Maps of Quaternary Deposits and Liquefaction Susceptibility in the Central San Francisco Bay Region, California

Part 3: Description of Mapping and Liquefaction Interpretation

in cooperation with the California Geological Survey

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TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

INTRODUCTION

This report presents new mapping of Quaternary deposits in the central part of the 9-county San Francisco Bay region (figure 1) and the resultant new map of liquefaction susceptibility. These supersede the equivalent area in the preliminary maps released five years ago for the whole 9-county region (Knudsen and others, 2000a). The susceptibility map is developed from the new 1:24,000-scale mapping of Quaternary deposits, historical observations of liquefaction-related ground failure, hydrologic information, and liquefaction analyses of geotechnical boring data. The study area includes parts of Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma Counties. Active faults capable of producing large earthquakes cross the study area; these faults include the Calaveras, Concord, Green Valley, Hayward, San Andreas and San Gregorio Faults (Figure 1). Potential earthquakes on these faults expose the entire region to long-duration ground motions with peak ground accelerations exceeding 0.3g (Frankel and others, 2002; Cao and others, 2003), sufficient to trigger liquefaction in susceptible natural deposits and artificial fill.

The new maps depict the regional distribution of Quaternary surficial deposits and relative liquefaction susceptibility zones in the central San Francisco Bay area and are appropriate for planning purposes. The maps lack the necessary resolution, however, for site-specific conclusions or design. The maps provide baseline data from which the California Geological Survey is developing State-mandated Seismic Hazard Zones of Required Investigation (CDMG, 1999).

Liquefaction-related ground failures caused by historical large-magnitude earthquakes in the San Francisco Bay area have resulted in loss of life and damage to property and lifelines. Spatial patterns of liquefaction effects produced during the 1906 San Francisco, 1989 Loma Prieta, and earlier earthquakes (Youd and Hoose, 1978; Tinsley and others, 1998), are not random. Instead, observations of surface deformation and damage produced by liquefaction indicate that the effects tend to occur in areas underlain by saturated, unconsolidated sand, silt and uncompacted artificial fill. Fortunately, areas susceptible to liquefaction can be identified through detailed geologic, geomorphic, and hydrologic mapping as demonstrated by hazard maps developed for the Monterey-Santa Cruz area (Dupré and Tinsley, 1980; and Dupré, 1990), the greater Los Angeles urban area (Tinsley and others, 1985), and the San Francisco Bay region (Youd and Perkins, 1987; Knudsen and others, 1997; Sowers and others, 1998; Knudsen and others, 2000a; Holzer and others, 2002). These publicly available maps allow planners, emergency responders, and property owners to identify and mitigate hazards in efforts to reduce losses caused by earthquake-induced liquefaction.

The Quaternary geologic and liquefaction susceptibility maps of this report are presented both as small-scale map images (Sheets 1 and 2) and as a detailed digital spatial database in which the polygons are coded both for Quaternary map unit and liquefaction susceptibility (see separate description of the digital database in Part 1). The new mapping builds directly upon the existing regional compilation of Quaternary geology and liquefaction susceptibility for the nine-county San Francisco Bay area by Knudsen and others (2000a). The new Quaternary geologic map presented here provides detailed map revisions for a subset of 68 quadrangles within the original nine-county map area and improves the scale of mapping for 29 quadrangles originally compiled at 1:100,000 scale by Knudsen and others (2000a) to 1:24,000. This next generation Quaternary geologic map builds upon the pioneering work of E.J. Helley and K.R. Lajoie (Helley and others, 1979) that provided the first region-wide characterization of surficial

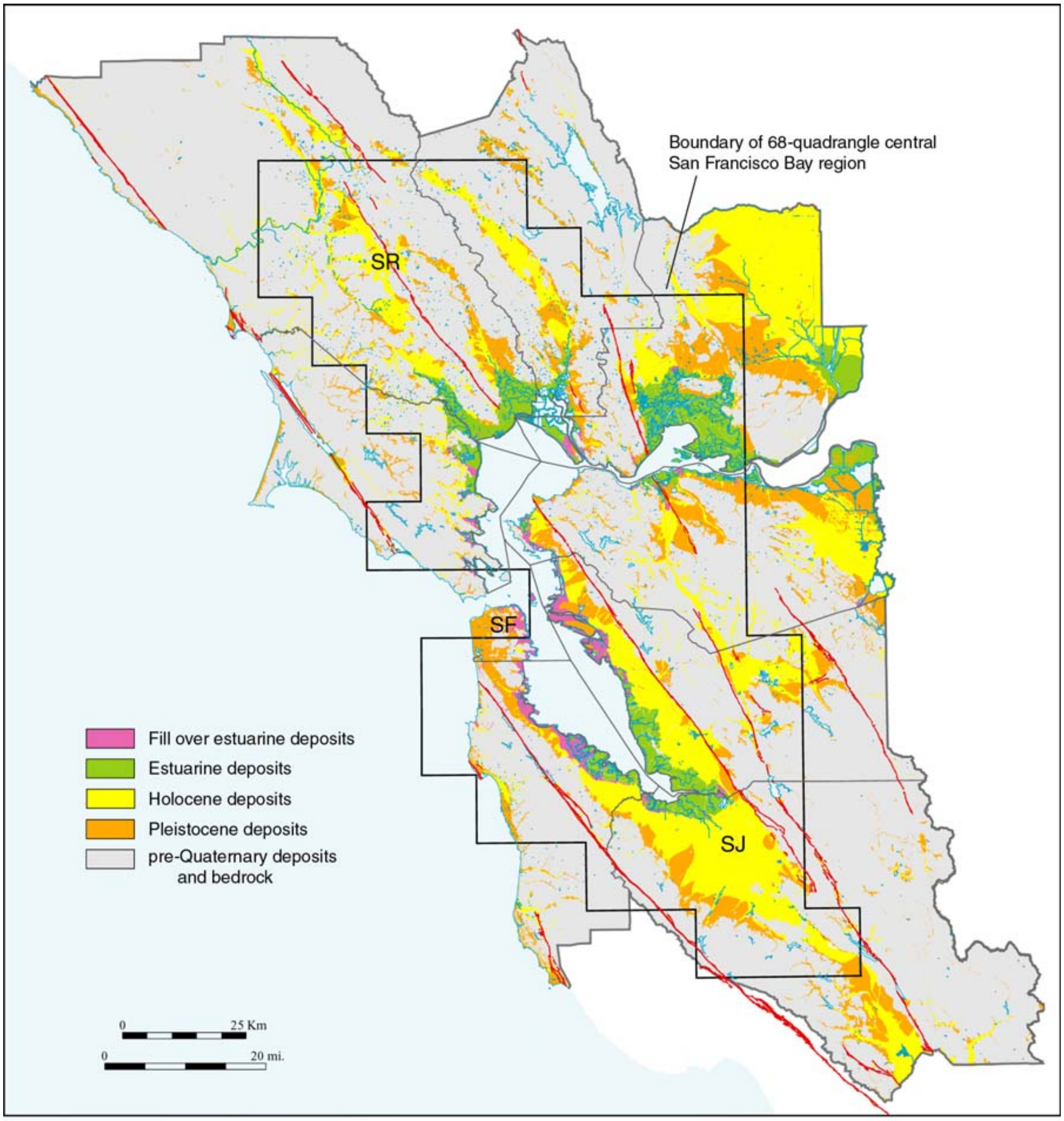

Figure 1. The nine-county San Francisco Bay region, showing the perimeter of the central San Francisco Bay region, the distribution of Quaternary deposits, and active faults (red). The active faults shown are those mapped within "Earthquake Fault Zones" by the California Geological Survey (Bryant and others, 2001) . County boundaries in gray. SF - San Francisco, SJ - San Jose, SR - Santa Rosa

deposits in the San Francisco Bay area. Improvements in the new liquefaction susceptibility map include a more accurate depiction of liquefaction related hazards based on susceptibility categories assigned using a revised criteria matrix. The susceptibility analysis incorporates quantitative analyses of geotechnical information contained in a regional borehole database compiled by the California Geological Survey (CGS) for the Santa Clara valley, San Francisco and East Bay areas. The susceptibility map delineates areas that are underlain by materials that have different relative susceptibilities to liquefaction; the map does not predict liquefaction-related ground failures, although ground failures may accompany liquefaction and are more likely to occur in areas with higher liquefaction susceptibility (Tinsley and others, 1985).

Acknowledgements

Conversations with John Baldwin and Keith Kelson, who shared their extensive knowledge and perspectives on the Quaternary geology in the San Francisco Bay region, significantly aided our mapping effort. Critical and constructive technical review comments from Kevin Clahan and William Lettis improved the maps. Jackie Bott, Anne Rosinski, and Mark Wiegers also provided useful input to the maps. The manuscript was clarified and focused through reviews by Russ Graymer, Tom Holzer, and John Tinsley. This research was supported by the U.S. Geological Survey (USGS) Earthquake Hazards Program and NEHRP award number 99-HQ-GR-0095, by the California Geological Survey's Seismic Hazards Mapping Program, and by the Professional Development fund of William Lettis & Associates, Inc.

BACKGROUND

Liquefaction is the transformation of saturated, unconsolidated granular material from a solid state to a liquid state as a consequence of increased pore pressures that reduce the effective strength of the material (Youd, 1973). Ground shaking from large earthquakes can produce increased pore pressures in unconsolidated deposits that may lead to localized liquefaction across much of western California. The process of liquefaction may or may not lead to ground deformation or related surface manifestations, including lateral spreading, ground settlement, bearing capacity failure, sand boils, and ground cracking. The effects of liquefaction often result in damage to the built environment and, in some cases, loss of life. Holzer (1998) and Youd and Hoose (1978) document liquefaction-related effects observed after previous large earthquakes in the San Francisco Bay region.

Liquefaction potential is a function of both the susceptibility of surficial deposits to liquefaction and the probability that earthquake ground motions will exceed a specified threshold level, or opportunity. A liquefaction susceptibility map reflects the distribution of surficial deposits with different physical properties and variations in hydrologic conditions. The opportunity for liquefaction is determined by the proximity of seismic sources, the magnitude and recurrence interval of earthquakes the seismic sources are capable of generating, and local site conditions that control the amplification or attenuation of shaking. A liquefaction potential map is the product of a liquefaction susceptibility map and a map depicting probabilistic ground motions (e.g., Frankel and others, 2002; Cao and others, 2003). Tinsley and others (1985) argued that liquefaction susceptibility maps for the Los Angeles region could serve as liquefaction potential maps because the opportunity for liquefaction across the region was relatively uniform. Although shaking potential is not uniformly distributed across the San Francisco Bay region, the use of liquefaction susceptibility maps as proxies for liquefaction potential maps is reasonable because probabilistic ground motions exceed levels sufficient to liquefy susceptible deposits across most of the region.

Sufficient liquefaction opportunity is justified for the San Francisco Bay region 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 and most are within 15 km; and (3) earthquakes on the Hayward/Rodgers Creek Fault (0.27 probability of a $M \geq 6.7$ between 2002 and 2030), San Andreas Fault (0.21 probability), Calaveras fault (0.11 probability) and San Gregorio Fault (0.10 probability), will produce long duration ground motions in excess of 0.3g over most of the study area (Working Group on California Earthquake Probabilities, 2003). 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. The assumption of sufficient liquefaction opportunity is conservative and valid, however, because most of these site-dependent variations in ground motion tend to enhance liquefaction.

METHODS

Previous evaluations of regional liquefaction hazards identify several geologic and hydrologic factors that influence the susceptibility of a deposit to liquefaction, including (1) the age and depositional environment of the deposit; (2) the relative consolidation of sands and silts; and (3) the local depth to ground water (Youd and others, 1973; Youd and others, 1975; Youd and Perkins, 1978; Tinsley and others, 1985). We developed a revised liquefaction susceptibility map by following the procedure outlined in previous assessments of liquefaction susceptibility in the San Francisco Bay area (Knudsen and others, 1997a, 1997b; Sowers and others, 1998; Knudsen and others, 2000a):

- Map surficial deposits on the basis of age and depositional environment;
- Estimate typical depth to ground water for each geologic unit;
- Evaluate historical liquefaction occurrences and relate observations of liquefaction to the associated geologic map unit;
- Develop a criteria matrix to classify all potential combinations of type and age of deposit with ground-water depth. Calibrate with historical liquefaction occurrence data, previous studies, and borehole (SPT) evaluations of liquefaction peak ground accelerations (PGA) thresholds; and
- Assign liquefaction susceptibility categories to geologic map units.

Quaternary deposits were characterized by age and depositional environment through the interpretation of historical topographic and coastal survey maps, aerial photography (both modern and historical), published soil surveys, review of previously published and unpublished geologic mapping, and limited field reconnaissance. Thirty-eight primary geologic map units that differ by age and depositional environment were identified in this study (Table 1; Figure 2). Mapping procedures and data sources used

Table 1. Correlation chart showing relationships between geologic map units characterized in this study, and the stratigraphic units shown on previous geologic maps.

Geologic Unit Description	This study	Knudsen and others, 2000	Knudsen and others, 1997	Sowers and others, 1995	Helley and Graymer, 1997a, b	Helley and others, 1994	Helley and Harwood, 1985	Helley and others, 1979	Wentworth and others, 1998
Artificial fill	**af**	af	af	af	af				af
Artificial fill over estuarine mud	**afem**	afbm							
Artificial fill, levee	**alf**	alf			alf				
Artificial fill, channel	**acf**								
Artificial fill, dams	**adf**								
Gravel quarries and percolation ponds	**gq**	gq	af		GP	PP,GP			PP,GP
Artificial stream channel	**ac**	ac			Qhasc				
Modern stream channel deposits	**Qhc**	Qhc	Qhc		Qhsc	Qhsc	Qsc	Qhsc	Qhc
Latest Holocene alluviual fan deposits	**Qhfy**	Qhfy			Qhaf1				
Latest Holocene alluvial fan levee deposits	**Qhly**	Qhly							
Latest Holocene stream terrace deposits	**Qhty**	Qhty			Qhfp1, Qhfp2				
Latest Holocene alluviual deposits, undifferentiated	**Qhay**	Qhay		Qhi					
Latest Holocene beach sand	**Qhbs**	Qhbs							
Holocene dune sand	**Qhds**	Qhds	Qhs	Qhs	Qhds			Qhs	
Holocene San Francisco Bay mud	**Qhbm**	Qhbm	Qhbm	Qhr	Qhbm	Qhbm		Qhbm	Qhbm
Holocene estuarine delta deposits	**Qhed**	Qhbm							
Holocene basin deposits	**Qhb**	Qhb	Qhb	Qhb	Qhb, Qhbs	Qhb	Qb		Qhb
Holocene fine grained alluvial fan-estuarine complex deposits	**Qhfe**	Qhfe				Qhbs			
Holocene alluvial fan deposits	**Qhf**	Qhf	Qhf	Qhf	Qhaf	Qhaf, Qhfp	Qa		Qhf, Qhfp

Geologic Unit Description	This study	Knudsen and others, 2000	Knudsen and others, 1997	Sowers and others, 1995	Helley and Graymer, 1997a, b	Helley and others, 1994	Helley and Harwood, 1985	Helley and others, 1979	Wentworth and others, 1998
Holocene alluvial fan deposits, fine grained facies	**Qhff**	Qhff			Qhb				
Holocene alluvial fan levee deposits	**Qhl**	Qhl	Qhl		Qhl	Qhl	Qa		Qhl
Holocene stream terrace deposits	**Qht**	Qht	Qht	Qht	Qhfp	Qhfp			Qht
Holocene alluvium, undifferentiated	**Qha**	Qha	Qha	Qha	Qhaf		Qa		Qha
Late Pleistocene to Holocene dune sand	**Qds**	Qds	Qps	Qs	Qms			Qps	
Late Pleistocene to Holocene basin deposits	**Qb**	Qb							Qt
Late Pleistocene to Holocene alluvial fan deposits	**Qf**	Qf	Qf	Qf					
Late Pleistocene to Holocene stream terrace deposits	**Qt**	Qt		Qt					
Late Pleistocene to Holocene alluvium, undifferentiated	**Qa**	Qa	Qa	Qa					Qa
Late Pleistocene alluvial fan deposits	**Qpf**	Qpf	Qpf	Qpf	Qpaf	Qpaf			Qpf
Late Pleistocene stream terrace deposits	**Qpt**	Qpt		Qpt					
Late Pleistocene alluvium, undifferentiated	**Qpa**	Qpa	Qpa	Qpa	Qpaf	Qpaf	Qmu, Qml	Qpa	Qpa
Pleistocene marine terrace deposits	**Qmt**	Qmt	Qmt	Qpm, Qom	Qmt			Qpmt	Qmt
Pleistocene bay terrace deposits	**Qbt**				Qmt				
Early to late Pleistocene pediment deposits	**Qop**	Qop							
Early to middle Pleistocene alluvial fan deposits	**Qof**	Qof			Qpaf, Qpoaf				Qof
Early to middle Pleistocene stream terrace deposits	**Qot**	Qot							
Early to middle Pleistocene undifferentiated alluvial deposits*	**Qoa**	Qoa	Qoa	Qoa	Qpaf, Qpoaf		Qru, Qrl	Qpea, Qpmc	Qoa
Early Quaternary and older (>1.4 Ma) deposits and bedrock	**br**	br				br			

Note: For each unit mapped in this study (shown in first column), the chart shows how previous studies typically mapped the same unit.

*Includes Colma Formation on the San Francisco peninsula.

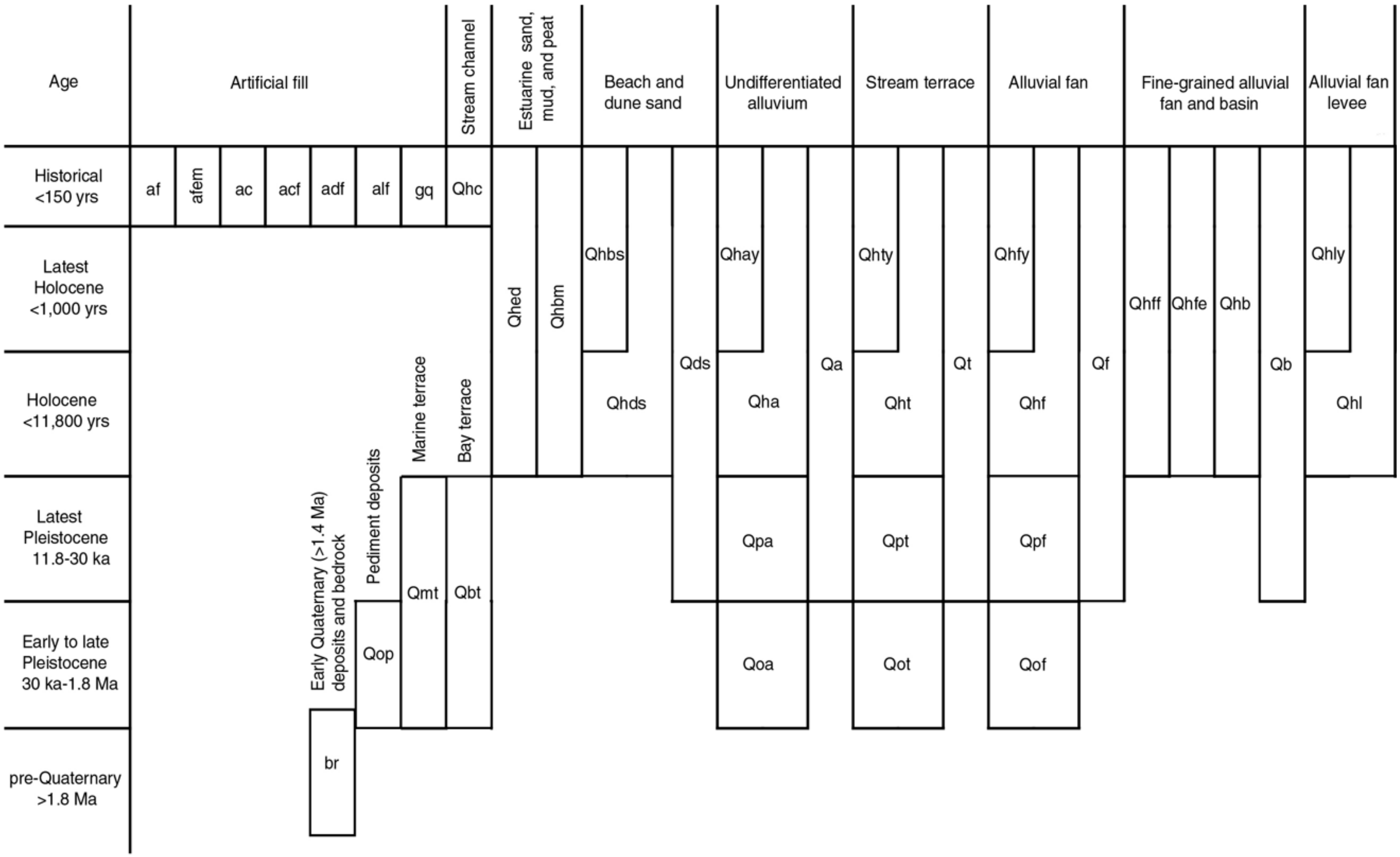

Figure 2. Correlation of geologic map units.

for each 7.5-minute quadrangle are listed in Table 2 and keyed to Figure 3. For each geologic map unit we assign a corresponding liquefaction susceptibility category (ranging from very low to very high) based on a criteria matrix that considers historical liquefaction occurrences, geotechnical analyses of limited borehole data, and estimated depth to ground water (Table 3). Note that this mapping procedure excludes Plio-Pleistocene deposits with poorly preserved geomorphic surfaces that have been largely destroyed through erosion or tectonic processes. Thus, early Quaternary and Pliocene deposits, such as the Montezuma and Santa Clara Formations, are not included in the map.

As a deposit ages, soil formation, weathering, diagenetic processes, and earthquake shaking lead to consolidation and cementation of the sediment. Older deposits are therefore generally less likely to liquefy. We used several criteria to assess the age of a deposit, including: (1) the relative degree of soil profile development; (2) relative extent of surface dissection or other surface modification; (3) relative topographic position and cross-cutting relations; (4) correlation to dated deposits in the region; and (5) correlation to the stratigraphic framework used by previous researchers (Table 1). Deposits that could not confidently be differentiated as either Holocene or latest Pleistocene are assigned an age that spans the Pleistocene-Holocene transition (11,800 years ago). This age category is also used where Holocene deposits are inferred to interfinger with, or form a thin veneer (< 5-feet thick) over, latest Pleistocene deposits. We use the term “latest Pleistocene” to refer to deposits younger than about 30,000 years–a different meaning than the commonly accepted <125,000 year age for late Pleistocene deposits. This categorization was adopted to permit distinction of these relatively young, but still Pleistocene deposits from older, more consolidated Pleistocene deposits and thereby distinguish deposits with different liquefaction susceptibilities.

Published soil surveys provide some of the primary data used to interpret the relative ages of a deposits that occur in the region. Quaternary geologic units of specific age and environment are characterized by individual soil series (e.g. Appendix B in Knudsen et al., 2000a). Soil surveys reviewed for the region include Bates and others (1977), Cosby (1941), Gardner and others (1958), Kashiwagi (1985), Kashiwagi and Hokholt (1991), Lindsey and Weisel (1974), Lambert and Kashiwagi (1978), Miller (1972), Wagner and Nelson (1961), and Welch (1977, 1981).

Data on the depth to ground water were acquired in several ways. Data on ground-water depths from boring logs for geotechnical studies were obtained from a regional boring database compiled by the California Geological Survey. Additional hydrologic information came 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 ground water in the area. We extrapolated water levels from field observations or boring log data to areas with little available ground-water data. In some cases we used the depth of stream incision as a maximum depth to ground water. Water levels in water wells were not used because the wells tap deep, in many places artesian, aquifers and the levels thus represent the potentiometric surface for the aquifer, not the depth to saturated sediment. We used historical high ground-water depths where available to be consistent with the approach used by the California Geological Survey in its Seismic Hazard Mapping Program (California Division of Mines and Geology, 1999).

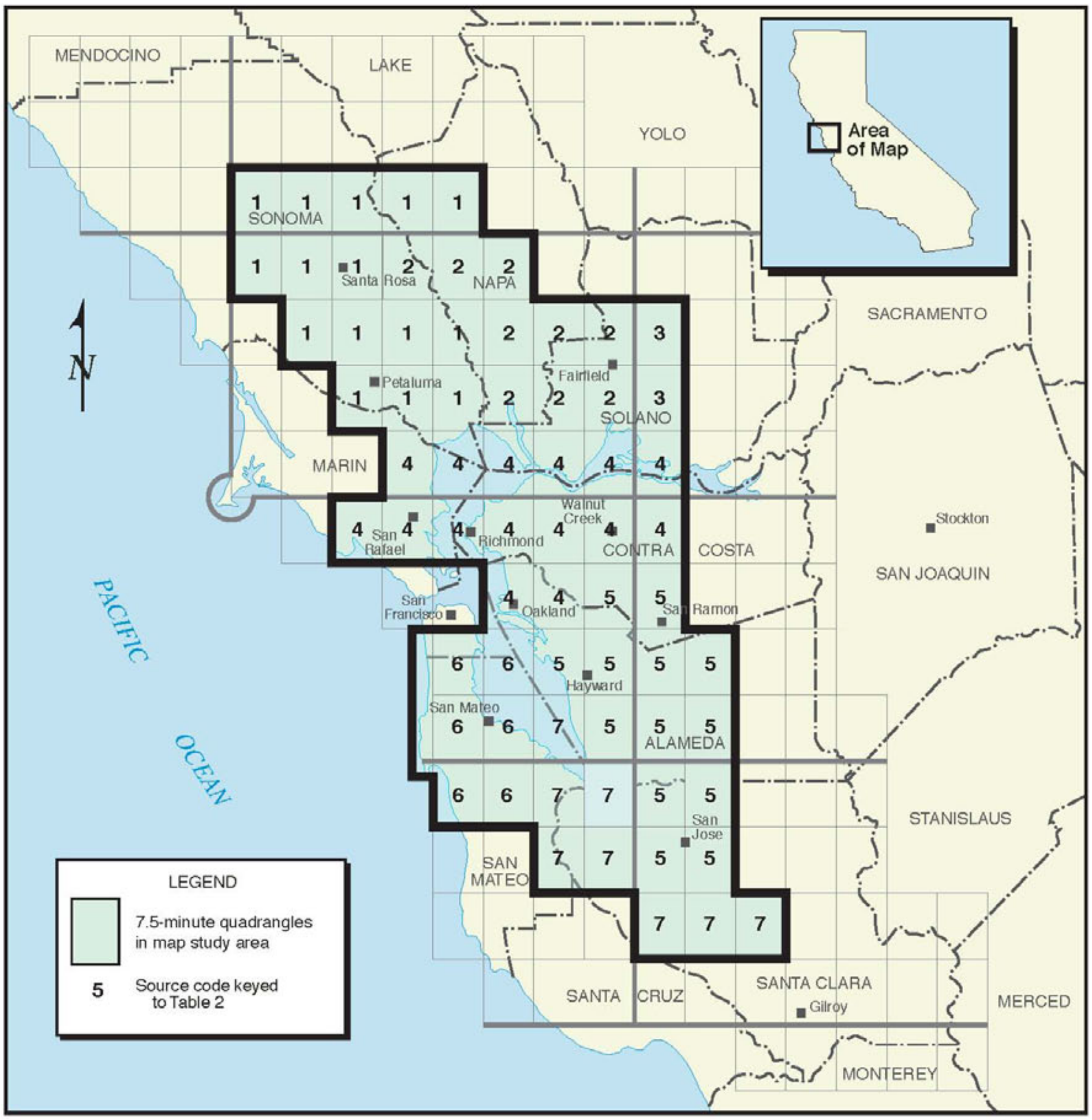

Figure 3. Index map to Table 2. Each rectangle represents one of 68 U.S. Geological Survey 7.5-minute quadrangles that encompass the densest development within the San Francisco Bay area urban core. Mapping procedures and sources represented by codes (1 to 7) are keyed to Table 2.

Table 2. Documentation of mapping procedures and data sources.

1. Interpretation of topographic contours, published soil surveys (e.g., Lambert and Kashiwagi, 1978; Miller, 1972), and aerial photography dating from 1942, 1953, 1968, 1973, 1976, 1984, and 1997, and limited field reconnaissance. Previous mapping reviewed includes: Fox and others (1973); Jennings (1988); Nichols and Wright (1971); and Sowers and others (1998). Lead authors: Koehler, Randolph, and Sowers. Map scale: 1:24,000.

2. Modified from Sowers and others (1997) and Bezore and others (2000). Extensive modifications were made based on interpretation of aerial photography dating from 1942, topographic contours, and published soil surveys (e.g. Bates and others, 1977; Lambert and Kashiwagi, 1978). Previous mapping reviewed includes: Fox and others (1973); Helley and others (1979); Nichols and Wright (1971); Sims and others (1973) and Sowers and others (1997). Lead authors: Sowers and Witter. Map scale: 1:24,000.

3. Interpretation of topographic contours shown on modern and/or historical (circa 1915) U.S. Geological Survey maps, and published soil surveys (e.g. Bates and others, 1977; Cosby, 1941). Previous mapping reviewed includes Helley and others (1979), Helley and Harwood (1985), and Nichols and Wright (1971). U.S. Geological Survey orthophotoquads dated 1970 were reviewed for the Elmira quadrangle. Lead authors: Knudsen and Witter. Map scale: 1:24,000.

4. Interpretation of topographic contours, published soil surveys (e.g. Bates and others, 1977; Cosby, 1941; Kashiwagi, 1985; Welch, 1977), and aerial photography dating from 1942, 1939, 1946, 1974, 1984, and 1995, and limited field reconnaissance. Previous mapping reviewed includes: Borchardt (1994); Clark and Brabb (1997); unpublished mapping by Ron Crane; Dibblee (1980a-e, 1981a-b); Galloway (1977); Haydon (1995); Helley and Graymer (1997a); Helley and others (1979); unpublished mapping by E.J. Helley and J.S. Noller; Knudsen and others (1997); Nichols and Wright (1971); Sims and others (1973); Radbruch (1969); Sowers (1995); and Sowers and others (1998). Lead author: Witter. Map scale: 1:24,000.

5. Interpretation of topographic contours, published soil surveys (e.g., Lindsey and Weisel, 1974; Welch, 1977, 1981), stereoscopic aerial photography dating from 1939 and 1949, historical wetlands data compiled by the Goals Project (1999), Sowers (1999), other historical wetlands data, and limited field reconnaissance. Previous mapping reviewed includes: Helley and Wesling (1989, 1990); Helley and Miller (1992); Helley and others (1994); Helley and Graymer (1997b); Kelson and others (1993); and Sawyer (1996). Lead author: Sowers. Map scale: 1:24,000.

6. Interpretation of topographic contours, published soil surveys (e.g., Kashiwagi and Hokholt, 1991; Wagner and Nelson, 1961), and stereoscopic aerial photography dating from 1943, and limited field reconnaissance. Previous mapping reviewed includes: Bonilla (1998); Brabb and others (1998a); Helley and others (1979); Knudsen and others (1997); and Pampeyan (1994). In these quadrangles Helley and Graymer (1997b) is based on previous mapping by Herd (1977). Mapping of marine terraces is modified from Weber and others (1993), and Lajoie and others (1974,1979). Lead author: Witter. Map scale: 1:24,000.

7. Interpretation of topographic contours, published soil surveys (e.g., Gardner and others, 1958), and stereoscopic aerial photography dating from 1943, and limited field reconnaissance. Previous mapping reviewed includes: Angell and others (1997); Brabb and others (1998b); Graymer, 1997; Helley and Brabb, 1971; Helley and others (1994); and Wentworth and others (1998). Lead author: Knudsen. Map scale: 1:24,000.

We use a criteria matrix to assign liquefaction susceptibility categories for each combination of geologic unit and depth to ground water that represent the relative likelihood that loose, saturated, granular materials are present (Table 3). Each of five categories, ranging from very low to very high, represents the relative liquefaction susceptibility of a geologic unit based on the combined assessment of historical observations of liquefaction, geotechnical analyses of borehole data, and estimated depth to groundwater. By intersecting the digital compilation of historical liquefaction-related ground effects for the San Francisco Bay area (Knudsen and others, 2000a, Appendix C) with the Quaternary geologic map, we evaluated whether historical liquefaction had occurred in each geologic unit and, if so, the number of liquefaction occurrences per square kilometer over which the unit is mapped (Table 3). Using procedures developed by Seed and Idriss (1971, 1982) and updated by Youd and others (2001), we calculated the percent of samples from each map unit that are susceptible to liquefaction (Table 3). This analysis used the 10% probability of exceedance in 50 years peak ground acceleration (PGA) from probabilistic hazard maps for the State of California (Cao and others, 2003). The PGA and earthquake magnitude are calculated for each boring location. The earthquake magnitude used in the liquefaction analysis is from the deaggregated probabilistic map and represents the magnitude of the earthquake for the source with the maximum contribution to the probabilistic ground motion. These geotechnical analyses were performed on an unpublished borehole database developed by the Seismic Hazard Mapping Program of the California Geological Survey (http://gmw.consrv.ca.gov/shmp/). Borehole data used in this analysis come from western Alameda County, northwestern Santa Clara County and the City and County of San Francisco.

RESULTS

Quaternary Geology

Depositional processes and environments operating in the San Francisco Bay region reflect the influence of active tectonics and climatic fluctuation during the Quaternary (Helley and others, 1979). For example, northwest-trending valleys are aligned with major strike-slip faults that contain sediments deposited by streams on flood plains, levees, alluvial fans, and basins. Broad piedmont alluvial fans are deposited along the flanks of northwest-trending mountain ranges undergoing active tectonic uplift. Flights of stream terraces (Kelson and others, 1993), aligned fan apices and abrupt changes in stream gradients (Hitchcock and Kelson, 1999) have been attributed to ongoing uplift of the ranges caused by transpressional deformation (Aydin and Page, 1984; Unruh and Lettis, 1998). Climatic influence on depositional systems is evidenced by latest Pleistocene fans deposited by streams graded to lowered base levels and eolian dunes on the San Francisco Peninsula and in Alameda that indicate westward migration of the shoreline during Wisconsin sea-level low stands (Atwater and others, 1977). Younger, Holocene, alluvial fans record deposition by streams responding to the marine transgression that culminated with the present sea-level high stand and formation of San Francisco Bay.

Deposits in coastal and estuarine environments also have been influenced by climate change and tectonics during the Quaternary. Step-like flights of late Pleistocene marine terraces tectonically raised above the modern shoreline along the San Mateo coast preserve sediments deposited in

Table 3. Criteria matrix for assigning liquefaction susceptibility categories to Quaternary geologic units. Categories 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. Shaded boxes show the preferred susceptibility assignment(s) for each geologic unit.

Geologic unit	Description	Historical liquefaction?	No. liquefaction occurrences per square kilometer[1]	Percent of samples that liquefy at 10% in 50 yr PGA[2]	Estimated PGA threshold[3]	Typical depth to ground water (ft)	Estimated depth to ground water (ft) and liquefaction susceptibility category assigned to geologic unit			
							<10	10 to 30	30 to 40	>40
af	Artificial fill	yes	0.41	19 (650)	0.3g[4]	<15	VH-VL[5]	VH-VL[5]	M-VL[5]	VL
afem	Artificial fill over estuarine mud	yes	0.27	n.d.	0.1g[4]	<5	VH	H	M	VL
alf	Artificial fill, levee	yes	0.05	32 (6)	0.1g[4]	<15	VH-H[5]	VH-M[5]	M	VL
acf	Artificial fill, channel	no?	0	n.d.	0.1g[4]	<10	VH	H	M	VL
adf	Artificial fill, dam	yes	0	n.d.	uncertain	variable	M-VL[5]	M-VL[5]	L-VL	VL
gq	Gravel quarry	no	0	n.d.	uncertain	variable	M	M	L	VL
ac	Artificial stream channel	yes	0.10	n.d.	uncertain	<10	VH-L[5]	L	L	L
Qhc	Modern stream channel deposits	yes	0.17	40 (17)	0.1g	<5	VH	H	M	VL
Qhfy	Latest Holocene alluvial fan deposits	yes	0.07	7 (15)	>0.2g	<10	H	H	M	L
Qhly	Latest Holocene alluvial fan levee deposits	yes	0.11	62 (88)	>0.1g	<10	VH	H	M	L
Qhty	Latest Holocene stream terrace deposits	yes	0.02	31 (33)	>0.1g	<10	H	H	M	L
Qhay	Latest Holocene alluvial deposits, undifferentiated	yes	0.34	n.d.	0.2g	<10	VH	H	M	L
Qhbs	Holocene beach sand	yes	0.45	n.d.	0.1g	<10	VH	H	M	VL
Qhds	Holocene dune sand	uncertain[6]	uncertain[6]	n.d.	>0.1g	<20	H	M	L	VL
Qhbm	Holocene San Francisco Bay mud	yes	0.01	7 (50)	0.2g	<5	M	L	L	VL

Geologic unit	Description	Historical liquefaction?	No. liquefaction occurrences per square kilometer[1]	Percent of samples that liquefy at 10% in 50 yr PGA[2]	Estimated PGA threshold[3]	Typical depth to ground water (ft)	Estimated depth to ground water (ft) and liquefaction susceptibility category assigned to geologic unit			
							<10	10 to 30	30 to 40	>40
Qhb	Holocene basin deposits	yes	0.05	n.d.	0.3g	<10	M	L	L	VL
Qhfe	Holocene fine grained alluvial fan-estuarine complex deposits	yes	0.21	15 (26)	>0.1g	<10	H	M	L	VL
Qhed	Holocene estuarine delta deposits	yes	1.05	n.d.	>0.1g	<5	H	M	L	VL
Qhf	Holocene alluvial fan deposits	yes	0.01	27 (1561)	>0.2g	<15	H	M	L	VL
Qhff	Holocene alluvial fan deposits, fine facies	yes	0.03	8 (57)	0.2g	<10	M	M	L	VL
Qhl	Holocene alluvial fan levee deposits	yes	0.03	29 (244)	>0.2g	<15-20	H	M	L	VL
Qht	Holocene stream terrace deposits	yes	0.01	22 (13)	0.3g	<15	H	M	L	VL
Qha	Holocene alluvial deposits, undifferentiated	yes	0.02	9 (9)	> 0.3g	<10	M	M	L	VL
Qds	Late Pleistocene to Holocene dune sand	yes	0.09	20 (401)	>0.6g	<15	H	M	L	VL
Qb	Late Pleistocene to Holocene basin deposits	no	0	n.d.	>0.2g	<15	M	L	L	VL
Qf	Late Pleistocene to Holocene alluvial fan deposits	no	0	21 (249)	>0.3g	>15	H	M	L	VL
Qt	Late Pleistocene to Holocene stream terrace deposits	yes	0.10	20 (5)	>0.3g	<20	H	M	L	VL
Qa	Late Pleistocene to Holocene alluvial deposits, undifferentiated	yes	0.04	12 (453)	>0.3g	<15	H	M	L	VL
Qpf	Late Pleistocene alluvial fan deposits	no	0	19 (1195)	>0.5g	<30	L	L	VL	VL
Qpt	Late Pleistocene stream terrace deposits	no	0	n.d.	>0.5g	<30	L	L	VL	VL
Qpa	Late Pleistocene alluvial deposits, undifferentiated	yes	0.05	n.d.	>0.5g	<30	L	L	VL	VL
Qmt	Pleistocene marine terrace deposits	no	0	n.d.	uncertain	<30	L	L	VL	VL

Geologic unit	Description	Historical liquefaction?	No. liquefaction occurrences per square kilometer[1]	Percent of samples that liquefy at 10% in 50 yr PGA[2]	Estimated PGA threshold[3]	Typical depth to ground water (ft)	Estimated depth to ground water (ft) and liquefaction susceptibility category assigned to geologic unit			
							<10	10 to 30	30 to 40	>40
Qbt	Pleistocene bay terrace deposits	uncertain[6]	uncertain[6]	9 (10)	uncertain	<10 to 15	L	L	VL	VL
Qop	Early to late Pleistocene pediment deposits	no	0	n.d.	uncertain	<40	L	VL	VL	VL
Qof	Early to middle Pleistocene alluvial fan deposits	no	0	n.d.	>0.6g	<40	L	VL	VL	VL
Qot	Early to middle Pleistocene stream terrace deposits	no	0	n.d.	>0.6g	<40	L	VL	VL	VL
Qoa	Early to middle Pleistocene alluvial deposits, undifferentiated	uncertain[6]	uncertain[6]	n.d.	>0.6g	<40	L	VL	VL	VL
br	Early Quaternary and older (>1.4 Ma) deposits and bedrock	no	0	n.d.	n.d.	variable	VL	VL	VL	VL

Notes: n.d., insufficient or no data.

[1]Number of liquefaction occurrences per square kilometer based on digital correlations of the locations of historical ground failures and effects (Youd and Hoose, 1978; Tinsley and others, 1998) with individual map units. Original digital compilation of historical liquefaction occurrence data was performed by Knudsen and others (2000, Appendix C).

[2]Percent of samples from units with susceptible textures that liquefy at 10% in 50 years PGA normalized to the total boring length calculated from unpublished CGS geotechnical data. Number of samples used in analyses shown in parentheses.

[3]Estimated peak ground acceleration (PGA) required to trigger liquefaction from quantitative analyses of regional borehole data compiled by CGS based on the Simplified Seed approach (Seed and Idriss, 1982; Youd and Idriss, 1997).

[4]Assuming non-engineered fill.

[5]The liquefaction susceptibility of artificial fill ranges widely, depending largely on the nature of the fill material and whether it was compacted. We use very high susceptibility for all fill on the margins of the San Francisco Bay, described separately as artificial fill over estuarine mud (afem). Artificial fill (af) and artificial stream channels (ac) are assigned the susceptibility of the underlying geologic map unit. Levees constructed of artificial fill (alf) are assigned very high susceptibility where they overlie estuarine deposits (e.g., Qhbm, Qhed, and Qhfe). Artificial levees overlying upland deposits are assigned high susceptibilities. Artificial fill emplaced for dams are assigned low susceptibility; however, site specific investigations are required to evaluate the liquefaction susceptibility at individual dams of variable age and material properties (see Appendix A for further explanations). Liquefaction susceptibility assignments for fewer than ten artificial fill (af) polygons are shown as VH to H, based on the occurrence of liquefaction in these areas.

[6]These occurrences are either not well located, or are poorly characterized in historical accounts and may not have been liquefaction related.

near-shore marine, lagoon, beach, dune and alluvial environments during past sea-level high stands. Sedimentary and erosional processes active along the coast are driven by wind, wave action and littoral currents. Lower energy processes control the deposition of fine-grained sediments in broad, low-lying marshes and distal alluvial fan-estuary complexes that fringe San Francisco Bay and the Sacramento/San Joaquin Delta. In southern San Francisco Bay, Holocene Bay mud deposits are subsiding due to tectonic and possibly isostatic forces (Atwater and others, 1977). Along San Pablo Bay, the Carquinez Straight and near Lake Merritt in Oakland, latest Pleistocene estuarine and bay margin deposits are preserved as Bay terraces that contain the articulated shells of oysters that lived in a bay formed by the stage 5e sea-level high stand 112 to 142 thousand years ago (Helley and others, 1993).

Physiographic differences among valleys, watershed area, and variations in the distribution of precipitation in the San Francisco Bay region also exert some control over depositional environments. Additional environmental controls on the sedimentary characteristics of a deposit may include vegetation, sediment load and bedrock geology. In the northern part of the region, watersheds containing the Napa River, Russian River and Sonoma Creek experience higher mean annual precipitation compared to the Santa Clara Valley and stream terraces and active flood plains are confined to narrow valleys. Along the margins of these valleys, smaller tributary streams that flow from the adjacent ranges form relatively small, steep alluvial fans. In contrast, broad coalescing alluvial fans, fan levees and inter-levee basins characterize depositional environments along Coyote Creek and Guadalupe Creek in the Santa Clara Valley and Walnut Creek basin where precipitation is generally lower and the valleys are less confined.

The new Quaternary geologic map presents a complete depiction of surficial deposits at a larger scale (1:24,000) in the most urbanized central core of the San Francisco Bay area compared to the nine-county maps developed by Knudsen and others (2000a). For example, twenty-nine quadrangles that were compiled at 1:100,000-scale for the nine-county map have been remapped at 1:24,000-scale for this project and most mismatched map units along quadrangle borders present in the nine-county map have been resolved. Figure 2 shows the stratigraphic correlations among the units by age, and Table 1 compares the geologic units with those of previous researchers who mapped parts of the area. Detailed descriptions of the Quaternary geologic units, including the newly defined Pleistocene Bay terrace deposits (Qbt), are presented in Appendix A. The general material properties of these units are characterized from subsurface information included in unpublished geotechnical and engineering reports and in an extensive borehole database compiled by the California Geological Survey covering the areas of western Alameda County (Haydon and others, 1995; 1999), San Francisco (DeLisle and Real, 1994) and the Santa Clara Valley (Clahan and others, 2000a; 2000b; 2000c; 2000d).

Man-made deposits cover approximately 3% of the region. These areas are mapped as either artificial fill (af), artificial fill over estuarine mud (afem), artificial levee fill (alf), artificial stream channel (ac), artificial channel fill (acf), artificial dams (adf), or gravel quarry and percolation pond (gq). Artificial fill over estuarine mud (afem) is mapped where fill was placed over Bay mud (Qhbm), bayward of the early historical extent of marshlands and bay (Nichols and Wright, 1971; Goals Project, 1999). Artificial levee fill (alf) is mapped where the map symbols for levees are shown on 7.5-minute USGS topographic quadrangles. Artificial levee deposits (alf) may not differ significantly from the underlying material, which is commonly Holocene Bay mud (Qhbm) or Holocene to historical alluvial fan levees (Qhly, Qhl) and stream terrace (Qhty, Qht) deposits. Artificial stream channels (ac), identified through interpretation of aerial photography and historical topographic maps, include modified channels, flood control channels and concrete canals. Artificial channel fill (acf) consists of human-emplaced materials within historical stream channels identified through inspection of topographic maps, aerial photographs and as mapped by Sowers (1995, 1997, 1999). Artificial dams (adf) include earthen embankments, rock-fill dams and artificial levees that impound water reservoirs, settling/cooling ponds, artificial lakes and stock ponds. Dams were identified through analyses of topographic maps and aerial photography. Gravel quarries and percolation ponds (gq) typically were mapped using information shown on 7.5-minute USGS topographic or orthophoto quadrangles.

Historical Liquefaction in the Central San Francisco Bay Region

Records of liquefaction-induced ground failures in the region are available for several historical earthquakes, including the two most damaging events: the 1906 San Francisco earthquake (Mw=7.7-7.9) (Youd and Hoose, 1978), and the 1989 Loma Prieta earthquake (Mw=7) (Plafker and Galloway, 1989; Seed and others, 1990; Tinsley and others, 1998). Other earthquakes that generated liquefaction failures in the study area include the 1838, 1865, 1868, and 1957 earthquakes (Youd and Hoose, 1978). Much of the 1989 liquefaction-related ground failures occurred in areas of previous recorded liquefaction (Dupré and Tinsley, 1998; Seed and others, 1990).

Knudsen and others (2000a) developed a preliminary spatial database of historical earthquake-related ground failures in the San Francisco Bay Region (Appendix C) and compared these data with the digital nine-county Quaternary geologic and liquefaction susceptibility maps. The ground-failure database contains historical observations of earthquake-triggered damage, as interpreted by Youd and Hoose (1978), and observations of liquefaction-related ground failures resulting from the 1989 Loma Prieta earthquake (Tinsley and others, 1998). Comparisons between the new Quaternary geologic map and the distribution of historical ground effects (Knudsen and others, 2000a) were used to calibrate the liquefaction susceptibility criteria matrix (Table 3) and as a predictive indicator for the likely distribution of future liquefaction-related ground effects (Table 4).

The greatest number of historical ground failures, 34% of the total observed effects in the core Bay area, occurred in the map unit artificial fill over estuarine mud (afem). In contrast, Knudsen and others (2000b) concluded that artificial fill over Bay mud hosted about 50% of all historical liquefaction occurrences in the nine-county San Francisco Bay area and about 80% of the liquefaction occurrences resulting from the Loma Prieta earthquake. The higher percentage of occurrences in artificial fill over Bay mud on the nine-county map reflects the high density of liquefaction-related ground failures documented in the San Francisco North quadrangle, which was not included within the map area for this study. For the Loma Prieta earthquake, the higher percentage may reflect the low accelerations necessary to trigger liquefaction in this unit and the relatively low accelerations produced by the Loma Prieta earthquake in much of the nine-county area. In many cases it is not known whether the failures were in the fill or in the underlying estuarine deposits. The high percentage of failures occurring in artificial fill over estuarine mud also may reflect amplified shaking levels due to the physical characteristics of Bay mud.

Table 4. Relations between regional liquefaction susceptibility by category and spatial distribution of historical liquefaction occurrences.

Geologic unit	Regional liquefaction susceptibility	Number of historical occurrences	Percent of total historical occurrences	Area (km^2)	Occurrences per km^2	Percent of occurrences by category	Occurrences per km^2 by category
afem	VH	49	34.0	180.6	0.27		
Qhc	VH	11	7.6	64.2	0.17		
Qhbs	VH	1	0.7	2.2	0.45	VH=45.1	VH=0.23
Qhly	VH	4	2.8	36.2	0.11		
acf	VH	0	0.0	1.0	0.00		
af	H (VH-VL)	19	13.2	46.3	0.41		
Qhay	H	8	5.6	23.7	0.34		
alf	H (VH-M)	3	2.1	61.1	0.05		
Qhfy	H	3	2.1	43.5	0.07	H=26.4	H=0.16
Qhed	H	2	1.4	1.9	1.05		
ac	H (VH-L)	1	0.7	9.7	0.10		
Qhfe	H	1	0.7	4.7	0.21		
Qhty	H	1	0.7	50.4	0.02		
Qhbm	M	4	2.8	582.0	0.01		
Qha	M	5	3.5	215.2	0.02		
Qhf	M	9	6.3	811.4	0.01		
Qds	M	2	1.4	23.3	0.09		
Qa	M	3	2.1	72.9	0.04		
Qhff	M	6	4.2	223.1	0.03		
Qhl	M	4	2.8	138.9	0.03	M=25.0	M=0.02
Qht	M	1	0.7	68.7	0.01		
Qhb	M	1	0.7	20.2	0.05		
Qt	M	1	0.7	10.3	0.10		
Qf	M	0	0.0	138.3	0.00		
gq	M	0	0.0	9.6	0.00		
Qhds	M	0	0.0	0.1	0.00		
Qpa	L	2	1.4	37.5	0.05		
Qmt	L	0	0.0	21.6	0.00		
Qbt	L	1	0.7	12.3	0.08		
Qb	L	0	0.0	5.7	0.00	L=2.1	L=0.01
Qpt	L	0	0.0	5.9	0.00		
Qpf	L	0	0.0	373.0	0.00		
adf	L (M to VL)	0	0.0	2.1	0.00		
Qoa	VL	2	1.4	193.5	0.01		
Qop	VL	0	0.0	6.4	0.00		
Qof	VL	0	0.0	75.7	0.00	VL=1.4	VL=0.0003
Qot	VL	0	0.0	1.0	0.00		
br*	VL	(15)*	0.0	5439.9	0.00		
	Totals =	144	100	9014	0.04	100	

Note: Distribution of historical liquefaction effects based on spatial database compiled by Knudsen and others (2000a).

*Bedrock does not liquefy; not included in calculations.

Ground Water

Estimated depths to ground water for each geologic unit (Table 3) come from regional borehole data compiled by CGS, field observations and published USDA soil surveys. The depth to ground water in areas underlain by Holocene alluvial, estuarine, and beach sediment is generally less than 10 feet throughout most of the study area. In general, ground water is deeper beneath topographically higher parts of the landscape (e.g., uplifted and dissected Pleistocene alluvial fans), and closer to the surface of topographically lower parts of the landscape (e.g., Holocene basins and terraces). Pronounced seasonal changes in ground-water levels occur in the San Francisco Bay area, with variations as large as tens of feet. When available, we use historical high ground-water levels measured during and soon after the rainy season of wetter years. Small, isolated alluviated valleys and pockets within the bedrock hills appear to have fairly shallow ground-water levels, generally less than 10 to 15 feet. Soil characteristics of wet environments are mapped in many of these valleys, and the few data available on depth to ground water indicate shallow ground-water levels.

Depths to ground water beneath marine terraces and dune sand can be significantly greater than other Quaternary deposits in the region. Ground water beneath uplifted marine terraces can be deeper than 40 feet, except where water is perched. Ground water beneath coastal dunes that form or mantle hills can be as deep as 50 to 100 feet, approximately equivalent to the elevation of the hills.

Liquefaction Susceptibility Categories

Liquefaction susceptibility categories assigned to each geologic map unit are judgments based on the evaluation of several factors: quantitative criteria presented in Table 3, correlations between historical liquefaction occurrences and geologic map units (Table 4), and qualitative considerations that relate the age, environment, and topographic setting of a deposit to its susceptibility to liquefaction. The five susceptibility categories (VERY LOW to VERY HIGH, Table 5) reflect the relative likelihood that a particular geologic map unit, with its assigned degree of water saturation (Table 3), will liquefy at a given threshold PGA. There is no explicit correlation, however, between each geologic unit and the quantitative data related to its liquefaction susceptibility, because of the regional focus of the liquefaction susceptibility map, the limited scope of the geotechnical and historical liquefaction occurrences datasets, and the application of geologic judgement in making the assignments.

Analysis of available historical liquefaction occurrence data, for example, shows only incomplete correlation between susceptibility category and liquefaction occurrence per unit area of a deposit. Not all map units assigned to the VERY HIGH or HIGH susceptibility categories have evidence of historical liquefaction during large magnitude earthquakes in the central San Francisco Bay region. Regardless, because of other criteria indicative of susceptibility (Table 3), we considered most latest Holocene to historical, granular deposits with low (0.1 to 0.2 g) PGA triggering thresholds and most artificial materials to be highly or very highly susceptible to liquefaction. Conversely, some historical liquefaction occurrences during the 1989 Loma Prieta, 1906 San Francisco and earlier earthquakes plot within map units assigned to the LOW and VERY LOW susceptibility categories, including 15 documented occurrences of liquefaction that plot within pre-Quaternary deposits and bedrock. These units are sufficiently consolidated that we question the association. Many of these localities probably reflect either liquefaction of highly susceptible materials in deposits too small to be delineated at 1:24,000 scale or inaccurate locations of the historical occurrences. The extremely small areal extents of several map units

Table 5. Summary descriptions of liquefaction susceptibility categories.

Category	Description
VERY LOW	Expect less than 2 percent of future liquefaction effects to occur within geologic units assigned VERY LOW susceptibility (with about 1 occurrence in any future earthquake for every 3,000 square kilometers). Units within this category include early to late Pleistocene and pre-Quaternary deposits and bedrock. Together, units assigned VERY LOW susceptibility cover over 5,716 square kilometers in the central San Francisco Bay region. About 1.4 percent of historical liquefaction occurrences fall within map units assigned VERY LOW susceptibility (0.0003 liquefaction occurrences per square kilometer) (Table 4). Results of quantitative liquefaction analyses (using borehole data) are not available for deposits with VERY LOW susceptibilities. An estimated PGA of greater than about 0.6 g is necessary to trigger liquefaction in deposits assigned VERY LOW susceptibility.
LOW	Expect about 2 percent of future liquefaction effects to occur within geologic units assigned LOW susceptibility (with about 1 occurrence for every 100 square kilometers). Geologic map units within this category include Pleistocene marine and Bay terrace deposits, late Pleistocene deposits and Holocene to latest Pleistocene basin deposits. Artificial (historical) earthen dams (adf) are also assigned to this category. Together, units assigned LOW susceptibility cover over 458 square kilometers in the central San Francisco Bay region. About 2.1 percent of historical liquefaction occurrences are located within map units assigned LOW susceptibility (about 0.01 occurrences per square kilometer) (Table 4). Few results of quantitative liquefaction analyses using borehole data are available; in two units, however, 9 to 19 percent of borehole samples are expected to liquefy at the 10% probability of exceedance in 50 year PGA (Table 3). An estimated PGA of greater than about 0.5 g is necessary to trigger liquefaction, although a lower level of shaking may trigger liquefaction in latest Pleistocene to Holocene basin deposits.
MODERATE	Expect about 20 to 30 percent of future liquefaction effects to occur within geologic units assigned MODERATE susceptibility (with about 1 occurrence for every 50 square kilometers). Geologic map units within this category include latest Pleistocene to Holocene deposits from a variety of environments. Gravel quarries and percolation ponds (historical) are also assigned to this category. Together, units assigned MODERATE susceptibility cover 2,314 square kilometers of the central San Francisco Bay region. About 25 percent of historical liquefaction occurrences fall within map units assigned MODERATE susceptibility (about 0.02 occurrences per square kilometer) (Table 4). The results of quantitative liquefaction analyses of several units (using borehole data) indicate that 7 (Qhbm) to 29 (Qhl) percent of samples are expected to liquefy at the 10% probability of exceedance in 50 year PGA (Table 3), and that 39 percent of samples of Ql may liquefy. PGAs of greater than 0.2 g to 0.3 g are necessary to trigger liquefaction of deposits assigned MODERATE susceptibility, although slightly lower and significantly higher shaking thresholds may control liquefaction in some deposits.
HIGH	Expect about 20 to 30 percent of future liquefaction effects to occur within geologic units assigned HIGH susceptibility (with about 1 occurrence for every 6 square kilometers). Geologic map units within this category include latest Holocene to historical alluvial fan, stream and estuarine deposits and many artificial fills. Together, units assigned HIGH susceptibility cover over 241 square kilometers of the central San Francisco Bay region. About 26 percent of historical liquefaction occurrences fall within map units assigned HIGH susceptibility (about 0.16 occurrences per square kilometer) (Table 4). Quantitative liquefaction analyses of several map units (using borehole data) indicate that 15 to 32 percent of samples are expected to liquefy at the 10% probability of exceedance in 50 year PGA (Table 3), but only 7 percent of samples of Qhfy are expected to liquefy. PGAs of

	greater than about 0.1 g to 0.2 g are necessary to trigger liquefaction of deposits assigned HIGH susceptibility.
VERY HIGH	Expect about 40 to 50 percent of future liquefaction effects to occur within geologic units assigned VERY HIGH susceptibility (with about 1 occurrence for every 4 square kilometers). Geologic map units within this category include latest Holocene to historical stream channel, natural levee and beach deposits and artificial fill placed over San Francisco Bay mud and historically active stream channels. Together, units with VERY HIGH susceptibility cover over 284 square kilometers in the central San Francisco Bay region. About 45 percent of historical liquefaction occurrences fall within map units assigned VERY HIGH susceptibility (about 0.23 occurrences per square kilometer) (Table 4). Quantitative liquefaction analyses performed for two map units (using borehole data) indicate that 40 (Qhc) to 62 (Qhly) percent of samples are expected to liquefy at the 10% probability of exceedance in 50 year PGA (Table 3). PGAs of about 0.1 g are necessary to trigger liquefaction in deposits assigned VERY HIGH susceptibility.

that have hosted historical liquefaction results in extremely high (and probably unrepresentative) statistics relating historical occurrence to unit area for these units (e.g., Qhbs and Qhed, Table 4). Some map units are composed of multiple components that conceptually should have different liquefaction susceptibilities (e.g. Qhbm, Qha, Qhf), and some have sufficient uncertainty about their character to warrant a higher susceptibility rating than LOW or VERY LOW (e.g., Qa, Qf, Qt). San Francisco Bay mud (Qhbm), for example, consists of estuarine mud with local stream-mouth deltas that ideally would be mapped as a separate, very different, unit. These heterogeneous or uncertain units are assigned to the MODERATE susceptibility category.

Only data on historical liquefaction occurrence within the map area was used in the analysis. Historical liquefaction occurrences in the San Francisco North quadrangle were thus excluded from the analysis, despite the numerous occurrences documented there by Youd and Hoose (1978) and Tinsley et al. (1998). Inclusion of the occurrences along the Bay shoreline of San Francisco, in particular, would undoubtedly have increased the number of liquefaction effects per unit area in artificial fill over estuarine mud (afem) reported in Table 4. We excluded documented effects described as hillside landslides and found no effective way to use locations where an absence of liquefaction-related ground failure was noted. Some of the historical effects were reported as lines or areas of relatively dense arrays of occurrences, rather than specific points, making it impossible to express these in terms of occurrence per square kilometer. Most of these effects depicted as lines or areas were used only qualitatively in our analysis with the following exceptions: seven line effects and five area effects were used in the analysis where the specific occurrences could be attributed to a single geologic unit (in all but two cases, artificial fill over estuarine mud) based on published reports (e.g., Youd and Hoose, 1978; Tinsley et al., 1998).

Summary descriptions of each liquefaction susceptibility category are provided in Table 5. The descriptions include the spatial abundance of future liquefaction occurrences, the age range of the deposits, the abundance of historical liquefaction occurrence by susceptibility category, the total map area of the units assigned to the category, the results of quantitative liquefaction analyses of limited geotechnical borehole information, and the estimated PGA triggering thresholds for the included units (Table 3).

REFERENCES CITED

Angell, M., Hanson, K., and Crampton, T., 1997, Characterization of Quaternary contractional deformation adjacent to the San Andreas Fault, Palo Alto, California: Unpublished consulting report prepared for the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-95-G-2586, 70 p. plus tables, figures and plates.

Atwater, B.F., 1982, Geologic maps of the Sacramento-San Joaquin Delta, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1401.

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.

Atwater, B.F., Ross, B.E., and Wehmiller, J.F., 1981, Stratigraphy of late Quaternary estuarine deposits and amino acid stereochemistry of oyster shells beneath San Francisco Bay, California: Quaternary Research. v. 16, p. 181-200.

Aydin, A., and Page, B.M., 1984, Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay region, California: Geological Society of America Bulletin, v. 95, p. 1303-1317.

Bates, L.A. and others, 1977, Soil Survey of Solano County: U.S. Department of Agriculture, Soil Conservation Service, 112 p., 54 map sheets at 1:24,000 scale.

Bezore, S.P., Sowers, J.M., and Randolph, C.E., 2000, Digital geologic map of the Fairfield South 7.5-minute quadrangle, Solano County, California: California Division of Mines and Geology Open-File Report in preparation, scale 1:24,000.

Bonilla, M.G., 1971, Preliminary geologic map of the San Francisco South 7.5-minute quadrangle and part of the Hunters Point 7.5-minute quadrangle, California; U.S. Geological Survey Miscellaneous Field Studies Map MF-311; scale 1:24,000.

Bonilla, M.G., 1998, Preliminary geologic map of the San Francisco South 7.5-minute quadrangle and part of the Hunters Point 7.5-minute quadrangle, California: a digital database: U.S. Geological Survey Open-File Report 98-354; scale 1:24,000.

Borchardt, G., 1994, The Sangamon strandline in northern San Francisco Bay and its significance for paleoseismic studies [abs]: in Prentice, C.S., Schwartz, D.P., and Yeats, R.S., eds., Proceedings of the workshop on Paleoseismology, U.S. Geological Survey Open-File Report 94-568, p. 24-25.

Brabb, E.E., Graymer, R.W., and Jones, D.L., 1998a, Geology of the onshore part of San Mateo County, California: A digital database: U.S. Geological Survey Open-File Report 98-137.

Brabb, E.E., Graymer, R.W., and Jones, D.L., 1998b, Geology of Palo Alto 30 X 60 minute quadrangle, California: A digital database: U.S. Geological Survey Open-File Report 98-348.

Bryan, K., 1923, Geology and ground-water resources of Sacramento Valley, California: U.S. Geological Survey Water-supply Paper 495, 286 p. plus plates.

California Division of Mines and Geology, 1999, Recommended criteria for delineating seismic hazard zones in California, CDMG Special Publication 118, 12 p.

Cao, T., Bryant, W.A., Rowshandel, B., Branum, D., and Wills, C.J., 2003, The Revised 2002 California Probabilistic Seismic Hazard Maps, June 2003: California Geological Survey web page, <http://www.consrv.ca.gov/cgs/rghm/psha/fault_parameters/pdf/2002_CA_Hazard_Maps.pdf> (November 18, 2005).

Clahan, K.B., Mattison, E., and Knudsen, K.L., 2000a, Liquefaction zones in the San Jose East 7.5-minute quadrangle, Santa Clara County, California in Seismic hazard evaluation of the San Jose East 7.5-minute quadrangle: California Division of Mines and Geology Open-File Report 2000-010.

Clahan, K.B., Mattison, E., and Rosinski, A.M., 2000b, Liquefaction zones in the Calaveras Reservoir 7.5-minute quadrangle, Santa Clara County, California in Seismic hazard evaluation of the San Jose East 7.5-minute quadrangle: California Division of Mines and Geology Open-File Report 2000-048.

Clahan, K.B., Mattison, E., and Rosinski, A.M., 2000c, Liquefaction zones in the Milpitas 7.5-minute quadrangle, Santa Clara County, California in Seismic hazard evaluation of the San Jose East 7.5-minute quadrangle: California Division of Mines and Geology Open-File Report 2000-051.

Clahan, K.B., Mattison, E., and Rosinski, A.M., 2000d, Liquefaction zones in the San Jose West 7.5-minute quadrangle, Santa Clara County, California in Seismic hazard evaluation of the San Jose East 7.5-minute quadrangle: California Division of Mines and Geology Open-File Report 2000-058.

Clark, J.C., and Brabb, E.E., 1997, Geology of Point Reyes National Seashore and Vicinity, California: A Digital Database, U.S. Geological Survey Open-File Report 97-456.

Cosby, S.W., 1941, Soil survey of the Sacramento - San Joaquin Delta area, California: U.S. Department of Agriculture, Bureau of Chemistry and Soils, series 1935, no. 21, 48 p.

Dibblee, T.W., 1980a, Preliminary geologic map of the Benicia quadrangle, Contra Costa and Solano Counties, California: U.S. Geological Survey Open-File Report OF-80-400, scale 1:24,000.

Dibblee, T.W., 1980b, Preliminary geologic map of the Briones Valley quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report OF-80-539, scale 1:24,000.

Dibblee, T.W., 1980c, Preliminary geologic map of the Clayton quadrangle, Contra Costa County, California: U.S. Geological Survey Open-File Report OF-80-547, scale 1:24,000.

Dibblee, T.W., 1980d, Preliminary geologic map of the Richmond quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report OF-80-1100, scale 1:24,000.

Dibblee, T.W., 1980e, Preliminary geologic map of the Walnut Creek quadrangle, Contra Costa County, California: U.S. Geological Survey Open-File Report OF-80-351, scale 1:24,000.

Dibblee, T.W., 1981a, Preliminary geologic map of the Mare Island quadrangle, Solano and Contra Costa Counties, California: U.S. Geological Survey Open-File Report OF-81-234, scale 1:24,000.

Dibblee, T.W., 1981b, Preliminary geologic map of the Port Chicago quadrangle, Solano and Contra Costa Counties, California: U.S. Geological Survey Open-File Report OF-81-108, 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.

Dupré, W.R., and Tinsley, J.C., 1998, Evaluation of liquefaction-hazard mapping in the Monterey Bay region, central California: in Holzer, T.L., ed., The Loma Prieta, California, Earthquake of October 17, 1989 - Liquefaction: U.S. Geological Survey Professional Paper 1551-B.

Fox, K.F. Jr., Sims, J.D., Bartow, J.A., and Helley, E.J., 1973, Preliminary geologic map of eastern Sonoma County, and western Napa County: U.S. Geological Survey Miscellaneous Field Studies Map MF-483, scale 1:62,500.

Frankel, A.D., M.D. Petersen, C.S. Mueller, K.M. Haller, R.L. Wheller, E.V. Leyendecker, R.L. Wesson, S.C. Harmsen, C.H. Cramer, D.M. Perkins, K.S. Rukstales, 2002, Documentation for the 2002 update of the national seismic hazard maps: U.S. Geological Survey Open-File Report 022-420, 33 p. Available at: http://geohazards.cr.usgs.gov/eq/of02-420/OFR02-420.pdf.

Galloway, A.J., 1977, Geology of the Point Reyes Peninsula, Marin County, California: California Division of Mines and Geology Bulletin 202, 72 p. plus 1:48,000-scale plate.

Gardner, R. A., Harradine, F. F., Hargreaves, G. H., Retzer, J. L., Bartholomew, O. F., and Glassey, T. W., 1958, Soil Survey of the Santa Clara Area, California, U. S. Department of Agriculture, Soil Conservation Service, Series 1914, No. 17, 202 p., 2 map sheets at 1:50,000 scale.

Goals Project, 1999, Bay lands ecosystem habitat goals. A report of habitat recommendations prepared by the San Francisco Bay Are Wetlands Ecosystem Goals Project: U.S. Environmental Protection Agency, San Francisco, CA / San Francisco Bay Regional Water Quality Control Board, Oakland, CA, 209 p. plus appendices.

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

Graymer, R. W., 1997, Geology of the southernmost part of Santa Clara County, California: a digital database: U.S. Geological Survey open-File Report 97-710.

Haydon, W.D., 1995, Landslide hazards in the Martinez-Orinda-Walnut Creek area Contra Costa County, California: Landslide Hazard Identification Map No. 32: California Department of Conservation, Division of Mines and Geology Open-File Report 95-12, pp. 40, Plates 32A-32D.

Haydon, W.D, Mattison, E., and Clahan, K.B., 1999, Liquefaction zones in Cities of Oakland and Piedmont, Alameda County, California in Seismic hazard evaluation of Cities of Oakland and Piedmont, Alameda County: California Division of Mines and Geology Open-File Report 1999-11.

Helley, E.J., and Brabb, E.E., 1971, Geologic map of late Cenozoic deposits, Santa Clara County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-335.

Helley, E.J., Fitzpatrick, J.A., and Bischoff, J.L., 1993, Uranium-series dates on oyster shells from marine terraces of San Pablo Bay, California: U.S. Geological Survey Open-File Report 93-286, 6 p.

Helley, E.J., and Graymer, R.W., 1997a, Quaternary geology of Contra Costa, and surrounding parts of Alameda, Marin, Sonoma, Solano, Sacramento, and San Joaquin Counties, California: a digital database: U.S. Geological Survey Open-File Report 97-98.

Helley, E.J., and Graymer, R.W., 1997b, Quaternary geology of Alameda County and parts of Contra Costa, Santa Clara, San Mateo, San Francisco, Stanislaus, and San Joaquin Counties, California: a digital database: U.S. Geological Survey Open-File Report 97-97.

Helley, E.J., Graymer, R.W., Phelps, G.A., Showalter, P.K., and Wentworth, C.M., 1994, Preliminary Quaternary geologic maps of Santa Clara Valley, Santa Clara, Alameda, and San Mateo Counties, California, a digital database: U.S. Geological Survey Open-File Report 94-231.

Helley, E.J., and Harwood, D.S., 1985, Geologic map of the Late Cenozoic deposits of the Sacramento Valley and northern Sierran Foothills, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1790, scale 1:62,500.

Helley, E.J., Lajoie, K.R., Spangle, W.E., and Blair, M.L., 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, 88 p.

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., 1989, Quaternary geologic map of the Milpitas quadrangle, California, 1:24,000: U.S. Geological Survey Open-File Report 89-671.

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.

Herd, D.G., 1977, Geologic map of the Las Positas, Greenville, and Verona Faults, eastern Alameda County, California: U.S. Geological Survey Open-file Report 77-689, 1:24,000.

Hitchcock, C.S., and Kelson, K.I., 1999, Growth of late Quaternary folds in southwest Santa Clara Valley, San Francisco Bay area, California: Implications of triggered slip for seismic hazard and earthquake recurrence, Geology, 27, 5, 391-394.

Holzer, T.L., Tinsley, J.C., III, Bennett, M.J., and Mueller, C.J., 1994, Observed and predicted ground deformation - Miller Farm lateral spread, Watsonville, California: Buffalo, New York, National Center for Earthquake Engineering Research Technical Report NCEER-94-0026, p. 79-99.

Holzer, T.L., Bennett, M.J., Noce, T.E., Padovani, A.C., Tinsley, J.C., III, 2002, Liquefaction hazard and shaking amplification maps of Alameda, Berkeley, Emeryville, Oakland, and Piedmont, California: a digital database, US Geological Survey Open-File Report 2002-296.

Holzer, T.L., ed., 1998, The Loma Prieta, California, Earthquake of October 17, 1989 - Liquefaction: U.S. Geological Survey Professional Paper 1551-B.

Jack, R.N., 1969, Quaternary sediments at Montara, San Mateo County, California: unpublished Masters Thesis, University of California, Berkeley, 133 p.

Jennings, C.W., 1988, Preliminary geology map of the northwest quarter of the Santa Rosa [7.5'] quadrangle, Sonoma County, California: California Division of Mines and Geology, Open-File Report 88-05, scale 1:24,000.

Kashiwagi, J., 1985, Soil Survey of Marin County, California: U.S. Department of Agriculture, Soil Conservation Service, 229 p., 13 map sheets at 1:24,000 scale.

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, 120 p., 12 map sheets at 1:24,000 scale.

Kelson, K.I., Simpson, G.D., Haraden, C.C., Sawyer, T.L., and Hemphill-Haley, M.A., 1993, Late Quaternary surficial deformation of the southern East Bay Hills: Final Technical Report, National Earthquake Hazards Reduction Program, U.S. Geological Survey, Award #1434-92-2209.

Knudsen, K.L., and Lettis, W.R., 1997, Preliminary maps showing Quaternary geology of twenty 7.5-minute quadrangles, eastern Stockton, California, 1:100,000 quadrangle: National Earthquake Hazards Reduction Program, U.S. Geological Survey, Final Technical Report , Award #1434-94-G-2499.

Knudsen, K.L., Noller, J.S., Sowers, J.M., Lettis, W.R., Graham, S.E., Randolph, C.E., and May, T.E., 1997, Quaternary geology and liquefaction susceptibility, San Francisco, California 1:100,000 quadrangle: a digital database: U.S. Geological Survey Open-File Report 97-715, scale 1:100,000.

Knudsen, K.L., J.M. Sowers, R.C. Witter, C.M. Wentworth, and E.J. Helley, 2000a, Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California: A Digital Database, U.S. Geological Survey Open-File Report 00-444. Digital Database by Wentworth, C.M., Nicholson, R.S., Wright, H.M., and Brown, K.H. Online Version 1.0.

Knudsen, K.L., DeLisle, M.D., Clahan, K.B., Mattison, E., Perkins, J.B., and Wentworth, C.M., 2000b, Applicability of Quaternary geologic mapping in assessing earthquake-induced liquefaction hazard: San Francisco Bay Region: Sixth International Conference on Seismic Zonation, Earthquake Engineering Research Institute, p. 154.

Lajoie, K.R., Helley, E.J., Nichols, D.R., and Burke, D.B., 1974, Geologic map of unconsolidated and moderately consolidated deposits of San Mateo County: U.S. Geological Survey Miscellaneous Field Studies Map MF-575, scale 1:62,500.

Lajoie, K.R., Weber, G.E., Mathieson, S., and Wallace, J., 1979, Quaternary tectonics of coastal Santa Cruz and San Mateo Counties, California, as indicated by deformed marine terraces and alluvial deposits, in Weber, G.E., Lajoie, K.R., and Griggs, G.B. eds., Coastal tectonics and coastal geologic hazards in Santa Cruz and San Mateo Counties, California: Field Trip Guide, Cordilleran Section of the Geological Society of America, 75th Annual Meeting, p. 61-80.

Lambert, G., and Kashiwagi, J., 1978, Soil Survey of Napa County, California: U.S. Department of Agriculture, Soil Conservation Service, 104 p., 47 map sheets at 1:24,000 scale.

Lindsey, W.D., and Weisel, C.J., 1974, Soil survey of the eastern Santa Clara area, California: U.S. Department of Agriculture, Soil Conservation Service, 90 p., 49 map sheets at 1:24,000 scale.

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.

Miller, V.C., 1972, Soil survey of Sonoma County, California: U.S. Department of Agriculture, Soil Conservation Service, 188 p., 123 map sheets at 1:20,000 scale.

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 Report, Basic Data Contribution 9, scale 1:125,000.

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.

Pampeyan, E.H., 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.

Radbruch, D.H., 1969, Areal and Engineering Geology of the Oakland East Quadrangle, California, Map GQ-769, U.S. Geological Survey, Washington D.C.

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.

Sarna, A., 1967, Aerial extent and thickness of the bay mud in northern Santa Clara County: unpublished report to Santa Clara County Planning Department.

Sawyer, T.L., 1996, Unpublished surficial mapping conducted in support of the following project: Unruh, J.R. and Sawyer, T.L., 1997, Assessment of blind seismogenic sources, Livermore Valley, eastern San Francisco Bay region: Final Technical Report, National Earthquake Hazards Reduction Program, U.S. Geological Survey, Award #1434-95-G-2611.

Seed, H.B., and Idriss, I.M., 1971, Simplified procedure for evaluating soil liquefaction potential: Journal of the Soil Mechanics and Foundations Division of ASCE, v. 97: SM9, p. 1,249-1,273.

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, 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.

Sims, J.D., Fox, K.F. Jr., Bartow, J.A., and Helley, E.J., 1973, Preliminary geologic map of Solano County, and parts of Napa, Contra Costa, Marin, and Yolo Counties: U.S. Geological Survey Miscellaneous Field Studies Map MF-484, scale 1:62,500.

Sowers, J.M., 1995, Creek & watershed map of Oakland and Berkeley: Oakland Museum of California, Oakland, California, scale approx. 1:26,000.

Sowers, J.M., 1997, Creek & watershed map of Hayward and San Leandro: Oakland Museum of California, Oakland, California, scale approx. 1:26,000.

Sowers, J.M., 1999, Creek and watershed map of Fremont and vicinity: Oakland Museum of California, Oakland, California, scale 1:26,000

Sowers, J.M., Noller, J.S., and Lettis, W.R., 1998, Quaternary geology and liquefaction susceptibility, Napa, California 1:100,000 quadrangle: a digital database: U.S. Geological Survey Open-File Report 98-460.

Thomasson, H.G., Olmsted, F.H., and LeRoux, E.F., 1960, Geology, Water Resources, and usable groundwater storage capacity of part of Solano County, California: U.S. Geological Survey Water-Supply Paper 1464, p. 48.

Tinsley, J.C., III, Egan, J.A., Kayen, R.E., Bennett, M.J., Kropp, A., and Holzer, T.L., 1998, Appendix: Maps and descriptions of liquefaction and associated effects: in Holzer, T.L., ed., The Loma Prieta, California, Earthquake of October 17, 1989 - Liquefaction: U.S. Geological Survey Professional Paper 1551-B.

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.

Unruh, J.R. and Lettis, W.R., 1998, Seismogenic deformation field in the Mojave block and implications for tectonics of the eastern California shear zone: Journal of Geophysical Research, v. 101, p. 8335-8361.

Wagner, R.J. and Nelson, R.E., 1961, Soil Survey of San Mateo Area, California: U.S. Department of Agriculture, Soil Conservation Service, Series 1954, no. 13, 112 p., 49 map sheets at 1:15,840 scale.

Weber, G.E., Nolan, J.M., and Zinn, E.N., 1993, Determination of Late Pleistocene and Holocene slip rates along the San Gregorio Fault zone, San Mateo County, California: Final Technical Report, National Earthquake Hazards Reduction Program, U.S. Geological Survey, Award # 1434-93-G-2336.

Welch, L.E., 1977, Soil survey Contra Costa County, California: U.S. Department of Agriculture, Soil Conservation Service, National Cooperative Soil Survey, 122 p., 54 map sheets at 1:24,000 scale.

Welch, L.E., 1981, Soil survey Alameda County, California, western part: U.S. Department of Agriculture, Soil Conservation Service, 103 p., 8 map sheets at 1:24,000 scale.

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, Series 1961, No. 41, 95 p., 42 map sheets at 1:20,000 scale.

Wentworth, C.M., Blake, M.C., McLaughlin, R. J., and Graymer, R.W., 1998, Preliminary geologic map of the San Jose 30 x 60 minute quadrangle, California: a digital database: U.S. Geological Survey Open-File Report 98-795, map scale 1:100,000.

Wolff, R.G., 1971, Paleoecology of a late Pleistocene (Rancholabrean) vertebrate fauna from Rodeo, California: unpublished Doctoral Dissertation, University of California, Berkeley, 136 p.

Working Group on California Earthquake Probabilities , 2003, Earthquake probabilities in the San Francisco Bay region: 2002-2031: U.S. Geological Survey Open-File Report 03-214.

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., Nichols, D.R., Helley, E.J., and Lajoie, K.R., 1975, Liquefaction potential, in Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Prof Paper 941-A, p. 68-74. Youd, T.L., and Idriss, I.M., 1997, editors, Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils: Nation Center for Earthquake Engineering Research Technical Report NCEER-97-0022, 276 p.

Youd, T. L., Idriss, I. M., Andrus, R. D., Arango, I., Castro, G., Christian, J. T., Dobry, R., Finn, W. D. L., Harder, L. F., Hynes, M. E., Ishihara, K., Koester, J. P., Liao, S. C., Marcuson, W. F., Martin, G. R., Mitchell, J. K., Moriwaki, Y., Power, M. S., Robertson, P. K., Seed, R. B. and Stokoe, K. H. (2001). "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils." Journal of Geotechnical and Geoenvironmental Engineering, 127 (10), 817-833.

Youd, T.L., and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering, American Society of Civil Engineers, v. 104, no. GT4, p. 433-446.

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.

Appendix A

DESCRIPTION OF GEOLOGIC UNITS

Map Symbol Unit Name and Description

HISTORICAL (<150 YEARS) DEPOSITS.

af **Artificial fill (historical)**. Material deposited by humans. Additional types of artificial fill are mapped as separate geologic map units, including: artificial fill over estuarine mud (afem), artificial levee fill (alf), dredge spoils (ads), artificial channel fill (acf), artificial dam fill (adf), and gravel quarries and percolation ponds (gq). Fill may be engineered and/or non-engineered material; each may occur within the same area on the map. Most of the artificial fill shown forms large highway and railroad embankments, consisting of engineered fill up to approximately 100 feet thick. Large earthen dams are mapped separately as artificial dam fill (adf). Our mapping of artificial fill on road and railroad embankments is based on interpretation of topographic contours on the most recent 7.5-minute U.S. Geological Survey (USGS) topographic quadrangles. Fill whose thickness is less than the contour interval (typically 5 to 10 ft) and fill emplaced after the topographic base maps were surveyed are not shown. 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 Holocene alluvial deposits that are too small to be mapped at this scale. On the San Francisco Peninsula, previous mapping by Bonilla (1971, 1998), and Pampeyan (1993, 1994) provide the primary basis from which to identify and map artificial fill. Elsewhere, mapping of artificial fill is based on inspection of topographic maps and aerial photographs.

Liquefaction susceptibility of artificial fill (af) may be very high to low depending on (1) the nature and thickness of the fill materials, (2) whether the fill was engineered or non-engineered, (3) the susceptibility of the deposit over which the fill lies, and (4) its depth of saturation. Most fill placed in the last few decades is engineered; older fill is less likely to be engineered. A large percentage of observed historical liquefaction in the area has occurred in artificial fill on the margins of San Francisco Bay; however, most of these artificial fill bodies are included within the map unit artificial fill over estuarine mud (afem). Artificial fill is assigned the susceptibility of the underlying deposit(s) with the exception that fill overlying deposits with very low susceptibility is assigned low susceptibility. Where more than one deposit with different liquefaction susceptibilities underlie an artificial fill map unit, the unit is subdivided and assigned susceptibilities to reflect the underlying geologic units. Where artificial fills are narrow, such as artificial levees, or road embankments, and overlie the boundary between two geologic map units, the higher susceptibility is assigned to the fill. Specific bodies of artificial fill (af) were assigned High or Very High susceptibilities based on the historical occurrence of liquefaction within or near these bodies.

afem **Artificial fill over estuarine mud (historical)**. Material deposited by humans over sediments along the margins of San Francisco Bay and other estuarine deposits mapped in the Sacramento/San Joaquin delta and along the outer Pacific coast. Fill may be engineered and/or non-engineered material; each may occur within the same area on the map. This mapped artificial fill overlies estuarine sediment and was placed to form new land (e.g., Goldman, 1969). Mapping of artificial fill over estuarine mud is based on comparison of present shorelines with those of the mid 19th century as shown by Nichols and Wright (1971), the Goals Project (1999) and Sowers (1995, 1997, 1999), and, to a limited extent, on inspection of topographic maps and aerial photographs. In many areas, a line delineating the middle 19th century (1850s-1860s) extent of marshland (Nichols and Wright, 1971) was used to delineate the landward boundary of this unit. Artificial fill placed inland of the Nichols and Wright (1971) line was mapped as artificial fill (af). The thickness of the fill overlying estuarine sediment is typically five to twenty feet. Included within this unit are small areas of estuarine deposits and Holocene alluvial deposits that are too small to be mapped at this scale of this project. Levees and dikes that overlie estuarine deposits are mapped as artificial levee fill (alf) and differentiated based on levees identified on USGS 7.5-minute topographic quadrangles. The levee materials may not differ from the adjacent artificial fill over estuarine mud material (afem). Other unmapped levees and dikes likely exist within mapped bodies of this unit (afem). This unit includes artificial fill placed over alluvial fan-estuarine complex deposits (Qhfe) and estuarine delta deposits (Qhed).

Liquefaction susceptibility is very high based on the numerous past occurrences of liquefaction in this unit. About 34% of all past occurrences of earthquake-induced liquefaction in the central San Francisco Bay region occurred in artificial fill over estuarine mud. Most fill emplaced over estuarine mud in the last few decades is engineered; older fill is less likely to be engineered. Many of the reports of damage in the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake involved failures in older fill that probably was not engineered; such fill was probably hydraulically emplaced. Where the material to be used as artificial fill was dredged or suctioned from sandy areas (e.g. near Oakland and the Marina District of San Francisco), the fill may be very susceptible to liquefaction. Typically, ground-water levels in this unit are close to the ground surface.

alf **Artificial levee fill (historical)**. Constructed levees bordering rivers, streams, salt ponds, sloughs, and delta islands for the purpose of containing flood or tidal waters. Some are compacted and quite firm, but levees built before 1965 (enactment of the Uniform Building Code) are likely to be uncompacted and made of poor quality fill. Levees bordering waterways of the Sacramento/San Joaquin Delta, mudflats, and large streams were first emplaced as much as 100 years ago. The mapped distribution of levee fill conforms to levees shown on the most recent USGS 7.5-minute topographic quadrangles. In some places this unit was compiled from recent mapping by R.W. Graymer and published in Helley and Graymer (1997a, 1997b), Helley and others (1994), and Brabb and others (1998a, 1998b).

Liquefaction susceptibility is estimated to be very high to moderate for all artificial levees, based on the abundance of older non-engineered levees, the nature of the fill materials, the susceptibility of the underlying deposit, the possible proximity of channel free faces vulnerable to lateral spreading, and their likelihood of saturation. Additionally, levees often are placed in areas where the substrate is highly susceptible to liquefaction. We assign a very high susceptibility to all artificial levees that overlie estuarine deposits, including San Francisco Bay mud (Qhbm), alluvial fan-estuarine complex deposits (Qhfe), and estuarine delta deposits (Qhed). Other levees emplaced over upland deposits are assigned High liquefaction susceptibility reflecting the susceptibility of underlying deposits. Artificial levees emplaced over deposits assigned low to very low susceptibilities are assigned moderate susceptibility.

acf **Artificial channel fill (historical)**. Artificial fill emplaced in historically active stream channels. The stream flow has been re-routed either to a pipe or channel in another location or in a pipe beneath or within the fill. The fill, emplaced to create level land for urban development, may be engineered and/or non-engineered material; each may occur within the same mapped unit. These human-emplaced materials may overlie modern stream channel deposits (Qhc) that consist of loose, unconsolidated, poorly to well-sorted sand, gravel and cobbles, with minor silt and clay. Artificial channel fill was identified through comparison of early twentieth century aerial photography and topographic maps with recent 7.5-minute topographic quadrangles and field inspection. In the Oakland, San Leandro, and Fremont areas of the East Bay, artificial channel fills were mapped from creek and watershed maps developed by Sowers (1995, 1997, 1999). Artificially-filled channels of very small streams are not delineated at 1:24,000 scale.

Liquefaction susceptibility is very high due to the likely presence of late Holocene, loose, granular stream channel deposits and high ground-water levels underlying the artificial fill.

adf **Artificial dam fill (historical)**. Earth dams, rock-fill dams, embankments and levees constructed to impound land-locked water bodies, including water reservoirs, cooling/settling ponds, artificial lakes, and stock ponds. Fill may be engineered and/or non-engineered material; each may occur within the same area on the map. As with the mapping of other human-emplaced fill, artificial dam fills are mapped through interpretation of topographic contours on the most recent 7.5-minute USGS topographic quadrangles. Dams with fill thicknesses that are less than the contour interval (typically 5 to 10 ft) and embankments emplaced after the topographic base maps were surveyed are not shown. This unit does not include dams constructed of concrete (e.g., concrete arch and gravity dams).

Liquefaction susceptibility of artificial dam fill (adf) may be moderate to very low. The variation in susceptibility of the materials relates to (1) the properties and thickness of the fill; (2) whether the dam is an engineered embankment or nonengineered; and (3) the depth of saturation, and, in some cases, (4) the nature of the native material underlying the dam. Most earthen dams constructed within the last few decades are engineered and have very low susceptibilities to liquefaction. Small stock ponds and older dams impounding large water reservoirs, particularly those constructed of hydraulically pumped fill built in the early twentieth century, are likely more susceptible to liquefaction. Because of variations in material and age of artificial dams and the uncertainty with regard to the degree of engineering used during construction, we assign a low susceptibility to all artificial dam fill (adf) units. Site-specific studies are required to assess the liquefaction potential at individual dam sites.

gq **Gravel quarries and percolation ponds (historical)**. This unit consists of excavations, associated spoil piles, and disturbed ground in stream channels or alluvial deposits that were or are being used for the purpose of extracting sand and gravel. Because many gravel pits are eventually used as recharge or percolation ponds, we include percolation ponds within this map unit. These areas are identified through interpretation of 7.5-minute topographic quadrangles and aerial photography.

Liquefaction susceptibility is moderate owing to the fact that the material is largely reworked late Holocene to historical stream channel deposits and likely saturated.

ac **Artificial stream channel (historical)**. Modified stream channels including straightened or realigned channels, flood control channels, and concrete canals. In most cases, artificial channels were differentiated from natural channels by interpretation of 7.5-minute topographic quadrangles. Additionally, field inspection and interpretation of aerial photographs were used to identify artificial channels. Deposits within artificial channels can range from almost none in some concrete canals, to significant thicknesses of loose, unconsolidated sand, gravel and cobbles, similar to deposits of modern stream channel deposits (Qhc).

Liquefaction susceptibility is very high to low, varying with the design of the channel and the nature of the channel and bank material. Channels that contain loose, sandy sediments like the Alameda Creek flood control channel on the Newark quadrangle are highly susceptible to liquefaction. Adjacent levees or banks may be subject to lateral spreading into the channel if not well engineered. Artificial stream channels are assigned the susceptibility of the underlying deposit(s). Where more than one deposit with different liquefaction susceptibilities underlie an artificial stream channel map unit, the unit is subdivided and assigned susceptibilities to reflect the underlying geologic units. Long, narrow artificial stream channels that overlie the boundary between two geologic map units are assigned the higher susceptibility of the underlying map units.

Qhc **Historical stream channel deposits**. Fluvial deposits within active, natural stream channels. Materials consist of loose, unconsolidated, poorly to well sorted sand, gravel and cobbles, with minor silt and clay. These deposits are reworked by frequent flooding and exhibit no soil development. These deposits, like most other alluvial deposits, fine downstream (i.e. sediment is coarser upstream). Mapping of modern stream channels is based on topographic map inspection augmented, in places, by interpretation of aerial photography or orthophoto quadrangles. Where available, we reviewed early twentieth century (1914-1916) topographic maps to evaluate whether stream channels shown on recent 7.5-minute maps have been altered since the early twentieth century. If the channels appear on recent maps as unchanged since the earlier maps, we map the channel and its banks as modern stream channel deposits. Contacts generally are shown near the top of the bank on either side of the channel, although the deposits actually lie near the bottom of the channel. Channels of very small streams are not delineated at the 1:24,000 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 to 81% of boreholes in latest Holocene alluvial deposits contain liquefiable materials, assuming ground-water levels at the surface, compared to 34 to 54% of boreholes in earlier Holocene alluvial deposits. Matti and Carson (1991) show similar relations pertain to 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 late Holocene, loose, granular sediment and high ground-water levels. Ground-water levels typically are at or near the surface in modern stream channel deposits.

LATEST HOLOCENE (<1,000 YEARS).

Qhfy Latest Holocene alluvial fan deposits. Alluvial fan sediment judged to be latest Holocene (<1,000 years) in age, based on records of historical inundation or the presence of youthful braid bars and distributary channels. Youthfulness of braid bars and distributary channels is evaluated using aerial photographs and orthophoto quadrangles. Alluvial fan sediment is deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains. Most apices of the mapped latest Holocene alluvial fan deposits occur partway down older piedmont alluvial fan complexes. The stream channel typically is incised into older fan deposits near the fan apex, then gradually is less incised down fan, until the stream becomes unconfined and distributes young sediment across the toe of the fan. A good example of these relationships is the Alameda Creek fan in Fremont and Union City. Sediment is moderately too poorly sorted and bedded, and may be composed of gravel, sand, silt and clay. Grain size generally fines down slope. Soils are minimally developed on this unit and include entisols and inceptisols.

Liquefaction susceptibility is high because these deposits are very young, loose and generally lack cohesion. There have been a significant number of past occurrences of liquefaction in this unit. Ground water typically is less than twenty feet below the surface because these deposits lie near active stream channels. If the stream channel is incised, a free face will be present and lateral spreading is likely if liquefaction does occur. However, lateral spreading is probably less likely in alluvial fan deposits than in laterally accreted fluvial deposits (J. Tinsley, pers. com., 2000).

Qhly Latest Holocene alluvial fan levee deposits. Natural levee deposits of alluvial fans judged to be latest Holocene (<1,000 years) in age based on records of historical inundation and/or the presence of youthful braid bars and distributary channels. This unit is mapped along the downstream reaches of Alameda Creek, Coyote Creek, and Guadalupe River. Levees are identified as long, low, sinuous ridges oriented down fan ("channel ridges" of Bryan, 1923 and Thomasson and others, 1960). On these very young levees, the stream often runs down the levee centerline. Levees contain coarser material than adjoining interlevee areas, being composed of overbank materials dropped as the stream spills over its banks (Helley and others, 1979). Soils are typically entisols (fluvents). Ground water typically is no deeper than the depth to flowing water in the stream.

Liquefaction susceptibility is very high because of the presence of very young, loose, likely saturated deposits. Additionally, there have been a significant number of past occurrences of liquefaction in this unit. If the stream channel is incised, a free face will be present and lateral spreading is likely if liquefaction does occur.

Qhty Latest Holocene stream terrace deposits. Stream terrace deposits judged to be latest Holocene (<1,000 years) in age based on records of historical inundation, the identification of youthful meander scars and braid bars on aerial photographs or orthophoto quadrangles, and/or geomorphic position (elevation) very close to the stream channel. Stream terraces are deposited as point bar and overbank deposits by major streams such as the Napa River, Russian River, Coyote Creek, and Alameda Creek. Although very young stream terrace deposits also are found along smaller streams, these may be too small in size to be shown at the 1:24,000 map scale and therefore are often included in the modern stream channel (Qhc) or Holocene stream terrace (Qht) map units. Stream terrace sediment includes sand, gravel, silt, and minor clay, is moderately to well sorted, and is moderately to well bedded. Where multiple stream terraces are identified, the younger deposits (Qhty1) are distinguished from older deposits (Qhty2).

Liquefaction susceptibility is high based on the abundance of sandy, cohesionless sediment, relatively high ground-water levels, and the presence of a free face at the channel banks, which makes lateral spreading likely if liquefaction occurs.

Qhay Latest Holocene alluvial deposits, undifferentiated. Fluvial sediment judged to be latest Holocene (<1000 years) in age based on records of historical inundation, the identification of youthful meander scars and braid bars on aerial photographs or orthophoto quadrangles, or geomorphic position very close in elevation to the stream channel. This sediment was deposited on modern flood plains, active stream channels, active alluvial fans, and flood-prone areas. Deposits are loose sand, gravel, silt and clay. This unit is mapped in areas that historically have been inundated by sediment-bearing water. Latest Holocene alluvial deposits may include terrace deposits (Qhty), deposits of the active stream channel (Qhc), alluvial fan deposits (Qhfy), basin deposits (Qhb), and levee deposits (Qhly). However, the small size of individual deposits of these map units prevented differentiation at the map scale used in this project. Typical soils developed on these deposits are entisols (fluvents).

Liquefaction susceptibility is high based on the presence of loose cohesionless sediment near the active stream channel. Proximity to the active stream channel indicates that (1) ground-water levels likely are close to the surface, and (2) a free face may be present.

Qhbs Latest Holocene beach sand. This unit includes active beaches in coastal environments. Beach deposits typically are well sorted fine to coarse sand with some fine gravel. Where the beach is adjacent to a sea cliff, beach sediment may form a veneer over a bedrock platform. In places, low unstable dunes and/or sandy islands may be included within this map unit.

Liquefaction susceptibility is very high because beach sand is well sorted, saturated, loose sand.

HOLOCENE (<11,800 YEARS).

Qhds Holocene dune sand. This unit includes active dunes along with recently stabilized dunes in coastal environments. Dune sand typically is very well sorted fine to medium sand. This unit commonly occurs near beaches, where Holocene age for much of the deposit is likely. Large latest Pleistocene dune fields like the Antioch-Oakley dunes, the Merritt Sand, and most of the dunes covering the northern San

Francisco Peninsula, which are mapped as latest Pleistocene to Holocene dune sand (Qds), likely contain areas of unmapped Holocene dune sand. Typical soils developed on this unit (Qhds) are inceptisols.

Liquefaction susceptibility is moderate because coastal dune environments typically have deeper ground-water levels. However, in areas of high ground water or perched water conditions, such as dunes near water bodies or low-lying areas between dune crests, liquefaction susceptibility may be high or very high.

Qhbm Holocene San Francisco Bay mud. Sediment deposited at or near sea level in the San Francisco Bay estuary that is presently, or was historically tidal marsh, mud flat or bay bottom. Bay mud sediment typically has low bulk density and includes silt, clay, peat, and fine sand (Atwater and others, 1977). This unit is time-transgressive and generally occupies the area between the modern shoreline and the historical limits of tidal marsh, as shown on the compilations by Nichols and Wright (1971), San Francisco Estuary Institute (1998), and Sowers (1995, 1997, 1999) 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 alluvial deposits too small to be mapped at the map scale used in this project. Especially relevant to the evaluation of liquefaction susceptibility 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. Bay mud deposits near the mouths of larger streams likely contain more sand and silt than the deposits that are distant from stream and river mouths. Soils developed on estuarine deposits typically are histosols, aquic entisols or mollisols. Bay mud is mainly 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). This unit is texturally and genetically similar to Holocene San Joaquin/ Sacramento Delta mud and peat, which Knudsen and others, (2000a) mapped upstream of the confluence between the Sacramento and San Joaquin rivers.

Although Bay mud primarily consists of clay and silt, we assign a moderate liquefaction susceptibility to this unit due to high ground-water levels (often tidally influenced) and the possible presence of sand lenses within the mud and peat. The mud itself is unlikely to liquefy due to the abundance of clay. Estuarine sediment near the mouths of major streams, such as Alameda Creek, is probably the most susceptible to liquefaction because the streams regularly deliver large volumes of sand and silt to the estuary. About 3% of all observed occurrences of liquefaction in the San Francisco Bay area have occurred within this unit.

Qhed   Holocene estuarine delta deposits. Estuarine sediment deposited in a delta at the mouths of tidally influenced coastal streams where fresh water mixes with seawater. Estuarine sediment primarily consists of silt and clay deposited by marine and fluvial processes with interbedded organic-rich layers composed of peat or woody debris. However, in larger streams and rivers along the coast where fluvial currents dominate tidal processes, deltaic sediments deposited in brackish water may consist of well sorted sand and/or gravel, forming channel bars and stream banks. Estuarine delta deposits mapped along the Pacific coast typically consist of a heterogeneous mixture of coarse and fine material generally coarser than estuarine deposits of the San Francisco Bay (Qhbm). Holocene estuarine delta deposits also are mapped near the mouths of streams along the northern margin of San Pablo Bay where small fluvial deltas have prograded out over Holocene Bay mud deposits (Qhbm). Examples include units mapped at the mouths of San Antonio Creek (Petaluma River quadrangle), and Sonoma Creek (Sears Point quadrangle).

Liquefaction susceptibility is high. The judgment that estuarine delta deposits (Qhed) are relatively more susceptible to liquefaction than San Francisco Bay mud (Qhbm, assigned moderate susceptibility) is based on the observation that fluvially dominated coastal streams deposit large volumes of sand. The combination of high ground water levels near the mouths of streams, the likely presence of loose saturated sand, and the possible occurrence of free faces along channel margins increase the relative susceptibility of these deposits to liquefaction.

Qhb Holocene basin deposits. Sediment that accumulates from standing or slow moving water in topographic basins. Basin deposits consist of fine-grained alluvium with horizontal stratification. These deposits can be interbedded with lobes of coarser alluvium from streams that flow into the basin. Interbeds of peat also may be present. Identification of basin deposits is based on surface morphology, topographic position, and soil type. This unit is similar to flood basin deposits (Qhfb) of the Sacramento/San Joaquin Delta area (Atwater, 1982), and is similar in texture to Holocene alluvial fan, fine facies (Qhff) deposits. Ground water is high, often at the surface, especially during the rainy season. Many basins contain, or historically contained, seasonal wetlands, for example, Lake Elizabeth in Fremont and Tulare Lake in the Pleasanton area. Typical soil series developed on basin deposits include Alamitos, Sunnyvale, Willows, Sycamore, and Clear Lake. These soils are clay rich with mottled subsoils, and may be somewhat saline or calcareous.

Liquefaction susceptibility is moderate. Although these deposits contain abundant clay, they also may contain layers of sand and silt. In a fluvial environment, we expect the distribution of sand to be irregular and discontinuous. Thus, we assume that layers of liquefiable material may be present within basins. Ground water at or near the ground surface makes liquefaction of surficial basin deposits possible.

Qhfe **Holocene alluvial fan-estuarine complex deposits**. Deposits that form in the transition zone from distal fan and basin environments to the estuarine environment. This unit is mapped along the southern San Francisco Bay margin between the Guadalupe River and Coyote Creek within the Milpitas 7.5-minute quadrangle. The deposits represent a transition zone from fluvial sand, silt, and clay (Qhf, Qhfy, Qhl, Qhly, Qhff) to Bay mud (Qhbm). Coarser fluvial sediment, some of which may be historical, typically forms a veneer over the finer sediment (Qhff) and may overlie or interfinger with Bay mud. Bay mud in this area is distinguished from fine-grained alluvial fan sediment (Qhff) by its compressibility, high water content, and peat content (Sarna, 1967).

Discontinuous sloughs oriented perpendicular to the bay margin are typical of this zone and are interpreted to be segments of abandoned creek channels whose upper reaches are filled by recent fluvial sediment. The lower reaches are maintained by a combination of ground-water seepage and tidal influx. This unit includes a tongue of Bay mud mapped by Sarna (1967) that extends up the Guadalupe River. Borings in this area indicate the presence of both Bay mud and very young fluvial sediment. We do not, however, include within this map unit a tongue of Bay mud mapped by Sarna (1967) along Coyote Creek. Borings in this area are concentrated along the creek channel where tidal influx within the channel itself may be responsible for the deposition of Bay mud. The area on either side of the Coyote Creek channel is mapped as a natural levee (Qhly), based on the shape of the ten-foot contour line and the presence of Mocho loam, an alluvial soil (Gardner and others, 1958).

Soils within this transition zone are strongly to moderately saline or alkaline; the native vegetation historically included salt grass and pickleweed (Goals Project, 1999). Soil series associated with this zone include the Alviso clay, tidal marsh, and the Mocho loam and fine clay loam over basin clays (Gardener and others, 1958). Ground water is tidally influenced owing to a direct hydraulic connection to deposits in stream channels and sloughs.

Liquefaction susceptibility is high based on the presence of shallow ground water, historical damage owing to liquefaction, and lenses of unconsolidated, very young, sandy, alluvial material.

Qhf **Holocene alluvial fan deposits**. Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains, including debris flow, hyperconcentrated mudflow, and braided stream deposits. Alluvial fan sediment includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Sediment clast size and general particle size typically decreases down slope from the fan apex. Many Holocene alluvial fans exhibit levee/interlevee topography, particularly the fans associated with creeks flowing west from the East Bay hills [see Holocene alluvial fan levee deposits (Qhl) below]. Alluvial fan surfaces are steepest near their apex at the valley mouth, and slope gently basin ward, typically with gradually decreasing gradient. Alluvial fan deposits are identified primarily on the basis of fan morphology and topographic expression. Holocene alluvial fans are relatively undissected when compared to older alluvial fans. In places, Holocene deposits may be only a thin veneer over Pleistocene deposits. Soils are typically entisols, inceptisols, mollisols, and vertisols. About 9% of the central San Francisco Bay area is covered by Holocene alluvial fan deposits; it is the most extensive Quaternary map unit in the region. In some areas of the map, the relative ages of younger (Qhf1), intermediate (Qhf2), and older (Qhf3) alluvial fan deposits are distinguished from one another.

Liquefaction susceptibility is moderate where ground water is within fifteen feet of the surface. Deposits may be less susceptible where ground-water levels are considerably lower such as near fan apices and near the range front along the East Bay Hills. Where an active channel is present but is not mapped through the fan because of the map scale, the liquefaction susceptibility may be underestimated.

Qhff Holocene alluvial fan deposits, fine facies. Fine-grained alluvial fan and flood plain overbank deposits laid down in very gently sloping portions of the alluvial fan or valley floor. Slopes in these distal alluvial fan areas are generally less than or equal to 0.5 degrees, soils are clay rich, and ground water is within 3 meters of the surface. Deposits are dominated by clay and silt, with interbedded lobes of coarser alluvium (sand and occasional gravel). Deposits of coarse material within these fine-grained materials are elongated in the down fan or down valley direction. These lobes are potential conduits for ground water flow. The surface contact with relatively coarser facies, fan (Qhf) and levee (Qhl), is both gradational and interfingering, thus is dashed. These deposits are similar to “basin deposits” mapped by Helley and Graymer (1997a, 1997b) and Helley and others (1994). Typical soil series developed on this unit include Sunnyvale, Orestimba, Clear Lake, Pescadero, Pacheco and Willows. These soils are clay rich with mottled or calcareous subsoils.

Liquefaction susceptibility is moderate based on shallow ground water and the presence of lenses of fine sand and silt.

Qhl Holocene alluvial fan levee deposits. Natural levee deposits of alluvial fans are formed by streams that overtop their banks and deposit sediment adjacent to the channel. Mapping of these deposits is based on interpretation of topography; levees are identified as long, low ridges oriented down fan [“channel ridges” of Thomasson and others (1960)]. They contain coarser material than adjoining interlevee areas, especially adjacent to creek banks where the coarsest material is deposited during floods (Helley and others, 1979). Levee deposits are loose, moderately to well sorted sand, silt and clay (Helley and Wesling, 1989). Soils are typically entisols, inceptisols, mollisols, and vertisols. In some parts of the map, the relative ages of younger (Qhl1), intermediate (Qhl2), and older (Qhl3) alluvial fan levee deposits are differentiated from one another.

Liquefaction susceptibility is moderate because of the presence of unconsolidated, sandy materials adjacent to an active or formerly active stream channel. However, the topographic elevation of natural levees above adjacent stream channels generally is associated with relatively deeper (15 to 20 ft) ground-water levels. Where streams are incised and form a free face along the channel margin, these deposits may be susceptible to lateral spreading.

Qht Holocene stream terrace deposits. Stream terrace deposits that were deposited in point bar and overbank settings. Terrace deposits include sand, gravel, silt, and minor clay, and are moderately to well-sorted, and moderately to well bedded. This unit is mapped where relatively smooth, undissected terraces are less than 25 to thirty feet above the active channel. Soils are typically entisols, inceptisols, and mollisols. Terrace deposits that are too small in extent to be shown at the map scale, such as those along small creeks, are included within the undifferentiated alluvial deposits (Qha and Qa) mapping units. Where multiple stream terraces are identified, the younger deposits (Qht1) are distinguished from older deposits (Qht2).

Liquefaction susceptibility is moderate because of the presence of loose, granular deposits and shallow ground water within fifteen feet of the ground surface. Should liquefaction occur, the presence of a free face and laterally extensive point bar deposits makes lateral spreading likely. Overbank deposits, which typically overlie point bar deposits, probably are not as susceptible to liquefaction, or to lateral spreading should liquefaction occur, as point bar deposits.

Qha Holocene alluvial deposits, undifferentiated. Alluvium deposited in fan, terrace, or basin environments. 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 alluvial deposits are mapped in relatively flat, smooth valley bottoms along small- to medium-sized streams. The planar and smooth geomorphic surfaces, with little to no dissection, indicate that there has been little post-stabilization modification/dissection of the surface; thus, deposits with smooth surfaces are interpreted to be Holocene in age. Undifferentiated Holocene alluvial deposits probably are intercalated sand, silt, and gravel that are poorly to moderately sorted. Soils are entisols, inceptisols, vertisols, and mollisols.

Liquefaction susceptibility is moderate, based on: (1) the presence of undifferentiated late Holocene channels and deposits; (2) relatively high ground-water levels; and (3) similarities in material properties and liquefaction susceptibility for fan, terrace, and basin deposits (Qhf, Qht, and Qhb).

HOLOCENE TO LATEST PLEISTOCENE (<30,000 YEARS).

Qds Latest Pleistocene to Holocene dune sand. Very well sorted fine to medium grained eolian sand (<30,000 years). Holocene sand may discontinuously overlie latest Pleistocene sand, both of which may form a mantle of varying thickness over older materials. Most of these deposits are thought to be associated with latest Pleistocene to early Holocene low sea level stands and subsequent transgression, during which large volumes of fluvial and glacially derived sediment from the Sierra Nevada via the Sacramento and San Joaquin Rivers were blown into dunes (Atwater and others, 1977). The deposits include the Merritt Sand in the Oakland area and the sand dunes that cover much of the northern San Francisco Peninsula. These dunes consist of fine to medium sand that is semiconsolidated and weakly cemented.

Liquefaction susceptibility is generally low, but may be high locally where ground water is shallow and sand is Holocene in age; therefore, we have assigned these deposits moderate liquefaction susceptibility. However, 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). Geotechnical boring information collected by CGS and Holzer and others (2002) indicate that some parts of the Merritt Sand and the dunes on the San Francisco Peninsula may liquefy during a large earthquake.

Qb Latest Pleistocene to Holocene basin deposits. Sediment deposited in topographic lows, such as a closed or semi-enclosed basin. These areas have a high ground-water table and soils characterized as poorly drained. Deposits are generally clay rich. This unit is mapped in the axis of Kenwood valley where the presence of both latest Pleistocene and Holocene deposits is suggested by a range in soil development that includes vertisols (relatively youthful clay rich soils) and durixeralfs (mature soils having a B horizon and hardpan).

Liquefaction susceptibility is low because of the fine-grained nature of these deposits and relative older age.

Qf Latest Pleistocene to Holocene alluvial fan deposits. This unit is mapped on gently sloping, fan-shaped, relatively undissected alluvial surfaces where the age of deposits is not known (either latest Pleistocene or Holocene in age) or where the deposits consist of thin "patches" of Holocene sediment overlying latest Pleistocene alluvial fan sediment. Fan sediment includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Soils formed on these deposits are typically mollisols, and alfisols. This unit includes active stream channels that are too narrow to show at the map scale used in this project.

Liquefaction susceptibility is moderate too low. Ground water is assumed to be greater than fifteen feet below the surface. However, because of the presence of sediment in stream channels not differentiated within this unit, historical observations of liquefaction within the map unit and geotechnical analyses of boring data, we assign a moderate susceptibility to the unit (Qf).

Qt Latest Pleistocene to Holocene stream terrace deposits. This unit is mapped on relatively flat, undissected stream terraces where deposit age is uncertain. Terrace deposits include sand, gravel, and silt, with minor clay, and are moderately to well sorted, and moderately to well bedded. Soils are typically inceptisols, mollisols, and alfisols. Ground-water depth is variable, but is generally less than thirty feet. This unit may include active stream channels, consisting dominantly of gravel and sand, that are too narrow to show at the map scale of this project. Where multiple stream terraces are identified, the younger deposits (Qt1) are distinguished from older deposits (Qt2).

Liquefaction susceptibility is moderate, where ground water is within twenty feet of the surface. The moderate susceptibility reflects the range or uncertainty in age of the terrace deposits. Liquefaction susceptibility in undifferentiated channels within these deposits, especially in point bar deposits, may be higher.

Qa Latest Pleistocene to Holocene alluvial deposits, undifferentiated. This unit is mapped in small valleys where separate fan, basin, and terrace units could not be delineated at the scale of this mapping, and where deposits might be of either latest Pleistocene or Holocene age. The unit includes flat, relatively undissected fan, terrace, and basin deposits, and small active stream channels. Soils formed on these deposits are mollisols, alfisols and vertisols.

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

LATEST PLEISTOCENE (11,800 to 30,000 YEARS).

Qpf Latest Pleistocene alluvial fan deposits. This unit is mapped on alluvial fans where latest Pleistocene age is indicated by greater dissection than is present on Holocene fans, and/or the development of alfisols. Latest Pleistocene alluvial fan sediment was deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains and includes debris flow, hyperconcentrated mudflow, and braided stream deposits. Alluvial fan sediment typically includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Sediment clast size and general particle size decreases down slope from the fan apex. Latest Pleistocene alluvial fan sediment is approximately 10% denser than Holocene alluvial fan sediment and has penetration resistance values about 50% greater than values for Holocene alluvial fan sediment (Clahan and others, 2000a, 2000b, 2000c, 2000d). Latest Pleistocene alluvial fans may be overlain by thin unmapped Holocene alluvial fan deposits. Where multiple alluvial fans are identified, the younger deposits (Qpf1) are distinguished from older deposits (Qpf2). Along the west-facing hills of Oakland and Berkeley, where latest 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 thin pediment deposits, and latest Pleistocene alluvial fan deposits.

Liquefaction susceptibility is low. Ground-water levels are variable, but generally are more than twenty feet below the surface. Deposits typically are very stiff to hard or medium dense to very dense (Haydon and others, 1999; Clahan and others, 2000a, 2000b, 2000c, 2000d).

Qpt **Latest Pleistocene stream terrace deposits**. This unit is mapped on relatively flat, slightly dissected stream terraces where latest Pleistocene age is indicated by the development of alfisols and height of the terrace above flood level. Terrace sediment includes sand, gravel, silt, with minor clay, and is moderately to well sorted, and moderately to well bedded. Terrace sediment typically was deposited in point bar and overbank settings and has since been elevated above the creek bottom by incision of the streambed. Latest Pleistocene terrace deposits that are too small in extent to be shown at the map scale, such as those along small creeks, may be included within the undifferentiated latest Pleistocene and latest Pleistocene to Holocene alluvial mapping units (Qpa and Qa).

Liquefaction susceptibility is low because of the age of the deposits and the likelihood that ground water is relatively deep. Should liquefaction occur, the presence of a free face makes lateral spreading likely.

Qpa **Latest Pleistocene alluvial deposits, undifferentiated**. This unit is mapped on gently sloping to level alluvial fan or terrace surfaces where latest Pleistocene age is indicated by depth of stream incision, development of alfisols, and lack of historical flooding. Undifferentiated latest Pleistocene alluvial deposits are mapped in small valleys where separate fan, basin, and terrace units could not be delineated at the mapping scale of this project. These undifferentiated latest Pleistocene alluvial deposits probably are intercalated sand, silt, and gravel that are poorly to moderately sorted.

Liquefaction susceptibility is low because of the age of the deposits and the probability that ground water is relatively deep (10 to 30 feet).

PLEISTOCENE (>11,800 to 1.8 MYRS).

Qmt **Pleistocene marine terrace deposits**. Deposits on uplifted marine abrasion platforms along the Pacific Ocean coast. Although, we have not evaluated the relative ages of all terrace deposits (e.g. late versus middle or early Pleistocene), for much of the western San Francisco Peninsula, we have assigned relative ages by numbering the deposits 1 through 4. However, the numbers identifying different aged terraces have not been applied consistently to all quadrangles. Sediment deposited on the strath platforms is typically greater than ten-feet thick and consists of moderately to well sorted, moderately to well bedded sand and gravel, which may be locally fossiliferous. We compiled and modified mapping of marine terrace deposits by Weber and others (1993), Jack (1969), and Lajoie and others (1974, 1979) in the southwestern part of the San Francisco Peninsula south to Santa Cruz County. Unpublished mapping by K. Lajoie also was used in mapping marine terraces along the Marin County coast. In some parts of the map, four marine terraces are distinguished as youngest (Qmt1), younger (Qmt2), older (Qmt3), and oldest (Qmt4) deposits.

Liquefaction susceptibility is low. Ground water is typically deeper than twenty feet, though areas may have perched ground water where marine sediment overlies relatively impermeable bedrock. Marine terrace sediment is typically too dense to liquefy.

Qbt Pleistocene bay terrace deposits. Estuarine and deltaic sediment on wave-cut platforms above present sea level along San Pablo Bay, the Carquinez Straight, and wave-beveled strath terraces near Lake Merritt, Oakland. Uranium-series dates on articulated, in-place oyster shells (Ostrea lurida) from terrace deposits around San Pablo Bay provide an age estimate from 112 to 142 ka correlative with the oxygen-isotope stage 5e sea-level highstand (Atwater and others, 1981; Helley and others, 1993). Vertebrate fossils preserved in terrace deposits at Rodeo on the south side of San Pablo Bay indicate a prograding deltaic environment entering a marine embayment (Wolff, 1971). Marine and estuarine fossil species in these deposits include sea otters (Enhydra lutris), oysters (Ostrea lurida), and the salt marsh harvest mouse, (Reithrodontomys raviventris) (Wolff, 1971). Terrace sediment up to 5.9-m-thick includes trough-cross bedded sand and rounded gravel deposited in a bay delta, and sand and silty clay with 35 to 100-cm-thick shell beds deposited in an estuarine environment (Borchardt, 1994). Terrace surfaces are planar to rounded and moderately to deeply dissected.

Liquefaction susceptibility is low because of the age and density of the deposits. Shallow ground water may be present where perched above less permeable bedrock abrasion platforms.

EARLY TO LATE PLEISTOCENE (>30,000 to 1.8 MYRS).

Qop Early to late Pleistocene pediment deposits. Alluvial deposits that form a thin veneer on broad, planar erosional surfaces cut on older sediment or bedrock. These pediments typically occur tens to hundred(s) of meters above the present stream channel and are extremely dissected. Bedrock and/or older sediment are exposed by dissecting channels at depths less than 5 meters beneath the alluvium, and, in places, only sparse sediment may remain from the original deposits. These deposits are mapped primarily based on their geomorphic expression as interpreted from topographic maps. These deposits are mapped on the west side of the East Bay hills from Oakland to Richmond and the western end of the Potrero Hills near Fairfield. Soils formed on these deposits typically are well developed, and include alfisols and ultisols.

Liquefaction susceptibility is very low because of the age of the deposits and their density. Because these deposits are typically at least tens of feet above present stream channels, ground water commonly is not present in these deposits.

Qof Early to late Pleistocene alluvial fan deposits. Moderately to deeply dissected alluvial deposits capped by alfisols, ultisols, or soils containing a silicic or calcic duripan. Early to middle Pleistocene alluvial fan sediment was deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains and includes debris flow, hyperconcentrated mudflow, and braided stream deposits. Because of the age of these deposits, the streams responsible for deposition of mapped bodies of early to middle Pleistocene alluvial fan sediment may have evolved and no longer be readily evident in today's topography. Alluvial fan sediment typically includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. This unit differs from undifferentiated early to middle Pleistocene alluvial deposits (Qoa) in that some original fan surface morphology is preserved.

Liquefaction susceptibility is very low because of the age and density of the sediment as well as large depths to ground water.

Qot Early to late Pleistocene stream terrace deposits. Moderately to deeply dissected alluvial terrace deposits capped by alfisols, ultisols, or soils containing a silicic or calcic hardpan. Terrace sediment includes sand, gravel, and silt, with minor clay, and is moderately to well sorted, and moderately to well bedded. Terrace sediment typically was deposited in point bar and overbank settings and has since been elevated above the creek bottom by incision of the streambed. This unit differs from Qoa in that some terrace surface morphology is preserved.

Liquefaction susceptibility is very low because of the age and density of the sediment.

Qoa Early to late Pleistocene alluvial deposits, undifferentiated. 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. Deposits mapped within this map unit can include alluvial fan, stream terrace, basin and channel deposits. This unit includes the Colma Formation on the San Francisco Peninsula (Bonilla, 1971), which has been described as a marine, estuarine and fluvial, unconsolidated fine to medium sand with silt and clay. It also includes Plio-Pleistocene deposits shed off the flanks of Mt Diablo that have been previously mapped by Helley and Graymer (1997a, 1997b).

Liquefaction susceptibility is very low because of the age and density of the sediment.

br Early Quaternary and older (>1.4 Ma) deposits and bedrock, undifferentiated. Primarily Jurassic to Pliocene sedimentary, metamorphic, volcanic and plutonic rocks, and poorly consolidated Tertiary sediment. Includes some Pliocene to Pleistocene sedimentary units such as the Glen Ellen Formation, Santa Clara Formation, Livermore gravels, and Merced Formation. Unit also includes landslides, talus, other bodies of colluvium, and small stream channel deposits in bedrock that could not be delineated at the map scales used in this project.

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