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DESCRIPTION OF MAPPING OF QUATERNARY DEPOSITS AND LIQUEFACTION SUSCEPTIBILITY, NINE-COUNTY SAN FRANCISCO BAY REGION, CALIFORNIA

by

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INTRODUCTION

A new map of Quaternary deposits and a derivative map of liquefaction susceptibility have been prepared for the nine-county San Francisco Bay region (figure 1). The maps are in the form of a digital database, produced from original 1:24,000- and 1:100,000-scale geologic mapping. These maps represent the first region-wide characterization of Quaternary deposits in the Bay region since the 1970s. The maps provide a modern and regionally consistent treatment of Quaternary deposits that builds on the pioneering work of Helley and others (1979) and the subsequent work of Atwater (1982), Helley and others (1994) and Helley and Graymer (1997a and 1997b). The Quaternary deposits map was originally produced with the intention of developing the derivative liquefaction susceptibility map. However, the Quaternary deposit map may be used for a variety of other purposes, including: neotectonic analyses; estimating earthquake shaking; as a screening tool in engineering geologic and geotechnical evaluations; evaluation of sand and gravel resources; landscape evolution modeling; and regional hydrologic and hydrogeologic characterizations. The maps also are intended to provide baseline data for use in development of liquefaction hazard zone maps by the Seismic Hazard Mapping Program of the California Division of Mines and Geology (CDMG). The map products of this study are not meant to replace those zonation maps; these maps serve a different role by providing a regional perspective on Quaternary deposits and liquefaction susceptibility.

Quaternary deposits are subdivided using two criteria: their age and their environment of deposition. The age of a deposit influences its density, degree of cementation, ability to transmit earthquake energy, and hydraulic conductivity. We use geomorphic relations, degree of soil profile development and erosional modification of geomorphic surfaces to evaluate the age of deposits. The size, shape and arrangement of grains, hydraulic conductivity, and lateral continuity of deposits are a function of the environment in which sediment was deposited. We use interpretation of topography and aerial photographs to identify landforms and relate the landforms to the environment in which they were formed. A material's age and environment of deposition also affects its likelihood of experiencing earthquake-induced liquefaction.

Earthquake-induced ground failures owing to liquefaction have caused loss of life and damage to property and infrastructure in many earthquakes. Liquefaction is the transformation of a saturated granular material from a solid to a liquefied state as a result of increased pore pressure and decreased effective stress (Youd, 1973). Observed types of ground failure resulting from liquefaction can include sand boils, lateral spreads, ground settlement, ground cracking and ground warping (Youd and Hoose, 1978). Observations of the effects of large-magnitude earthquakes show that the distribution of liquefaction phenomena is not random; it occurs in areas underlain by loose, saturated, cohesionless sand, silt and gravel. Areas susceptible to liquefaction can be delineated on the basis of geologic, geomorphic, and hydrologic mapping and map analyses (Dupré and Tinsley, 1980; Youd and Perkins, 1987; Tinsley and Holzer, 1990; Sowers and others, 1995; Knudsen and others, 1997; Tinsley and others, 1999). In this study, we use the new Quaternary map (Map Sheet 1) together with information about past liquefaction effects and estimates of ground-water levels to produce a liquefaction susceptibility map of the

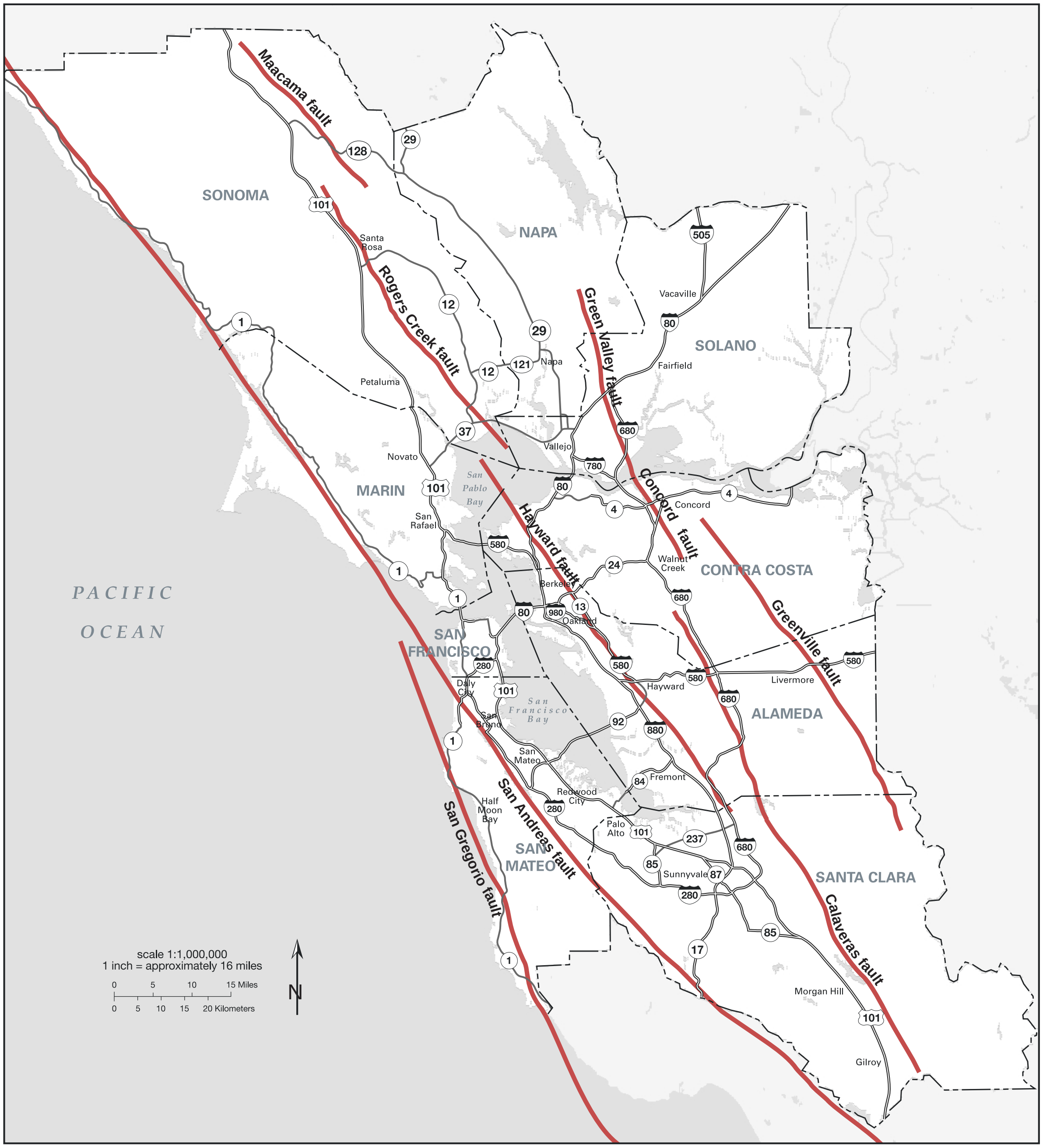

Figure 1. The nine-county San Francisco Bay Region, with major faults. Modified from Perkins and others (1999)

San Francisco Bay region (Map Sheet 2). The geologic materials most susceptible to liquefaction include Holocene stream channel deposits, Holocene beach deposits, and artificial fill overlying Bay Mud; these deposits are widely present in the region. The analysis of liquefaction susceptibility is patterned after studies by Dupré and Tinsley (1980) and Dupré (1990) in the Monterey-Santa Cruz area, Tinsley and others (1985) in the Los Angeles area, Youd and Perkins (1987) in San Mateo County, California, Sowers and others (1995) in the northern San Francisco Bay area, and Knudsen and others (1997) in the central San Francisco Bay area. Users of the maps should recognize that the susceptibility map is not a ground failure map; it shows the susceptibility of materials to liquefaction. Ground failures commonly accompany liquefaction, however, and may be expected in areas with higher susceptibility levels (Tinsley and others, 1985).

The new Quaternary maps are an improvement over the 1970s-vintage maps of Helley and others (1979) in that (1) much of the mapping is at a scale of 1:24,000, (2) a detailed stratigraphic nomenclature has been developed that is based on age and environment of deposition, (3) a revised model of landscape evolution has been used, and (4) the mapping procedures and source materials used are documented for each 7.5-minute quadrangle. Much of the area here presented at a scale of 1:100,000 is being revised at a scale of 1:24,000 by William Lettis & Associates, Inc. (WLA), the California Division of Mines and Geology, and the U.S. Geological Survey for subsequent incorporation into a revised version of the Quaternary deposits database. Thus, the present report is an interim product. Because we will be refining existing mapping and inserting more detailed mapping into the database, we have not resolved all quadrangle-boundary problems.

Use of the digital database should not violate the spatial resolution of the data. Resolution higher than that of the original mapping is not present and enlargement of the database and maps to larger scales will not yield greater detail.

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Conservation, Division of Mines and Geology, and the Earthquake Hazards Program of the U.S. Geological Survey.

METHODS

Quaternary deposits are mapped chiefly through the interpretation of 1:24,000-scale topographic maps, aerial photographs, and soil surveys, by reference to published and unpublished geologic maps, and by field reconnaissance. Categories of age and environment distinguished in this study are listed in table 1 and shown in figure 2.

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

Age (1)	Depositional Environment
Material deposited by humans (a) (2)	Active stream channel (c)
Modern (<150 yrs)	Alluvial terrace (t)
Latest Holocene (Qh_y) (<~1000 yrs)	Alluvial fan (f)
Late Holocene (Qh) (<~3000 yrs)	Alluvial fan levee (l)
Holocene (Qh) (<10,000 yrs)	Fine grained (distal) alluvial fan (ff)
Latest Pleistocene to Holocene (Q) (<~30,000 yrs)	Alluvial fan-estuary transition (fe)
Latest Pleistocene (Qp) (10,000 to ~30,000 yrs)	Alluvial basin and flood basin (b, fb)
Early to late Pleistocene (Qo) (~30 kyrs to 1.6 myrs)	Alluvial floodplain (fp)
	Undifferentiated alluvial (a)
	Estuary/bay (bm)
	Estuary/delta (dm)
	Beach (bs)
	Dune (ds)
	Marine terrace (mt)
	Pediment (p)

Notes: (1) We use several age boundaries in defining map units in this study other than the standard Quaternary boundaries (Harland and others, 1990) to permit effective distinction of materials with different susceptibilities to liquefaction. Thus, in the Holocene, we distinguish materials deposited within the past 150 years (by humans), within the past 1,000 years (latest Holocene), and within the past 3,000 years (late Holocene) from materials simply designated as Holocene. In the Pleistocene we distinguish materials less than 30 thousand years old (latest Pleistocene) from older ones (late to early Pleistocene), because these younger Pleistocene materials are more likely to liquefy. With additional effort, further differentiation of Pleistocene deposits would be possible.

(2) Abbreviations used in unit designations are shown in parentheses.

We delineate landforms and Quaternary deposits, including stream and marine terraces, alluvial fans and levees, beaches, dunes, and marshes, principally from interpretation of topographic

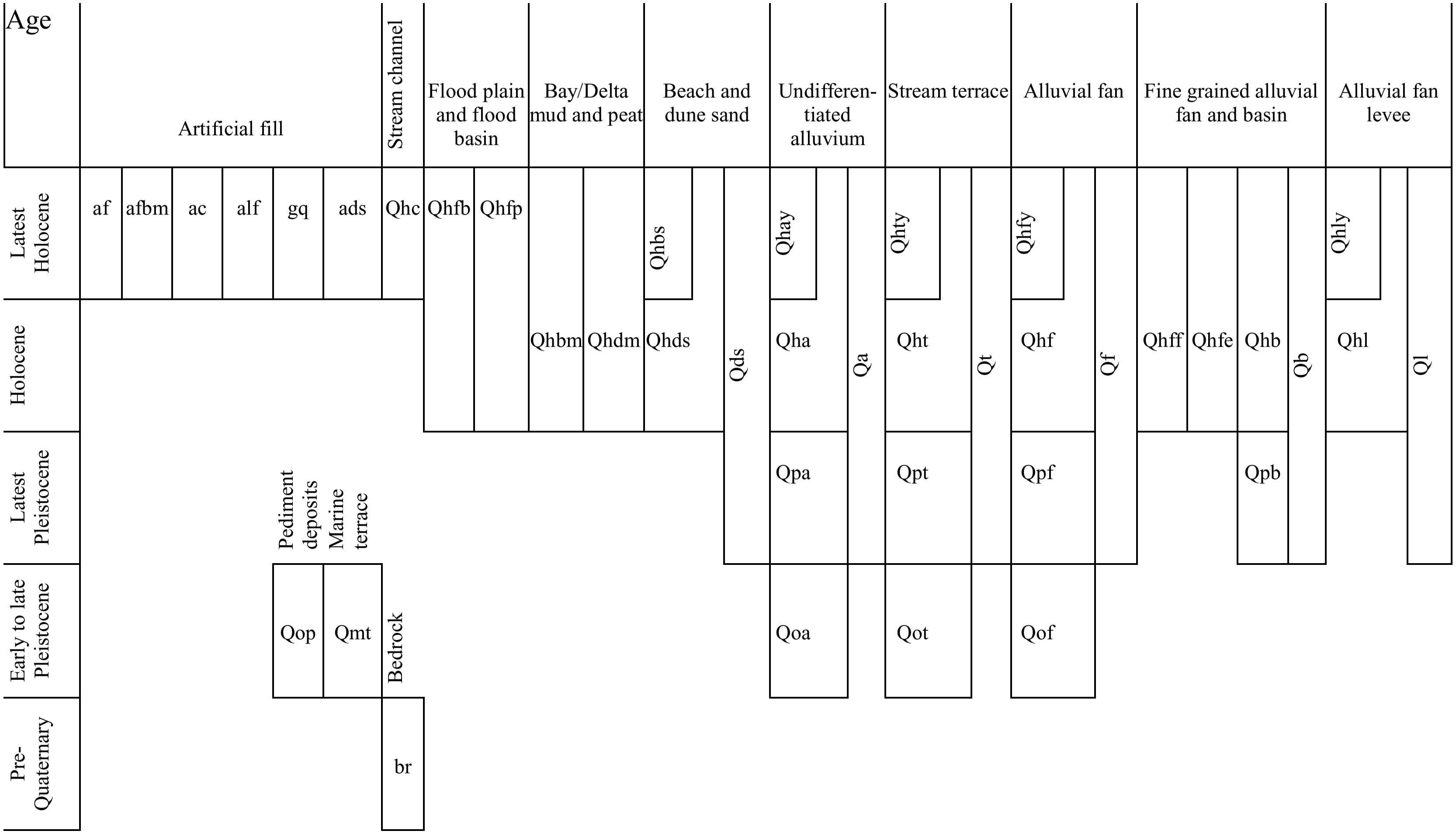

Figure 2. Correlation of geologic map units

maps and aerial photographs. Early 20th century 1:24,000-scale and 1:62,500-scale topographic maps were used to characterize pre-development topography and identify landforms and streams that have since been altered by development. The oldest available aerial photography was used in order to evaluate landforms prior to their modification by recent development. For much of the San Francisco Bay region, the earliest aerial photographs are approximately 1:20,000-scale, 1939 photographs.

Criteria used to evaluate age of deposits include landform shape and relative geomorphic position, cross-cutting relations and superposition, depth and extent of erosional dissection, relative degree of soil profile-development, and correlation to dated deposits. Additionally, deposits are correlated to the stratigraphic framework used by previous researchers (table 2). Such previous studies include research in the Sacramento Valley (Helley and Harwood, 1985), eastern San Joaquin Valley (Marchand and Harden, 1978; Marchand and Allwardt, 1978, 1981; Atwater, 1982; Harden, 1987), western San Joaquin Valley (Lettis 1982, 1985; Bartow and others, 1985; Sowers and others, 1993a,b; Noller and others 1993), and the San Francisco Bay area (Atwater and others 1977; Helley and others, 1979; Atwater, 1982; Knudsen and others, 1997). Deposits that could not be confidently distinguished as either Holocene or latest Pleistocene are assigned the age designation of latest Pleistocene to Holocene. This designation is also used where Holocene deposits are inferred to form a thin veneer over latest Pleistocene deposits.

A major challenge in this project was to map each of the one hundred sixty-six quadrangles in the San Francisco Bay area using consistent stratigraphy, nomenclature, style, and level of detail. The maps we present are a combination of original mapping and previous mapping that has been modified to fit our stratigraphy, nomenclature, and mapping style (see table 3). In some cases the modifications are minor, such as changing the unit symbol for Holocene alluvial fan from Qhaf, used by Helley and Graymer (1997a, b), to Qhf. In other cases modifications are extensive and include original mapping or revision of age assignments. Table 3 and figure 3 document the origin of the mapping and the extent and basis for revisions or modifications for each quadrangle. Most areas were mapped at a scale of 1:24,000. Areas mapped at a scale of 1:100,000 include parts of the San Francisco, San Jose and Napa 1:100,000 quadrangles. In addition to showing the sources and methods used for each quadrangle, figure 3 also shows the estimated “percent completion” of each quadrangle. A value of 100 percent indicates that we feel confident in the mapping and that all of the following methods were used in developing the map: review of previous maps, interpretation of landforms through analysis of topographic contours on 7.5-minute quadrangles, inspection of stereo-paired aerial photographs, review of soil survey maps, and field reconnaissance. Completion percent values of less than 100 percent indicate, in a relative way, the level of effort completed to date, with 50 percent indicating that existing mapping has simply been reinterpreted and modified to fit the stratigraphic nomenclature used herein. A value of 100 percent does not indicate that the map cannot be improved, it means that the above-listed standards for this study have been met.

Table 2. Correlation chart showing relations between the stratigraphy used in this study and the stratigraphies of previous researchers.

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

Blank cells indicate that the unit either was not mapped, or was included in another unit.

UNIT	Knudsen and others, 2000 (This study)	Knudsen and others, 1997, San Francisco 1:100,000	Sowers and others, 1995, 1998; Napa 1:100,000	Helley and Graymer, 1997a, b; Alameda & Contra Costa Counties digital 7.5' quadrangles	Atwater, 1982; Sacramento, San Joaquin Delta 1:24,000	Helley and others, 1994; Santa Clara Valley, 1:24,000	Helley and Harwood, 1985; Sacramento Valley, 1:62,500	Helley and others, 1979; San Francisco Bay area; 1:125,000	Wentworth and others, 1998; San Jose 1:100,000
Artificial fill	af	af	af	af					af
Artificial fill over Bay Mud	afbm								
Artificial fill, levee	alf			alf					
Dredge spoils	ads				Qds				
Gravel quarries and percolation ponds	gq	af		GP		PP,GP			PP,GP
Artificial stream channel	ac			Qhasc					
Modern stream channel deposits	Qhc	Qhc		Qhsc		Qhsc	Qsc	Qhsc	Qhc
Latest Holocene alluvial fan deposits	Qhfy			Qhaf1					
Latest Holocene alluvial fan levee deposits	Qhly								
Latest Holocene stream terrace deposits	Qhty			Qhfp1,2					
Latest Holocene alluvial deposits, undifferentiated	Qhay		Qhi						
Latest Holocene beach sand	Qhbs								
Late Holocene alluvial floodplain deposits, undivided	Qhfp				Qfp				
Late Holocene flood basin deposits	Qhfb				Qfb		Qb		
Holocene dune sand	Qhds	Qhs	Qhs	Qhds				Qhs	
Holocene San Francisco Bay mud	Qhbm	Qhbm	Qhr	Qhbm		Qhbm		Qhbm	Qhbm
Holocene San Joaquin/ Sacramento Delta mud and peat	Qhdm			Qhpm	Qpm		Qp		
Holocene basin deposits	Qhb	Qhb	Qhb	Qhb, Qhbs	Qyymc, Qym	Qhb	Qb		Qhb
Holocene fine grained alluvial fan-estuarine complex deposits	Qhfe					Qhbs			
Holocene alluvial fan deposits	Qhf	Qhf	Qhf	Qhaf		Qhaf, Qhfp	Qa	Qham, Qhac	Qhf, Qhfp
Holocene alluvial fan deposits, fine grained facies	Qhff							Qhaf	
Holocene alluvial fan levee deposits	Qhl	Qhl		Qhl	Ql	Qhl	Qa		Qh1
Holocene stream terrace deposits	Qht	Qht	Qht	Qhfp		Qhfp			Qht
Holocene alluvium, undifferentiated	Qha	Qha	Qha	Qhaf			Qa		Qha

Table 2. (continued) Correlation chart showing relations between the stratigraphy used in this study and the stratigraphies of previous researchers.

UNIT	Knudsen and others, 2000 (This study)	Knudsen and others, 1997, San Francisco 1:100,000	Sowers and others, 1995, 1998; Napa 1:100,000	Helley and Graymer, 1997a, b; Alameda & Contra Costa Counties digital 7.5' quadrangles	Atwater, 1982; Sacramento, San Joaquin Delta 1:24,000	Helley and others, 1994; Santa Clara Valley, 1:24,000	Helley and Harwood, 1985; Sacramento Valley, 1:62,500	Helley and others, 1979; San Francisco Bay area; 1:125,000	Wentworth and others, 1998; San Jose 1:100,000
Latest Pleistocene to Holocene dune sand	Qds	Qps	Qs	Qms	Qm2e			Qps	
Latest Pleistocene to Holocene basin deposits	Qb								Qt
Latest Pleistocene to Holocene alluvial fan deposits	Qf	Qf	Qf						
Latest Pleistocene to Holocene alluvial fan levee deposits	Ql								
Latest Pleistocene to Holocene stream terrace deposits	Qt		Qt						
Latest Pleistocene to Holocene alluvium, undifferentiated	Qa	Qa	Qa						Qa
Latest Pleistocene basin deposits	Qpb								
Latest Pleistocene alluvial fan deposits	Qpf	Qpf	Qpf	Qpaf	Qm, Qch	Qpaf			Qpf
Latest Pleistocene stream terrace deposits	Qpt		Qpt						
Latest Pleistocene alluvium, undifferentiated	Qpa	Qpa	Qpa	Qpaf		Qpaf	Qmu, Qml	Qpa	Qpa
Pleistocene marine terrace deposits	Qmt	Qmt	Qpm, Qom	Qmt				Qpmt	Qmt
Early to late Pleistocene pediment deposits	Qop								
Early to late Pleistocene alluvial fan deposits	Qof			Qpaf, Qpoaf					Qof
Early to late Pleistocene stream terrace deposits	Qot								
Early to late Pleistocene undifferentiated alluvial deposits*	Qoa	Qoa	Qoa	Qpaf, Qpoaf			Qru, Qrl	Qpea, Qpmc	Qoa
bedrock	br					br			

* Includes Colma Formation.

Table 3. Documentation of mapping procedures and sources of information.

1. Original mapping conducted for this project by Keith L. Knudsen, Janet M. Sowers, and Robert C. Witter. The mapping is based on:

    1a. Interpretation of topographic contours, published soil surveys, stereoscopic aerial photography dating from 1939 and 1949, historical wetlands information compiled by the San Francisco Estuary Institute (1998), Sowers (1999), other historical wetlands information, and limited field reconnaissance. Previous mapping reviewed includes Helley and Wesling (1989, 1990), Helley and Miller (1992), Helley and others (1994), and Helley and Graymer (1997b). Lead author: Sowers. Map scale: 1:24,000.

    1b. Interpretation of topographic contours, published soil surveys, and stereoscopic aerial photography dating from 1939 to 1960, and limited filed reconnaissance. Previous mapping reviewed includes Helley and others (1979), Brabb and others (1998a and 1998b), and Angell and others (1997). Mapping of marine terraces is modified from Weber and others (1993), and unpublished mapping by K.R. Lajoie. Lead authors: Knudsen, Sowers, and Witter. Map scale: 1:24,000.

    1c. Interpretation of topographic contours shown on modern and/or historical (circa 1915) U.S. Geological Survey maps, and published soil surveys. Previous mapping reviewed includes Helley and others (1979), and Helley and Harwood (1985), and unpublished maps of marine terraces by Ken Lajoie. U.S. Geological Survey orthophotoquads dated 1970 were reviewed for the Dozier, Elmira, and Allendale quadrangles. Lead author: Knudsen. Map scale: 1:24,000.

    1d. Interpretation of topographic contours, published soil surveys, stereoscopic aerial photography dating from 1939 to 1960, and limited field reconnaissance. Previous mapping reviewed includes Bonilla (1998), Brabb and others (1998a) Lajoie and others (1974), Lajoie and others (1979), Nichols and Wright (1971) and Pampeyan (1994). Lead author: Witter. Map scale: 1:24,000

2. Modified from Helley and Graymer (1997a, b). Unit names and symbols were modified to conform to stratigraphic nomenclature for this project. Map scale: 1:24,000.

    2a. Minor to moderate revisions were made to unit contacts or age estimations of units to conform to more recent observations on this or adjacent quadrangles. Atwater (1982) also was consulted for the Brentwood quadrangle. Lead authors: Knudsen and Sowers.

    2b. Extensive revisions were made based on interpretation of topographic contours and soil surveys. Many unit contacts were redrawn and new units may have been delineated. Age estimates of units may have been changed. In these quadrangles Helley and Graymer (1997b) is based on previous mapping by Herd (1977). Lead author: Sowers.

    2c. Extensive revisions were made based on interpretation of topographic contours, 1949 stereoscopic aerial photography, and published soil surveys. Many unit contacts were redrawn and new units may have been delineated. Age estimates of units may have been changed. In this area Helley and Graymer (1997b) is based on previous mapping of Herd (1977). Lead author: Sowers.

3. Modified from Helley and others (1994). Unit names and symbols were modified to conform to stratigraphic nomenclature for this project. Lead author: Sowers. Map scale: 1:24,000.

    3a. Minor to moderate modifications were made to unit contacts or age estimates of units.

    3b. Extensive modifications were made based on the interpretation of orthophotoquads (dating from 1970 to the present), topographic contours, and published soil surveys. Many unit contacts were redrawn and new units may have been delineated. Age estimates of units may have changed.

4. Modified from Sawyer (1996). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Minor revisions were made to unit contacts based on interpretation of aerial photography dating from 1939 and 1949, topographic contours, and published soil surveys. Lead author: Sowers. Map scale: 1:24,000.

5. Modified from Kelson and others (1993). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Minor revisions were made to unit contacts based on interpretation of aerial photography dating from 1939 and 1949, topographic contours, and published soil surveys. Lead author: Sowers. Map scale: 1:24,000.

6. Sowers and others (1998). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Map scale: 1:100,000.

7. Sowers and others (1997). Unit names and symbols were modified to conform to stratigraphic nomenclature for this project. Map scale: 1:24,000.

8. Bezore, Sowers, and Randolph (2000). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Map scale: 1:24,000.

9. Modified from Atwater (1982). Unit names and symbols were modified to conform to stratigraphic nomenclature for this project. Mapping of artificial levees and older alluvial fans was added based on interpretation of modern and/or historical (circa 1915) topographic maps. Lead author: Knudsen. Map scale: 1:24,000.

10. Knudsen and others (1997). Unit names and symbols were modified to conform to stratigraphic nomenclature for this project. Map scale: 1:100,000.

11. Modified from Wentworth and others (1998). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Lead authors: Sowers and Knudsen. Map scale: 1:100,000.

    11a. Minor modifications were made based on the interpretation of topographic contours and published soil surveys.

    11b. Extensive modifications were made based on the interpretation of topographic contours, 1970 orthophotoquads, and published soil surveys. Many unit contacts were redrawn and new units may have been delineated. Age estimates of units may have changed. Helley and Nakata (1991) was referred to for the Gilroy quadrangle.

12. Knudsen and Lettis (1997). Additional published mapping for these quadrangles includes Sowers and others (1993a and b), Noller and others (1993), and Atwater (1982). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Map scale: 1:24,000.

13. Modified from Graymer (1997). Unit names and symbols were modified to conform to stratigraphic nomenclature used in this project. Lead author: Sowers. Map scale: 1:24,000.

    13a. Minor modifications were made based on the interpretation of topographic contours and published soil surveys.

    13b. Extensive modifications were made based on the interpretation of topographic contours and published soil surveys. Contacts between the Holocene deposits were redrawn. Age estimates of terraces along the Pajaro River were revised.

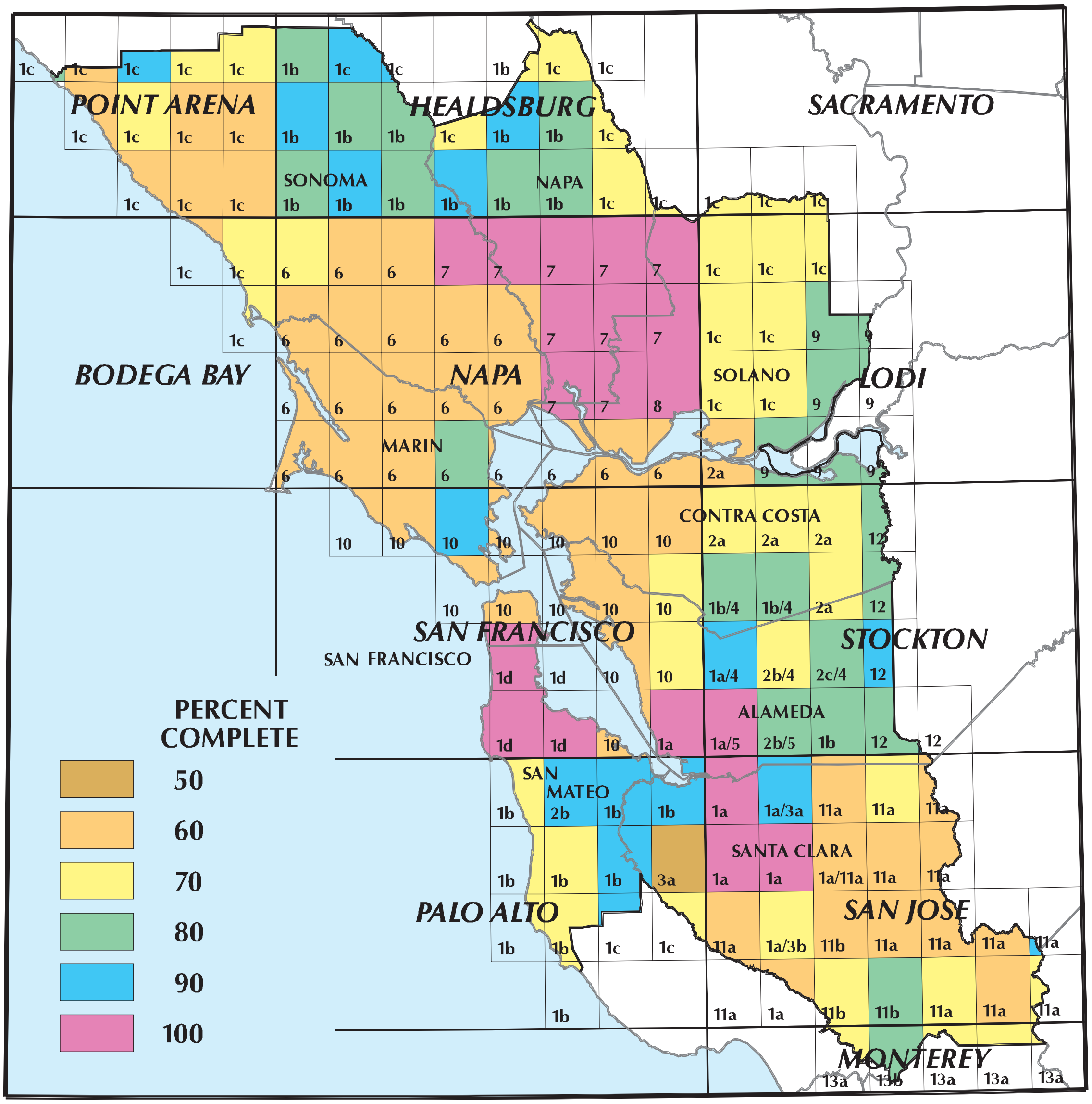

Figure 3. Index map to Table 3. Each rectangle represents a U.S. Geological Survey 7.5-minute quadrangle partly or wholly within the nine-county San Francisco Bay Region. Mapping procedures and sources represented by codes (1a to 13b) are keyed to Table 2: Documentation of mapping procedures and data sources. Colors indicate relative completion of Quaternary mapping. At 50-percent completion, existing mapping has been reinterpreted and modified to fit the stratigraphic nomenclature used herein, whereas 100 percent indicates original mapping involving: (1) review of existing maps, (2) interpretation of topography and landforms using maps and stereo-paired aerial photographs, (3) review of soil surveys published by the U.S. Natural Resources Conservation Service, and (4) field reconnaissance. Counties and 1:100,000-scale U.S. Geological Survey quadrangles are also shown.

The new mapping followed a standard procedure. We assembled and reviewed available sources of information, including published soil surveys, historical topographic and early U.S. Coast Survey maps, aerial photography, previously published and unpublished geologic mapping, and personal field notes and observations. From the 1:24,000-scale topographic map we traced water bodies, artificial levees, gravel quarries, and stream channels having a watershed area of about 5 square km or greater. Our mapping of these features therefore reflects the current edition of the topographic map. Where equivalent, the digital representations of these water boundaries were taken instead from standard U.S. Geological Survey Digital Line Graphs (DLGs). Next, using pre-development (1939-1960) stereoscopic aerial photography and topographic contours on 7.5-minute quadrangles, we mapped bedrock/alluvial contacts, boundaries of stream terraces, extent of older alluvial fan remnants, and other fluvial features visible either in the topography or as tonal features apparent on aerial photographs.

Published soil surveys served as one of the primary sources of information on ages of deposits. Individual soil series in the region typically are associated with Quaternary units of specific age and environment of deposition (Appendix B), although their mapped boundaries may not match well with our unit boundaries because of differences in mapping techniques. Soil surveys for the study area include Bates (1977), Cosby (1941), Gardner and others (1958), Kashiwagi (1985), Lambert and Kashiwagi (1978), Lindsey and Weisel (1974), Miller (1972), Welch (1977, 1981), and Welch and others (1966).

Historical maps and compilations of San Francisco Bay shoreline and tidal marshes were used to delineate the margins of the Holocene Bay Mud (Qhbm) and the extent of Bay Mud now buried beneath artificial fill (afbm). Mapping of the extent of artificial fill and artificial levees by R.W. Graymer (Helley and Graymer, 1997a, 1997b) also was used. The U.S. Coast Survey mapped the entire San Francisco Bay shoreline and tidal marshes between 1850 and 1900 . These maps were compiled on modern base maps by Nichols and Wright (1971). For most areas, the tidal marsh limit as shown on the Nichols and Wright (1971) compilation was used as a proxy to delineate the extent of Bay mud. The San Francisco Estuary Institute Goals Project (1998) produced a later map that incorporates additional historical information and includes revised registration of the U.S. Coast Survey maps, but this map and its documentation were not available for all areas. These maps, and creek and watershed maps by Sowers (1995, 1997, 1999), which use data from the San Francisco Estuary Institute (1998), the U.S. Coast Survey maps, and early aerial photography, also were consulted when mapping late Holocene features and deposits.

The resulting manuscript maps were digitized at the U.S. Geological Survey under the direction of Carl Wentworth. Each map was scanned, vectorized, edited and attributed. A proof plot was reviewed and revised by the lead authors. Boundary problems between adjacent quadrangles were identified and corrected, where possible. Some boundary problems remain but will be resolved in the future as we finish inserting new, 1:24,000-scale original mapping into the database.

Table 3 describes: (1) the procedure used in developing the Quaternary geologic maps, (2) the sources of information and references used, and (3) the relative level of detail or map scale. The numbers in the table are keyed to the accompanying index map (figure 3). This information is intended both to document and credit our sources and to assist the reader in judging the relative quality of the mapping. For example, mapping that includes the interpretation of stereoscopic aerial photography can be expected to be more accurate and precise than that based solely on the interpretation of topographic contours and soil surveys.

Previous studies document a correlation between the age and environment of deposition and the tendency of a deposit to liquefy (Tinsley and others, 1985; Tinsley and Holzer, 1990). Age is important because sediment becomes more consolidated, weathered, and cemented with time. Depositional environment is important because different environments produce deposits with different sorting, bedding, and grain-size characteristics. Stream channel deposits, for example, are likely to contain sand and silt, and where young (late Holocene), they are likely to be loose and nearly cohesionless.

Liquefaction susceptibility units were designated on the basis of a criteria matrix that assigns susceptibility values to all combinations of geologic unit (type and age of the deposit) and ground-water level (table 4). The resulting units reflect the likelihood that loose, saturated, granular sediment is present within 50 feet of the ground surface. The matrix was calibrated using information on past occurrences of liquefaction, previous geologic and geotechnical studies by WLA., and limited boring log data that includes standard penetration test (SPT) information. Where appropriate SPT data were available, they were analyzed to evaluate the typical peak ground acceleration (PGA) needed to cause liquefaction using the Seed Simplified procedure (Seed and Idriss, 1971, 1982; Youd and Idriss,1997). Because extensive borehole analysis was beyond the scope of this study, we have relied on these limited analyses, WLA's experience on other projects in the area, and an unpublished database developed by CDMG in its seismic hazard zonation mapping of the cities of Oakland and San Francisco.

Data on the depth to ground water were developed in several ways. Information on ground-water depths from boring logs for geotechnical studies was obtained from the California Department of Transportation, the Bay Area Rapid Transit District, and from reports on file with several county and city governments in the region. 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 into which the stream is incised. We also used the depth of stream incision as a proxy default maximum depth to ground water. In making these measurements, we assumed that the stream bed was representative of the level of shallow ground water in the area. From those observations or boring log data we extrapolated water levels to areas with little available ground-water data. Levels in water wells were not used because these represent the potentiometric surface of the ground-water aquifer in which the well is completed, not the depth to shallow saturated sediment. Where historical high ground-water levels are known, we use those levels to ensure conservatism in our liquefaction susceptibility assignments. This use of historical high ground-water levels is consistent with CDMG's use of historical high ground-water levels in its Seismic Hazard Mapping Program.

Table 4. Criteria matrix for assigning liquefaction susceptibility units.
Units indicate relative susceptibility of deposits to liquefaction as a function of groundwater depth within that deposit. VH = very high, H = high, M = moderate, L = low, and VL = very low to none. The shaded boxes show the selected susceptibility assignment(s) for each geologic unit.

Geologic unit	Description	Historical occurrence of liquefaction in unit?	Estimated acceleration to trigger liquefaction in sandy and silty material (1)	Typical depth to ground water (ft)	Depth to groundwater (ft) and liquefaction susceptibility category assigned to geologic unit			
					<10	10 to 30	30 to 50	>50
af	Artificial fill (2)	yes	0.1g (3)	<10	**L (2)**	**L (2)**	to V	VL
afbm	Artificial fill over Bay Mud	yes	0.1g (3)	<10	**VH**	H	M	VL
alf	Artificial fill, levee	yes	0.1g (3)	<15	VH	**H**	M	VL
ads	Dredge spoils	no	0.1g (3)	<10	**VH**	VH	M	VL
gq	Gravel quarry	no	uncertain	variable	**H**	M	L	VL
ac	Artificial stream channel	no	uncertain	<5	**L**	L	L	L
Qhc	Modern stream channel deposits	yes	0.1g	<5	**VH**	H	M	VL
Qhfy	Latest Holocene alluvial fan deposits	yes	0.2g	<20	**VH**	H	M	L
Qhly	Latest Holocene alluvial fan levee deposits	yes	0.2g	<20	**VH**	H	M	L
Qhty	Latest Holocene stream terrace deposits	uncertain (4)	0.2g	<10	**VH**	H	M	L
Qhay	Latest Holocene alluvial deposits, undifferentiated	yes	0.2g	<10	**VH**	H	M	L
Qhfp	Late Holocene alluvial floodplain deposits, undifferentiated	no	0.2g	<10	**VH**	H	M	L
Qhfb	Late Holocene flood basin deposits	no	0.2g	<10	**H**	H	M	L
Qhbs	Holocene beach sand	yes	0.1g	<10	**VH**	H	M	VL
Qhds	Holocene dune sand	uncertain (4)	0.2g	<20	VH	**H**	M	VL
Qhbm	Holocene San Francisco Bay mud	yes	0.2g	<5	**H**	H	M	VL
Qhdm	Holocene San Joaquin/ Sacramento Delta mud and peat	uncertain (4)	0.2g	<5	**H**	H	M	VL
Qhb	Holocene basin deposits	uncertain (4)	0.2 to 0.4g	<10	**H**	M	L	VL
Qhfe	Holocene fine grained alluvial fan-estuarine complex deposits	yes	0.2 to 0.4g	<10	**H**	M	L	VL
Qhf	Holocene alluvial fan deposits	yes	0.3 to 0.5g	<15	M	**M**	L	VL
Qhff	Holocene alluvial fan deposits, fine facies	yes	0.3 to 0.5g	<10	**H**	M	L	VL
Qhl	Holocene alluvial fan levee deposits	yes	0.3 to 0.5g	<15	M	**M**	L	VL

Table 4 (continued). Criteria matrix for assigning liquefaction susceptibility units.
Units indicate relative susceptibility of deposits to liquefaction as a function of groundwater depth within that deposit. VH = very high, H = high, M = moderate, L = low, and VL = very low to none. The shaded boxes show the selected susceptibility assignment for each geologic unit.

Geologic unit	Description	Historical occurrence of liquefaction in unit? (see table 5)	Estimated acceleration to trigger liquefaction in sandy and silty material (1)	Typical depth to groundwater (ft)	Depth to groundwater (ft) and liquefaction susceptibility category assigned to geologic unit			
					<10	10 to 30	30 to 50	>50
Qht	Holocene stream terrace deposits	yes	0.2 to 0.3g	<10	H	H	M	VL
Qha	Holocene alluvium, undifferentiated	yes	0.2 to 0.5g	<10	H	H	M	VL
Qds	Latest Pleistocene to Holocene dune sand	yes	>0.3g	<25	M	M	L	VL
Qb	Latest Pleistocene to Holocene basin deposits	no	>0.3g	<15	M	L	L	VL
Qf	Latest Pleistocene to Holocene alluvial fan deposits	yes	>0.3g	<25	M	L	L	VL
Ql	Latest Pleistocene to Holocene alluvial fan levee deposits	no	>0.3g	<25	M	L	L	VL
Qt	Latest Pleistocene to Holocene stream terrace deposits	no	>0.3g	<15	M	M	L	VL
Qa	Latest Pleistocene to Holocene alluvium, undifferentiated	yes	>0.3g	<15	M	M	L	VL
Qpb	Latest Pleistocene basin deposits	no	uncertain	<20	L	L	VL	VL
Qpf	Latest Pleistocene alluvial fan deposits	yes	>0.5g	<30	L	L	VL	VL
Qpt	Latest Pleistocene stream terrace deposits	no	>0.5g	<30	L	L	VL	VL
Qpa	Latest Pleistocene alluvium, undifferentiated	no	>0.5g	<30	L	L	VL	VL
Qmt	Pleistocene marine terrace deposits	uncertain (4)	uncertain	<30	L	L	VL	VL
Qop	Early to late Pleistocene pediment deposits	no	uncertain	<40	L	VL	VL	VL
Qof	Early to late Pleistocene alluvial fan deposits	no	>0.6g	<40	L	VL	VL	VL
Qot	Early to late Pleistocene stream terrace deposits	no	>0.6g	<40	L	VL	VL	VL
Qoa	Early to late Pleistocene alluvium, undifferentiated	uncertain (4)	>0.6g	<40	L	VL	VL	VL
br	Bedrock	no	NA	variable	VL	VL	VL	VL

Notes:
(1) Based on the Simplified Seed approach (Seed and Idriss, 1982, Youd and Idriss, 1997) and a limited number of borehole analyses for some units.
(2) The liquefaction susceptibility of artificial fill ranges widely, depending largely on the nature of the fill and whether it was compacted. We use very high susceptibility for all fill on the margins of the San Francisco Bay (afbm), and somewhat arbitrarily assign a low susceptibility to all upland fills (af). Liquefaction susceptibility assignments for fewer than ten artificial fill (af) polygons are shown as VH of H, based on the occurrence of liquefaction in these areas.
(3) Assuming non-engineered fill.
(4) These occurrences are either not well located, or are poorly characterized in historical accounts and may not have been liquefaction related.

RESULTS

Quaternary deposits in the region occur in many settings, including: (1) northwest-trending, structurally controlled valleys; (2) alluvial piedmonts sloping away from the flanks of northwest-trending mountainous ranges; (3) areas of primarily latest Pleistocene sand dunes on the northern San Francisco Peninsula, in the Oakland area, and near the Sacramento/San Joaquin Delta; (4) deltaic, beach and marine terrace environments along the Pacific coast; and (5) estuarine environments around the margins of San Francisco Bay and the Sacramento/San Joaquin Delta. Large northwest-trending valleys, such as those adjacent to Walnut Creek, Coyote Creek, Guadalupe Creek, Russian River, and Napa River, contain sediment deposited by streams on flood plains, alluvial fans, and basins. Sedimentary deposits in smaller intermontane valleys are similar to those of the larger valleys, but are thinner and smaller in areal extent. Along the west side of the East Bay hills, coalescing alluvial fans have formed a broad alluvial piedmont that extends from Richmond southeast past Oakland and Fremont. Eolian deposits mantle the northern San Francisco Peninsula and interfinger with bay margin sediment along the shoreline near Oakland and Antioch (Atwater and others, 1977; Rogers and Figuers, 1991). Coastal and estuarine areas contain deltaic sediment, beach and dune sand, and marine terrace deposits.

Appendix A presents descriptions of the Quaternary stratigraphic units mapped in the region. Figure 2 shows the stratigraphic relations among the units, and table 2 compares the stratigraphic units with those of previous researchers in the area. We characterize engineering geologic properties of some of the units in a preliminary way using subsurface information gathered by WLA in consulting investigations and by the CDMG Seismic Hazards Mapping Program in the areas of Oakland (Haydon and others, 1999), San Francisco (DeLisle and Real, 1994) and the San Jose East quadrangle (Clahan and others, 2000).

Man-made deposits cover approximately 2 percent of the region. These areas are mapped as either artificial fill (af), artificial fill over Bay Mud (afbm), artificial levee fill (alf), dredge spoils (ads), or gravel quarry and percolation pond (gq). Artificial fill over Bay Mud (afbm) is mapped where fill was placed over Bay Mud, bayward of the early historical extent of marshlands and bay (Nichols and Wright, 1971; Goals Project, 1999). Artificial levee fill (alf) was mapped where the map symbols for levees are shown on 7.5-minute U.S. Geological Survey topographic quadrangles. Artificial levee deposits (alf) may not differ significantly from the underlying material where this material is artificial fill over Bay Mud (afbm) or artificial fill (af). Atwater's (1982) mapping of dredge spoils (ads) was adopted in the San Joaquin/Sacramento Delta area. Dredge spoils (ads) may be very similar in nature to artificial fill over Bay Mud (afbm). The unit gravel quarry and percolation pond (gq) typically was mapped using information shown on 7.5-minute U.S. Geological Survey topographic or orthophoto quadrangles.

The region included within the nine counties bordering the San Francisco Bay is approximately 18,000 square kilometers in area. We map about 70 percent of this area as bedrock, about 19 percent as Holocene deposits, and about 9 percent as latest Pleistocene or latest Pleistocene to Holocene undifferentiated. Almost 6 percent of the area is mapped as Holocene alluvial fan deposits, the most areally extensive Quaternary unit. The units latest Pleistocene alluvial fan deposits, Holocene Bay Mud, and Holocene alluvial fan deposits fine grained facies, each account for between 3 and 4 percent of the total area.

Ground water

Liquefaction of sediment requires that the sediment be water saturated. For this regional characterization, we have estimated a typical depth to ground water for each Quaternary map unit (table 4). In more detailed work, in contrast, depth to water would be treated as a continuous and independent variable. 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 (for example, uplifted and dissected Pleistocene alluvial fans), and closer to the surface of topographically lower parts of the landscape (for example, Holocene basins and terraces). Pronounced seasonal changes in ground-water levels occur in the region, with variations as large as tens of feet. Thus, in order to use historical high ground-water levels consistently, we have sought information on 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, generally less than 10 to 15 feet. Soils characteristic of wet environments are mapped in many of these valleys, and the few data available on depth to ground water indicate shallow ground-water levels. Depths to ground water beneath marine terraces and dune sand can be significantly greater than beneath 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, equivalent to the elevation of the hills.

Historical liquefaction in the nine-county San Francisco Bay Region

Records of liquefaction-induced ground failures in the region are available for several historic earthquakes; including the two most damaging events: the 1906 San Francisco earthquake (M=8.3) (Youd and Hoose, 1978), and the 1989 Loma Prieta earthquake (M=7.1) (Plafker and Galloway, 1989; Seed and others, 1990; 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 (for example 1906) liquefaction (Dupré and Tinsley, 1990; Seed and others, 1990).

We have developed a preliminary spatial database of earthquake-induced ground effects in the San Francisco Bay Region (Appendix C) and compared the locations of past ground effects with the new digital Quaternary deposits map. The ground-failure database contains historical observations interpreted from Youd and Hoose (1978), and observations of liquefaction-related ground effects resulting from the 1989 Loma Prieta earthquake, (Tinsley and others, 1998). The ground effects database (Appendix C) is preliminary and will receive additional review and revision in the near future. Table 5 shows the results of our preliminary analysis relating the location of liquefaction-related ground effects in the San Francisco Bay Region to the Quaternary map units.

Table 5. Preliminary evaluation of relations between mapped occurrences of liquefaction and Quaternary geologic map units and liquefaction susceptibility assignments in the nine-county San Francisco Bay region.

Map unit symbol	# of occurrences pre-Loma Prieta	# of occurrences Loma Prieta	**Percent of total**	Regional liquefaction susceptibility assignments (1)	Map unit symbol	# of occurrences pre-Loma Prieta	# of occurrences Loma Prieta	**Percent of total**	Regional liquefaction susceptibility assignments (1)
af	11		**3**	L	Qhl	8		**2**	M
afbm	88	112	**47**	VH	Qht	3		**1**	H
alf	1	4	**1**	H	Qha	22		**5**	H
ads			**0**	VH	Qds	16		**4**	M
gq			**0**	H	Qb			**0**	L
ac			**0**	L	Qf	1		**0**	L
Qhc	14		**3**	VH	Ql			**0**	L
Qhfy	7		**2**	VH	Qt			**0**	M
Qhly	3	1	**1**	VH	Qa	12		**3**	M
Qhty			**0**	VH	Qpb			**0**	L
Qhay	8		**2**	VH	Qpf	2		**0**	L
Qhbs	1	3	**1**	VH	Qpt			**0**	L
Qhfp			**0**	VH	Qpa			**0**	L
Qhfb			**0**	H	Qmt	1		**0**	L
Qhds			**0**	VH	Qof			**0**	VL
Qhbm	17	1	**4**	H	Qop			**0**	VL
Qhdm			**0**	H	Qot			**0**	VL
Qhb			**0**	H	Qoa	9		**2**	VL
Qhfe		1	**0**	H	br (2)	31		**7**	VL
Qhf	12		**3**	M	water	14	13	**6**	---
Qhff	10		**2**	H					
					totals	291	135	100	---

Notes:

(1) See next section for discussion of liquefaction susceptibility categories; VH-very high; H-high; M-moderate; L-low; VL-very low.

(2) The occurrence of many liquefaction-induced ground failures in the map units bedrock and water is a reflection of the preliminary nature of the liquefaction occurrence database.

A prominent conclusion is that the map unit "afbm" (artificial fill over Bay Mud) has hosted about 50 percent of all historical liquefaction occurrences in the San Francisco Bay Region and about 80 percent of the liquefaction occurrences resulting from the Loma Prieta earthquake. For the Loma Prieta earthquake, the higher percentage may reflect that only low accelerations are needed to trigger liquefaction in this unit, and that most of the region experienced only relatively low accelerations from the Loma Prieta earthquake. In many of theses cases, however, it is not known whether the liquefaction was in the fill or in the underlying Bay Mud deposits. The high percentage of failures occurring in artificial fill over Bay Mud also may reflect amplification of the shaking by the soft Bay Mud.

Liquefaction susceptibility units

Tinsley and others (1985) defined liquefaction susceptibility units based on quantitative evaluation of SPT values from boreholes in the Los Angeles area. In their analyses, they assumed a relatively constant shaking hazard across the study area and also assumed that potential shaking levels everywhere within the Los Angeles region are sufficient to trigger liquefaction of susceptible materials. Deposits rated Very High and High by Tinsley and others (1985) are expected to capture most of the liquefaction that occurs in an earthquake of magnitude 6.5 or greater. Parts of deposits rated Moderate are expected to liquefy in a magnitude 8 event but not a magnitude 6.5 event, and deposits rated Low or Very Low are unlikely to liquefy, even in a magnitude 8 earthquake. Our liquefaction susceptibility methodology and categories parallel those of Tinsley and others (1985).

The liquefaction susceptibility units defined in this report are based on peak ground accelerations (PGA) necessary to trigger liquefaction and estimated ground-water levels for each map unit (table 4). The PGA values required to trigger acceleration that are presented in table 4 are estimates only, and are provided only to indicate relative levels of shaking necessary to liquefy different geologic units. Typical PGAs necessary to induce liquefaction of sandy or silty materials range from as low as 0.1 g for saturated artificial fill and modern stream channel deposits, to much greater than 0.5 to 0.6 g for saturated latest Pleistocene alluvial deposits.

On the basis of the liquefaction failures that occurred during past earthquakes, we expect that at least 80 percent of future liquefaction failures will take place in areas judged to have High or Very High susceptibilities. We expect that 20 percent or less of future liquefaction will take place in areas judged to be Moderate and Low, and that less than 1 percent will take place in areas judged Very Low. Geologic units known to have liquefied in previous earthquakes generally are assigned to the Very High category, although where either the location of the event or the actual occurrence of liquefaction is in question, we may have assigned the geologic unit to the “High” or “Moderate” susceptibility units, depending on the geologic unit.

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APPENDIX A

DESCRIPTION OF GEOLOGIC UNITS

by

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APPENDIX A. DESCRIPTION OF GEOLOGIC UNITS.

Map Symbol	Unit Name and Description
	MODERN (<150 YEARS) DEPOSITS.
af	**Artificial fill (historical).** Material deposited by humans other than artificial fill over Bay Mud (afbm), artificial levee fill (alf), dredge spoils (ads), and gravel quarries and percolation ponds (gq), which are mapped as separate units. 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 embankments, consisting of engineered fill up to approximately 100 feet thick, large earthen dams, and railroad grades. 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 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 alluvium that are too small to be mapped at the scale of 1:24,000. On the San Francisco Peninsula, identification and mapping of artificial fill primarily is based on previous mapping by Bonilla (1971, 1998), Schlocker, (1974), and Pampeyan (1993, 1994). 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 very low depending on (1) the nature and thickness of the fill materials, (2) whether the fill was engineered or non-engineered, and (3) its depth of saturation. Most fill 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 Bay Mud (afbm). Most artificial fill mapped in upland areas or comprising highway embankments or dams is assigned a low susceptibility because it is likely to be engineered and unsaturated. However, many bodies of artificial fill (af) were assigned High or Very High susceptibilities based on the historical occurrence of liquefaction within or near these bodies.
afbm	**Artificial fill over Bay Mud (historical).** Material deposited by humans over Bay Mud (Qhbm) or San Joaquin/Sacramento Delta mud and peat (Qhpm). 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 (Goldman, 1969). Mapping of artificial fill over Bay Mud is based on comparison of present shorelines with those of the mid 19th century as shown by Nichols and Wright (1971) and Sowers (1995, 1997, 1999), and, to a limited extent, on inspection of topographic maps and aerial photographs. 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 5-20 feet. Included within this unit

are small areas of estuarine deposits and Holocene alluvium that are too small to be mapped at the scale of 1:24,000. Levees and dikes mapped within this unit (alf) are based on identification of levees on U.S. Geological Survey 7.5-minute topographic quadrangles. These levee materials may not differ from the underlying artificial fill over Bay Mud material (afbm). Other unmapped levees and dikes likely exist within mapped bodies of this unit.

Liquefaction susceptibility is very high based on the numerous past occurrences of liquefaction in this unit. About half of all past occurrences of earthquake-induced liquefaction in the San Francisco Bay area occurred in artificial fill over Bay Mud. Over 80 percent of the liquefaction that was observed following the 1989 Loma Prieta earthquake occurred in this unit. Most fill emplaced over Bay 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 likely hydraulically emplaced. Where the material to be used as artificial fill was dredged or suctioned from sandy areas (for example near Oakland and the Golden Gate), the fill can be expected to 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 150 years ago. The mapped distribution of levee fill conforms to levees shown on the most recent U.S. Geological Survey 7.5-minute topographic quadrangles. Much of our mapping of this unit was compiled from recent mapping by Russ 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 high for all artificial levees, based on the abundance of older unengineered levees and their likelihood of saturation. Additionally, levees typically are placed in areas where the substrate is highly susceptible to liquefaction.

ads **Dredge spoils (historical).** This unit, mapped and described by Atwater (1982), consists of sand, locally laminated, and subordinate silt, clay, and peat, that has been deposited as hydraulic dredge spoils during attempts to widen, straighten, and/or deepen the Sacramento and San Joaquin Rivers. The large body of sand near the Montezuma Hills was probably emplaced between 1908 and 1941 (Atwater, 1982). This unit is mapped only in a few quadrangles within the San Joaquin/Sacramento Delta.

Liquefaction susceptibility of dredge spoils is very high based on the abundance of loose sand and probable high ground-water levels.

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.

Liquefaction susceptibility is high.

ac **Artificial stream channel (historical).** Modified stream channels including straightened or realigned channels, flood control channels, channels bordered by dikes or levees, 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 nonexistent in some concrete canals, to loose, unconsolidated sand, gravel and cobbles, similar to deposits of modern stream channel deposits (Qhc).

Liquefaction susceptibility is generally low, but varies with the design of the channel and the nature of the bank material. Adjacent levees or banks may be subject to lateral spreading into the channel if not well engineered.

Qhc **Modern 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 (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; even larger streams may not be delineated where mapping is at the 1:100,000 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 percent of boreholes in latest Holocene alluvium contain liquefiable materials, assuming ground-water levels at the surface, compared to 34 to 54 percent of boreholes in earlier Holocene alluvium. Matti and Carlson (1991) show that similar relations pertain in 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 was evaluated using aerial photographs and orthophotoquadrangles. Alluvial fan sediment is deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains. Most of the mapped latest Holocene alluvial fan deposits originate from a point partway down the alluvial fan slope. The stream channel typically is incised into older fan deposits near the fan apex, then gradually is less incised downfan, until the stream becomes unconfined and distributes young sediment across the toe of the fan. A good example of this is the Alameda Creek fan in Fremont and Union City. Sediment is moderately to poorly sorted and bedded, and may be composed of gravel, sand, silt and clay. Grain size generally fines downslope. Minimally developed soils on this unit are entisols and inceptisols.

Liquefaction susceptibility is very high because these deposits are loose and generally lack cohesion. Additionally, there have been a significant number of past occurrences of liquefaction in this unit. Ground water typically is less than 20 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, oral. 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. 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 downfan ("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 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 orthophotoquadrangles, 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 and especially the 1:100,000 map scales, 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.

Liquefaction susceptibility is very high based on the abundance of sandy, cohesionless sediment, high ground-water levels, and the presence of a free face at the channel banks, which makes lateral spreading likely. The relative lateral extent of many stream terrace deposits makes these deposits more likely to experience lateral spreading than alluvial fan deposits.

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 orthophotoquadrangles, 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 scales used in this project. Typical soils developed on these deposits are entisols (fluvents).

Liquefaction susceptibility is very 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 seacliff, 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.

LATE HOLOCENE (<3,000 YEARS).

Qhfp **Late Holocene alluvial floodplain deposits, undifferentiated**. Atwater (1982) mapped this unit in the western San Joaquin and Sacramento valleys to indicate a time-transgressive floodplain of the San Joaquin River. This unit is mapped on the Clifton Court Forebay and Woodward Island 7.5-minute quadrangles. Most, if not all, of this area has been inundated historically during large floods. Part of this area was covered historically with tidal-wetland peat, but underlying deposits have since been exhumed by wind erosion. Much of the area mapped by Atwater (1982) as late Holocene alluvial floodplain deposits is now protected by artificial levees (alf) and is farmed. These deposits are younger than, and lap onto, the Antioch-Oakley dune field, which may be coeval with the upper member of the Modesto Formation (Atwater, 1982) and some deposits mapped as the Merritt Sand by previous researchers. This unit includes abandoned oxbows, channels and interdistributary basins, flood basins and basin rims, distal alluvial fans, and low natural levees adjacent to the San Joaquin River. This unit generally slopes downstream at low gradients parallel to the San Joaquin River. Atwater's (1982) mapping of this unit is adopted with very few modifications. Soils formed on this unit include the Columbia, Sacramento, and Ramada soils of Retzer and others (1951).

Liquefaction susceptibility is very high because of the recency of inundation, high ground-water levels, and proximity to active stream channels.

Qhfb **Late Holocene flood-basin deposits** This unit (<3,000 years), mapped and described by Atwater (1982), formed in the supratidal reaches of basins flanking the Sacramento

River and in interdistributary basins cut off from tidal waters. Atwater (1982) mapped this map unit on four quadrangles: Courtland, Dozier, Liberty Island and Rio Vista within the nine-county area. Deposits are firm to stiff silty clay, clayey silt, and silt, commonly with $CaCO_3$ nodules and locally with black spherules (Mn and/or Fe oxides). Native vegetation was dominated by Scirpus acutus (tule). The deposits laterally grade into peaty mud and mud of tidal wetlands. Locally, the deposits are veneered with silty, reddish-brown alluvium of historic age, some of which may have resulted from hydraulic mining in the Sierra Nevada during the late 1800s. Cosby (1941) mapped this unit as Sacramento and Columbia-over-Sacramento soils.

Liquefaction susceptibility is high because of the recency of inundation, high ground-water levels, and proximity to active stream channels. Much of the sediment mapped within this unit is fine grained, and is not likely to liquefy. However, the deposits' youthfulness, high ground-water levels and presence of lenses and sheets of sandy material indicate a high susceptibility to liquefaction in places.

HOLOCENE (<10,000 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 is mapped in only a few places, typically 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.

In areas of high ground water or perched water conditions, such as beaches or dunes near water bodies, liquefaction susceptibility is 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 alluvium too small to be mapped at the map scales 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. Soils developed on estuarine deposits typically are histosols, aquic entisols or mollisols. Bay Mud is mainly latest 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 we map upstream of the confluence between the Sacramento and San Joaquin rivers.

Liquefaction susceptibility is high due to high ground-water levels (often tidally influenced) and the 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 5 percent of all observed occurrences of liquefaction in the San Francisco Bay Area have occurred within this unit.

Qhdm **Holocene San Joaquin/Sacramento Delta mud and peat**. Sediment deposited at or near sea level in the Sacramento/San Joaquin Delta that is presently, or was once tidal marsh. Mapping of this unit is based on Atwater's (1982) mapping of "Qpm – Peat and mud of tidal wetlands and waterways". Delta peat and mud typically have low bulk density and include silt, clay, and peat with minor sand (Atwater, 1982). This unit generally occupies historical lowlands (tidal wetlands and waterways) that are now dry because of the construction of dikes and levees. Delta mud is late Holocene in age with many areas still subject to modern deposition and flooding if levees are breeched. Much of the area mapped as Delta mud and peat is now below sea level because of historical subsidence and deflation of now unsaturated marsh surfaces. Soils are histosols, aquic entisols or mollisols and are mapped as Correra, Venice, Staten, Egbert, Ryde, Burns and Roberts soil series of Cosby (1941, in Atwater, 1982). Also included within this unit are small areas of artificial fill too small to be mapped at the scale of this project.

Liquefaction susceptibility is high because ground water is near the surface and there are many lenses of sand within the mud and peat.

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 drain into the basin. Interbeds of peat may also 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 high. 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.

Qhf **Holocene alluvial fan deposits.** Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains as debris flows, hyperconcentrated mudflows, or braided stream flows. Alluvial fan sediment includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Sediment clast size and general particle size typically decreases downslope from the fan apex. Many Holocene alluvial fans exhibit levee/interlevee topography, particularly the fans associated with creeks flowing west from the eastern San Francisco Bay Area hills [See Holocene alluvial fan levee deposits (Qhl) below]. Alluvial fan surfaces are steepest near their apex at the valley mouth, and slope gently basinward, 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, especially 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. Greater than 5 percent of the nine-county San Francisco Bay Area is covered by Holocene alluvial fan deposits; it is the most extensive Quaternary map unit in the region.

Liquefaction susceptibility is moderate where ground water is within 30 feet of the surface, which we believe to be the case for most Holocene alluvial fan deposits. Alluvial fan deposits are judged to be less susceptible to surface deformation from liquefaction than terrace deposits (Qht) of the same age because: (1) alluvial fan deposits have relatively poor sorting and coarse grain size; (2) alluvial fan deposits are typically lenticular, thus, liquefaction within alluvial fan deposits may be confined to small "pockets" of susceptible material; and (3) stream terrace deposits commonly have a free face as one boundary, making lateral spreading a hazard. Where an active channel is present but is not mapped through the fan because of the map scale, the liquefaction susceptibility may be underestimated.

Qhl **Holocene alluvial fan levee deposits.** 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.

Liquefaction susceptibility is moderate, similar to Holocene alluvial fan deposits. Where streams are incised, these deposits may be susceptible to lateral spreading.

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 downfan 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 high based on shallow ground water and the presence of lenses of coarse sandy material.

Qhfe **Holocene fine-grained 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 channel is mapped as a natural levee (Qhly), based on the shape of the 10-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.

Liquefaction susceptibility is high based on the presence of shallow ground water, historical inundation, and lenses of coarse material.

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. Typically, this unit is mapped where relatively smooth, undissected terraces are less than 25 to 30 ft above the active channel. Soils are typically entisols, inceptisols, and mollisols. Ground-water levels are generally within 10 ft of the surface, especially during the wet winter months. 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 alluvium (Qha and Qa) mapping units.

Liquefaction susceptibility is high because of the presence of loose, granular deposits and shallow ground water. 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, are not as susceptible to liquefaction, or to lateral spreading should liquefaction occur, as point bar deposits.

Qha **Holocene alluvium, 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 alluvium is mapped in relatively flat, smooth valley bottoms of small- to medium-sized drainages. 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 high to moderate, based on: (1) historical liquefaction occurrences (for example Colma Creek valley); (2) the presence of undifferentiated late Holocene channels and deposits; (3) high ground-water levels; (4) the presence of small unmapped, potentially unengineered bodies of artificial fill; and (5) a combination of the susceptibility assignments for channel, fan, terrace, and basin deposits (Qhc, Qhf, Qht, and Qhb). However, for purposes of this project, we assume that the liquefaction susceptibility of this unit is high.

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 were blown into dunes (Atwater and others, 1977). The deposits include the Merritt Sand in the Oakland area, the sand dunes that cover much of the northern San Francisco Peninsula, and the Antioch-Oakley dune field that Atwater (1982) maps as “Qm2e – Eolian deposits of the upper member of the Modesto Formation". These deposits (Qds) consist of fine to medium sand that is semiconsolidated and weakly cemented.

The Oakley-Antioch dune field is composed of materials having both Sacramento River and San Joaquin River origins. Atwater (1982) suggests that the dunes in the Antioch-Oakley dune field are likely 10,000 to 14,000 years old. In many areas, leveling of agricultural fields, fluvial reworking and inundation by alluvial fan materials has obscured the original dune morphology of these deposits. Soils formed on these deposits are typically entisols, and include the Piper and Oakley soil series of Cosby (1941). Depth to ground water varies, primarily with the height of the dune, but is generally greater than ten feet.

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. Deposits of this unit hosted about 4 percent of all observed occurrences of liquefaction. 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).

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.

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 might be 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 separately at the map scales used in this project.

Liquefaction susceptibility is generally low. Ground water is assumed to be greater than ten feet below the surface. Sediment in stream channels that have not been differentiated within this unit may be moderately susceptible to liquefaction.

Ql **Latest Pleistocene to Holocene alluvial fan levee deposits.** Levee deposits on smooth, relatively undissected alluvial fans where deposit age is uncertain. This unit is mapped on the southern part of the Alameda Creek fan. Here, although fan geomorphology is relatively youthful, a pre-Holocene age is suggested by the presence of a fault-related ridge that now blocks deposition on this part of the fan by Alameda Creek, as well as development of mollisols and alfisols on the levee surface.

Liquefaction susceptibility is low. Ground water is assumed to be greater than ten feet below the surface.

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 30 feet. This unit may include active stream channels that are too narrow to show separately at the map scales of this project. Sediment in the stream channel is dominantly gravel and sand.

Liquefaction susceptibility is low to high, where ground water is within 10 feet of the surface. The range in susceptibility is a reflection of the range or uncertainty in age of the terrace deposits. However, overall, the unit is assumed to have a moderate liquefaction susceptibility. Liquefaction susceptibility in undifferentiated channels within these deposits, especially in point bar deposits, is high.

Qa **Latest Pleistocene to Holocene alluvium, 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 20 feet. The moderate susceptibility assignment is a reflection of uncertainties and local variability in the both the nature and age of these deposits.

LATEST PLEISTOCENE (10,000 TO ~30,000 YEARS).

Qpb **Latest Pleistocene basin deposits**. This unit was mapped by Atwater (1982), who describes it as follows: "Older alluvium of Putah Creek is widely but sparsely exposed at the toe of the Putah Creek fan, most commonly in basins between stream-built ridges of younger alluvium. In the Saxon 7.5-minute quadrangle, …, it locally forms hills as much as 5 ft high and 100 to 1000 ft across, conceivably the remnants of steam-built ridges or an interglacial flood basin similar to Yolo Basin." Soils formed on this unit are San Ysidro and Antioch series (Bates, 1977).

Liquefaction susceptibility is low based on the age of the deposits and their fine-grained texture.

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 as debris flows, hyperconcentrated mudflows, or braided stream flows. 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 typically decreases downslope from the fan apex. Latest Pleistocene alluvial fan sediment is approximately 10 percent denser than Holocene alluvial fan sediment and has penetration resistance values about 50 percent greater than values for Holocene alluvial fan sediment (Clahan and others, 2000). Pleistocene alluvial fans may be veneered or incised by thin unmapped Holocene alluvial fan deposits. 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 late 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 20 feet below the surface. Deposits typically are very stiff to hard or medium dense to very dense (Haydon and others, 1999; Clahan and others, 2000).

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 alluvium, 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 alluvium is 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 (10,000 to 1.6 MYRS).

Qmt **Pleistocene marine terrace deposits.** Deposits on uplifted marine abrasion platforms along the Pacific Ocean. In many cases, we have not evaluated the age of the deposits (for example late versus middle or early Pleistocene), however, for much of the western San Francisco Peninsula, we have assigned relative ages by numbering the deposits 1 through 4. Sediment deposited on the strath platforms is typically greater than 10 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 unpublished mapping by K. Lajoie 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 and Sonoma County coasts.

Liquefaction susceptibility is low. Ground water is typically deeper than 20 feet, though areas may have perched ground water where marine sediment overlies relatively impermeable bedrock. Marine terrace sediment is typically too dense to liquefy.

EARLY TO LATE PLEISTOCENE (~30,000 to 1.6 MYRS).

Qop **Early to late Pleistocene pediment deposits.** Alluvial deposits that form a thin veneer on broad, planar erosional surfaces cut on bedrock or older sediment. 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. 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 late Pleistocene alluvial fan sediment was deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains as debris flows, hyperconcentrated mudflows, or braided stream flows. Because of the age of these deposits, the streams responsible for deposition of mapped bodies of early to late 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 late Pleistocene alluvium (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; Schlocker, 1974), which has been described as a marine, estuarine and fluvial, unconsolidated fine to medium sand with silt and clay. It also includes Pliocene to Pleistocene deposits shed off the flanks of Mt Diablo that have been previously mapped by Helley and Graymer (1997a and b).

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

br **Pre-Quaternary 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.

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APPENDIX B

RELATION OF SOIL SERIES TO QUATERNARY UNITS

by

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APPENDIX B:
RELATION OF SOIL SERIES TO QUATERNARY UNITS

Specific soil series typically are associated in the region with Quaternary deposits of specific age and environment of deposition. We used published soil information to help understand the age and nature of the Quaternary deposits. The first column in the following table lists the soil series known to occur on alluvial deposits in the San Francisco Bay Region, as mapped and described by soil scientists of the U. S. Department of Agriculture. The second column shows the soil classification, or a brief description of the soil, based on the soil survey. The third column shows the Quaternary map units that are associated with each of the soil series in this report. These associations are based on our interpretation of the description of soil-profile development, physical properties, parent material, and geomorphic setting presented in the soil surveys, and our observations of the typical geomorphic position occupied by each soil. After establishing these associations we were able to use the soil survey maps as a tool in interpreting the Quaternary geology. Soil-profile development was especially helpful in assigning age estimates to Quaternary deposits. Soil series boundaries were moderately helpful in defining Quaternary geologic contacts, but were less important than the interpretation of topography and aerial photography. For additional information on soil taxonomy or methods and nomenclature used by soil scientists, please refer to "Keys to Soil Taxonomy" (U.S. Department of Agriculture, Soil Survey Staff, 1994).

1. Santa Clara area

Soil survey reference: 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 1941, No. 17, 202 p., 2 map sheets at 1:50,000 scale.

Quadrangles covered: Milpitas, Mountain View, San Jose East, San Jose West, Cupertino, Los Gatos, Santa Teresa Hills, and parts of Lick Observatory, Calaveras Reservoir, Morgan Hill, Palo Alto, Mindego Hill, Castle Rock Ridge, and Loma Prieta.

Soil Series	Soil description	Typical Quaternary unit(s)
Alamitos	Black clay with mottled subsoil, often in a drained freshwater marsh	Qhfe, Qhff
Alviso	Saline clay at tidal marsh margin with calcareous subsoil	Qhfe, Qhff
Azule	Silty clay on old terraces, especially the Santa Clara formation	Qoa, Qof
Bayshore	Calcareous clay loam at basin margins, high groundwater	Qhfe, Qhff
Campbell	Dark gray clay loam to silty clay with mottled calcareous subsoil	Qhf , Qhff
Castro	Dark gray clay to silty clay with lime hardpan and mottling in the subsoil	Qhf, Qhff

Clear Lake	Dark gray clay with calcareous subsoil	Qhf, Qhff
Cropley	Dark gray gravelly clay loam to clay with calcareous subsoil	Qhf
Dublin	Dark gray clay to clay loam, non-calcareous subsoil	Qhf
Edenvale	Dark gray clay formed from alluvium derived from basic igneous rocks	Qhf
Milpitas	Brown acid loam to clay loam over reddish brown claypan	Qpa, Qoa
Mocho	Brown gravelly, sandy, or clay loam, deposited by major creeks	Qht, Qhty, Qhl, Qhly, Qhf, Qhfy Qhff
Orestimba	Grayish brown clay loam to silty clay loam with calcareous, mottled subsoil; some areas affected by alkali	Qhff, Qhf
Pescadero	Dark grayish brown clay with mottled, calcareous subsoil; some areas affected by alkali	Qhff, Qhf
Pleasanton	Brown gravelly loam to clay loam with compact subsoil	Qpf
Positas-Saratoga	Brown to reddish-brown acid loam to gravelly loam with claypan subsoil	Qoa
San Ysidro	Brown loam to clay loam with claypan subsoil, on same terraces with Pleasanton soils	Qpf
Sorrento	Brown gravelly, sandy, or silty loam to clay loam, recently deposited by creeks	Qhf, Qht, Qhl
Sunnyvale	Black clay to clay loam with strongly calcareous, mottled subsoil	Qhff, Qhb
Tidal marsh	Land periodically covered by the tide	Qhbm
Yolo	Brown gravelly or sandy loam to clay loam recently deposited by creeks	Qht, Qhty, Qhl, Qhly, Qhf, Qhfy
Zamora	Brown gravelly clay loam, silty clay loam, or clay loam with slightly compact subsoil	Qhf, Qht, Qhl

2. Eastern Santa Clara area

Soil survey reference: 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.

Quadrangles covered, or partially covered: Calaveras Reservoir, Mt. Day, Eylar Mountain, Mt. Boardman, Lick Observatory, Isabel Valley, Mt. Stakes, Morgan Hill, Mt. Sizer, Mississippi Creek, Mustang Peak, Mt. Madonna, Gilroy, Gilroy Hot Springs, Pacheco Peak, Pacheco Pass, Watsonville East, Chittendon, San Felipe, Three Sisters

Soil Series	**Soil Classification**	**Typical Quaternary unit(s)**
Arbuckle	Typic Haploxeralf	Qhf, Qf

Azule	Mollic Haploxeralf	Qoa, Qof
Campbell	Aquic Xerorthent	Qhf, Qhff
Clear Lake	Typic Pelloxerert	Qhf, Qhff
Cortina	Typic Xerofluvent	Qhf, Qhl, Qht, Qhty
Cropley	Chromic Pelloxerert	Qhf
Esparto	Typic Haploxeralf	Qhf, Qf
Garretson	Typic Xerorthent	Qht, Qhty, Qhl, Qhf
Hillgate	Typic Palexeralf	Qpf, Qpa, Qoa
Keefers	Mollic Haploxeralf	Qpf
Los Robles	Mollic Haploxeralf	Qpf, Qf
Maxwell	Typic Pelloxerert	Qhf, Qf
Pacheco	Aquic Haploxeroll	Qhf, Qhff
Pleasanton	Mollic Haploxeralf	Qpf, Qf
Rincon	Mollic Haploxeralf	Qpf, Qf, Qhf
San Ysidro	Typic Palexeralf	Qpf
Sunnyvale	Typic Calciaquoll	Qhf, Qhff
Willows	Typic Pelloxerert	Qhf, Qhff
Yolo	Typic Xerorthent	Qhf, Qht, Qhl, Qhfy, Qhly, Qhty
Zamora	Mollic Haploxeralf	Qhf, Qht, Qhl

3. Alameda area

Soil survey reference: Welch, L. E., Huff, R. C., Dierking, R. A., Cook, T. D., Bates, L. A., and Andrews, W. F., 1966, Soil survey of the 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

Quadrangles covered, or partially covered: Oakland East, Las Trampas Ridge, Tassajara, Byron Hot Springs, Bethany, Hayward, Dublin, Livermore, Altamont, Midway, Niles, La Costa Valley, Mendenhall Springs, Cedar Mountain, Milpitas

Soil Series	**Soil Description**	**Typical Quaternary unit(s)**
Azule	Grayish-brown clay loam with dark grayish-brown clay subsoil	Qoa, Qof

Clear Lake	Dark gray clay with calcareous silty clay subsoil	Qhf, Qhff, Qhb
Danville	Grayish-brown silty clay loam	Qhf
Livermore	Brown, gravelly, sandy loam	Qht, Qhty, Qhf, Qhfy
Pescadero	Gray clay, alkaline	Qhb, Qhff
Pleasanton	Grayish-brown gravelly loam with brown gravelly clay loam subsoil	Qpf, Qf
Positas	Brown gravelly loam with reddish-brown clay subsoil	Qoa
Rincon	Grayish-brown clay loam with brown clay subsoil	Qpf, Qf, Qhf
San Ysidro	Pale brown massive loam with hard, brown clay subsoil	Qpf
Solano	Pale brown fine sandy loam, saline-alkaline	Qhf, Qhff, Qhb
Sunnyvale	Gray clay loam with strongly calcareous silty clay subsoil with mottles	Qhf, Qhff, Qhb
Sycamore	Light brownish-gray silt loam	Qhf, Qhff
Yolo	Loam to sandy or gravelly loam	Qhf, Qht, Qhl, Qhfy, Qhly, Qhty
Zamora	Grayish brown silty clay loam with clay loam subsoil	Qhf, Qht, Qhl

4. Western Alameda County

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

Quadrangles covered, or partially covered: Oakland West, Oakland East, San Leandro, Hayward, Newark, Niles, Milpitas

Soil Series	**Soil Classification**	**Typical Quaternary unit(s)**
Azule	Mollic Haploxeralf	Qoa, Qof
Botella	Pachic Argixeroll	Qhf , Qhff
Clear Lake	Typic Pelloxerert	Qhf, Qhff
Danville	Pachic Argixeroll	Qhf
Lagenour	Aeric Fluvaquent	Qhf
Marvin	Aquic Haploxeralf	Qhf, Qhff
Pescadero	Aquic Natrixeralf	Qhb, Qhf
Pleasanton	Mollic Haploxeralf	Qpf, Qf

Reyes	Sulfic Haplaquept	Qhbm
Rincon	Mollic Haploxeralf	Qf, Qhf, Qpf
Sycamore	Aeric Haplaquept	Qhf, Qhfy
Tierra	Mollic Palexeralf	Qoa
Willows	Typic Pelloxerert	Qhf, Qhff, Qhb
Yolo	Typic Xerorthent	Qhf, Qhl, Qht, Qhfy, Qhly, Qhty

5. Contra Costa County

Soil survey reference: Welch, L. E., 1977, Soil survey of 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.

Quadrangles covered, or partially covered: Mare Island, Benecia, Port Chicago, Honker Bay, Antioch North, Jersey Island, Bouldin Island, San Quentin, Richmond, Briones Valley, Walnut Creek, Clayton, Antioch south, Brentwood, Woodward Island, Oakland East, Las Trampas Ridge, Diablo, Tassajara, Byron Hot Springs, Bethany, Dublin

Soil Series	Soil Classification	Typical Quaternary unit(s)
Antioch	Typic Natrixeralf	Qpf, Qf
Botella	Pachic Argixeroll	Qhf
Brentwood	Typic Xerochrept	Qhf, Qha
Capay	Typic Chromoxerert	Qf, Qhf, Qhff
Clear Lake	Typic Pelloxerert	Qhf, Qhff, Qhb, Qf
Conejo	Pachic Haploxeroll	Qhf
Cropley	Chromic Pelloxerert	Qha, Qhf, Qa
Delhi	Typic Xeropsamment	Qps, Qhs
Garretson	Typic Xerorthent	Qht, Qhty, Qha, Qhay, Qhf, Qhfy
Lagenour	Aeric Fluvaquent	Qht, Qhty, Qha, Qhay, Qhf, Qhfy
Los Robles	Typic Xerochrept	Qhf
Merritt	Fluvaquentic Haploxeroll	Qha
Omni	Fluvaquentic Haplaquoll	Qhf, Qhff
Pescadero	Aquic Natrixeralf	Qhff, Qhb

Positas	Mollic Palexeralf	Qoa
Rincon	Mollic Haploxeralf	Qpf, Qf, Qhf
Sacramento	Vertic Haplaquoll	Qhfb
San Ysidro	Typic Palexeralf	Qpf
Solano	Typic Natrixeralf	Qhf, Qhff, Qhb
Sorrento	Calcic Haploxeroll	Qhf
Sycamore	Aeric Haplaquept	Qhf , Qhff, Qhfb
Zamora	Mollic Haploxeralf	Qhf, Qht, Qhl, Qf

6. Solano County

Soil survey reference: Bates, Leland A., 1977, Soil survey of Solano County, California: United States Department of Agriculture, Soil Conservation Service, 112 p., 54 map sheets at 1:24,000 scale.

Quadrangles covered, or partially covered: Mount Vaca, Allendale, Dixon, Saxon, Mount George, Fairfield North, Elmira, Dozier, Liberty Island, Cordelia, Fairfield South, Denverton, Birds Landing, Rio Vista, Mare Island, Benicia, Port Chicago, Honker Bay, Antioch North, Jersey Island

Soil Series	Soil Classification	Typical Quaternary unit(s)
Alviso	Typic fluvaquent	Qhb, Qhdm, Qhbm
Antioch	Typic Natrixeralf	Qpf, Qf
Brentwood	Typic Xerochrept	Qhf, Qha, Qhay
Capay	Typic Chromoxerert	Qhf, Qhff
Clear Lake	Typic Pelloxerert	Qhf, Qhff
Columbia	Aquic xerofluvent	Qht, Qhty, Qhay, Qhfp
Conejo	Pachic Haploxeroll	Qhf
Corning	Typic Palexeralf	Qoa
Egbert	Fluvaquentic Haplaquoll	Qhff
Joice	Typic Medisaprist	Qhbm, Qhdm
Omni	Fluvaquentic Haplaquoll	Qhff, Qhf
Pescadero	Aquic Natrixeralf	Qhff

Reiff	Typic Xerofluvent	Qhf
Reyes	Sulfic Haplaquepts	Qhdm, Qhbm
Rincon	Mollic Haploxeralf	Qpf, Qf, Qhf
Ryde	Cumulic Haplaquoll	Qhdm
Sacramento	Vertic Haplaquoll	Qhff, Qhfb
San Ysidro	Typic Palexeralf	Qpf, Qpb
Solano	Typic Natrixeralf	Qhf, Qhff, Qpf
Sycamore	Aeric Haplaquept	Qhf, Qhfy
Willows	Typic Pelloxerert	Qhf, Qhff
Yolo	Typic Xerochrept	Qhf, Qhfy, Qhl, Qhly, Qht, Qhty, Qha, Qhay

7. Sonoma County

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

Quadrangles covered, or partially covered: Gualala, Ornbaum Valley SW, McGuire Ridge, Gube Mountain, Big Foot Mountain, Asti, The Geysers, Whispering Pines, Stewarts Point, Annapolis, Tombs Creek, Skaggs Springs, Geyserville, Jimtown, Mount St. Helena, Plantation, Fort Ross, Cazadero, Guerneville, Healdsburg, Mark West Springs, Calistoga, Arched Rock, Duncan Mills, Camp Meeker, Sebastopol, Santa Rosa, Kenwood, Rutherford, Bodega Head, Valley Ford, Two Rock, Cotati, Glen Ellen, Sonoma, Point Reyes SE, Petaluma, Petaluma River, Sears Point, Petaluma Point

Soil Series	Soil Classification	Typical Quaternary unit(s)
Arbuckle	Mollic Haploxeralf	Qf, Qpf
Baywood	Pachic Haploxeroll	Qds, Qmt
Blucher	Typic Haplaquoll	Qhf, Qha, Qhb
Clear Lake	Typic Pelloxerert	Qhf, Qhff, Qhb
Cole	Pachic Argixeroll	Qhf, Qha, Qht
Cortina	Typic Xerofluvent	Qhf, Qhfy, Qht, Qhty, Qhc
Haire	Abruptic Palexeroll	Qoa
Huichica	Abruptic, Haplic Durixeralf	Qoa

Los Robles	Mollic Haploxeralf	Qf, Qpf
Pajaro	Typic Haplaquoll	Qhf, Qha, Qhb
Pleasanton	Mollic Haploxeralf	Qpf, Qpa, Qf
Positas	Mollic Palexeralf	Qoa, Qof, Qot, Qpa, Qpf, Qpt
Reyes	Fluventic Haplaquept	Qhbm
Rohnerville	Typic Tropohumult	Qmt
Wright	Typic Albaqualf	Qoa, Qb
Yolo	Typic Xerorthent	Qhf, Qhfy, Qht, Qhty, Qha, Qhay, Qhl, Qhly
Zamora	Mollic Haploxeralf	Qf, Qt, Qa, Qhf, Qha, Qht

8. Napa County

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

Quadrangles covered, or partially covered: Jericho Valley, Knoxville, Detert Reservoir, Aetna springs, Walter Springs, Brooks, Calistoga, St. Helena, Chiles Valley, Lake Berryessa, Kenwood, Rutherford, Yountville, Capell Valley, Sonoma, Napa, Mt. George, Fairfield North, Cuttings Wharf, Cordelia

Soil Series	Soil Classification	Typical Quaternary unit(s)
Bale	Cumulic Ultic Haploxeroll	Qhf, Qha, Qht
Clear Lake	Typic Pelloxerert	Qhf, Qhff, Qhb
Cole	Pachic Argixeroll	Qha, Qhf, Qht
Coombs	Ultic Haploxeralf	Qoa, Qof, Qpa, Qpf
Cortina	Typic Xerofluvent	Qhf, Qhfy, Qht, Qhty, Qhc
Egbert	Cumulic Haplaquoll	Qhff, Qhf
Haire	Typic Haploxerult	Qoa
Maxwell	Typic Pelloxerert	Qhff, Qhf, Qf

Perkins	Mollic Haploxeralf	Qf, Qhf
Pleasanton	Mollic Haploxeralf	Qpf, Qpa, Qf
Reyes	Fluventic Haplaquept	Qhbm
Yolo	Typic Xerorthent	Qhf, Qhfy, Qht, Qhty, Qha, Qhay, Qhl, Qhly
Zamora	Mollic Haploxeralf	Qf, Qt, Qa, Qhf, Qha, Qht

9. Marin County

Soil survey reference: Kashiwagi, James H., 1985, Soil Survey of Marin County, California: United States Department of Agriculture, Soil Conservation Service, 229 p., 13 map sheets at 1:24,000 scale.

Quadrangles covered, or partially covered: Valley Ford, Two Rock, Tomales, Point Reyes NE, Petaluma, Petaluma River, Drakes Bay, Inverness, San Geronimo, Novato, Double Point, Bolinas, San Rafael, San Quentin, Point Bonita, San Francisco North

Soil Series	**Soil Classification**	**Typical Quaternary unit(s)**
Ballard	Typic Argixeroll	Qhf, Qht
Blucher	Fluvaquentic Haploxeroll	Qhf, Qha, Qhay, Qhfy
Clear Lake	Typic Pelloxerert	Qhb, Qhf
Cole	Pachic Argixeroll	Qhf, Qha, Qhay, Qhfy
Cortina	Typic Xerofluvent	Qhf, Qhfy
Fluvents, channeled	Fluvent	Qhc, Qhay
Olompali	Ultic Palexeralf	Qmt
Reyes	Sulfic Fluvaquent	Qhbm
Rodeo	Aquic Paleustoll	Qa
Sirdrak	Ustic Dystropept	Qds

10. Western San Mateo County

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

Quadrangles covered, or partially covered: Montara Mountain, Half Moon Bay, Woodside, San Gregorio, La Honda, Mindego Hill, Pigeon Point, Franklin Point, Big Basin, Ano Nuevo

Soil Series	**Soil Description**	**Typical Quaternary unit(s)**
Baywood	Gray sandy loam formed from eolian sand blown from beaches	Qmt, Qds
Botella	Very dark gray loam over dark grayish brown clay loam with subangular blocky structure	Qha, Qht, Qhf, Qa, Qt, Qf
Corralitos	Grayish brown sandy loam over stratified sand or loamy sand (entisol)	Qhf, Qht, Qha, Qhfy, Qhty, Qhay
Denison	Dark-colored clay loam on granitic alluvium (mollisol to vertisol)	Qht, Qhf, Qha
Dublin	Dark-colored clay on sedimentary alluvium	Qhf, Qha, Qht
Elkhorn	Dark gray sandy loam over brown medium acid sandy clay loam with blocky structure	Qmt
Farallone	Dark-gray loamy coarse sand to loam (mollisol)	Qhf, Qha, Qht
Lockwood	Gray loam over grayish brown slightly acid clay loam, on alluvium derived from siliceous shale	Qf, Qa, Qt
Soquel	Dark-colored loam over stratified alluvial sediments derived from sedimentary rocks and older soils	Qha, Qht, Qhf
Tunitas	Dark-colored loam to clay loam on alluvium derived from sedimentary and basic igneous rocks	Qf, Qa, Qt, Qha, Qht, Qhf
Watsonville	Dark gray acid loam with a light gray leached horizon over a yellow-brown clay pan subsoil	Qmt

11. Eastern San Mateo County and San Francisco County

Soil survey reference: Kashiwagi, J. H., and Hokholt, L. A., 1991, Soil Survey of San Mateo County, eastern part, and San Francisco County, California: United States Department of Agriculture, Soil Conservation Service, 120 p., 12 map sheets at 1:24,000 scale.

Quadrangles covered, or partially covered: San Mateo, Mountain View, Woodside, Mindego Hill, La Honda, Montara Mountain, Redwood Point, Hunters Point, San Francisco South, Oakland West, San Francisco North

Soil Series	**Soil Description**	**Typical Quaternary unit(s)**
Botella	Pachic Argixeroll	Qha, Qht, Qhf, Qa, Qt, Qf, Qpf, Qpa
Francisquito	Typic Haploxeralf	Qpf, Qpa, Qoa, br
Novato	Typic Hydraquent	Qhbm

Reyes	Sulfic Fluvaquent	Qhbm
Sirdrak	Ustic Dystropept	Qds
Typic Argiustoll	Typic Argiustoll	Qmt

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APPENDIX C

A PRELIMINARY DIGITAL COMPENDIUM OF GROUND EFFECTS ASSOCIATED WITH EARTHQUAKES IN THE SAN FRANCISCO BAY REGION

prepared by

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from the work of

Youd and Hoose, 1978, and Tinsley and others, 1998

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INTRODUCTION

Ground effects such as sand boils, lateral spreads, and landslides have been associated with numerous damaging earthquakes in the San Francisco Bay region, particularly the 1906 San Francisco and 1989 Loma Prieta earthquakes. Knowledge of the location and character of past ground failures provides a guide to their future occurrence, particularly through association with the various Quaternary map units in the region. Past effects have been mapped and compiled for northern California by Tinsley and others (1998) for the 1989 Loma Prieta earthquake and by Youd and Hoose (1978) for previous historic earthquakes.

We have assembled this information in a digital database for the nine-county San Francisco Bay region as points, lines, and polygons (areas) with associated attributes, working from the published 1:100,000- and 1:24,000-scale maps of Tinsley and others (1998) and from 1:24,000-scale relocations of the historic data catalogued by Youd and Hoose (1978). The locations, station numbers, and summary of effects are shown on map sheet 2, Liquefaction Susceptibility, and are included in the database. Original station numbers from the two source documents are recorded in the database and shown on the map to facilitate recovery of complete descriptions for each station.

Youd and Hoose (1978) include landslides in their compilation and refer to the earthquake effects in aggregate as "ground failures", whereas Tinsley and others (1998) exclude landslides and refer in aggregate to "ground effects". We follow our sources by including catalogued historic landslides that were caused by earthquakes prior to 1989 but not Loma Prieta landslides, and refer in aggregate to ground effects, recognizing that many are ground failures and presuming that all but the landslides are probably related to earthquake-triggered liquefaction. No distinction is made here between ground failures due to liquefaction and those caused by deformation of soft clay. More complete information about earthquake-related landslides in the region can be obtained from Keefer, 1998, and references cited therein.

There are inherent difficulties in converting locations and descriptions from the source documents into precise digital spatial data because of uncertainties in the location, the areal extent around points and along and across mapped lines, and the limits to mapped areas. This is particularly true for the historic dataset. The database as a whole has a scale resolution no better than 1:100,000, although some map elements are more accurately located, particularly the San Francisco localities digitized at 1:24,000. The accuracy of location for each digital element is categorized by individual mapped occurrence in the database. These uncertainties in location require that the digital data not be used blindly, especially in precise GIS operations, and that the resolution of the data be respected.

Design of the database, digital encoding of the Loma Prieta data, and preparation of the final aggregate database and its graphic representation are the responsibility of Wentworth and Nicholson; relocation, interpretation, and digital encoding of the historic data are the responsibility of Wong, Aue, and Knudsen.

HISTORIC GROUND EFFECTS

Youd and Hoose (1978) catalogued and interpreted descriptions of observed ground effects in northern California for several major earthquakes and the great 1906 San Francisco earthquake from many sources, including newspaper articles and earlier technical reports. Within the nine-county region, the ground failures catalogued by Youd and Hoose (1978) occurred during the period 1838 through 1969. Sites of the catalogued effects were numbered and located on topographic maps using symbols representing the different types of effects. The maps are at a scale of 1:250,000 except for localities within the City of San Francisco, which are shown at 1:24,000. Accuracy of location was rated in three categories (table 1), and descriptions from the original compilation sources were quoted.

Table 1. Location-Accuracy Categories of Youd and Hoose (1978).

A	"a site that can be accurately relocated"
B	"a site that can be relocated to within a few kilometers and probably could be located more accurately with further investigation"
C	"a site where the information is insufficient to allow precise location"

Relocation

Many of the historic sites of Youd and Hoose (1978) can be placed more accurately at 1:24,000 than is shown on the 1:250,000 maps through comparison of the quoted descriptions in their tables 6, 7, and 8 with more detailed topographic maps. In relocating sites by reference to cultural features, the earliest available 1:62,500- and 1:24,000-scale maps are used, because some bridges and roads have been moved during the past century and some cultural features identified in the descriptions are shown only on earlier maps or are renamed on more recent maps. Modern 1:24,000 contours are used where location was described in terms of topography and where the location of landslides can be estimated from their topographic expression.

A few localities that experienced liquefaction were placed by the descriptions in areas of exposed bedrock. Where possible, these localities are moved onto nearby surficial deposits using recent geologic maps. The extent of ground failure was described numerically for a few locations, and this information is recorded in the extent field (EXT) of the database.

The accuracy of each relocation is separately rated according to the categories of table 2. These accuracies are specific to the individual relocated map elements (points, lines, areas), whereas the Youd and Hoose accuracies refer to their numbered localities, which can include several ground effects that are distinguishable at 1:24,000.

Table 2. Relative Accuracy of Relocated Historic Effects

P	located to within 100 meters
Q	located to within 500 meters
R	located to within 1 kilometer
S	location is indefinite or approximate

Digital Representation

Relocated occurrences of the historic ground effects are represented by points, lines, and polygons that have been digitized at a scale of 1:24,000. Station numbers are those of Youd and Hoose, and therefore are not unique identifiers of the relocated occurrences where more than one mapped occurrence has been extracted from one Youd and Hoose locality.

Accuracy ratings are reported as presented by Youd and Hoose (table 1), and where different table entries for the same locality were given different ratings, these are aggregated for the locality (for example, ‘B,C’) and are assigned to each of the relocated occurrences for that locality. Accuracy ratings for the relocated occurrences (table 2) are separately assigned. The resulting accuracy ratings for each map element in the ACC database field thus have two parts, a Youd-and-Hoose rating followed by a relocation rating, the two separated by a colon (for example ‘A:P’).

Points are used to record the location of small features that cannot be shown as polygons at 1:24,000 and for occurrences that cannot be accurately located, including areas that are only generally identified or have unspecified dimensions, such as landslides.

Lines are used to record linear features or a continuous or intermittent series of occurrences described along a linear feature such as a stream or road or along a linear trend. Locations are approximate along the lines and width of occurrence is generally unspecified. The locations of the ends of the lines are generally only approximate.

Polygons are used to record areas having identifiable boundaries and a size sufficient to show at 1:24,000. Where boundaries cannot be delineated with reasonable confidence, a point is used. Typically, the polygon areas represent the distribution of discontinuous effects, such as scattered sand boils.

LOMA PRIETA GROUND EFFECTS

Tinsley and others (1998) present the map location of liquefaction and associated effects triggered by the 1989 Loma Prieta earthquake for much of the region at a scale of 1:100,000 and for San Francisco at 1:24,000, and provide tabular descriptions of the mapped occurrences. The occurrences range from Richmond Harbor and Bolinas Lagoon south to the Salinas Valley, but only those within the nine-county San Francisco Bay region are included here. In contrast to the historic dataset, the Loma Prieta effects were carefully mapped soon after the earthquake, making relocation from the descriptions unnecessary (except for some lines, see Digital Representation below).

Many of the map locations were presented by Tinsley and others (1998) as numbered station points with associated effect symbols, but other point locations lack the station point and have less certain locations. Some station points are accompanied by arrows designating the extent of the effect (for example, along a road or stream), although none of these occur within the nine-county region. Areas of sand boils are shown by regular patterns of dots, the boundaries of most of which seem to have been carefully delimited. Some of these patterned areas are irregular in shape, others involve two parallel lines of dots along a linear feature such as a highway. One other area of indistinct perimeter is shown by a group of five different effect symbols (station 50).

Digital Representation

The locations of the occurrences are represented as points, lines, and polygons that have been digitized from the published 1:100,000- and 1:24,000-scale maps. These maps provide the most accurate source available for the dataset (Tinsley, oral commun., 2000). Station numbers are as assigned by Tinsley and others (1998). Accuracy ratings are assigned according to the relocation categories of table 2, based on the kind of map representation presented by Tinsley and others. Stations with location points, all lines, and well delineated areas are rated P, whereas stations without location points and the indistinctly defined area (station 50) are rated Q.

Most stations are represented by points in the database, including localities without location points. All areas on the source maps are shown as polygons in the database, except for several patterned areas that seem from the descriptions to represent extents along roads or other linear features; these are represented in the database as lines drawn along those linear features on the published maps.

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