MAPS SHOWING QUATERNARY GEOLOGY AND LIQUEFACTION SUSCEPTIBILITY, NAPA, CALIFORNIA, 1:100,000 QUADRANGLE: A DIGITAL DATABASE

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I. PURPOSE OF THE PROJECT

Earthquake-induced ground failures such as liquefaction have historically brought loss of life and damage to property and infrastructure. Observations of the effects of historical large-magnitude earthquakes show that the distribution of liquefaction phenomena is not random. Liquefaction is restricted to areas underlain by loose, cohesionless sands and silts that are saturated with water. These areas can be delineated on the basis of thorough geologic, geomorphic, and hydrologic mapping and map analysis (Tinsley and Holzer, 1990; Youd and Perkins, 1987). Once potential liquefaction zones are delineated, appropriate public and private agencies can prepare for and mitigate seismic hazard in these zones.

In this study, we create a liquefaction susceptibility map of the Napa 1:100,000 quadrangle using Quaternary geologic mapping, analysis of historical liquefaction information, groundwater data, and data from other studies. The study is patterned after state-of-the-art studies by Youd (1973) Dupré and Tinsley (1980) and Dupré (1990) in the Monterey-Santa Cruz area, Tinsley and others (1985) in the Los Angeles area, and Youd and Perkins (1987) in San Mateo County, California.

The study area comprises the northern San Francisco Metropolitan Area, including the cities of Santa Rosa, Vallejo, Napa, Novato, Martinez, and Fairfield (Figure 1). Holocene estuarine deposits, Holocene stream deposits, eolian sands, and artificial fill are widely present in the region (Helley and Lajoie, 1979) and are the geologic materials of greatest concern. Six major faults capable of producing large earthquakes cross the study area, including the San Andreas, Rodgers Creek, Hayward, West Napa, Concord, and Green Valley faults (Figure 1).

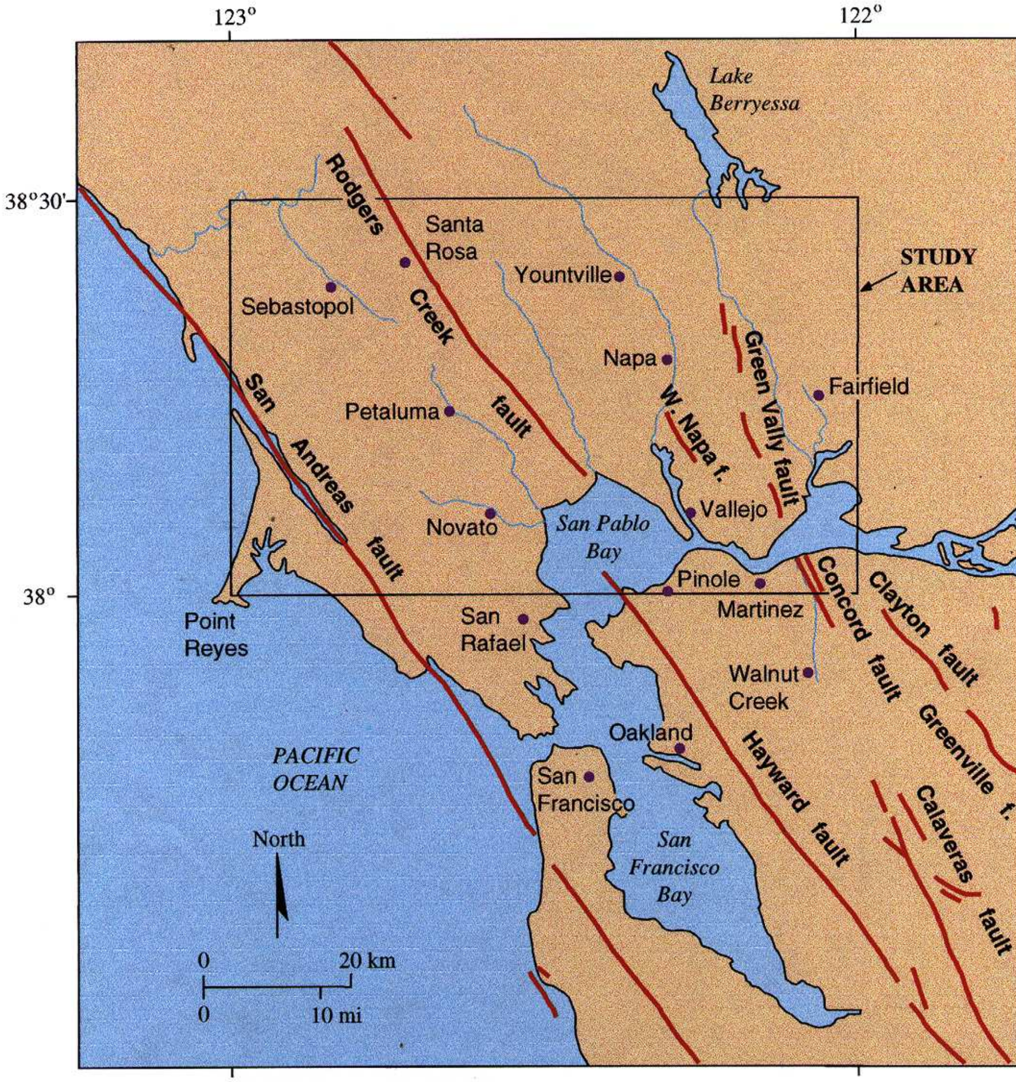

Figure 1. Location of the Napa 1:100,000 quadrangle in the San Francisco Bay area, showing active faults. Faults shown are those along which Holocene or historical displacement has occurred (Jennings, C. W., 1992).

II. BACKGROUND

A. Liquefaction and liquefaction-induced ground failures

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

B. Liquefaction potential, susceptibility, and opportunity

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

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

III. METHODS

We assess liquefaction susceptibility on the basis of three factors: (1) presence of loose, cohesionless, sandy or silty deposits within 50 feet of the surface (depth threshold defined by Tinsley and others (1985)), (2) presence of groundwater which saturates these deposits, and (3) historical records of liquefaction during previous earthquakes (data compiled by Youd and Hoose (1978)). Our procedure for assessing these factors is shown on Figure 2.

Procedure

1. Map surficial deposits on the basis of age and depositional environment.
2. Determine groundwater levels.
3. Examine historical liquefaction occurrences.
4. Develop criteria matrix to classify all potential combinations of type and age of deposit with groundwater depth. Calibrate with historical data and comparison with criteria matrix of Tinsley and others (1985).
5. Assign liquefaction susceptibility categories to map units.

Figure 2. Procedure for developing liquefaction susceptibility map

Previous studies document a correlation between the origin and age of a deposit and its tendency to liquefy (Tinsley and others, 1985; Tinsley and Holzer, 1990). Age is important because deposits become more consolidated, weathered, and cemented with age. Depositional environment is important because each environment is characterized by deposits with different sorting, bedding and grain-size characteristics. For example, river channel deposits are likely to contain sand and silt, and young (i.e., late Holocene age) deposits are likely to be loose and cohesionless. Categories of age and environment distinguished in this study are listed in Figure 3 and map units are correlated in Figure 4.

In mapping the Quaternary geology we first interpreted aerial photographs and topographic maps to determine the depositional environment and to estimate relative age by evaluating landforms and geomorphic relationships. Second, we interpreted published soil survey data to further assess the character and the age of near-surface deposits. The soil surveys, published by the Soil Conservation Service (SCS), provide information on composition, soil profile development, and available moisture (e.g., depth to groundwater) of the surface deposits (Bates, 1977, Lambert and Kashiwagi, 1978, Kashiwagi, 1985; Miller, 1972; and Welch, 1977). Soil profile development was used to estimate the ages of soils and surficial deposits. Geologic unit descriptions contain information on soils characteristics of each unit (Table 1). Additional data on the distribution of Quaternary alluvial and flatland deposits (including marine and estuarine mud) were compiled from published sources (Dibblee, 1981a and 1981b; Huffman and Armstrong, 1980; Helley and Lajoie, 1979; Galloway, 1978, Sedway and Cooke, 1977; Frizzel and others, 1974; Fox and others, 1973; Sims and others, 1973; Nichols and Wright, 1971; Kunkel and Upson, 1960; Thomasson and others, 1956 and 1960; and Cardwell, 1958).

Age	**Depositional environments**
Latest Holocene (<1000 yrs) (Qh, Qhi)	Stream channel and terrace (t)
Earlier Holocene (Qh)	Alluvial fan (f)
Late Pleistocene to Holocene (Q)	Alluvial basin (b)
Late Pleistocene (Qp)	Undifferentiated alluvial (a)
Early to middle Pleistocene (Qo)	Estuary (r)
	Beach and dune (s)
	Marine terrace (m)
	Artificial fill (af)

Figure 3. Categories of age and depositional environment distinguished in Quaternary geologic mapping.Abbreviations used in unit designations are shown in parentheses.

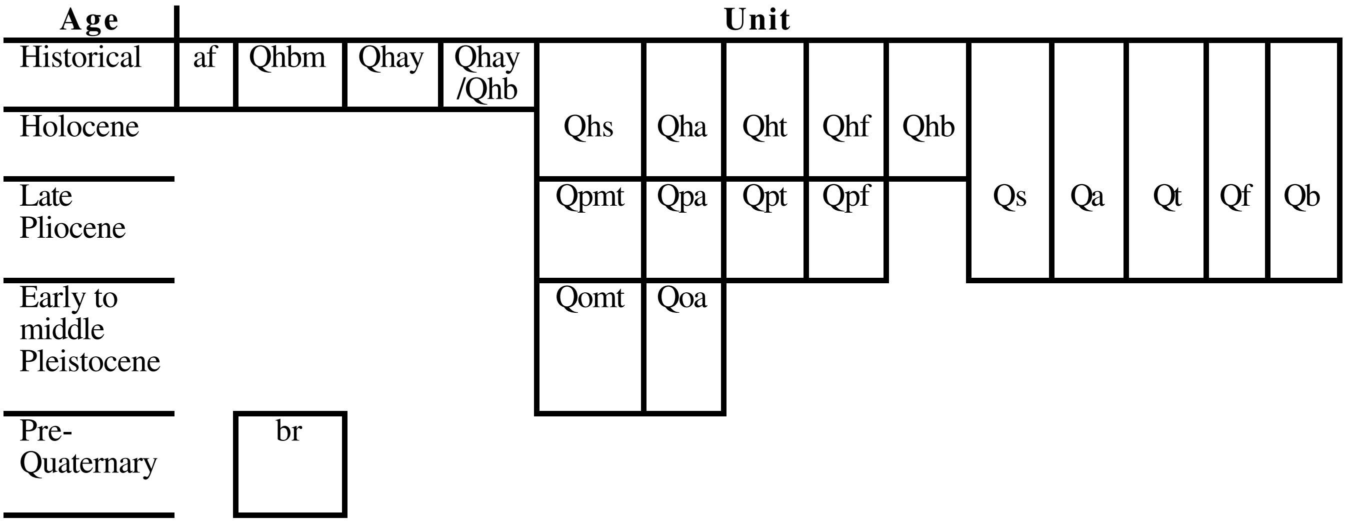

Figure 4. Correlation of geologic map units

Data on the depth to groundwater were acquired in two ways. Most data were taken from boring logs recorded for geotechnical studies. These logs were obtained from the California Department of Transportation, and from reports on file with county and city governments in the study area. The remainder of the data were collected in the field during spring 1992 by measuring the depth to the water surface in streams, creeks, and drainage ditches below the adjacent terrace or fan surface. In making these measurements, we assumed that the stream level was representative of the level of shallow groundwater in the local area. Data from water wells were not utilized because these wells tap deep, in many places artesian aquifers, thus observed water levels represent the potentiometric surface of the aquifer, not the depth below which the ground is saturated.

Liquefaction susceptibility units were designated on the basis of a criteria matrix that correlates the geologic unit (type and age of the deposit) with groundwater levels (Table 3). Liquefaction susceptibility units reflect the probable presence of saturated, loose, unconsolidated, sandy materials, within 50 feet of the surface. The matrix is calibrated using Tinsley and others (1985) quantitative analysis of borehole data in the Los Angeles basin, and historical liquefaction data for the study area (Table 2). Tinsley and others (1985) analyzed blow count data and lithologic logs for approximately 4000 borings to develop a criteria matrix for loose, cohesionless alluvium of latest Holocene, earlier Holocene, and late Pleistocene ages as a function of groundwater levels (Figure 2). Extensive borehole analysis was beyond the scope of this study, thus we rely on the analysis of Tinsley and others (1985) as a general guide. Geologic units known to have liquefied in previous earthquakes are as a rule assigned to the "Very High" liquefaction susceptibility unit. Historical occurrences of liquefaction in the study area are shown in Table 2, together with the geologic map unit that appears to have liquefied.

IV. DATA

A. Quaternary geology

Quaternary deposits in the study area (Figures 3 and 4, Plate 1) occur in four general settings: (1) large northwest-trending valleys, (2) small intermontane valleys, (3) estuaries, and (4) coastal environments (Plate 1). The large northwest trending valleys, such as Napa Valley, Sonoma Valley, and Santa Rosa-Petaluma Valley, and the somewhat smaller Olema, Vaca, and Suisun valleys, contain sediments deposited by streams on flood plains, alluvial fans, and basins. Sedimentary deposits in small intermontane valleys are similar in type to those of the larger valleys but are thinner, and smaller in areal extent. Estuaries contain both sediments dumped by streams as they enter bays or the ocean, and fine-grained sediments distributed by slow currents at the margins of bays. Coastal depositional environments include beaches, eolian dunes, and marine terraces.

B. Groundwater

The depth to saturated deposits in areas underlain by Quaternary alluvial, estuarine, and beach sediments is generally less than 10 feet throughout most of the study area. The free groundwater table is at sea level near the bays and ocean, and increases gradually with distance up the valleys. Within a valley, groundwater depth is generally shallowest near the axis of the valley and deepens gradually toward the flanks. A sharp increase in depth occurs near the contact between valley alluvium and bedrock along the valley margins. Small alluviated valleys and pockets within the bedrock hills also appear to have fairly shallow groundwater, generally less than 10 feet. Soils characteristic of wet environments are mapped in many of these valleys, and the few data available on depth to groundwater indicate shallow groundwater levels.

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

C. Historical liquefaction

Records of liquefaction in the study area are available for four earthquakes: the 1906 San Francisco earthquake (m=8.3), the 1892 Winters earthquake (m=6) (Unruh and Moores, 1992), the 1898 Mare Island earthquake (m=6.6) (Topozada, 1992), and the 1969 Santa Rosa earthquake (m=5.7). These records chronicle observations and contain data on ground failures consistent with liquefaction, which are used as calibration points for this study. Data were compiled primarily from Youd and Hoose (1978). Individual sites of known liquefaction are tabulated in Table 2 and are shown on Plate 2 differentiated as to type of failure.

Historical liquefaction most commonly occurred in Holocene estuarine sediments (11 reports + 2 questionable). These sediments are young, saturated, and contain silt and sand, especially near the mouths of rivers. The second most common deposit to liquefy was artificial fill (7 reports + 1 questionable); especially fill overlying estuarine sediments. It is not known to what extent the failures were in the fill itself or in the estuarine deposits beneath the fill. Third most common was latest Holocene alluvial deposits (3 reports + 1 questionable), and fourth was Holocene terrace deposits (2 reports + 3 questionable). Less than 2 incidents each were reported in Holocene fan deposits (Qhf), late Pleistocene to Holocene alluvium (Qa), Holocene sand dunes (Qhs), and Holocene basin sediments (Qhb).

D. Liquefaction susceptibility units

Tinsley and others (1985) defined liquefaction susceptibility units based on quantitative evaluation of SPT data from boreholes in the Los Angeles area. Deposits marked Very High and High are expected to liquefy in an earthquake of magnitude 6.5 or greater. Deposits marked Moderate are expected to liquefy in a magnitude 8 event but not a magnitude 6.5 event, and deposits marked Low or Very Low will not liquefy, even in a magnitude 8 earthquake. Our map units, because they are based in part on the criteria matrix developed by Tinsley and others in the Los Angeles study, can be interpreted in a similar manner.

We expect that 80 percent of future liquefaction will take place in areas marked High or Very High. The experience of Dupré and Tinsley (1990) in the Monterey area is that the areas that liquefied in the 1906 San Francisco earthquake are the same areas that liquefied in the 1989 Loma Prieta earthquake. We expect that 20 percent of future liquefaction will take place in areas marked Moderate, Moderate-High, Low-High, and Moderate-Low, and that less than 1 percent will take place in areas marked Low or Very Low.

V. SUMMARY

A liquefaction susceptibility map was created for the Napa 1:100,000 quadrangle on the basis of Quaternary geologic mapping, groundwater levels, and historical occurrences of liquefaction. The Quaternary map differentiates deposits on the basis of age and depositional environment -- two of the criteria necessary to locate loose cohesionless sands and silts. Age is evaluated because deposits become more compact (dense) and cemented with age. Depositional environment is evaluated because each is characterized by deposits with different sorting, bedding, and grain sizes.

A criteria matrix was developed that matches age and type of deposit with groundwater levels to yield relative liquefaction susceptibility. The criteria matrix is calibrated with data of Tinsley and others (1985) and with historical liquefaction occurrences. Sediments most susceptible to liquefaction in the study area are estuarine deposits, artificial fill emplaced over estuarine sediments, and latest Holocene stream deposits. Other susceptible deposits include Holocene stream terrace deposits, Holocene beach and dune sands, Holocene undifferentiated alluvium, Holocene basin deposits, and undifferentiated late Pleistocene to Holocene alluvium.

This map shows general conditions in the region for planning purposes only and cannot be used to assess the presence or absence of liquefiable sediments for specific sites. Site-specific geotechnical investigations must be conducted to make that assessment. Communities within or immediately adjacent to areas over 1 km^2 in size having high or very high liquefaction susceptibility include Petaluma, Santa Rosa, Sebastopol, Novato, Napa, Yountville, Pinole, Benicia, Martinez, Vallejo, Fairfield, Cordelia, Suisun City. Communities within or immediately adjacent to areas over 1 km^2 in size having moderate to high liquefaction susceptibility Santa Rosa, Cotati, and Rohnert Park.

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Table 1. Description of geologic units

Map symbol	Unit name and description
af	**Artificial fill.** Material constructed or deposited by humans. Fill may be engineered or non-engineered material. Most artificial fill in the study area overlies estuarine sediments and forms new land, levees, or dikes near sea level (Goldman, 1969). Thickness of the fill overlying estuarine sediments is typically 5-20 feet thick. Other fill includes large highway embankments, consisting of engineered fill up to approximately 100 feet thick. Liquefaction susceptibility may be very high to very low depending on (1) the nature and thickness of the fill materials, (2) whether the fill was engineered or non-engineered, and (3) its depth of saturation. Most fill emplaced in the last few decades is engineered; older fill is less likely to be engineered. Many of the reports of damage in the 1906 San Francisco earthquake involved failures in fill that probably was not engineered. We judged that parcels of fill located within estuaries might have very high liquefaction susceptibility because water levels are close to the surface, there is a significant possibility fill might not be engineered, and the fill may be a relatively thin cover over very susceptible estuarine sediments. Artificial fill comprising the large highway embankments mapped in the Vallejo area is presumed to be engineered, fairly thick, and have groundwater below 30 feet, thus to have very low susceptibility to liquefaction. Site specific studies should be conducted to determine the condition and liquefaction susceptibility of any artificial fill.
Qhr	**Estuarine deposits (bay mud).** Sediments deposited in a tidal marsh, estuary, delta, or lagoon. The water table is very high, usually at the surface. Sediments are silts, fine sands, peats, and clays and include materials mapped by Helley and Lajoie (1979) as bay mud. The limits of this unit were compiled chiefly from mapping of historical tidal marshlands by Nichols and Wright (1971). Soils are histosols, aquic entisols or mollisols. Age is Holocene with most areas being late Holocene and subject to modern deposition and flooding. Some areas are diked and drained for farming; the water table in these areas is artificially lowered to several feet below the surface. Liquefaction susceptibility is very high. Historical reports (Table 2) indicate that liquefaction of these sediments was widespread during past earthquakes. Estuarine sediments near the mouths of major streams (Napa River, Petaluma River, Suisun Creek, Olema Creek, and Sonoma Creek) are probably the most susceptible because the streams regularly deliver large volumes of sand and silt to the estuary. Three miles of train track reportedly sank in the marsh near the mouth of Suisun Creek (Table 2, location 254) during the 1906 San Francisco earthquake.
Qhr/af	**Estuarine deposits with areas of artificial fill.** Complex of estuarine sediments and bodies of artificial fill that are too small to delineate at map scale. Liquefaction susceptibility is very high.

Qhi **Latest Holocene alluvial deposits.** Fluvial sediments judged to have been deposited in the last approximately 1000 years. Includes modern flood plains, active stream channels, active alluvial fans, flood-prone areas, and areas known to have flooded historically. Does not include flood-prone areas characterized by erosional topography. These areas, though occasionally flooded, are eroding faster than aggrading, thus would not be underlain by significant thicknesses of recent flood deposits. Sediments are loose sands, gravels, silts and clays. Typical soils developed on these sediments are fluvents. This mapping unit does not include basin or estuarine sediments, which tend to be more fine-grained and cohesive. Liquefaction susceptibility is high to very high. Tinsley and others (1985) present an analysis of borehole data in the Los Angeles area which shows that 76-81 % of boreholes in latest Holocene alluvium contain liquefiable materials, assuming water levels at the surface, compared to 34-54 % of boreholes in earlier Holocene alluvium. Deposits are designated "Very High" if historical liquefaction has taken place, e.g. the flood plain deposits of Olema Creek, Petaluma Creek, and Putah Creek (Table 2).

Qhi/Qhb **Latest Holocene flood plain and basin deposits** along Laguna de Santa Rosa. The area is a complex of flood plain, basin, and marsh depositional environments. Water draining from the Cotati-Rohnert Park basin and Santa Rosa Creek collects in this area and moves northward to the Russian River. The water table is close to the surface. Liquefaction susceptibility is high.

Qhs **Holocene dune and beach sand.** Beach and beach-derived dune sand in predominantly coastal environments. Beach sediments are well-sorted fine to coarse sands with some gravel. Where the beach is adjacent to a seacliff, beach sediments probably form a veneer 1 to 10 feet thick over a bedrock platform. Dune sands are very well-sorted fine to medium sands.

In areas of high groundwater or perched water conditions, liquefaction susceptibility is high to very high. Where sand boils occurred in Holocene sand dunes near Dillon Beach during the 1906 earthquake (Table 2, location 280), deposits are designated "very high". Sand of Limantour spit, where sands are probably thicker than sands veneering a bedrock platform, are also designated "very high".

Qhb **Holocene basin deposits.** Sediments of late Holocene age deposited in topographic lows. These areas have a high water table and are subject to flooding. Sediments are more fine-grained than flood plain and fan sediments because basins collect standing water allowing clays to deposit. Typical soils are vertisols and aquic mollisols.

Liquefaction susceptibility is moderate to high. Although these sediments contain abundant clay, they may also contain layers of sand and silt. For example, the Cotati-Rohnert Park basin is covered over most of its area by a layer of black clay several feet thick. Shallow boreholes show, however, that sands and silts are present intermittently below the black clay. Of the 32 borehole logs available, 10 record sands, silty sands, or sandy silts that are at least 3 feet thick, saturated, and have blow counts under 20 blows per foot. In a fluvial environment we expect the distribution of sands to be intermittent and seemingly random. Therefore we assume that layers of liquefiable materials could be present anywhere in the basin. Their relative abundance should be less in this basin environment than in a flood plain environment because of the greater proportion of clays in basin sediments, therefore these and other basin sediments are assigned moderate to high liquefaction susceptibility, instead of high susceptibility.

Qht **Holocene terrace deposits** Stream-terrace deposits of early Holocene to present age deposited as point bar and overbank deposits by major streams such as the Napa River. Although terrace deposits are also found along smaller streams, these are generally too small in extent to be shown at this map scale and therefore are included in Qa and Qha mapping units. Terrace sediments include sand, gravel, silt, with minor clay, moderately to well-sorted, and moderately to well-bedded. Soils are typically entisols, inceptisols, and mollisols.

Liquefaction susceptibility is high where groundwater is within 10 feet of the surface, and moderate where it is between 10 and 30 feet of the surface. Three areas have very high liquefaction susceptibility because they have liquefied historically (Table 2, locations 266, 282, and 283). All are located along coastal streams within 2 km of the estuary boundary.

Qhf **Holocene fan deposits.** Holocene alluvial fan sediments, deposited by streams emanating from the mountains as debris flows, hyperconcentrated mudflows, or braided stream flows. Sediments include sand, gravel, silt, and clay, that are moderately to poorly sorted, and moderately to poorly bedded. Some Holocene fans exhibit levee/interlevee topography, particularly the Suisun Creek and Santa Rosa Creek fans. The levees are identified as long, low ridges oriented down fan, and contain coarser material than adjoining interlevee areas.

Liquefaction susceptibility is moderate where groundwater is within 10 feet of the surface, and low to very low elsewhere. Fan deposits are judged to be less susceptible than terrace deposits (Qht) of the same age due to poorer sorting and coarser grain size.

This unit includes active stream channels which are too narrow to show separately at this map scale. Sediments in the stream channel are dominantly gravel and sand. Liquefaction susceptibility in these channels, especially point bar deposits, is high.

The City of Santa Rosa sits on the Santa Rosa Creek fan; one of the larger Holocene fans in the study area. The fan forms a wedge of sediment overlying the older alluvium (Qoa) identified as the Glen Ellen Formation (Cardwell, 1958), and exhibits strong levee/interlevee topography. Santa Rosa Creek is at present incised as much as 25 feet into fan sediments near the fan apex, thus sediments are judged to be pre-historical.

Liquefaction susceptibility is moderate, however, local areas may have greater susceptibility. The downtown Santa Rosa area sustained considerable damage in the 1969 Santa Rosa earthquake. Eugene Miller (in Steinbrugge and others, 1970) attributes the severity of the damage partly to amplification of ground motions by soft alluvial materials underlying central Santa Rosa. Reports of ground cracking, settlement, along Santa Rosa and Matanzas Creek and in other parts of Santa Rosa in the 1969 Santa Rosa and 1906 San Francisco earthquakes (Table 2) suggest that liquefaction hazards in the Santa Rosa area should be further evaluated.

Qha **Holocene alluvium, undifferentiated.** Alluvium of Holocene age, deposited in fan, terrace, or basin environments. Unit is mapped where separate types of deposits could not be delineated either due to complex interfingering of depositional environments or the limited size of the area.

Liquefaction susceptibility is moderate to high, where groundwater is within 10 feet of the surface. This assignment is based on a combination of the susceptibilities of fan, terrace, and basin sediments (Qhf, Qht, and Qhb)

Qs **Late Pleistocene to Holocene dune sands.** Very well-sorted fine to medium eolian sands derived from beach sediments in coastal environments. Holocene sands discontinuously overlie late Pleistocene sands, both of which form a mantle of varying thickness over marine terraces and bedrock hills. Depth to free groundwater 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 groundwater is shallow and sands are Holocene in age.

Qt **Late Pleistocene to Holocene terrace deposits.** This unit is mapped on relatively flat undissected stream terraces where late Pleistocene or Holocene age was uncertain or where the deposits of different age interfingered such that they could not be delineated at the map scale. Soils are typically inceptisols, mollisols, and alfisols. Groundwater depth is variable, but is generally less than 30 feet. Liquefaction susceptibility is low to high, where groundwater 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.
This unit includes active stream channels which are too narrow to show separately at this map scale. Sediments in the stream channel are dominantly gravel and sand. Liquefaction susceptibility in these channels, especially in point bar deposits, is high.

Qf **Late Pleistocene to Holocene fan deposits.** This unit is mapped on gently sloping, fan-shaped, relatively undissected alluvial surfaces where late Pleistocene vs Holocene age was uncertain or where the deposits of different age interfingered such that they could not be delineated at the map scale. Sediments include sand, gravel, silt, and clay, that are moderately to poorly sorted, and moderately to poorly bedded. Soils are typically inceptisols, mollisols, and alfisols. Groundwater depth is variable, but is generally less than 30 feet. Liquefaction susceptibility is low-to-moderate where groundwater is within ten feet of the surface.
This unit includes active stream channels which are too narrow to show separately at this map scale. Sediments in the stream channel are dominantly gravel and sand. Liquefaction susceptibility in these channels, especially in point bar deposits, is high.

Qa **Late Pleistocene to Holocene alluvium, undifferentiated.** This unit is typically mapped in small valleys where separate fan, basin, and terrace units could not be delineated at the map scale, and where Holocene or Pleistocene age was uncertain. The unit includes flat, relatively undissected fan, terrace, and basin deposits, and small active stream channels. Groundwater depth is variable, but is generally less than 30 feet. Liquefaction susceptibility is low-to-high, where groundwater is within ten feet of the surface. The wide range in liquefaction susceptibility is a reflection of uncertainties and local variability in the both the nature and age of the deposits.

Qpt **Late Pleistocene terrace deposits.** This unit is mapped on relatively flat undissected to slightly dissected stream terraces where a late Pleistocene age is

indicated by the development of alfisols. For example, the extensive terraces bordering Sonoma Creek are capped by alfisols and are incised such that they no longer aggrade. Liquefaction susceptibility is moderate where groundwater is within ten feet of the surface, and low to very low elsewhere.
Small inset terraces and the active channel deposits of Sonoma Creek are also included in this unit because they are too narrow to delineate at the map scale. These deposits are Holocene to present in age and consist of unconsolidated sand and gravel, thus have high liquefaction suceptibility.

Qpf **Late Pleistocene fan deposits** This unit is mapped on gently sloping, fan-shaped alluvial surfaces where late Pleistocene age is indicated by slight dissection and/or the development of alfisols.
Liquefaction susceptibility is low where groundwater is within ten feet of the surface, and is very low elsewhere.

Qpa **Late Pleistocene alluvium, undifferentiated** This unit is mapped on gently sloping to level alluvial fan or terrace surfaces where a late Pleistocene age is indicated by slight dissection and/or the development of alfisols.
Liquefaction susceptibility is moderate-to-low where groundwater is within ten feet of the surface, and is low to very low elsewhere.

Qpm **Late Pleistocene marine terrace deposits.** Deposits on uplifted marine abrasion platforms along the Pacific coast and the margin of Tomales Bay. Some terraces along the margin of Tomales Bay may be partly alluvial in origin (Grove and Neimi, 1992). The terraces are 40-160 ft above sea level. Sediment veneer on the platform is typically greater than 10 feet thick and consists of moderately to well-sorted, moderately to well-bedded sands and gravels, which may locally be fossiliferous. Groundwater is generally deeper than 20 feet, though areas may have perched groundwater where the marine sediments overlie relatively impermeable bedrock. Liquefaction susceptibility is generally very low over most of the terraces but is designated low in this study to account for areas of perched groundwater.

Qoa **Early or middle Pleistocene fan or terrace deposits.** Moderately to deeply dissected alluvial deposits capped by alfisols, ultisols, or soils containing a silica or calcic hardpan. Unit includes areas of the Llano de Santa Rosa mapped by Cardwell (1958) as the Glen Ellen Formation of late Tertiary to early Pleistocene age. Liquefaction susceptibility is very low.

Qom **Early to middle Pleistocene marine terrace deposits.** Gently undulating, dissected marine terraces near Point Reyes Station. Additional older terraces, not mapped in this study, are also present along the western flank of Bolinas Ridge (Keenan, J. L., 1976). Both mapped and unmapped terraces may be partly alluvial in origin (Grove and Neimi, 1992). Liquefaction susceptibility is very low.

br **Pre-Quaternary deposits and bedrock, undifferentiated.** Primarily Jurassic to Pliocene sedimentary and volcanic rock and sediments. Unit also includes landslides, other bodies of colluvium, and small stream channels in bedrock that could not be delineated at the map scale. Liquefaction susceptibility is very low, except in stream channels where it may be low to high.

w **Water.** This unit includes lakes, reservoirs, bays, ponds, and sea.

Table 2. Historical occurrences of liquefaction in the study area correlated with probable geologic units affected Geologic units are queried where uncertainty in the exact location of the liquefaction occurrence led to considerable uncertainty identifying the geologic unit affected. Locations of occurrences are shown on Plate 2. Location numbers are from Youd and Hoose (1978). See Youd and Hoose (1978) and Steinbrugge and others (1970) for historical quotations which further describe each location and the nature of failure.

Location # (plate 2)	**Year of earthquake**	**Geologic unit(s) (probable)**	**Nature of failure**
250	1906	Qhr/af	ground settlement
251	1906, 1898	af over Qhr	miscellaneous effects
252	1906	Qhr, af over Qhr	lateral spread
254	1906	Qhr	ground settlement
255**	1892	Qha? Qhf? Qf? Qa?	ground cracks
256**	1892	Qhi, Qht Qha?	sand boils, ground cracks, disturbed wells, streambank landslides
260	1906	Qhr	lateral spread
264	1906	Qht	ground settlement
266	1906	Qhi, Qhr, af over Qhr*, Qht	ground cracks, lateral spread, ground settlement
267	1906	Qhr, af over Qhi*	ground cracks, lateral spread, ground settlement
269	1906	Qhr, af over Qhr*	ground settlement
270	1906	Qhr	miscellaneous effects
271	1906	Qhr	lateral spread, ground cracks
277	1906	af* over Qhs or Qs	ground settlement
279	1906	Qhr	ground settlement
280	1906	Qhs	sand boils
282	1906	Qhr? Qht? Qha?	lateral spread
283	1906	Qht? Qhr?	lateral spread

284	1906	Qha, Qhr	lateral spread
287	1906	Qhi	ground settlement, sand boils
288	1906	Qhb?	ground cracks
289	1906	Qhb, Qhf, Qoa	no cracks found
293	1906	Qhi/Qhb? br?	lateral spread
295	1906	Qa, marshy or low areas*	ground settlement, miscellaneous effects, ground cracks
295	1969	Qa, af over marshy substrata*	ground cracks
		Qhf	ground cracks
296	1906	Qa, marshy area*	ground settlement, stream bank slip

Note: * Unit or sub-unit not delineated on map. Body of material which failed is too small to show at map scale and is mapped as part of a larger unit.
** Located in the Winters-Vacaville area, east of the map boundary.

Table 3. 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, and includes areas of historical liquefaction, H = high, M = moderate, L = low, and VL = very low to none. A groundwater depth of less than 10 feet was assumed for nearly all localities, so most of the categories with greater depths are hypothetical.

Map symbol	Age and Type of Deposit	Depth to Groundwater (ft)			
		<10	10-30	30-50	>50
Qhr	Holocene estuarine deposits	VH	H	L	VL
af	Artificial fill	L-VH	L-H	VL-L	VL
Qhi	Late Holocene flood plain deposits	VH, H	H	L	VL
Qhs	Holocene dune and beach sands	VH, H	H	L	VL
Qhb	Holocene basin deposits	M-H	L-M	VL	VL
Qht	Holocene stream terrace deposits	H	M	L	VL
Qhf	Holocene alluvial fan deposits	M	L	VL	VL
Qha	Holocene alluvium, undifferentiated	M-H	L-M	VL-L	VL
Qs	Late Pleistocene to Holocene dune sand	L-H	L-M	VL-L	VL
Qt	Late Pleistocene to Holocene stream terrace deposits	L-H	L-M	VL-L	VL
Qf	Late Pleistocene to Holocene alluvial fan deposits	L-M	VL-L	VL	VL
Qa	Late Pleistocene to Holocene alluvium, undifferentiated	L-H	L-M	VL-L	VL
Qpt	Late Pleistocene stream terrace deposits	L-M	L	VL	VL
Qpf	Late Pleistocene alluvial fan deposits	L	VL	VL	VL
Qpa	Late Pleistocene alluvium, undifferentiated	L	L	VL	VL
Qpm	Late Pleistocene marine terrace deposits	L	L	VL	VL
Qoa	Older alluvial fan and stream terrace deposits	VL	VL	VL	VL
Qom	Older marine terrace deposits	VL	VL	VL	VL
br	Bedrock	VL	VL	VL	VL

Note: Separation of unit designations by a dash indicates that the susceptibility in the mapped area could range from the lower to the higher designation. This range reflects uncertainty or variability in the geologic nature (age, texture, cohesion) or groundwater conditions of the unit. The range may be narrowed in a specific area if additional information is available.

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