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Maps showing Quaternary geology and liquefaction susceptibility, San Francisco, California, 1:100,000 quadrangle

by

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I. PURPOSE OF THE PROJECT

Earthquake-induced liquefaction has historically caused loss of life and damage to property and infrastructure. Observations of the effects of historical large-magnitude earthquakes show that the distribution of liquefaction phenomena is not random. Liquefaction is restricted to areas underlain by saturated, loose, cohesionless sand and silt. Areas susceptible to liquefaction can be delineated on the basis of geologic, geomorphic, and hydrologic mapping and map analyses (e.g., Youd and Perkins, 1987; Tinsley and Holzer, 1990; Sowers and others, 1995). Once liquefaction susceptibility zones are delineated, public agencies, private organizations, and individuals can prepare for and mitigate liquefaction hazards in these zones.

In this study, we develop a liquefaction susceptibility map of the San Francisco 1:100,000 quadrangle using Quaternary geologic mapping, historical liquefaction information, groundwater data, and previous studies. The study is patterned after studies by Dupré and Tinsley (1980) and Dupré (1990) in the Monterey-Santa Cruz area, Tinsley and others (1985) in the Los Angeles area, Youd and Perkins (1987) in San Mateo County, California, and Sowers and others (1995) in the northern San Francisco Bay area.

The study area includes the San Francisco Peninsula, the eastern San Francisco Bay area, and part of the northern San Francisco Bay area, including the cities of Burlingame, Concord, Oakland, Richmond, San Francisco, San Mateo, San Rafael, and Walnut Creek (Figure 1). Holocene estuarine deposits, Holocene stream deposits, Holocene eolian and beach deposits, and artificial fill are widely present in the region (Plate 1), and are typically the geologic materials most susceptible to liquefaction. Major faults capable of producing large earthquakes cross the study area, including the Concord, Hayward, San Andreas, and San Gregorio faults (Figure 1). These earthquakes expose the entire study area to long-duration ground motions with peak ground accelerations in excess of 0.2 g, sufficient to trigger liquefaction in highly susceptible natural deposits and artificial fill.

The maps (Plates 1 and 2) are in the form of a digital database. The maps were digitized from 1:100,000 scale compilations of 1:24,000 scale geologic mapping. These are regional maps depicting the distribution of Quaternary deposits and liquefaction susceptibility and are not meant to substitute for site-specific studies.

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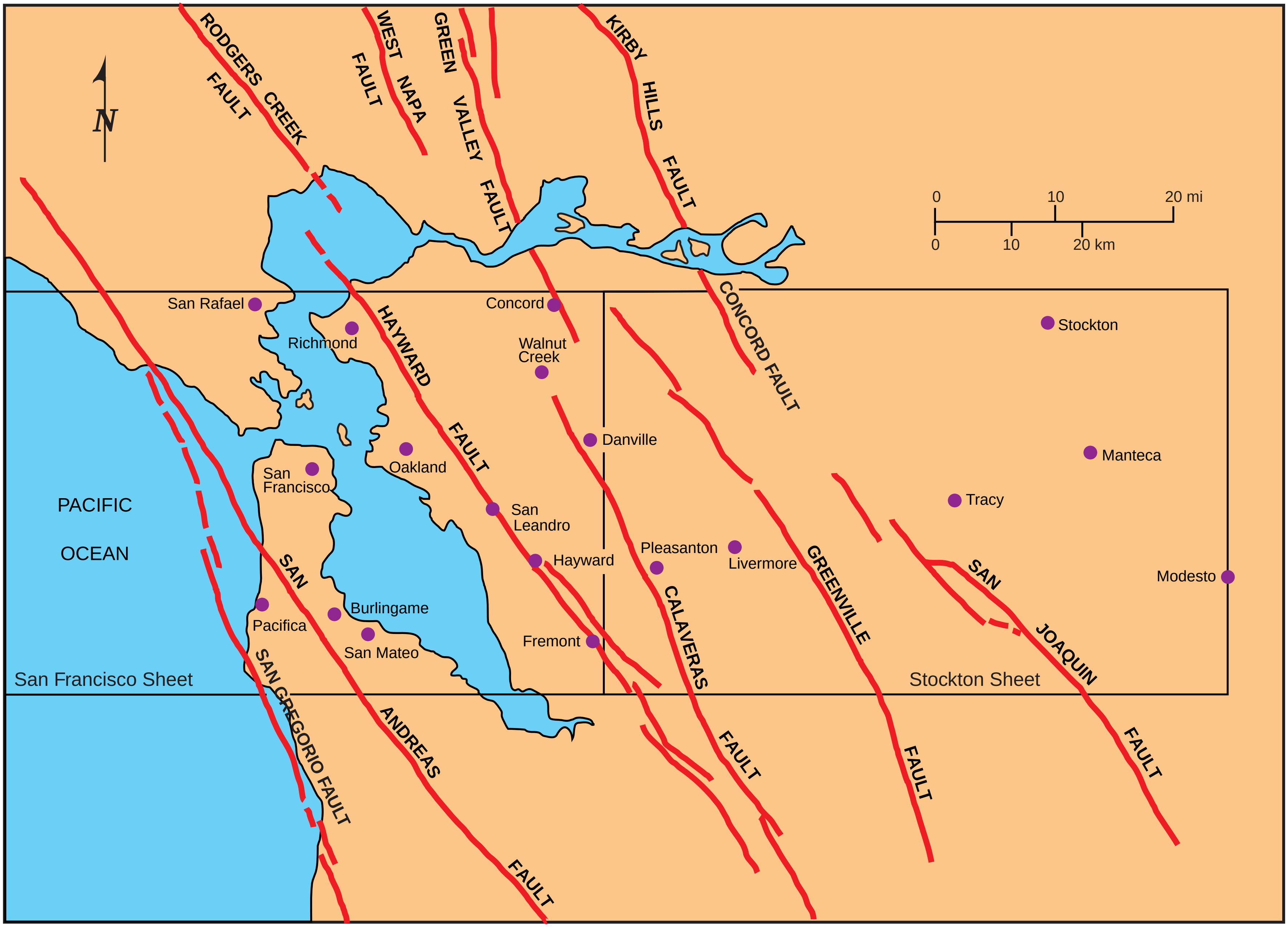

Figure 1. Location of San Francisco 1:100,000 quadrangle. Map also shows faults with Holocene or historical activity (Jennings, 1994).

II. BACKGROUND

Liquefaction is the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore pressure and decreased effective stress (Youd, 1973). Increased pore pressures in unconsolidated sediment, especially in western California, are most typically seismically induced. Observed types of ground failure resulting from liquefaction can include sand boils, lateral spreads, ground settlement, ground cracking and ground warping (Youd and Hoose, 1978).

The *potential* for liquefaction to occur depends on both the *susceptibility* of near-surface deposits to liquefaction, and the likelihood of ground motions to exceed a specified threshold level, or *opportunity*. A liquefaction susceptibility map is based on the physical properties of near-surface deposits and the depth to groundwater. The liquefaction opportunity map is based on proximity to seismic sources capable of producing long duration strong vibratory ground motions. The liquefaction susceptibility map of the San Francisco quadrangle presented here could be viewed as a liquefaction potential map. Relatively uniform liquefaction opportunity can be justified on the following grounds: (1) active faults capable of generating large-magnitude earthquakes are distributed throughout the study area (Figure 1); (2) no site is more than 30 km from an active fault capable of generating a magnitude 6.5 or larger earthquake; most sites are within 15 km of a fault; and (3) earthquakes on the San Andreas fault (Peninsula segment, 22% probability in 30 years), Hayward fault (northern segment, 28% probability), and Rodgers Creek fault (23% probability), will produce long duration ground motions in excess of 0.2 g over most of the study area (U.S. Geological Survey, 1990).

Although we recognize that ground response is highly dependent on site specific variations in the duration (cycles), strength, and frequency (especially potential for amplified low frequencies) of ground motions (Clough and others, 1994), the assumption of uniform liquefaction opportunity is conservative and valid because most of these site dependent variations in ground motion tend to enhance liquefaction. Analysis of historical data by Tinsley and others (1985) and Dupré and Tinsley (1990) shows that liquefaction has occurred up to 20 km from the epicenter of an M 6.5 earthquake, and up to 50 km from an M 7.0 earthquake. The 1989 Loma Prieta earthquake (M=7.1) dramatically illustrated the potential for liquefaction at great distances from the epicenter given appropriate geologic and hydrologic conditions and amplification of ground motions at lower frequencies. The assumption of relatively uniform liquefaction opportunity was also made by Tinsley and others (1985) for the Los Angeles region, and Sowers and others (1995) for the Napa 1:100,000 sheet.

III. METHODS

We assess liquefaction susceptibility on the basis of four factors: (1) presence of loose, cohesionless, sandy or silty deposits within 50 feet of the surface (depth threshold defined by Tinsley and others (1985)), (2) presence of groundwater that saturates these deposits, (3) historical records of liquefaction during previous earthquakes (data compiled by Youd and Hoose (1978), and Seed and others (1990)), and (4) limited borehole [standard penetration test (SPT)] data and the modified Seed-Idriss approach to evaluating liquefaction susceptibility. Our procedure for assessing these factors is as follows:

1. Map surficial deposits on the basis of age and depositional environment.
2. Characterize groundwater levels.
3. Evaluate historical liquefaction occurrences.
4. Develop criteria matrix to classify all potential combinations of type and age of deposit with groundwater depth. Calibrate with historical data, previous studies and borehole (SPT) evaluations of liquefaction peak ground accelerations (PGA) thresholds.
5. Assign liquefaction susceptibility categories to geologic map units.

Previous studies document a correlation between the age and environment of deposition of a deposit and its tendency to liquefy (Tinsley and others, 1985; Tinsley and Holzer, 1990). Age is important because deposits become more consolidated, weathered, and cemented with age. Depositional environment is important because each environment is characterized by deposits with different sorting, bedding, and grain-size characteristics. For example, stream channel deposits are likely to contain sand and silt, and young (i.e., late Holocene age) deposits are likely to be loose and relatively cohesionless. Categories of age and environment distinguished in this study are listed in Table 1 and shown in Figure 2.

Age	Depositional Environment
Holocene (<10,000 yrs) (Qh)	Alluvial terrace (t)
Late Pleistocene to Holocene (Q)	Alluvial fan (f)
Late Pleistocene (Qp)	Alluvial basin (b)
Early to middle Pleistocene (Qo)	Undifferentiated alluvial (a)
	Estuary/bay mud (bm)
	Beach and dune (s)
	Marine terrace (mt)
	Active stream channel (c)
	Artificial fill (af)

Note: Abbreviations used in unit designations are shown in parentheses.

Table 1. Categories of age and depositional environment used in Quaternary geologic mapping.

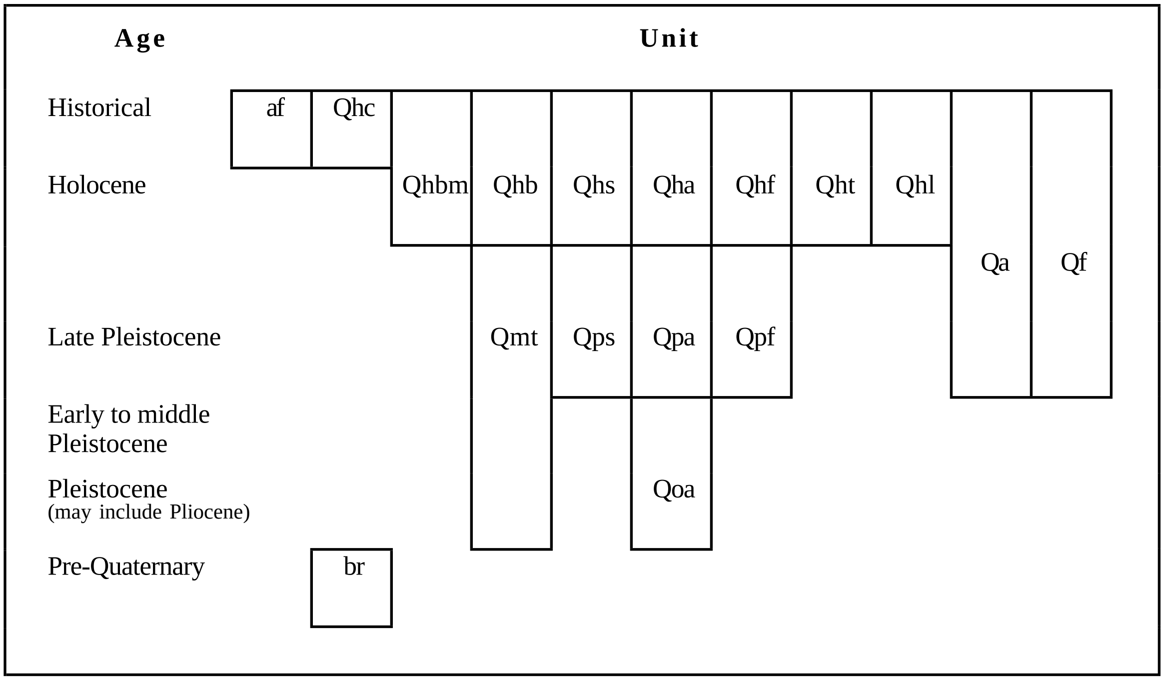

Figure 2. Correlation of geologic map units.

Our Quaternary geologic mapping consisted of several steps: First, we first compiled previous geologic mapping (Figure 3). Second, we interpreted aerial photographs, topographic maps and soil survey maps to verify and modify, as required, the compiled geologic maps, and to evaluate the depositional environment and relative age of deposits by identifying landforms and geomorphic relationships. The published soil survey data (Welch and others, 1966; Welch, 1977 and 1981; Kashiwagi, 1985; and Kashiwagi and Hokholt, 1991) provide information on composition, soil profile development, and available moisture (e.g., depth to groundwater) of the surface deposits. The degree of soil profile development was used to estimate the ages of soils and surficial deposits. Third, we performed field reconnaissance and localized detailed mapping to further verify and modify, as required, our air-photo interpretation. Lastly, we used geotechnical borehole data to locally evaluate the character and depositional environment of depositional units.

Data on the depth to groundwater were acquired in several ways. Data on groundwater depths from boring logs for geotechnical studies were obtained from the California Department of Transportation, the Bay Area Rapid Transit District, and from reports on file with county and city governments in the study area. Data also were collected in the field by measuring the depth to the water surface in streams, creeks, and drainage ditches with respect to the adjacent terrace or fan surface. In making these measurements, we assumed that the stream level was representative of the level of shallow groundwater in the area. From field observations or boring log data we extrapolated water levels to areas with little available groundwater data. We also used the depth of stream incision as a default maximum depth to groundwater. Data from water wells were not

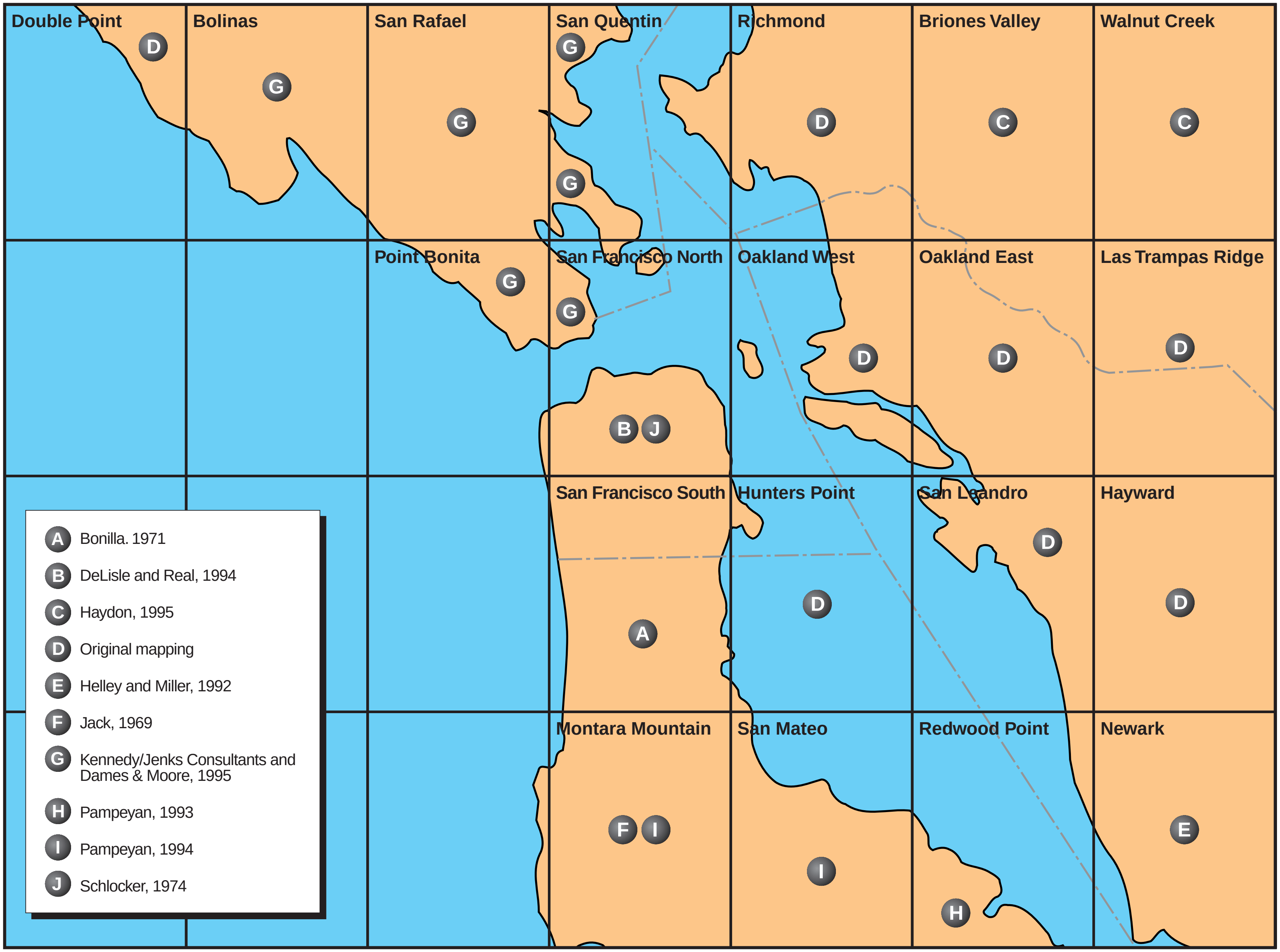

Figure 3. Previous mapping used in developing Quaternary geologic maps of the San Francisco 1:100,000 quadrangle.

utilized because these wells tap deep, in many places artesian aquifers; thus, these observed water levels represent the potentiometric surface of the aquifer, not the depth to saturated sediment. Where data are available, we use historic high groundwater levels to ensure a degree of conservatism in our liquefaction susceptibility assignments.

Liquefaction susceptibility units were designated on the basis of a criteria matrix that assigns a susceptibility unit to all combinations of geologic unit (type and age of the deposit) and groundwater level. Liquefaction susceptibility units reflect the probability of saturated, loose, unconsolidated, granular materials being present within 50 feet of the surface. The matrix was calibrated using historical data, previous studies, and limited boring log standard penetration test (SPT) data. In a few cases, SPT data were analyzed for liquefaction threshold peak ground acceleration (PGA) needed to cause liquefaction using a Macintosh-based computer program. This program is based on the work of Chen (1988), Seed and Idriss (1982), Seed and others (1985), Law and others (1990), and Idriss (1997). Extensive borehole analysis was beyond the scope of this study, thus we rely on our limited analyses, our experience on other projects in the area (e.g., Kennedy/Jenks Consultants and Dames & Moore, 1995), and existing studies (e.g., DeLisle and Real, 1994).

IV. DATA

A. Quaternary geology

Quaternary deposits in the study area (Plate 1) occur in five general settings: (1) northwest-trending, generally structurally-controlled valleys, (2) alluvial piedmonts sloping southwestward from the eastern San Francisco Bay area hills and northwestward from hills of the San Francisco Peninsula, (3) areas of early Holocene and late Pleistocene dunes on the northern San Francisco Peninsula and in the Oakland area, and (4) deltaic, beach and terrace deposits along the Pacific coast, and (5) estuarine environments around the margins of San Francisco Bay (Plate 1). The large northwest-trending valleys, such as those adjacent to Walnut Creek, Colma Creek, and San Anselmo Creek, contain sediment deposited by streams on flood plains, alluvial fans, and basins. Sedimentary deposits in small intermontane valleys are similar in type to those of the larger valleys but are thinner, and smaller in areal extent. Along the west side of the eastern San Francisco Bay hills, coalescing alluvial fans have formed a broad alluvial piedmont that extends from Richmond south past Fremont and Hayward. Eolian deposits mantle the northern San Francisco Peninsula and interfinger with bay margin sediment along the shoreline near Oakland (Atwater and others, 1977; Rogers and Figuers, 1991). Coastal and estuarine areas contain deltaic sediment deposited by streams as they enter bays or the ocean, beach sand, marine terrace deposits, and fine-grained sediment distributed by slow currents at the margins of bays. Table 2 presents descriptions of each Quaternary stratigraphic unit identified in the San Francisco Bay area. We also compiled a correlation chart that compares these stratigraphic units with those of previous researchers (Table 3).

Table 2. Description of geologic units.

Map Symbol	Unit name and description
af	**Artificial fill.** Material deposited by humans. Fill may be engineered and/or non-engineered material; each may occur within the same area on the map. Much of the mapped artificial fill overlies estuarine sediment and forms new land, levees, or dikes near sea level (Goldman, 1969). The thickness of the fill overlying estuarine sediment is typically 5-20 feet thick. Other fill shown includes large highway embankments, consisting of engineered fill up to approximately 100 feet thick, and large earthen dams. Small bodies of fill, such as small road embankments and earthen dams for farm ponds, are not shown. Included within this unit are small areas of estuarine deposits and Holocene alluvium that are too small to be mapped at this scale. On the San Francisco Peninsula, identification of artificial fill is based primarily on previous mapping by Bonilla (1971), Schlocker, (1974), and Pampeyan (1993, 1994). Elsewhere, mapping of artificial fill is based on comparison of present shorelines with those of the mid 19th century as shown by Nichols and Wright (1971) and Sowers (1995, 1997), and on inspection of topographic maps and aerial photographs. Liquefaction susceptibility may be very high to very low depending on (1) the nature and thickness of the fill materials, (2) whether the fill was engineered or non-engineered, and (3) its depth of saturation. Most fill emplaced in the last few decades is engineered; older fill is less likely to be engineered. A large percentage of historical liquefaction events in the study area occurred in artificial fill on the margins of San Francisco Bay (Plate 2). Many of the reports of damage in the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake (Plate 2) involved failures in fill that probably was not engineered; such fill was likely hydraulically emplaced. We assigned very high liquefaction susceptibility to fill located within estuaries or outside the circa 1850 shoreline because water levels are close to the surface, there is a significant possibility the fill was hydraulically emplaced and was not engineered, and the fill may be a relatively thin cover over susceptible estuarine sediments. Artificial fill mapped in upland areas or comprising highway embankments or dams is assigned a low susceptibility because it is likely to be engineered and unsaturated. Site specific studies should be conducted to evaluate the condition and liquefaction susceptibility of any artificial fill.
Qhc	**Modern stream channel deposits.** Fluvial deposits within active, non-engineered stream channels. Materials consist of loose, unconsolidated, poorly to well-sorted sand, gravel and cobbles with minor silt. Parts of these deposits are mobilized and redeposited during large flood events. Contacts are generally shown near the top of the bank on either side of the channel. Channels of very small streams are not delineated at this map scale. Liquefaction susceptibility is very high. Tinsley and others (1985) present an analysis of borehole data in the Los Angeles area that shows that 76-81% of boreholes in latest Holocene alluvium contain liquefiable materials, assuming water levels at the surface, compared to 34-54% of boreholes in earlier Holocene alluvium. Matti and Carlson (1991) show similar relationships for the San Bernardino Valley of Southern California. Dupré (1990), Holzer and others (1994), and Mejia and others (1992) describe liquefaction along the coast south and west of the 1989 Loma Prieta epicenter, most of which occurred because of the presence of young, loose, granular sediment and high

groundwater levels. Groundwater levels typically are within 5 feet of the surface in modern stream channel deposits.

Qhbm **Holocene bay mud.** Sediment deposited at or near sea level in the San Francisco Bay estuary that is presently, or was once tidal marsh or mud flat. Bay mud sediment typically has low bulk density and includes silt, clay, peat, and fine sand (Atwater and others, 1977). This unit generally occupies the area between the modern shoreline and the historical limits of tidal marsh, as shown on the compilation by Nichols and Wright (1971) and Sowers (1995, 1997) of historical surveys of tidal marshlands circa 1850. We include areas that are presently, or were recently, used as salt evaporation ponds within this unit. Also included within this map unit are small areas of artificial fill and Holocene alluvium too small to be mapped at this scale. Especially relevant to this study are the many small marsh channels that are too small to map, yet likely contain sandy substrates and may be more susceptible to liquefaction than the silt, clay and peat of the marsh deposits. Soils developed on these estuarine deposits typically are histosols, aquic entisols or mollisols. Bay mud is late Holocene in age with many areas presently subject to deposition and flooding. Some areas have been diked for farming, salt evaporators, or other purposes. Bay mud deposits thin landward and may be as thick as 40 m along the bay margin (Rogers and Figuers, 1991).

Liquefaction susceptibility is high due to high groundwater levels (often within 5 feet of the surface) and the presence of sand lenses within the mud and peat. Estuarine sediments near the mouths of major streams, such as Alameda Creek, are probably the most susceptible to liquefaction because the streams regularly deliver large volumes of sand and silt to the estuary.

Qhs **Holocene dune and beach sand.** Beach and beach-derived dune sand in predominantly coastal environments. Beach deposits are well sorted fine to coarse sands with some fine gravel. Where the beach is adjacent to a seacliff, beach sediment probably forms a veneer 1 to 10 feet thick over a bedrock platform. Dune sands are very well-sorted fine to medium sands. This unit includes active beaches and dunes in coastal environments. Holocene dune sand that covers much of the northern San Francisco Peninsula has been extensively modified and likely consists of remobilized Pleistocene dune sand that now veneers a thicker stack of Pleistocene dune deposits. Typical soils developed on this unit are inceptisols.

In areas of high groundwater or perched water conditions such as beaches or dunes near water bodies, liquefaction susceptibility is very high. However, dune fields on the northern San Francisco Peninsula are designated moderate following analyses of DeLisle and Real (1994). The veneer of Holocene dune sand over Pleistocene dune sand may be thin, thus, the absence of historical liquefaction in predominantly Pleistocene dune deposits is not so surprising. Groundwater levels on the San Francisco Peninsula may be more than 30 feet below the surface of dune deposits (DeLisle and Real, 1994).

Qhb **Holocene basin deposits.** Sediment of late Holocene age deposited in topographic lows such as at the distal end of alluvial fans, between fan levees, and adjacent to floodplains. Areas with basin deposits typically have a water table within 10 ft of the surface and are (or were) subject to flooding. Basin sediment consists of organic-rich, dark-colored clay and silt that settles out of seasonal standing water collected in the basins. Typical soils are vertisols and aquic mollisols. Identification of basin deposits is based on surface morphology, topographic position, and soil type.

Liquefaction susceptibility is high. Although these sediments contain abundant clay, they also may contain layers of sand and silt. In a fluvial environment, we expect the distribution of sand to be intermittent and discontinuous. Therefore, we assume that layers of liquefiable materials could be present anywhere in the basin. Historical liquefaction near the mouth of Alameda Creek (Plate 2) is a probable example of liquefaction of sand lenses within a basin environment.

Qht **Holocene terrace deposits.** Point bar and overbank deposits that form low terraces adjacent to major streams make up most of this unit. Terrace deposits that are too small in extent to be shown at this map scale, such as those along small creeks, are included within the Qha and Qa mapping units. Terrace deposit sediment includes sand, gravel, silt and minor clay, is moderately to well-sorted, and moderately to well-bedded. Typically, this unit is mapped where relatively smooth, undissected terraces are less than 25 to 30 ft above the active channel. Soils are typically entisols, inceptisols, and mollisols. Groundwater levels are generally within 10 ft of the surface, especially during the wet winter months.

Liquefaction susceptibility is high because of the presence of loose, granular deposits and shallow groundwater. Should liquefaction occur, the presence of a free face makes lateral spreading likely.

Qhf **Holocene alluvial fan deposits.** Sediment deposited by streams emanating from the mountain canyons onto alluvial valley floors or alluvial plains as debris flows, hyperconcentrated mudflows, or braided stream flows. Alluvial fan sediment includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Sediment clast size generally decreases downslope of the fan apex. Many Holocene alluvial fans exhibit levee/interlevee topography, particularly the fans associated with creeks flowing west from the eastern San Francisco Bay area hills (See Qhl below). Alluvial fan surfaces are steepest near their apex at the valley mouth, and slope gently basinward with gradually decreasing gradient. Alluvial fan deposits are identified primarily on the basis of fan morphology. Holocene alluvial fans are relatively undissected, especially when compared to older alluvial fans. Soils are typically entisols, inceptisols, mollisols, and vertisols.

Liquefaction susceptibility is moderate where groundwater is within 30 feet of the surface, which we believe to be the case for most Holocene alluvial fan deposits along the bay margin. Fan deposits are judged to be less susceptible to surface deformation from liquefaction than terrace deposits (Qht) of the same age because of their relatively poor sorting, coarse grain size, and the lenticular nature of deposits within a fan. Where an active channel is present but is not mapped through the fan because of the map scale, the liquefaction susceptibility may be underestimated.

Qhl **Holocene alluvial fan levee deposits.** Alluvial fan levee sediment is overbank material that forms natural levees adjacent to a stream channel on an alluvial fan. The levees are identified as long, low ridges oriented down fan, and contain coarser material than adjoining interlevee areas, especially adjacent to creek banks where the coarsest material is deposited during floods. Levee deposits are loose, moderately to well sorted sand, silt and clay (Helley and Wesling, 1990). Soils are typically entisols, inceptisols, mollisols, and vertisols.

Liquefaction susceptibility is moderate, similar to Holocene alluvial fan deposits.

Qha **Holocene alluvium, undifferentiated.** Alluvium deposited in fan, terrace, or basin environments. The surface is generally planar and smooth with little to no dissection. This unit is mapped where separate types of alluvial deposits could not be delineated either due to complex interfingering of depositional environments or the small size of the area. Typically, undifferentiated alluvium is mapped in relatively flat, smooth valley bottoms of small- to medium-sized drainages. Deposits probably are intercalated sand, silt, and gravel that are poorly to moderately sorted. Soils are entisols, inceptisols, vertisols, and mollisols.

Liquefaction susceptibility is high to moderate, based on historical liquefaction occurrences (Colma Creek valley), the presence of unmapped late Holocene channels and deposits, high groundwater levels, the presence of small unmapped, potentially unengineered bodies of artificial fill, and a combination of the susceptibility assignments for channel, fan, terrace, and basin sediments (Qhc, Qhf, Qht, and Qhb).

Qf **Late Pleistocene to Holocene fan deposits.** This unit is mapped on gently sloping, fan-shaped, relatively undissected alluvial surfaces where deposits might be of either late Pleistocene or Holocene age or where the deposits of different age interfinger such that they can not be delineated at the map scale. Fan sediment includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Soils are typically inceptisols, mollisols, and alfisols. This unit includes active stream channels that are too narrow to show separately at this map scale.

Liquefaction susceptibility is moderate to low. Groundwater is assumed to be greater than ten feet below the surface. Sediment in the undifferentiated stream channels is dominantly gravel and sand that is more susceptible to liquefaction.

Qa **Late Pleistocene to Holocene alluvium, undifferentiated.** This unit is typically mapped in small valleys where separate fan, basin, and terrace units could not be delineated at the map scale, and where deposits might be of either late Pleistocene or Holocene age. The unit includes flat, relatively undissected fan, terrace, and basin deposits, and small active stream channels.

Liquefaction susceptibility is moderate. Groundwater depth is variable, but is generally less than 20 feet. The moderate susceptibility assignment is a reflection of uncertainties and local variability in the both the nature and age of these deposits.

Qpf **Late Pleistocene alluvial fan deposits.** This unit is mapped on alluvial fans where late Pleistocene age is indicated by greater dissection than is present on Holocene fans, and/or the development of alfisols. Pleistocene fans may be either overlapped or incised by Holocene fans. Along the west-facing hills of Oakland and Berkeley where late Pleistocene alluvial fan deposits are mapped, the age of these deposits is not well constrained and the deposits may actually be a combination of early to middle Pleistocene alluvial fan and pediment deposits, and late Pleistocene alluvial fan deposits.

Liquefaction susceptibility is low. Groundwater levels are variable, but generally are more than 20 feet below the surface.

Qpa **Late Pleistocene alluvium, undifferentiated.** This unit is mapped on gently sloping to level alluvial fan or terrace surfaces where a late Pleistocene age is indicated by slight dissection, the development of alfisols, and lack of historical flooding.

Liquefaction susceptibility is low.

Qps **Late Pleistocene dune sands.** Most of these deposits are thought to be associated with late Pleistocene to early Holocene low sea level stands and subsequent transgression, during which large volumes of fluvial and glacially derived sediment were blown into dunes (Atwater and others, 1977). The deposits include the Merritt Sand. These deposits consist of fine to medium sands that are semiconsolidated and weakly cemented.

Liquefaction susceptibility is low. There were no reports of liquefaction within the Merritt sand for either the 1906 or 1989 earthquakes (Youd and Hoose, 1978; Seed and others, 1990).

Qmt **Pleistocene marine terrace deposits.** Deposits on uplifted marine abrasion platforms along the Pacific coast and margins of large bays, where late versus middle or early Pleistocene age is not evaluated. Sediment veneer on the platform is typically greater than 10 feet thick and consists of moderately to well sorted, moderately to well bedded sands and gravels, which may locally be fossiliferous. Marine terraces on the southwestern part of the San Francisco Peninsula are from the mapping by Jack (1969).

Liquefaction susceptibility is generally very low over most of the terraces but is designated low for the youngest, lowest terraces in a sequence. Groundwater is typically deeper than 20 feet, though areas may have perched groundwater where marine sediments overlie relatively impermeable bedrock.

Qoa **Early or middle Pleistocene undifferentiated alluvial deposits.** Moderately to deeply dissected alluvial deposits capped by alfisols, ultisols, or soils containing a silicic or calcic hardpan. Topography often consists of gently rolling hills with little or none of the original planar alluvial surface preserved. This unit includes areas of the Colma Formation on the San Francisco Peninsula (Bonilla, 1971; Schlocker, 1974), which is described as an unconsolidated fine to medium sand with silt and clay.

Liquefaction susceptibility is very low.

br **Pre-Quaternary deposits and bedrock, undifferentiated.** Primarily Jurassic to Pliocene sedimentary, metamorphic, volcanic and plutonic rocks, and poorly consolidated Tertiary sediment. Unit also includes landslides, talus, other bodies of colluvium, and small stream channel deposits in bedrock that could not be delineated at the map scale.

Liquefaction susceptibility is very low. Stream channels within areas mapped as bedrock may contain small areas of Holocene deposits; susceptibility of these deposits may be low to very high.

w **Water.** Lakes, reservoirs, bays, ponds, and ocean.

UNIT	Knudsen and others, 1997; San Francisco 1:100,000 (this study)	Sowers and others, 1995; Napa 1:100,000	Helley and Graymer, 1996a, b; Alameda & Contra Costa Counties digital 7.5' quadrangles	Pampeyan, 1993, 1994; Montara Mtn., San Mateo, Redwood Pt. 7.5' quadrangles	Helley & Miller, 1992; Newark 7.5' quadrangle	Helley & Wesling, 1990; San Jose East & Milpitas 7.5 ' quadrangles	Helley & LaJoie, 1979; San Francisco Bay area; 1:125,000	Schlocker, 1974; San Francisco North 7.5' quadrangle	Bonilla, 1965; San Francisco South 7.5' quadrangle
Gravel pit	af				GP	GP			
Artificial fill	af	af	af	Qf1, Qf2		Qha		Qaf	Qaf, Qafs
Artificial stream channel					Qhasc				
Modern stream channel deposits	Qhc	Qhi	Qhsc	Qya	Qhsc		Qhsc		
Latest Holocene flood plain & basin deposits		Qhi/Qhb							
Holocene stream channel						Qhsc			
Holocene estuarine deposit with areas of fill		Qhr/af							
Holocene estuarine deposit (Bay)	Qhbm	Qhr	Qhbm	Qm	Qhbm	Qhbm	Qhbm	Qm	Qm
Holocene marsh channel					Qhsc1				
Holocene dune and beach sand	Qhs	Qhs	Qhds	Qb, Qd	Qhbs		Qhs	Qb, Qd	Qb, Qd
Holocene flood plain			Qhfp		Qhfp	Qhfp			
Holocene basin deposit	Qhb	Qhb	Qhb, Qhbs			Qhb, Qhbs			
Holocene alluvial terrace deposits	Qht	Qht		Qst		Qhfp1, Qhfp2			
Holocene alluvial levee deposits	Qhl		Qhl		Qhl	Qhl			
Holocene alluvial fan deposits	Qhf	Qhf	Qhaf		Qhaf	Qhaf, Qhaf1			
Holocene fine-grained alluvium				Qaf			Qhaf, Qhafs		
Holocene medium-grained alluvium				Qam			Qham		
Holocene coarse-grained alluvium				Qac			Qhc		
Holocene alluvium, undifferentiated	Qha	Qha		QTs	Qhb			Qal	Qal
Holocene slope debris & ravine fill				Qsr				Qsr	Qsr
Late Pleistocene to Holocene dune sand		Qs	Qhds (Merritt sand)					Qd	
Late Pleistocene to Holocene alluvial terrace deposits	Qt	Qt		Qst					
Late Pleistocene to Holocene alluvial fan deposits	Qf	Qf							
Late Pleistocene to Holocene alluvium, undifferentiated	Qa	Qa		QTs					
Late Pleistocene dune and beach sand (includes Merritt sand)	Qps						Qps	Qob, Qd	Qob
Late Pleistocene alluvial terrace deposits		Qpt		Qst					
Late Pleistocene alluvial fan deposits	Qpf	Qpf	Qpaf		Qpaf	Qpaf, Qpaf1			
Late Pleistocene alluvium, undifferentiated	Qpa	Qpa		QTs		Qpa	Qpa	Qal	Qal
Early or Middle Pleistocene alluvium (1)	Qoa	Qoa	Qpaf1, Qpaf2, QTlu?	Qoa, Qc, QTs, QTss, Qtsc, Qs		QTsc	Qpea, Qpmc	Qc	Qc, QTm
Early to Late Pleistocene marine terrace deposits	Qmt	Qpm, Qom		Qmt			Qpmt		Qt
Undivided Quaternary				Qu, QTs			Qu	Qu	Qu
Landslide deposits				Qyl, Qol	Qls	Qls		Ql, Qly, Qlo	Ql

(1) Includes Colma Formation, Santa Clara Formation, and Merced Formation.

Table 3. Correlation chart showing relationships between stratigraphy used in this study and that of previous researchers.

Figure 3 shows some of the sources of data that were utilized in our compilation and mapping. We directly used research and mapping by DeLisle and Real (1994) of the San Francisco North quadrangle for the northern San Francisco Peninsula. Previous mapping of Quaternary geology and liquefaction susceptibility by William Lettis & Associates was utilized with minor modifications for much of Marin County (Kennedy/Jenks Consultants and Dames & Moore, 1995). Mapping of Pampeyan (1993, 1994) was modified based on aerial photograph inspection and interpretation of topography for the Montara Mountain, San Mateo and Redwood Point quadrangles. Bonilla's (1971) mapping of the San Francisco South quadrangle was used, but we remapped many of the Quaternary deposits based on interpretation of topography and aerial photographs. The mapping of Helley and Miller (1992) was modified for the Newark quadrangle. Additional mapping by Haydon (1995), Jack (1969), and Schlocker (1974) also was consulted during the mapping process. We referred to Youd and Perkins (1987) while mapping San Mateo County. Faults shown on Plate 1 were compiled from California Division of Mines and Geology Special Studies zone maps (California Division of Mines and Geology, 1974 a, b, c, 1982 a through h, and 1993).

B. Groundwater

The depth to groundwater in areas underlain by Holocene alluvial, estuarine, and beach sediments is generally less than 10 feet throughout most of the study area. In general, groundwater is deeper beneath topographically higher parts of the landscape (e.g., uplifted and dissected Pleistocene alluvial fans), and more shallow beneath topographically lower parts of the landscape (e.g., Holocene basins and terraces). Groundwater typically is deeper beneath Pleistocene deposits; generally these older deposits are higher than the present valley bottoms. Streams in the San Francisco Bay area typically are not incised more than 10 to 20 feet below the Holocene surfaces, thus groundwater levels in the winter are within 10 to 20 feet of the surface in nearly all valleys. Seasonal changes in groundwater levels are pronounced in the San Francisco Bay area, with variations as large as tens of feet. Small, isolated alluviated valleys and pockets within the bedrock hills appear to have fairly shallow groundwater, generally less than 10 to 15 feet. Soils characteristic of wet environments are mapped in many of these valleys, and the few data available on depth to groundwater indicate shallow groundwater levels. We present generalized depths to groundwater for each geologic unit in Table 4.

Marine terraces and dune sands typically have significantly greater depths to groundwater than other Quaternary deposits in the study area. Groundwater beneath uplifted marine terraces can be deeper than 40 feet, except where water is perched. Groundwater beneath coastal dunes that form or mantle hills can be as deep as 50 to 100 feet, equivalent to the elevation of the hills.

C. Historical liquefaction

Records of liquefaction in the study area are available for several earthquakes; the two earthquakes causing most damage are the 1906 San Francisco earthquake (m=8.3) (Youd and Hoose, 1978), and the 1989 Loma Prieta earthquake (M=7.1) (Plafker and Galloway, 1989; Seed and others, 1990). Additional earthquakes that generated liquefaction in the study area include the 1838, 1865, 1868, and 1957 earthquakes (Youd and Hoose, 1978). The records of historical liquefaction

Geologic unit	Description	Historical occurrence of liquefaction in unit?	Estimated liquefaction triggering acceleration (1)	Typical depth to ground-water (ft)	Depth to groundwater (ft) (2)			
					<10	10 to 30	30 to 50	>50
af	Artificial fill (3)	yes	0.1g (4)	<10	VH to L	H to L	L to VL	VL
Qhc	Modern stream channel deposits	yes	0.1g	<5	VH	H	M	VL
Qhbm	Holocene bay mud	yes	0.2g	<5	H	H	M to L	VL
Qhs	Holocene dune and beach sand	yes	0.1g	<10	VH	H to M	M	VL
Qhb	Holocene basin deposits	uncertain (5)	0.2 to 0.3g	<10	H	M	L	VL
Qht	Holocene terrace deposits	no	0.2g	<10	H		M to L	VL
Qhf	Holocene alluvial fan deposits	uncertain (5)	0.3 to 0.4g	<20	M	M	L	VL
Qhl	Holocene alluvial fan levee deposits	uncertain (5)	0.3 to 0.4g	<20	M	M	L	VL
Qha	Holocene alluvium, undifferentiated	yes	0.2g	<10	H	H to M	M to L	VL
Qf	Late Pleistocene to Holocene alluvial fan deposits	no	0.3 to 0.4g	<20	M	M to L	L	VL
Qa	Late Pleistocene to Holocene alluvium, undifferentiated	no	0.3 to 0.4g	<20	M	M	L	VL
Qpf	Late Pleistocene alluvial fan deposits	no	0.5 to 0.6g	>20	L	L	VL	VL
Qpa	Late Pleistocene alluvium, undifferentiated	no	0.5 to 0.6g	>20	L	L	VL	VL
Qps	Late Pleistocene dune and beach sand	no	uncertain	>20	L	L	VL	VL
Qmt	Late Pleistocene marine terrace deposits	no	uncertain	>20	L	L	VL	VL
Qoa	Early to middle Pleistocene alluvium, undifferentiated	no	NA	>30	L	VL	VL	VL
br	Bedrock	no	NA	>30	VL	VL	VL	VL

Notes:

(1) Based on the modified Seed approach and a small number of borehole analyses for some units.
(2) The shaded boxes show the susceptibility assignment for each geologic unit on this map.
(3) The liquefaction susceptibility of artificial fill ranges widely, depending largely on the nature of the fill and whether it was compacted during emplacement. We use very high susceptibility for all fill on the margins of the San Francisco Bay, and somewhat arbitrarily assign a low susceptibility to all upland fills. Exceptions to this rule include fill placed on the northwestern San Francisco Peninsula that has historically liquefied.
(4) Assuming non-engineered fill.
(5) These occurrences are either not well located, or are poorly characterized in historical accounts and may not have been liquefaction related.

Table 4. Criteria matrix for assigning liquefaction susceptibility units.
Units indicate relative susceptibility of deposits to liquefaction as a function of groundwater depth within that deposit. VH = very high, H = high, M = moderate, L = low, and VL = very low to none.

chronicle observations and contain data on ground failures consistent with liquefaction, which are used as calibration points for this study. Individual sites of known liquefaction are shown on Plate 2 and are differentiated by the type of failure. Not all 1989 liquefaction events in the City of San Francisco are shown. Many of the 1989 events occurred in areas of 1906 liquefaction (Dupré and Tinsley, 1990; Seed and others, 1990).

Historical liquefaction has occurred most commonly in artificial fill overlying Holocene bay mud (Plate 2). In many cases, it is not known to what extent the failures were in the fill itself or in the estuarine deposits beneath the fill. Silty and sandy artificial fill materials near the San Francisco Bay margin are typically saturated; most of the failures likely occurred in such hydraulically-emplaced artificial fill.

D. Liquefaction susceptibility units

Tinsley and others (1985) defined liquefaction susceptibility units based on quantitative evaluation of SPT data from boreholes in the Los Angeles area. Deposits marked Very High and High by Tinsley and others (1985) are expected to liquefy in an earthquake of magnitude 6.5 or greater. Deposits marked Moderate are expected to liquefy in a magnitude 8 event but not a magnitude 6.5 event, and deposits marked Low or Very Low will not liquefy, even in a magnitude 8 earthquake.

Our map units can be interpreted in a similar manner. Estimated triggering PGAs for each geologic unit are listed in Table 4. These values are estimates only, and are provided only to indicate relative levels of shaking necessary to liquefy the different geologic map units. The estimates are based on limited borehole analyses and should not be used as substitutes for site-specific investigations. Triggering PGAs range from approximately 0.1g for saturated artificial fill and modern stream channel deposits, to approximately 0.5 to 0.6 g for saturated late Pleistocene alluvial deposits.

We expect that 80 percent of future liquefaction will take place in areas marked High or Very High. Dupré and Tinsley (1990) show that, in the Monterey area, the areas that liquefied in the 1906 San Francisco earthquake are the same areas that liquefied in the 1989 Loma Prieta earthquake. We expect that 20 percent or less of future liquefaction will take place in areas marked Moderate and Low, and that less than 1 percent will take place in areas marked Very Low. Geologic units known to have liquefied in previous earthquakes are generally assigned to the "Very High" liquefaction susceptibility unit, although, where either the location of the event or the actual occurrence of liquefaction is in question, we may have assigned the geologic unit to the “High” susceptibility unit. Historical occurrences of liquefaction in the study area are shown on Plate 2.

V. SUMMARY

A liquefaction susceptibility map is developed for the San Francisco 1:100,000 quadrangle on the basis of Quaternary geologic mapping, groundwater levels, historical occurrences of liquefaction, and limited analyses of borehole (SPT) data. The Quaternary geologic map differentiates deposits on the basis of age and depositional environment -- two of the criteria necessary to locate loose, cohesionless sand and silt. Age is evaluated because deposits become more compact (dense) and cemented with age. Depositional environment is evaluated because each environment is characterized by deposits with different sorting, bedding, and grain-size characteristics. A criteria matrix is developed that matches age and type of deposit and groundwater levels to yield relative liquefaction susceptibility. The criteria matrix is calibrated with data of Tinsley and others (1985), historical liquefaction occurrences, and with limited Seed-Idriss evaluations of borehole data.

Deposits most susceptible to liquefaction in the study area are non-engineered artificial fill emplaced over estuarine sediments, and latest Holocene stream deposits. Other susceptible deposits include estuarine deposits, Holocene stream terrace deposits, Holocene beach and dune sands, Holocene undifferentiated alluvium, and Holocene basin deposits. Communities within or directly adjacent to areas over 1 km^2 in size having high or very high liquefaction susceptibility include Alameda, Albany, Berkeley, Burlingame, Corte Madera, El Cerrito, Foster City, Oakland, Pacifica, Richmond, San Francisco, San Leandro, San Mateo, and San Rafael. Communities within or adjacent to areas over 1 km^2 in size having moderate to high liquefaction susceptibility include nearly every city in the map area.

This map shows general conditions in the region for planning purposes only and cannot be used to assess the presence or absence of liquefiable sediments for specific sites. Site-specific geotechnical investigations must be conducted to make that assessment.

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VII. REFERENCES

Atwater, B.F., Hedel, C.W., and Helley, E.J., 1977, Late Quaternary depositional history, Holocene sea-level changes, and vertical crustal movement, southern San Francisco Bay, California: U.S. Geological Survey Professional Paper 1014, 15 p.

Bonilla, M.G., 1971, Preliminary geologic map of the San Francisco South quadrangle and part of the Hunters Point quadrangle, California; U.S. Geological Survey Miscellaneous Field Studies Map MF-311; scale 1:24,000.

California Division of Mines and Geology, 1974a, Special studies zone, Bolinas quadrangle: scale 1:24,000.

_______ 1974b, Special studies zone, Double Point quadrangle: scale 1:24,000.

_______ 1974c, Special studies zone, San Mateo quadrangle: scale 1:24,000.

_______ 1982a, Special studies zone, Montara Mountain quadrangle: scale 1:24,000.

_______ 1982b, Special studies zone, San Francisco South quadrangle: scale 1:24,000.

_______ 1982c, Special studies zone, Oakland East quadrangle: scale 1:24,000.

_______ 1982d, Special studies zone, Oakland West quadrangle: scale 1:24,000.

_______ 1982e, Special studies zone, Richmond quadrangle: scale 1:24,000.

_______ 1982f, Special studies zone, San Leandro quadrangle: scale 1:24,000.

_______ 1982g, Special studies zone, Hayward quadrangle: scale 1:24,000.

_______ 1982h, Special studies zone, Newark quadrangle: scale 1:24,000.

_______ 1993, Special studies zone, Walnut Creek quadrangle: scale 1:24,000.

Chen, A.T., 1988, PETAL3: PEnetration Testing And Liquefaction, An Interactive Computer Program: U.S. Geological Survey Open-File Report 88-540, 34 p.

Clough, G.W., Martin, J.R. II, and Chameau, J.L., 1994, The Geotechnical Aspects *in* Practical Lessons from the Loma Prieta Earthquake, Report from a symposium sponsored by the National Research Council: National Academy Press, Washington, D.C.

DeLisle, M.J., and Real, C.R., 1994, Preliminary Seismic Hazard Zone Map, Liquefaction hazard zones for a portion of the San Francisco North quadrangle: California Division of Mines and Geology, scale 1:24,000.

Dupré, W.R., 1990, Maps showing geology and liquefaction susceptibility of Quaternary deposits in the Monterey, Seaside, Spreckels, and Carmel Valley quadrangles, Monterey, California: U.S. Geological Survey, Map MF-2096.

Dupré, W.R., and Tinsley, J.C., 1980, Maps showing geology and liquefaction potential of northern Monterey and southern Santa Cruz counties, California: U.S. Geological Survey Miscellaneous Field Studies MF-1199.

_______ 1990, Geologic controls on liquefaction-induced ground failure in the Monterey Bay area, California, during the Loma Prieta earthquake, October 17, 1989: Geological Society of America, Abstract with Programs, v. 22, no. 7, p. A188.

Goldman, H.B., ed., 1969, Geologic and engineering aspects of San Francisco Bay fill: California Division of Mines and Geology Special Report 97.

Haydon, W.D., 1995, Landslide hazards in the Martinez-Orinda-Walnut Creek area, Contra Costa County, California: California Division of Mines and Geology Open-File Report 95-12, 4 plates, scale 1:24,000.

Helley, E.J., and Lajoie, K.R., 1979, Flatland deposits of the San Francisco Bay Region, California - Their geology and engineering properties, and their importance to comprehensive planning: U.S. Geological Survey Professional Paper 943.
Helley, E.J., and Miller, D.M., 1992, Geologic map of the Newark 7.5 minute quadrangle, Alameda County, California: U.S. Geological Survey Open-File Report 92-312, scale 1:24,000.
Helley, E.J., and Wesling, J.R., 1990, Quaternary geologic map of the San Jose East quadrangle, Santa Clara County, California: U.S. Geological Survey Open-File Report 90-427.
Helley, E.J., and Graymer, R.W., 1996a, Quaternary geology of Alameda County, California, and surrounding areas: derived from digital database U.S. Geological Survey Open-File Report 96-??, Draft.
_______ 1996b, Quaternary geology of Contra Costa County, California, and surrounding areas: derived from digital database U.S. Geological Survey Open-File Report 96-??, Draft.
Idriss, I.M., 1997, Evaluation of liquefaction potential and consequences, historical perspective and updated procedures: *in* D'Opazio, ed., Seismic Short Course on Evaluation and Mitigation of Earthquake Induced Liquefaction Hazards - Proceedings, March 13-14, 1997, 16 p.
Jack, R.N., 1969, Quaternary sediments of the Montara Mountain area, San Mateo County, California: unpublished Masters Thesis, University of California, Berkeley.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Division of Mines and Geology Geologic Data Map No. 6., scale 1:750,000.
Kashiwagi, J., 1985, Soil Survey of Marin County, California: U.S. Department of Agriculture, Soil Conservation Service.
Kashiwagi, J.H. and Hokholt, L.A., 1991, Soil survey San Mateo County, eastern part, and San Francisco County, California: U.S. Department of Agriculture, Soil Conservation Service.
Kennedy/Jenks Consultants and Dames & Moore, 1995, Integrated system reliability study, Final report: unpublished consulting report submitted to Marin Municipal Water District, Corte Madera, California.
Law, K.T., Cao, Y.L., and He, G.N., 1990, An energy approach for assessing seismic liquefaction potential: Canadian Geotechnical Journal, v. 27, p. 320-329.
Matti, J.C., and Carson, S.E., 1991, Liquefaction susceptibility in the San Bernardino Valley and vicinity, Southern California - A regional evaluation: U.S. Geological Survey Bulletin 1898, 53 p. plus plates.
Mejia, L.H., Hughes, D.K., and Sun, J.I., 1992, Liquefaction at Moss Landing during the 1989 Loma Prieta Earthquake: Proceedings of the Tenth World Conference, Earthquake Engineering, p. 1435-1440.
Nichols, D.R., and Wright, N.A., 1971, Preliminary map of historical margins of marshland, San Francisco Bay, California: U. S. Geological Survey Open-File Map.
Pampeyan, E.H., 1993, Geologic map of the Palo Alto and part of the Redwood Point 7-1/2' quadrangles, San Mateo and Santa Clara Counties, California: U. S. Geological Survey Miscellaneous Investigation Series I-2371, scale 1:24,000.
_______ 1994, Geologic map of the Montara Mountain and San Mateo 7-1/2' quadrangles, San Mateo County, California: U. S. Geological Survey Miscellaneous Investigation Series I-2390, scale 1:24,000.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.
Rogers, J.D., and Figuers, S.H., 1991, Engineering geologic site characterization of the greater Oakland-Alameda area, Alameda and San Francisco Counties, California: Final Report to the National Science Foundation, Grant no. BCS - 9003785.
Schlocker, J., 1974, Geology of the San Francisco North quadrangle; U.S. Geological Survey Professional Paper 782, 109 p., plates scale 1:24,000.
Seed, H.B., and Idriss, I.M., 1982, Ground motions and soil liquefaction during earthquakes: Earthquake Engineering Research Institute, Engineering Monograph v. 5, 134 p.
Seed, H. B., Tokimatsu, K., Harder, L. F., and Chung, R. M., 1985, Influence of SPT procedures in soil liquefaction resistance evaluations: Journal of Geotechnical Engineering, ASCE, v. 111, no. 12, p. 1425-1445.
Seed, R.B., Dickenson, S.E., Riemer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, A., Harder, L.F., Jr., and Power, M.S., 1990, Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake, Earthquake Engineering Research Center, Report No. UCB/EERC-90/05.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1995, Maps showing geology and liquefaction susceptibility of the Napa 1:100,000 sheet: U.S. Geological Survey Open-File Report 95-205.
Sowers, J.M., 1995, Creek & watershed map of Oakland and Berkeley: Oakland Museum of California, Oakland, California, scale approx. 1:22,000.
_______ Creek & watershed map of Hayward and San Leandro: Oakland Museum of California, Oakland, California, scale approx. 1:22,000.
Tinsley, J.C., and Holzer, T.L., 1990, Liquefaction in the Monterey Bay Region, *in* National Hazards Reductions Program, Summaries of Technical Reports, Vol. XXX, U.S. Geological Survey Open-File Report 90-334, p. 642-643.
Tinsley, J.C., Youd, T.L., Perkins, D.M., and Chen, A.T.F, 1985, Evaluating Liquefaction Potential, *in* Ziony, J.I., ed., Evaluating earthquake hazards in the Los Angeles Region - an earth-science perspective: U.S. Geological Survey Professional Paper 1360, p. 263-316.
United States Geological Survey, 1983, 1:100,000-scale metric topographic map of San Francisco, California: U.S. Geological Survey, Denver, Colorado.
_______ 1990, Probabilities of large earthquakes in the San Francisco Bay Region, California: U.S. Geological Survey Circular 1053.
Welch, L.E., 1977, Soil survey Contra Costa County, California: U.S. Department of Agriculture, Soil Conservation Service.
_______ 1981, Soil survey Alameda County, California, western part: U.S. Department of Agriculture, Soil Conservation Service.
Welch, L.E., Huff, R.C., Dierking, R.A., Cook, T.D., Bates, L.A., Andrews, W.F., 1966, Soil survey Alameda area, California: U.S. Department of Agriculture, Soil Conservation Service.
Youd, T.L., 1973, Liquefaction, flow and associated ground failure: U.S. Geological Survey Circular 688, 12 pp.
Youd, T.L., and Hoose, S.N., 1978, Historical ground failures in Northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993.

Youd, T.L., and Perkins, J.B., 1987, Map showing liquefaction susceptibility of San Mateo County, California: U.S. Geological Survey, Map I-1257-G.