco. Holocene estuarine sediments (bay mud) accumulated during the sea level rise that followed the last glaciation. The rising sea is estimated to have entered the Golden Gate 10,000 to 11,000 years ago (Helley and Lajoie, 1979, p. 18). The bay mud, generally a soft silty clay or clayey silt, formed the bottom of Marina cove and underlies most of the Marina. As shown on Figure 4, the top of the Holocene bay sediments is rather even, but the bottom descends eastward and the bay mud thickens greatly east of Fillmore Street, and then lenses out eastward. The valley-like shape of the bottom of the bay mud extends northward to Marina Boulevard (O'Rourke and Roth, 1990; O'Rourke *et al.*, 1991a, Fig. 15). As discussed below, the Holocene bay sediments were apparently deposited on a late Pleistocene erosion surface, which accounts for their irregular bottom.

A layer of green sand and clay, often described as hard, underlies the bay sediments in 80% of the borings made for the 1915 Panama-Pacific International Exposition, and most of the Exposition piles were founded in this layer. About 90% of the Exposition borings reached a "yellow hardpan" beneath the hard green sand and clay. Although descriptions vary, several 1989 and 1990 borings found a similar zone containing hard or firm layers, which produced high peaks on the cone penetrometer test records. The hard zone has an irregular surface not only in the section along Beach Street but in other parts of the Marina as well. The yellow hardpan is probably a soil zone that formed on an erosion surface developed during the low sea level of the last glaciation, and the green layer (sand and clay) formed in the early stages of bay deposition. Inclusion of the green layer within the bay sediments is supported by the fact that it is locally interbedded with the bay sediments (Whitworth, 1932, borings 2, 11, and probably 14A). If this interpretation is correct, the hard zone (i.e., the hardpan and the hard sand and clay) is near the local boundary between the Holocene and Pleistocene.

General descriptions of bay mud are given by Schlocker (1974) and Helley and Lajoie (1979), and some of the geotechnical properties of the bay mud in the Marina are given by Kayen *et al.* (1990).

Holocene Beach and Dune Sand

Holocene beach sand underlies the northwest part of the Marina and forms a narrow strip in the southeast part. That in the northwest forms a sand spit formerly called Strawberry Island; old maps show that the spit was growing eastward prior to placement of artificial fill. Based on line patterns on old maps, and photographs taken in the 1860s, much of the beach sand had a thin discontinuous cover of dune sand (Fig. 2). Old maps, photographs, and historical accounts show that dune sand (wind-deposited sand) underlies the eastern and southeastern part of the Marina.

The bulk of both the beach and dune sediments consists of clean, well-sorted sand. Detailed descriptions and analyses of the beach and dune sands are given by Schlocker (1974).

Holocene Marsh Sediments

Tidal marsh sediments, now covered by artificial fill, underlie a narrow band in the southwest part of the Marina and continue westward into the Presidio. Their original extent is shown by diagonal ruling on an 1851 map (Fig. 5). The marsh sediments consist of clay and silt containing small quantities of marsh vegetation. The marsh sediments grade into the bay sediments that underlie the Marina and in places interfinger with beach sand. General descriptions of marsh sediments around San Francisco Bay are given by Helley and Lajoie (1979) and Atwater *et al.* (1979).

Artificial Fills

Artificial fills cover a large part of the Marina. Their distribution and ages are shown on Figure 2, and their history and nature are described in the following section.

HISTORY

Human modification of the natural environment of the Marina, particularly the emplacement of artificial fill, has had important effects on subsurface conditions there. To understand the changes better, the development of the Marina is outlined. First the original, natural, conditions are described, and then the modifications that occurred during settlement of the area.

Historical Development of the Marina

The earliest accurate map of the Marina, dated 1851 (Fig. 5), shows a small embayment (Marina cove) west of the bedrock headland now occupied by Fort Mason. The map also shows a meandering tidal slough draining a marsh that extended west of the Marina. North of this principal slough was a broad sand spit, covered discontinuously by dune sand, referred to as Strawberry Island

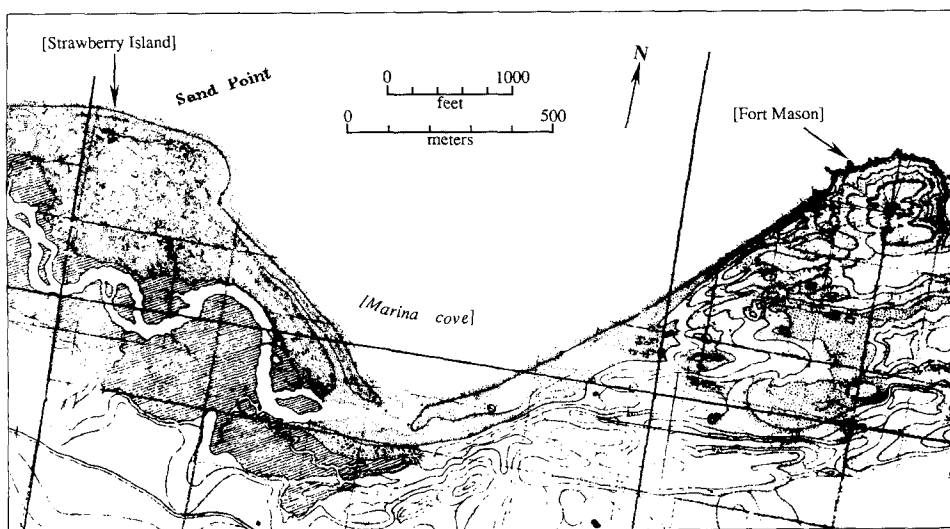


FIG. 5. Part of U.S. Coast Survey chart No. 314, dated 1851. Diagonal lines indicate marsh areas. Bracketed labels are not on original map, which is at 1 : 10,000 scale.

(Dow, 1973). The north edge of Strawberry Island is labelled Sand Point on the 1851 map. A narrow waterway extended northwest of the mouth of the principal slough, just reaching the present position of Beach Street. Another small waterway, trending northeast, lay east of the principal slough. A narrow strip of beach sand was to the north and a broad area of dune sand was to the east of this waterway. The features shown on an 1857 U.S. Coast Survey map are almost the same, except for shortening of the narrow northwest-trending waterway and an eastward shift in the positions of the mouth of the principal tidal slough and associated sand spits at the south end of the Marina cove. These changes were very likely natural, as no roads or structures are shown near the shores.

By 1869 (Fig. 6), the mouth of the principal slough had shifted westward, probably by natural processes, and the northwest- and northeast-trending narrow waterways mentioned above no longer existed. Probably both of the narrow waterways were artificially filled, at least in part, as roads are shown crossing their former sites. A roadway, undoubtedly on fill, is shown partially crossing the principal slough along the present position of Divisadero Street at Francisco Street. The Fillmore Street wharf, built in 1863 and 120 m (400 ft) long (Dow, 1973, p. 95), is shown extending into Marina cove north of the present position of Bay Street at Fillmore Street; presumably the wharf was built on piles. East of the Fillmore Street wharf is an artificial fill, perhaps 30 m (100 ft) long, along the east side of the present position of Webster Street and south of the present position of North Point Street. The symbol used on the 1869 map suggests that this fill was of sand.

In the 1860s, a hotel, shooting gallery, and other structures were built north of the present site of the Palace of Fine Arts. The Santa Cruz Power Co. had a

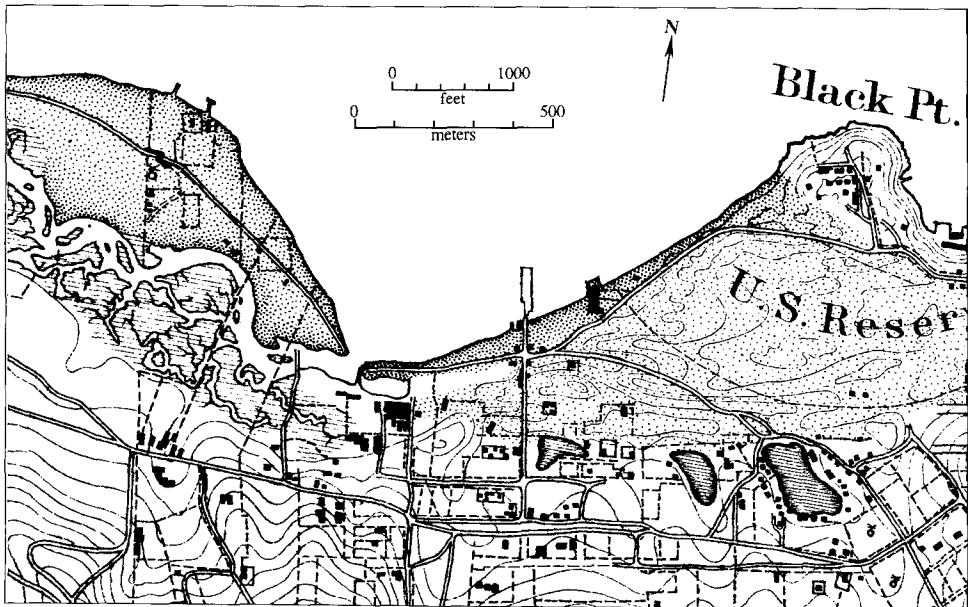


FIG. 6. Part of U.S. Coast Survey map No. 3055, dated 1869. Black Point is now part of Fort Mason. Long wharf is north of present position of Bay Street at Fillmore Street. The original map is at 1:40,000 scale and has a 20-foot contour interval. Surveys for this map were done in 1850 to 1857 and 1867 to 1868.

small wharf in the same vicinity (Dow, 1973), probably one of the two wharves shown on Figure 6 northwest of Marina cove at a site north of the present-day Marina Boulevard. The Phelps Manufacturing plant, which made bolts, heavy forgings, railroad cars, and cable, was built in 1882 in a triangular area bounded by present-day Fillmore, Bay, and Buchanan Streets (Dow, 1973, p. 95).

In 1891, the San Francisco Gas Light Company made a wharf extending 300 m (1000 ft) north of Bay Street at its property east of the Phelps plant (Dow, 1973, p. 97) (Fig. 7). This wharf is referred to as an "earthen mole" on the Sanborn Ferris Map Co. (1899) map, and it had a rock retaining wall around it (Olmsted *et al.*, 1977, p. 667).

By 1894, a sea wall had been built around property owned by J. G. Fair (Dow, 1973, p. 96). The sea wall was built of rock dumped from cable-drawn railroad cars operating on a pile trestle (Olmsted *et al.*, 1977, p. 716 and Plate 20). According to Dow (1973, p. 101), this is the sea wall that retained the hydraulic fill placed for the 1915 Panama-Pacific International Exposition, and was at or near the present sea wall north of Marina Boulevard. The sea wall (?) shown on a map surveyed in 1895 (Fig. 7) only partly coincides with the present sea wall and does not reach the east or west shores of the lagoon, but the 1899 map shows the sea wall reaching both shores (Sanborn Ferris Map Co., 1899).

In 1906, the Marina cove was enclosed, except for a narrow opening to the north, and had a rim of artificial fill around it (Fig. 8). Little historical information is at hand as to the method of placement or nature of this fill, but

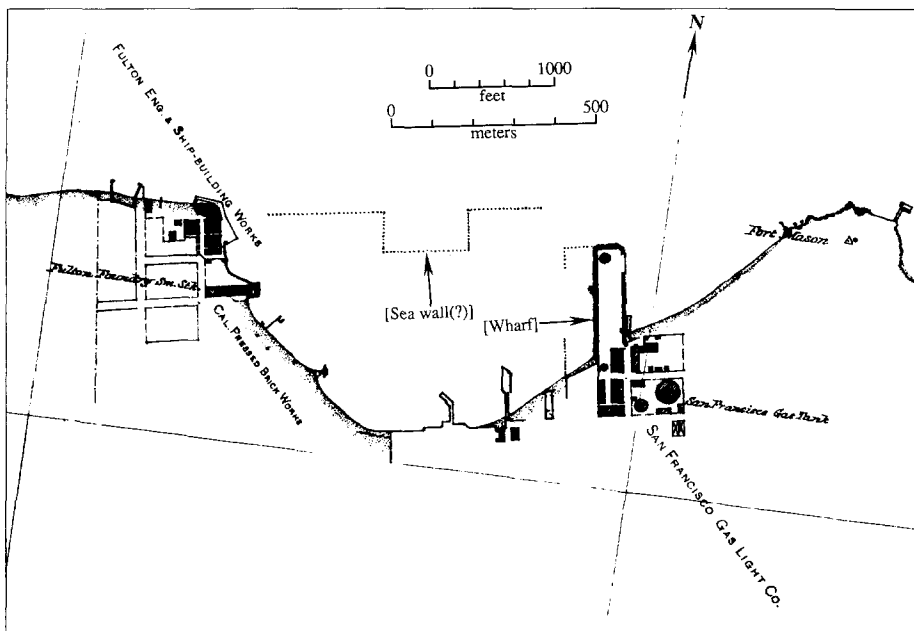


FIG. 7. Part of U.S. Coast and Geodetic Survey Register No. 2205, surveyed in 1895. The intersection of North Point and Buchanan Streets is in the center of the San Francisco Gas Light Co. group of buildings. The building in the southeast corner of the intersection still exists and is called the Pacific Union Company building. The "Cal. Pressed Brick Works" is northeast of the intersection of Jefferson and Broderick Streets. The boundary of the Presidio in 1895 is shown as a dash-dot line. Bracketed labels are not on original map, which is at 1 : 10,000 scale.

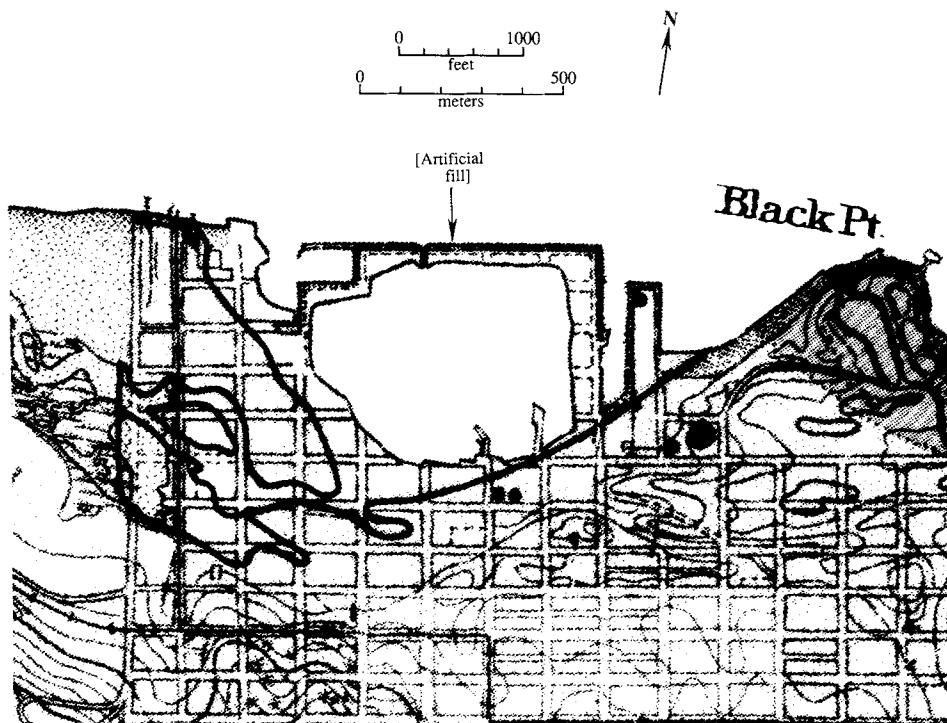


FIG. 8. Part of the geologic map published in the report on the 1906 earthquake (Lawson et al., 1908, Map No. 17, 1:40,000 scale). Bracketed label is not on original map, which identified by color the area of artificial fill surrounding Marina cove.

segments of the sea walls (?) shown on the 1895 map and Fair's sea wall must have been incorporated in it. Two borings made through the fill in 1975 encountered sand containing some rock fragments, brick, and other rubble (Dames and Moore, 1976). Artificial fill had also been placed over the eastern part of the principal slough as far west as the present position of Lyon Street. A photograph of Marina cove taken in 1912 prior to hydraulic filling (Fig. 9) shows conditions similar to those shown on the 1908 map, except that the photograph shows a broader area of fill on the east side of the cove. The general outline of the western edge of this 1906 to 1912 fill, shown on Figure 2, was interpreted from Figure 3 of Leurey (1914), which shows a contour line near mean high water. How much debris from the 1906 earthquake and fire was incorporated in fills in the Marina is unknown and, as described in a following section, 1906 debris would be difficult to distinguish from the Panama-Pacific International Exposition debris. There was a refuse dump at the foot of Webster and Bay Streets in the 1900s (Khorsand, 1973, p. 35). From the context of the description, this dump probably predated the 1906 earthquake. Two historical accounts that cover the Marina (Dow, 1973; Khorsand, 1973) make no mention of any dumping of 1906 debris at Harbor View (present-day Marina). Two general reports on the 1906 earthquake state that debris from the main part of San Francisco was dumped in Mission Bay (in eastern part of San Francisco), and some was hauled by barges to the vicinity of Mile Rock, west of the Golden Gate (Bronson, 1959, p. 170; Sutherland, 1959, p. 197). Considering its age however, the 1906 to 1912 fill could include debris from the 1906 earthquake.



FIG. 9. Photograph of the Marina area taken in April (?) 1912. Shortly after the photograph was taken the cove in the right middle ground was hydraulically filled for the Panama-Pacific International Exposition. Sand was pumped from the bottom of the Bay, transported by pipeline, and discharged into the cove. The pond in the left part of the photo is now part of the lagoon at the Palace of Fine Arts. Next to the pond is Baker Street, and then Broderick Street. Photo courtesy of Archives, San Francisco Main Library.

Logs of four borings (Whitworth 1932, holes 10A, 14A, 14B, and 15) within this fill area do not mention debris, although the ambiguous term “fill” is used in one log. Another boring, USGS Marina 5 (Bennett, 1990, Appendix B), on the border of the fill, encountered a railroad tie and gravel in the upper meter (3 ft) and a boulder at a depth of 3 m (9.8 ft). Probably a small amount of 1906 debris is in the fills.

In the post-1906 period, the largest changes in the Marina were made in connection with the 1915 Panama-Pacific International Exposition. In 1912, large hydraulic fills were placed in the central part of the Marina and in adjacent parts of the Presidio. Smaller hydraulic and other fills were placed through 1917, during restoration of the site of the Exposition. These changes are described in detail in the section on artificial fills.

After restoration of the Exposition site, the land was unused until 1924, when sale of the land to developers quickly led to residential construction (Dow, 1973, p. 103–108). Various modifications were made in the yacht harbor area, north of Marina Boulevard (Fig. 1). These included enlargement of the harbor, changes in breakwaters and sea walls, and the addition of some small fills.

Artificial Fills Related to the Panama-Pacific International Exposition

In the post-1906 period, the largest changes in the Marina were made in connection with the 1915 Panama-Pacific International Exposition, and therefore these changes are described in detail. Hydraulic filling of what remained of the Marina cove was done from 13 April to 7 September 1912. The cove was “. . . 12 feet in depth to the mud at mean high tide, formed by a sea-wall running east and west along the line of what became the northern boundary of

the grounds.” (Markwart, 1915a, p. 63). A suction dredge was positioned about 90 m (300 ft) offshore and generally moved parallel to the shore. If the discharge had too much fine material, the dredge was moved to get a larger proportion of sand. The Marina cove that was being filled contained semi-fluid sludge. A gate was left in the old sea wall so that the sand, discharged on the landward side, would displace as much as possible of the soft material into the Bay. To help remove mud from the bottom of the original basin, “. . . at times water was pumped instead of sand and this carried out considerable mud in solution through the waste gate” (Markwart 1915a, p. 64–65). The fill was about 70% sand and 30% mud (Todd, 1921, v. 1, p. 300).

Hydraulic fill was also used west of Lyon Street in a low-lying area along the old tidal channel shown in Figure 5. The rougher water offshore from this area required a sea-going dredge (Todd, 1921, vol. 1, p. 300). This fill did not exceed 1.8 m (6 ft) in depth, and it was “. . . mostly sand with a slight percentage of mud and frequently large boulders . . .” (Markwart, 1915b).

“Six or eight acres, on part of which lay the eastern half of the Court of the Four Seasons, had to be filled by scrapers to bring it up to grade . . .” (Todd, 1921, vol. 1, p. 162). The center of this court was southeast of the intersection of Beach and Broderick, on the old sand spit formerly called Strawberry Island. The northwest-trending waterway mentioned above in connection with the 1851 map was in this area and may account for the need for a special fill. The east half of this court would cover only about one acre. This is probably the same fill described by Dow (1973, p. 101) as covering 12 acres. Dow logically infers that the source of this fill was dune sand from the undeveloped land at the east end of the Exposition grounds (Dow, 1973, p. 101–102).

The method of placement of the fill in a band one-half block wide between the 1895 to 1906 fill and the 1891 San Francisco Gas Light Company wharf is uncertain. The 1906 map shows a sand pattern without a definite boundary to the north, which suggests that natural sedimentation was taking place there. This strip was filled by the time of the Panama-Pacific International Exposition, and no doubt was filled for the exposition, but the information at hand does not indicate the method of filling.

Exposition Piles

A large number of wooden piles from the Panama-Pacific International Exposition probably still exist in the Marina (Bonilla, 1990). More than 15,000 piles were used for the principal buildings (Leurey, 1914), and piles were used in some buildings not included in that total (Leurey, 1914, p. 254). The locations of buildings with pile foundations are shown on Figure 10, and the number of piles is given in Table 1. An understanding of the spacing of the piles can be gained from the specifications for the Mines Building and Varied Industries Building, which call for structural piles to be clustered in groups of two to ten, the clusters to be about 9 m (28 ft) apart from north to south and 25 m (82 ft) apart from east to west (Markwart, 1915a, Appendix B). In addition to supporting structural frames of buildings, piles were used to support floors and to support columns for concrete fire walls (Markwart, 1913, 1915b; Leurey, 1914).

Piles were as much as 23 m (75 ft) long, and many were to be driven into a layer of green sand and clay (Markwart, 1913) that is described above under “Holocene Bay Sediments.” However, sand of pre-exposition artificial fill

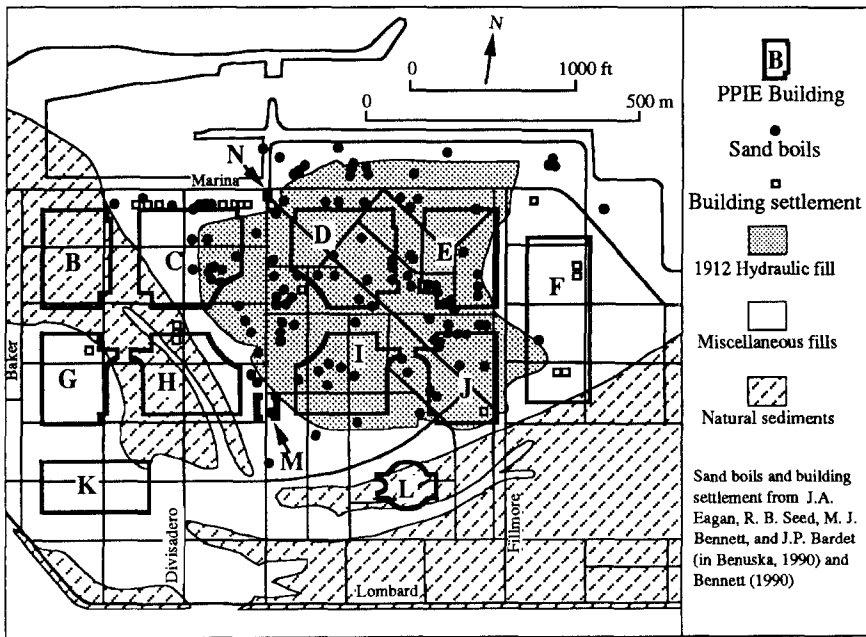


FIG. 10. Principal buildings of the 1915 Panama-Pacific International Exposition (PPIE; see Table 1 for names), sand boils, and modern buildings that settled during 1989 earthquake. Sand boils probably related to pipeline breaks are not shown. Exposition building locations from Todd (1921). Location of buildings with respect to modern streets based on Scott Street, the only Exposition street that was centered on existing San Francisco streets (Markwart, 1915a, p. 75), and the Palace of Fine Arts.

TABLE 1

PANAMA-PACIFIC INTERNATIONAL EXPOSITION BUILDINGS AND PILING

Letter Code*	Building*	Number of Piles	Average Length (ft) [†]
A	Fine Arts	1051	25.6
B	Food Products	665	14.5
C	Agriculture	1374	41.8
D	Transportation	4541	63.2
E	Mines	2026	46.1
F	Machinery	1577	28.6
G	Education	634	15.7
H	Liberal Arts	751	13.0
I	Manufactures	1591	35.7
J	Varied Industries	1444	34.3
K	Horticulture	#	
L	Festival Hall	Δ	
M	Tower of Jewels	Δ	
N	Tower of Progress	Δ	

*Shown on Figure 10, except for Palace of Fine Arts, which is shown on Figure 1.

[†]Length below cutoff.

#, Piles under dome at east end, number unknown.

Δ, Number unknown.

provided suitable support for piles of the Education Building (Leurey, 1914, p. 254). Reference to Figure 2 and Figure 10 shows that the Education Building site is underlain by fill placed in 1895 to 1906. One of the reasons for the extensive use of piles for Exposition buildings was greater safety in case of earthquakes (Markwart, 1913, p. 902; Leurey, 1914, p. 254).

Specifications for dismantling of the exposition include the statement that piles "... shall be cut off two (2) feet below the surface of the ground as it existed at the time the site was taken over" (Todd, 1921, Vol. 5, Appendix p. 134). Unfortunately, the position of the ground surface referred to by Todd is unknown. The exposition structures were designed for a life span of only a few years, and the piles were probably not treated with creosote. Thus, the parts of the piles above the water table may have deteriorated because of decay and termite action; however, wooden piles that are submerged, i.e., below the water table in the case of the Marina, last a very long time. Modern borings indicate that the depth to the water table at Exposition building sites ranges from about 2 to 3 m (7 to 10 ft); as discussed below, the former Exposition ground surface locally has 1.5 m (5 ft) of artificial fill above it.

Demolition of Exposition Buildings and Restoration of Site

After the Exposition closed in December of 1915, dynamite was used to bring down buildings and other structures, most of which were of wood. Wood that could not be economically salvaged was burned on the site on a daily basis by the fire department (Todd, 1921, vol. 5, p. 246-247). Reinforced concrete fire-walls, foundations, and transformer vaults were dynamited and broken up by a pile hammer (Todd, 1921, vol. 5, p. 246). As previously stated, piles were not removed but foundation obstructions were removed to some unknown depth (Todd, 1921, vol. 5, p. 247). Post-exposition filling was also done, and it was described as follows: "Some of the lands had not been filled up to the terms of the leases when they were built upon, and it was now necessary to carry out this part of the Exposition's obligations. They were filled partly by the public dump method, but by September, 1916, a suction dredge went to work pumping mud over them, and finished by January, 1917" (Todd, 1921, vol. 5, p. 247). One public dump was at Lobos Square, which is now the site of the Marina Jr. High School and the Moscone Recreation Center, southeast of the intersection of Bay and Webster Streets. The locations of other dumps are not given. The hydraulic fills in the post-Exposition period required construction of retaining levees, but their thickness and areal extent are unknown.

Changes after 1917

The land on which the Exposition stood was unused until 1924, when residential construction began (Dow, 1973, p. 103-108). Any fills related to residential construction are probably very small. Some modifications have also been made in the yacht harbor area, including enlargement of the harbor, changes in breakwaters and sea walls, addition of some small fills, and construction of a major sewer line under Marina Boulevard in the early 1980s.

General Distribution, Age, and Nature of Artificial Fills

The areas of artificial fills of various ages are shown on Figure 2. The fill boundaries are based on superimposing, on a 1973 map, shorelines shown on the maps of 1851, 1869, 1895, and 1908, supplemented by descriptions of the

Panama-Pacific International Exposition fills. Shorelines and other features on the old maps cannot be precisely related to modern maps because the positions of many natural and cultural landmarks are shown differently on the old and new maps, and a best-fit compromise must be made by superimposing the maps at a common scale. Thus, the fill boundaries and other features shown may be in error by 30 m (100 ft) or more. The northeast-trending line in the southwest part of the map separating the 1869 to 1895 fill from the 1895 to 1906 fill is taken from the 1899 edition of a topographic map that was surveyed 1892 to 1894 (Lawson, 1914, *Topography, San Francisco Quadrangle*) and is less accurate than other boundaries. The major time spans during which the fills were emplaced are shown on Figure 2, but each of the outlined areas may contain small fills younger than the designated ages. Small fills also exist beyond the areas of fills shown on Figure 2.

Part of the shoreline in 1851 is shown by a dashed, curved line that trends generally northwest. This shoreline is not shown as a fill boundary because the area between this line and the edge of the 1869 to 1895 fill probably grew by natural sedimentation. The narrow northwest- and northeast-trending 1851 to 1869 fills may include naturally deposited material along waterways, as mentioned previously.

The 1869 to 1895 fill probably consists mostly of sand, which was locally available from nearby beach and dune deposits. Locally, debris from factories and other sources probably is contained in the fill also. In places, it contains riprap (large blocks of stone) placed for protection from wave action. For example, the rectangular, north-trending area in the northeast part of the 1869 to 1895 fill (Fig. 2) is the site of the 1891 San Francisco Gas Light Co. wharf, which had a rim of riprap.

The source and method of emplacement of the 1895 to 1906 fill are largely unknown. The fill no doubt contains remnants of the sea walls (?) shown on the 1895 map and J. G. Fair's sea wall. The 1906 to 1912 fill probably contains debris from the 1906 earthquake and fire, but how much is problematical.

The 1912 to 1917 fills were emplaced principally in 1912 for the Panama-Pacific International Exposition, using the hydraulic fill methods previously described. As noted before, this area also includes an area of scraper fill, post-1915 hydraulic fill of unknown dimensions, and public dumps, all related to the Exposition.

Four borings, one at 614 m (2014 ft) and three near 1100 m (3600 ft) on the horizontal scale of Figure 4, support the historical data indicating that fill was placed after the 1912 hydraulic fill. These borings were made in 1912, after placement of the main hydraulic fill. Since then, about 1.5 m (5 ft) more fill has been placed above the 1912 surface at the sites of these borings, probably during restoration of the 1915 Exposition site. The apparent fill over the boring near 330 m (1085 ft) on the horizontal scale of Figure 4 (Boring 54 of Leurey, 1914) is unexplained; possibly an unrecorded small fill exists there.

A small body of artificial fill in the western part of section A-A' was placed on a marsh area near the Palace of Fine Arts. Some of this was probably placed by hydraulic methods in 1912 for the Exposition.

The bulk of the fills in the Marina are principally sand obtained from nearby sites on land or offshore. However, the varied history of development of the area, both cultural and physical, implies that a great variety of materials are locally incorporated in the fills. The following two excerpts from drillers' logs

illustrate the point. "Heavy timbers in bottom—moved over 3 feet. Dug down 10 feet. Bored down 5 feet to elevation - 11. Rocks too big. Could not get a 6-inch auger through them. Moved 20 feet away. Dug down 8 feet to big rocks. Abandoned." (Whitworth, 1932, Hole 19, dated 1/24/23, near Beach and Webster streets). "Made two attempts through sand filling to depth of 22 feet. Encountered large rocks. Abandoned." (Whitworth, 1932, Hole 22, dated 1/24/23, near southwest end of San Francisco Gas Light Co. wharf).

EARTHQUAKE EFFECTS

An earthquake in 1868 on the Hayward fault produced minor effects and the 1906 earthquake on the San Andreas fault produced substantial effects in the Marina. In the 1868 earthquake, a fissure opened on the beach at the foot of Webster Street below the high water mark (Lawson *et al.*, 1908, p. 438). Based on this description and the 1869 map, this fissure was about halfway between Bay Street and North Point Street. Shaking intensity in the Marina during the 1906 earthquake was in the second highest category on the intensity scale used by Lawson *et al.* (1908, Map 19). Buildings were not numerous in the Marina, however, and the map of Lawson *et al.* shows that assignment of intensity rating was equivocal for part of the area. Some frame buildings were tilted, and some foundation walls were cracked. The Baker Street sewer north of North Point Street was broken and "frail frame buildings were thrown out of the vertical" (Lawson *et al.*, 1908, p. 232). Damage to the San Francisco Gas Light Co. buildings (Fig. 7) was more severe. Humphrey's (1907) description of the damage to those buildings reveals information on ground deformation, quality of construction, and apparent direction of shaking:

... none of the buildings escaped damage. The collapse of the stack wrecked the light slate-covered iron roof of the power house and started the fire that destroyed the roof of the boiler house. The ground settled very considerably under the vibrations of the earthquake, and further destruction was caused by the unequal settling of the building. The main shock appeared to come from the north, and the north walls received the greatest damage. The end wall of the retort house was pushed out 1 foot at the center, but was saved from collapse by the tie-rods which held it to the roof truss. The walls were cracked at the northwest and northeast corners. The scrubber and gas-tar holder houses were wrecked, the heavy wooden roof truss collapsing. Nearly every wall was moved slightly, but the brickwork was generally very good, and apparently had cement in it. The exhaust house had three intermediate walls, 18 inches thick at the top. The north wall and the next one fell into the building, the side walls being pushed out 6 inches. The building had wooden roof trusses and the north truss cracked at the center mortise. The floor settled badly around the condensers. The gas holder collapsed from the sudden release of the gas due to a break in the mains. The trestle pier extending into the bay also collapsed. (Humphrey, 1907, p. 27-28.)

The damage described above is not clearly related to areas of artificial fill. Although the locations of some individual buildings mentioned in the quotation are not known because some names on the Sanborn Ferris Map Co. (1899) maps

differ from those used by Humphrey, the buildings as a group, labeled "San Francisco Gas Light Co." on Figure 7, straddle various materials, including dune sand, beach sand, and artificial fill. The damage was thus not confined to artificial fill. The distribution of areas of various intensities shown in the 1906 report in other parts of the Marina is also not clearly related to areas of artificial fill (Lawson et al., 1908, Maps 17 and 19).

During the Loma Prieta earthquake and its aftershocks, ground motion in the Marina was amplified in comparison to sites on bedrock. This amplification occurred both at sites underlain by natural sediments and at sites underlain by artificial fill (U.S. Geological Survey Staff, 1990; Boatwright *et al.*, 1990; Boatwright *et al.*, 1991). Building damage severe enough to represent a safety hazard occurred both at sites underlain by natural sediments and at sites underlain by artificial fill (Seekins *et al.*, 1990). However, general and differential settlement of the ground and of buildings, and damage to pipelines, to building foundations, and to pavements, curbs, and sidewalks was almost entirely confined to areas of artificial fill; some of these effects were clearly related to liquefaction and others were not (Bennett, 1990; Benuska, 1990, p. 89-114; O'Rourke and Roth, 1990). Thus, shaking apparently was amplified throughout the Marina and led to severe building damage at various sites, but settlement, ground failure, and attendant damage were essentially limited to areas of artificial fill.

Ongoing studies in the Marina of post-1989 earthquakes show that amplification of ground motion at the top of the sedimentary section compared to the bedrock differs depending on the direction from which the seismic waves come (Liu *et al.*, 1991). Liu *et al.* suggest that the configuration of the sedimentary basin probably affects the ground motion.

The Exposition piles may have had a local effect on the damage that occurred in the 1989 earthquake. Driving of the piles probably caused local densification of the hydraulic fill. Ground settlement and local liquefaction associated with pile driving have recently been reviewed by Carter and Seed (1988), who cite many case histories and discuss the mechanics of the process. The piles remaining after the Exposition may have provided some resistance to long-term ground settlement and to earthquake-related liquefaction and vertical or horizontal ground displacements. Comparison of sand boils to the sites of pile-supported Exposition buildings shows no obvious negative correlation between the two (Fig. 10). A similar comparison (not illustrated here) between these building sites and damage to pavements and sidewalks reported in Benuska (1990) and Bennett (1990) also shows no obvious negative correlation. Similarly, O'Rourke *et al.* (1991b) found no correlation between sites of pile-supported Exposition buildings and contours of earthquake-related settlement. These comparisons relate to the ground plan of the buildings rather than to the individual structural pile clusters, which, as described above, are probably 9 to 25 m apart. Thus, the inferred remnant piling apparently had no broad areal effect on liquefaction, earthquake-related settlement contours, or damage to pavements and sidewalks; however, the pile clusters may have had local effects that have not been detected by the comparisons made to date. For example, differential settlement along the pile-supported Pierce Street sewer (O'Rourke *et al.*, 1991b) caused damage to sewers and buildings (Celebi, 1990; Bennett, 1990; O'Rourke *et al.*, 1991b), yet the earthquake-related settlement contours (O'Rourke *et al.*, 1991b, Fig. 7) do not reflect that differential settlement.

CONCLUSIONS

Knowledge of site conditions is necessary for understanding effects of past and future earthquakes. The Marina District is worthy of study because much information is available on both site conditions and earthquake effects there. Site conditions are complex. A prominent valley cut in bedrock is filled mostly by thick Pleistocene bay sediments overlain by an extensive Pleistocene sand layer. Above these are Holocene bay sediments, covered by Holocene sands in some places and a variety of artificial fills in other places.

Although the damage in the Marina during the 1906 earthquake was high compared to nearby areas, not all of it was clearly related to fill. High amplification of ground motion and severe damage to buildings in the 1989 earthquake sequence occurred on natural ground as well as on artificial fill. These facts suggest that the configuration, thickness, and nature of the natural materials had a strong influence on shaking. Liquefaction, settlement, and damage to foundations, streets, curbs, sidewalks, and pipelines during the 1989 earthquake, however, was largely confined to areas underlain by artificial fill. Thus, the natural geologic conditions apparently were responsible for the greater shaking in the Marina compared to adjacent areas, but behavior of the artificial fills increased particular types of damage. More complete analysis of the available data and of new data should provide insights that can be used in anticipating the effects of future earthquakes, not only in the Marina but in other places having similar conditions.

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