SEISMIC HAZARD ZONE REPORT 111

# SEISMIC HAZARD ZONE REPORT FOR THE PALO ALTO 7.5-MINUTE QUADRANGLE, SAN MATEO AND SANTA CLARA COUNTIES, CALIFORNIA

**2006**

**DEPARTMENT OF CONSERVATION**
***California Geological Survey***

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**How to view or obtain the map**

Seismic Hazard Zone Maps, Seismic Hazard Zone Reports and additional information on seismic hazard zone mapping in California are available on the California Geological Survey's Internet page: http://www.conservation.ca.gov/CGS/index.htm

Paper copies of Official Seismic Hazard Zone Maps, released by CGS, which depict zones of required investigation for liquefaction and/or earthquake-induced landslides, are available for purchase from:

BPS Reprographic Services
945 Bryant Street
San Francisco, CA 94103
(415) 512-6550

Seismic Hazard Zone Reports (SHZR) summarize the development of the hazard zone map for each area and contain background documentation for use by site investigators and local government reviewers. These reports are available for reference at CGS offices in Sacramento, San Francisco, and Los Angeles. **NOTE: The reports are not available through BPS Reprographic Services.**

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|---|---|
| April 18, 2006 | Preliminary Release for 90-day review period. |
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# EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the Palo Alto 7.5-Minute Quadrangle, San Mateo and Santa Clara counties, California. The map displays zones of required investigation for liquefaction and earthquake-induced landslides over an area of approximately 62 square miles at a scale of 1 inch = 2,000 feet.

The southern half of the Palo Alto consists of rough terrain of the Santa Cruz Mountains while most of the northern half is occupied by coalescing alluvial fans and salt evaporation ponds at the edge of San Francisco Bay. Included in the study area are parts of the incorporated cities of Atherton, East Palo Alto, Los Altos, Los Altos Hills, Menlo Park, Palo Alto, Portola Valley, Redwood City, San Carlos, and Woodside.

Most of the area covered by zones of required investigation for liquefaction lies within Santa Clara Valley in the northern third and along the northeastern margin of the quadrangle. A single large zone encompasses parts of the cities of Palo Alto, East Palo Alto, Redwood City, Menlo Park, and San Carlos. Less extensive zones for liquefaction encompass all of Portola Valley as well as most of Francisquito, Los Trancos, Madera, and smaller stream canyons and valleys emanating from the Santa Cruz Mountains.

Earthquake-induced landslide zones affect only a small fraction of land within the quadrangle. The largest of these covers much of the steep-sloped highlands southwest of Portola Valley. Most of the remaining areas consist of relatively small, isolated zones in the hilly terrain between Portola Valley and Highway 280.

The map was prepared by employing geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information considered includes topography, geology, borehole data, historical ground-water levels, existing landslides, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. The ground motion inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years.

# INTRODUCTION

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate seismic hazard zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. City, county, and state agencies are directed to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold development permits for a site within a zone until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans. The Act also requires sellers (and their agents) of real property within a mapped hazard zone to disclose at the time of sale that the property lies within such a zone. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

The Act directs SMGB to appoint and consult with the Seismic Hazards Mapping Act Advisory Committee (SHMAAC) in developing criteria for the preparation of the seismic hazard zone maps. SHMAAC consists of geologists, seismologists, civil and structural engineers, representatives of city and county governments, the state insurance commissioner and the insurance industry. In 1991 SMGB adopted initial criteria for delineating seismic hazard zones to promote uniform and effective statewide implementation of the Act. These initial criteria, which were published in 1992 as CGS Special Publication 118, were revised in 2004. They provide detailed standards for mapping regional liquefaction and landslide hazards. The Act also directed CGS to develop a set of probabilistic seismic maps for California and to research methods that might be appropriate for mapping earthquake-induced landslide hazards.

In 1996, working groups established by SHMAAC reviewed the prototype maps and the techniques used to create them. The reviews resulted in recommendations that 1) the process for zoning liquefaction hazards remain unchanged and 2) earthquake-induced landslide zones be delineated using a modified Newmark analysis.

In April 2004, significant revisions of liquefaction zone mapping criteria relating to application of historically high ground-water level data in desert regions of the state were adopted by the SMGB. These modifications are reflected in the revised CGS Special Publication 118, which is available on the Internet at: http://gmw.consrv.ca.gov/shmp/webdocs/sp118_revised.pdf

This Seismic Hazard Zone Report summarizes the development of the hazard zone map for the Palo Alto 7.5-minute quadrangle. The process of zoning earthquake loading for liquefaction uses a combination of Quaternary geologic mapping, ground-water information, and subsurface geotechnical data. The process for zoning earthquake-induced landslides incorporates earthquake loading, existing landslide features, slope gradient, rock strength, and geologic structure.

Probabilistic seismic hazard maps, which are the underpinning for delineating seismic hazard zones, have been prepared for peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years (Petersen and others, 1996) in accordance with the mapping criteria.

This report summarizes seismic hazard zone mapping for potentially liquefiable soils and earthquake-induced landslides in the Palo Alto 7.5-Minute Quadrangle.

# SECTION 1

# Liquefaction Zones of Required Investigation in the Palo Alto 7.5-Minute Quadrangle

**By**
**Anne Rosinski**

**CALIFORNIA DEPARTMENT OF CONSERVATION**
**CALIFORNIA GEOLOGICAL SURVEY**

## PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. City, county, and state agencies are directed to use seismic hazard zone maps developed by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within seismic hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of liquefaction analysis, evaluation, and mitigation techniques (SCEC, 1999). This text is also on the Internet at: http://www.scec.org/

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Palo Alto 7.5-Minute Quadrangle. Section 2 (addressing earthquake-induced landslides) and Section 3 (addressing potential ground shaking) complete the report, which is one of a series that summarizes production of similar seismic hazard zone maps within the state (Smith, 1996). Additional information on seismic hazards zone mapping in California is on CGS's Internet web page: http://www.conservation.ca.gov/CGS/shmp

## BACKGROUND

Liquefaction-induced ground failure historically has been a major cause of earthquake damage in northern California. During the 1989 Loma Prieta and 1906 San Francisco earthquakes, significant damage to roads, utility pipelines, buildings, and other structures in the San Francisco Bay Area was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 50 feet of the ground surface. These geological and ground-water conditions are widespread in the San Francisco Bay Area, most notably in some densely populated valley regions and alluviated floodplains. In addition, the potential for strong earthquake ground shaking is high because of the many nearby active faults. The combination of these factors constitutes a significant seismic hazard, especially in areas marginal to the bay, including areas in the Palo Alto Quadrangle.

## METHODS SUMMARY

Characterization of liquefaction hazard presented in this report requires preparation of maps that delineate areas underlain by potentially liquefiable sediment. The following were collected or generated for this evaluation:

- Existing geologic maps were used to provide an accurate representation of the spatial distribution of Quaternary deposits in the study area. Geologic units that generally are susceptible to liquefaction include late Quaternary alluvial sedimentary deposits and artificial fill
- Shallow ground-water maps were constructed
- Geotechnical data were analyzed to evaluate liquefaction potential of deposits
- Information on potential ground shaking intensity based on CGS probabilistic shaking maps

The data collected for this evaluation were processed into a series of geographic information system (GIS) layers using commercially available software. The liquefaction zone of required investigation map was derived from a synthesis of these data and according to criteria adopted by the SMGB (DOC, 2004).

## SCOPE AND LIMITATIONS

Evaluation for potentially liquefiable soils generally is confined to areas covered by Quaternary (less than about 1.8 million years) deposits. Such areas within the Palo Alto Quadrangle consist mainly of low-lying shoreline regions, alluviated valleys and coalescing alluvial fans emanating from the Santa Cruz Mountains. CGS's liquefaction hazard evaluations are based on information on earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and ground-water depth. Although selection of data used in this evaluation was rigorous, the quality of the data used varies. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data obtained from outside sources.

Liquefaction zone of required investigation maps are intended to prompt more detailed, site-specific geotechnical investigations, as required by the Act. As such, liquefaction zone maps identify areas where the potential for liquefaction is relatively high. They do not predict the amount or direction of liquefaction-related ground displacements, or the amount of damage to facilities that may result from liquefaction. Factors that control liquefaction-induced ground failure are the extent, depth, density, and thickness of liquefiable materials, depth to ground water, rate of drainage, slope gradient, proximity to free faces, and intensity and duration of ground shaking. These factors must be evaluated on a site-specific basis to assess the potential for ground failure at any given project site.

Information developed in the study is presented in two parts: physiographic, geologic, and hydrologic conditions in PART I, and liquefaction and zoning evaluations in PART II.

## PART I

## PHYSIOGRAPHY

The Palo Alto 7.5-minute quadrangle encompasses an area of approximately 60 square miles in San Mateo and Santa Clara counties. Approximately 40 percent of the map area lies in Santa Clara County in the southeastern corner of the quadrangle, including the Cities of Palo Alto, Los Altos, and, Los Altos Hills. The remaining 60 percent of the map area lies in San Mateo County and includes the cities of Atherton, East Palo Alto, Menlo Park, Portola Valley, Redwood City, San Carlos, and Woodside.

The map area straddles the crest of the northwest-trending Santa Cruz Mountains in the Coast Ranges geomorphic province. The axis of the Santa Cruz Mountains and several broad-crested ridges are aligned roughly parallel to the northwest-trending San Andreas Fault zone, which cuts across the southwestern corner of the quadrangle, in the vicinity of Portola Valley. Numerous creeks and small streams originate in the Santa Cruz Mountains and flow into San Francisco Bay. Among the larger creeks in the map area are Cordilleras, San Francisquito, Barron, and Matadero creeks. There are several lakes and reservoirs in the Palo Alto Quadrangle, including Searsville Lake near the northwest end of Jasper Ridge, Bear Gulch Reservoir, in the southwest corner of the map area, and Felt Lake, in the south-central region of the map area. Elevations within the map area range from approximately 1400 feet in the Santa Cruz Mountains in the southwest corner of the quadrangle, to sea level along the shoreline of San Francisco Bay. The majority of development in the Palo Alto Quadrangle is concentrated in the relatively broad, flatland areas between the base of the Santa Cruz Mountains and the shoreline of San Francisco Bay. Development in hill-slope areas mainly consists of low-density residential structures. The cities of Los Altos, Los Altos Hills and Palo Alto occupy the Santa Clara County portion of the map area. A substantial portion of the undeveloped land in the map area in both San Mateo and Santa Clara counties is parkland managed by California State Parks, Santa Clara County, San Mateo County, or the Midpeninsula Regional Open Space District.

Major transportation routes in the map area include northwest-trending State Highway 280 which runs through the southwest corner of the quadrangle, and northwest-trending State Highway 101, that runs near the shoreline of San Francisco Bay through the northeast portion of the map area. Additional access is provided by a network of county roads and private roads in developed areas and by fire roads and trails in undeveloped areas.

## GEOLOGY

Geologic units that generally are susceptible to liquefaction include late Quaternary alluvial sedimentary deposits and artificial fill. To evaluate the areal and vertical distribution of shallow Quaternary deposits and to provide information on subsurface geologic, lithologic and engineering properties of the units in the Palo Alto Quadrangle, recently completed maps of the nine-county San Francisco Bay Area showing Quaternary deposits (Witter and others, 2006) and bedrock units (Brabb et al., 1998) were obtained from the U.S. Geological Survey in digital form. These GIS maps were combined, with modifications along the bedrock/Quaternary contact, to form a single, 1:24,000-scale geologic map of the Palo Alto Quadrangle. The distribution of Quaternary deposits on this map (summarized on Plate 1.1) was used in combination with other data, discussed below, to evaluate liquefaction susceptibility and develop the Seismic Hazard Zone Map.

Other geologic maps and reports were reviewed, including Helley and others, (1979), and Brabb and others, (1998). Limited field reconnaissance was conducted to confirm the location of geologic contacts, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units.

In the Palo Alto Quadrangle there are 20 Quaternary units mapped by Witter and others (2006). Roughly half of the Palo Alto Quadrangle is covered by Quaternary alluvial sediment shed from the northwest-trending Santa Cruz Mountains that occupy the south and southwest portion of the quadrangle (Plate 1.1). Early to late Pleistocene undifferentiated alluvial deposits (Qof) are mapped along the range front, and, near the junction of San Francisquito and Los Trancos creeks near the center of the quadrangle. Small areas of Late Pleistocene stream terrace deposits are mapped along upstream portions of San Francisquito Creek, in the vicinity of Bear Gulch. Latest Pleistocene alluvial fan deposits (Qpf) also are mapped along the base of the Santa Cruz Mountains. Small areas of Latest Pleistocene to Holocene alluvial fan deposits (Qf) are mapped along the upstream portion of the un-named creek just south of Bear Gulch Reservoir and, along the upstream portion of Matadero creek at the south edge of the quadrangle. Small areas of

Latest Pleistocene to Holocene stream terrace deposits (Qt) are mapped along the upstream portion of San Francisquito Creek in the vicinity of Bear Gulch, the un-named creek just south of Bear Gulch Reservoir near the southwest edge of the quadrangle, and near the southeast edge of the quadrangle, along Matadero Creek. Latest Pleistocene to Holocene alluvium, undifferentiated (Qa) is mapped in small upland valleys, along the un-named creeks north of Woodside Road, and just south of Bear Gulch Reservoir, as well as along Los Trancos and Barron Creeks, near the southeast edge of the quadrangle.

Holocene alluvium, undifferentiated (Qha) is mapped in long, narrow bands along the banks of several creeks, including Sausal and Corte Madera Creeks in Portola Valley in the southwestern portion of the quadrangle, and, San Francisquito and Matadero Creeks. Holocene stream terrace deposits(Qht) are mapped along Corte Madera Creek in Portola Valley and along upstream portions of San Francisquito Creek. Witter and others (2006) report Holocene alluvial fan levee deposits (Qhl) "are formed by streams that overtop their banks and deposit sediment adjacent to the channel". In the Palo Alto Quadrangle, Holocene alluvial fan levee deposits (Qhl) emanate at, and/or near, where creeks emerge from the Santa Cruz Mountains, and extend northeast towards San Francisco Bay. Holocene alluvial fan (Qhf) and Holocene alluvial fan deposits, fine facies (Qhff) account for the majority of Quaternary sediment deposited in the Palo Alto Quadrangle. Coarser grained Holocene alluvial fan (Qhf) deposits cover the steepest parts of the valley adjacent to the base of the Santa Cruz Mountains, and as the gradient decreases, grade into Holocene alluvial fan deposits, fine facies (Qhff) near the shoreline of San Francisco Bay. Holocene basin deposits (Qhb), described as "sediment that accumulates from standing or slow moving water in topographic basins (Witter and others, 2006), is mapped along Sausal Creek in Portola Valley, in the southwest corner of the quadrangle. Holocene San Francisco Bay Mud, "…that is presently, or was historically tidal marsh, mud flat or bay bottom" (Witter and others, 2006) is mapped between the shoreline of San Francisco Bay and the northern edge of the quadrangle.

Modern stream channel deposits (Qhc) "fluvial deposits within active, natural stream channels" (Witter and others, 2006) are mapped along almost all streams in the Palo Alto Quadrangle. Artificial levee fill (alf), and artificial stream channels (ac) are mapped along most of the major creeks. To accommodate larger flows in the winter months, some reaches of these watercourses have been engineered within concrete-lined structures. Artificial fill over Bay Mud (afbm); consisting of engineered and/or non-engineered fill, is mapped at various locations along the margin of San Francisco Bay. Artificial fill over Bay Mud (afbm) is mapped bayward of the 1850's-era shoreline. Artificial fill (af) that does not overlie Bay Mud is mapped landward of the 1850's shoreline (Witter and others, 2006). The differentiation of these units is significant because afbm historically has been more susceptible to liquefaction. Artificial fill (af) also is mapped as small, isolated bodies throughout the Palo Alto Quadrangle, and is commonly associated with infrastructure such as roads and earth fill dams, as well as small-scale construction projects.

The Quaternary geologic mapping methods described by Witter and others (2006) consist of interpretation of topographic maps, aerial photographs, and soil surveys, as well as compiled published and unpublished geologic maps. The authors estimate the ages of deposits using: landform shape, relative geomorphic position, cross cutting relationships, superposition, depth and degree of surface dissection, and relative degree of soil profile development. Table 1.1 compares stratigraphic nomenclature used in Witter and others (2006) and the CGS GIS database, with that of several previous studies performed in northern California.

| UNIT | Witter and others (2006) | Helley and others (1979) | Brabb and others, 1998) | CGS GIS database |
|---|---|---|---|---|
| Artificial fill | af | - | - | af |
| Artificial fill over Bay Mud | afbm | - | - | afbm |
| Artificial fill, levee | alf | - | - | - |
| Artificial stream channel | ac | - | - | ac |
| Modern stream channel deposits | Qhc | Qhsc | Qhsc | Qhc |
| Latest Holocene alluvial fan levee deposits | Qhly | - | - | Qhly |
| Holocene San Francisco Bay Mud | Qhbm | Qhbm | Qhbm | Qhbm |
| Holocene basin deposits | Qhb | - | - | Qhb |
| Holocene alluvial fan deposits | Qhf | Qham, Qhac | Qhaf, Qhfp | Qhf |
| Holocene alluvial fan deposits, fine facies | Qhff | Qhaf | Qhaf | Qhff |
| Holocene alluvial fan levee deposits | Qhl | - | - | Qhl |
| Holocene stream terrace deposits | Qht | - | - | Qht |
| Holocene alluvial deposits, undifferentiated | Qha | - | - | Qha |
| Late Pleistocene to Holocene alluvial fan deposits | Qf | - | - | Qf |
| Late Pleistocene to Holocene stream terrace deposits | Qt | - | - | Qt |
| Late Pleistocene to Holocene alluvium, undifferentiated | Qa | - | - | Qa |
| Late Pleistocene alluvial fan deposits | Qpf | - | - | Qpf |
| Latest Pleistocene stream terrace deposits | Qpt | - | - | - |
| Latest Pleistocene alluvium, undifferentiated | Qpa | Qpa | - | - |
| Early to middle Pleistocene alluvial fan deposits | Qof | - | - | Qof |
| bedrock | br | - | - | br |

Table 1.1 Correlation Chart of Quaternary Stratigraphic Nomenclatures Used in Previous Studies. **For this study, CGS has adopted the nomenclature of Witter and others (2006).**

Bedrock units exposed in the three assemblages in the Palo Alto Quadrangle (Brabb and others, 1998) consist of the following Mid- to Late Mesozoic through Late Cenozoic map units, from oldest to youngest: Franciscan Complex (sp, fmm, fc, fu, fg, fss, fpl), Unnamed shale (Ksh), Whiskey Hill Formation (Tw, Tws), Butano Sandstone (Tb), Page Mill Basalt (Tpm), Monterey Formation (Tm), Ladera sandstone (Tld), Purisima Formation (Tp), Merced Formation (QTm), and Santa Clara Formation (QTsc). See the Earthquake Induced Landslide portion (Section 2) of this report for further description of bedrock geology.

### Structural Geology

The stratigraphic assemblages of the Santa Cruz Mountains were deposited and deformed in separate depositional basins. Later, these stratigraphic assemblages were truncated and juxtaposed against one another by a complex system of Tertiary and Quaternary strike-slip and dip-slip faults. The transform boundary between the Pacific and North American plates distributes shearing across a complex system of primarily northwest-trending, right-lateral, strike-slip faults that include the San Andreas, Hayward, and Calaveras faults. The San Andreas Fault includes many individual fault strands in a zone that ranges in width from several hundred feet to more than a thousand feet. Some of the individual fault strands ruptured to the surface during the 1906 earthquake.

## ENGINEERING GEOLOGY

Deposits that contain saturated loose sandy and silty soils are most susceptible to liquefaction. Lithologic descriptions and soil test results reported in geotechnical borehole logs provide valuable information regarding subsurface geology, ground-water levels, and the engineering characteristics of sedimentary deposits. For this investigation, borehole logs were collected from the files of the Cities of Atherton, East Palo Alto, Menlo Park, Palo Alto, Portola Valley, Los Altos, Los Altos Hills and Redwood City, as well as from San Mateo and Santa Clara counties. Data from 264 borehole logs were entered into a CGS geotechnical GIS database (Table 1.2).

Of particular value in liquefaction evaluations are logs that report the results of downhole Standard Penetration Tests. Standard Penetration Tests (SPTs) provide a standardized measure of the penetration resistance of geologic deposits and commonly are used as an index of soil density. This in-field test consists of counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil. The driving force is provided by dropping a 140-pound hammer weight 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (ASTM, 2004). Recorded blow counts for non-SPT geotechnical sampling where the sampler diameter, hammer weight or drop distance differs from that specified for an SPT (ASTM D1586), are converted to SPT-equivalent blow counts. The actual and converted SPT blow counts are normalized to a common-reference, effective-overburden pressure of 1 atmosphere

| GEOLOGIC MAP UNIT | | DRY DENSITY (pounds per cubic foot) | | | | | | STANDARD PENETRATION RESISTANCE (blows per foot, $(N_1)_{60}$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit [(1)] | Texture[(2)] | Number of Tests | Mean | C[(3)] | Median | Min | Max | Number of Tests | Mean | C[(3)] | Median | Min | Max |
| af | ine | 4 | 92 | 0.1 | 90 | [illegible] | [illegible] | 9 | 18 | 0.7 | 14 | [illegible] | [illegible] |
| | oarse | - | - | - | - | - | - | 1 | 28 | - | 28 | [illegible] | [illegible] |
| afbm | Fine | 16 | 98 | 0.2 | 104 | 59 | 113 | 21 | 16 | 0.8 | 11 | 1 | 58 |
| | Coarse | 4 | 121 | 0.1 | 123 | 103 | 133 | 4 | 17 | 0.8 | 14 | 4 | 36 |
| alf | ine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | oarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| ac | Fine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | Coarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| Qh | ine | 7 | 979 | 0.2 | 98 | [illegible] | [illegible] | 15 | 11 | 0.7 | 9 | [illegible] | [illegible] |
| | oarse | 4 | 96 | 0.1 | 95 | [illegible] | [illegible] | 4 | 12 | 0.8 | 10 | [illegible] | [illegible] |
| Qhly | Fine | 69 | 99 | 0.1 | 99 | 76 | 121 | 89 | 17 | 0.8 | 13 | 2 | 70 |
| | Coarse | 13 | 100 | 0.2 | 99 | 80 | 137 | 13 | 22 | 0.6 | 6 | 1 | 14 |
| Qhb | ine | 5 | 90 | 0.2 | 99 | [illegible] | [illegible] | 0 | - | - | - | - | - |
| | oarse | 1 | 124 | - | 124 | [illegible] | [illegible] | 10 | 6 | 0.6 | 6 | 1 | [illegible] |
| Qhb | Fine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | Coarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| Qh | ine | 166 | 106 | 0.1 | 105 | [illegible] | [illegible] | 295 | 24 | 0.8 | 19 | [illegible] | [illegible] |
| | oarse | 25 | 111 | 0.1 | 108 | [illegible] | [illegible] | 68 | 28 | 0.7 | 21 | [illegible] | [illegible] |
| Qhff | Fine | 112 | 98 | 0.1 | 98 | 65 | 132 | 145 | 19 | 0.7 | 17 | 4 | 92 |
| | Coarse | 12 | 106 | 0.1 | 105 | 85 | 120 | 19 | 21 | 0.7 | 15 | 4 | 57 |
| Qh | ine | 103 | 104 | 0.1 | 104 | [illegible] | [illegible] | 159 | 21 | 0.7 | 17 | [illegible] | [illegible] |
| | oarse | 22 | 104 | 0.1 | 103 | [illegible] | [illegible] | 42 | 24 | 0.7 | 19 | [illegible] | [illegible] |
| Qht | Fine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | Coarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| Qh | ine | 14 | 86 | 0.1 | 84 | [illegible] | [illegible] | 21 | 17 | 0.5 | 16 | [illegible] | [illegible] |
| | oarse | 5 | 90 | 0.1 | 89 | [illegible] | [illegible] | 10 | 34 | 0.4 | 36 | [illegible] | [illegible] |
| Qf | Fine | 12 | 102 | 0.1 | 103 | 87 | 117 | 29 | 20 | 0.7 | 15 | 4 | 48 |
| | Coarse | 4 | 103 | 0.0 | 104 | 97 | 106 | 17 | 29 | 0.5 | 24 | 8 | 55 |
| Qt | ine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | oarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| Qa | Fine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | Coarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| Qp | ine | 136 | 104 | 0.1 | 104 | [illegible] | [illegible] | 270 | 19 | 0.6 | 16 | [illegible] | [illegible] |
| | oarse | 40 | 115 | 0.1 | 115 | [illegible] | [illegible] | 121 | 28 | 0.6 | 25 | [illegible] | [illegible] |
| Qpt | Fine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | Coarse | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| Qp | ine | 0 | - | - | - | - | - | 0 | - | - | - | - | - |
| | oarse | 1 | 95 | - | 95 | [illegible] | [illegible] | 0 | - | - | - | - | - |
| Qof | Fine | 8 | 108 | 0.1 | 109 | 98 | 116 | 13 | 30 | 0.6 | 34 | 9 | 58 |
| | Coarse | 3 | 101 | 0.1 | 102 | 87 | 113 | 1 | 32 | - | 32 | 32 | 32 |

**Table 1.2 Summary of geotechnical characteristics for Quaternary geological units in the Palo Alto Quadrangle.**

(1) See Table 1.3 for names of the units listed here.
(2) Fine soils (silt and clay) contain a greater percentage passing the #200 sieve (<.074 mm); coarse soils (sand and gravel) contain a greater percentage not passing the #200 sieve.
(3) C = coefficient of variation (standard deviation divided by the mean)

(approximately 1 ton per square foot) and a hammer efficiency of 60 percent using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$.

## GROUND WATER

Saturation reduces the effective normal stress of near-surface sediment, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). CGS compiles and interprets ground-water data to identify areas characterized by, or anticipated to have in the future, near-surface saturated soils. For purposes of seismic hazard zonation, “near-surface” means at a depth less than 50 feet.

Natural hydrologic processes and human activities can cause ground-water levels to fluctuate through time. Therefore, it is impossible to predict depths to saturated soils during future earthquakes. One method of addressing time-variable depth to saturated soils is to establish an anticipated high ground-water level based on historical ground-water data. In areas where ground water is either currently near-surface or could return to near-surface levels within a land-use planning interval of 50 years, CGS constructs regional contour maps that depict these levels. In some areas with low precipitation, such as Antelope Valley, records may indicate that near-surface ground water existed during historical time, but withdrawal and low recharge rates preclude a return to those conditions within 50 years. For these areas, the historically highest ground-water level is not used to establish the anticipated depth to saturated soil for hazard evaluation. For these and all other areas, CGS delineates present or anticipated near-surface saturated soils caused by locally perched water and seepage from surface-water bodies.

Future initiation of large-scale, artificial recharge programs could result in a significant rise in ground-water levels over 50 years. When alerted of such programs, CGS will evaluate their impact relative to liquefaction potential and revise official seismic hazard zone maps, if necessary. Plate 1.2 depicts areas characterized by present or anticipated shallow ground water within the Palo Alto Quadrangle.

California State Water Resources Control Board. The depths to first-encountered unconfined ground water were plotted onto a map of the project area and contoured to constrain the estimate of historically shallowest ground water. Water depths from boreholes known to penetrate confined aquifers were not used.

Depths to first-encountered water range from 0 to 46 feet below the ground surface in the north-northeastern portion of the Palo Alto Quadrangle, between the base of the Santa Cruz Mountains and the shoreline of San Francisco Bay. Ground water levels gradually deepen to the southwest towards the base of the Santa Cruz Mountains. In the southwest corner of the quadrangle, along Corte Madera and Sausal Creeks, in the vicinity of the City of Portola Valley, depths to first-encountered water range from 4 to 17 feet (Plate 1.2).

# PART II

## LIQUEFACTION POTENTIAL

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. Liquefied sediment loses strength and may fail, causing damage to buildings, bridges, and other structures. Many methods for mapping liquefaction hazard have been proposed. Youd (1991) highlights the principal developments and notes some of the widely used criteria. Youd and Perkins (1978) demonstrate the use of geologic criteria as a qualitative characterization of liquefaction susceptibility and introduce the mapping technique of combining a liquefaction susceptibility map and a liquefaction opportunity map to produce a liquefaction potential map. Liquefaction susceptibility is a function of the capacity of sediment to resist liquefaction. Liquefaction opportunity is a function of the potential ground shaking intensity.

The method applied in this study for evaluating liquefaction potential is similar to that of Tinsley and others (1985). Tinsley and others (1985) applied a combination of the techniques used by Seed and others (1983) and Youd and Perkins (1978) for their mapping of liquefaction hazards in the Los Angeles region. CGS's method combines geotechnical analyses, geologic and hydrologic mapping, and probabilistic earthquake shaking estimates, but follows criteria adopted by the SMGB (DOC, 2004).

## LIQUEFACTION SUSCEPTIBILITY

Liquefaction susceptibility reflects the relative resistance of a soil to loss of strength when subjected to ground shaking. Physical properties of soil such as sediment grain-size distribution, compaction, cementation, saturation, and depth govern the degree of resistance to liquefaction. Some of these properties can be correlated to a sediment's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment. Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not addressed in this investigation. Soil characteristics and processes that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. Thus, blow count and cone penetrometer values are useful indicators of liquefaction susceptibility.

Saturation is required for liquefaction, and the liquefaction susceptibility of a soil varies with the depth to ground water. Very shallow ground water increases the susceptibility to liquefaction (soil is more likely to liquefy). Soils that lack resistance (susceptible soils) typically are saturated, loose and sandy. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's map inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross-sections, geotechnical test data, geomorphology, and ground-water hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to ground water are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on similar soil observations, liquefaction susceptibility maps typically are similar to Quaternary geologic maps. CGS's qualitative relations among susceptibility, geologic map unit and depth to ground water are summarized in Table 1.3.

In the Palo Alto Quadrangle, Holocene through Latest Pleistocene alluvial fan deposits have a high clay content, however these deposits also contain lenses of granular material that can be loose. Most Holocene alluvial fan deposits where water levels are within 30 feet of the ground surface have been given susceptibility assignments of high (H) to very high (VH) (Table 1.3). In addition, Holocene stream terrace deposits (Qht), and Late Pleistocene to Holocene stream terrace deposits (Qt), which contain lenses of potentially liquefiable material have been assigned high (H) susceptibility. Holocene alluvial fan, fine facies (Qhff) deposits (greater than 76% clays), and Holocene alluvial deposits, undifferentiated (Qha), primarily are composed of fine-grained material and are assigned a correspondingly lower susceptibility rating of moderate (M). Due to the lack of available geotechnical data, Holocene basin deposits (Qhb), a unit characterized by accumulation of fine-grained sediment, also are assigned a moderate (M) susceptibility. All late Pleistocene and older deposits within 30 feet of the ground surface have low (L) susceptibility assignments except Latest Pleistocene to Holocene alluvial fan deposits (Qf), and, latest Pleistocene to Holocene undifferentiated alluvium (Qa). These deposits may contain lenses of potentially liquefiable material (Table 1.3) and, therefore, are assigned moderate susceptibility.

## LIQUEFACTION OPPORTUNITY

Liquefaction opportunity is a measure, expressed in probabilistic terms, of the potential for strong ground shaking. Analyses of in-situ liquefaction resistance require assessment of liquefaction opportunity. The minimum level of seismic excitation to be used for such purposes is the level of peak ground acceleration (PGA) with a 10 percent probability of exceedance over a 50-year period (DOC, 2004). The earthquake magnitude used in CGS's analysis is the magnitude that contributes most to the calculated PGA for an area.

For the Palo Alto Quadrangle, PGAs of 0.59 to 0.81 g, resulting from earthquakes of magnitude 7.9 on the San Andreas Fault, were used for liquefaction analyses. The magnitude values were based on de-aggregation of the probabilistic hazard at the 10 percent in 50-year hazard level (Petersen and others, 1996). See the ground motion section (3) of this report for further description of ground shaking hazards.

| Geologic Unit [1] | Description | Total Layer Thickness (ft) | Composition by Soil Type (Unified Soil Classification System Symbols) | Depth to ground water (ft) [2] and liquefaction susceptibility assigned to geologic unit | | | |
|---|---|---|---|---|---|---|---|
| | | | | <10 | 10 to 30 | 30 to 40 | >40 |
| **af** | Artificial fill [3] | 273 | CL 14%; Other 86% | H- | H-I | M-L | VL |
| **afbm** | Artificial fill over Bay Mud | 154 | CL 68%; OH 13%; GM 9%; SM 6%; ML 5% | VH | H | M | VL |
| **alf** | Artificial fill, levee | 0 | n/a | H- | H-I | M-L | VL |
| **ac** | Artificial stream channel | 0 | n/a | VH-L | H | M | VL |
| **Qhc** | Modern stream channel deposits | 84 | L 67%; SM 15%; SC-CL 8% Other 10% | VH | H | M | VL |
| **Qhly** | Latest Holocene alluvial fan levee deposits | 553 | CL 65%; SM 11%; ML 9%; Other 15% | VH | H | M | VL |
| **Qhb** | Holocene San Francisco Bay Mud | 84 | CL 68%; OH 11%; ML 8%; GW 8%; SC 6% | H | M | L | VL |
| **Qhb** | Holocene basin deposits | 0 | n/a | M | M | L | VL |
| **Qhf** | Holocene alluvial fan deposits | 1523 | L 58%; ML 12%; SC 8%; S 6%; Other 16% | H | M | L | VL |
| **Qhff** | Holocene alluvial fan, fine facies | 735 | CL 76%; SM 8%; SC 5%; ML 5%; Other 6% | M | M | L | VL |
| **Qhl** | Holocene alluvial fan levee deposit | 897 | L 54%; SM 10%; ML 9%; S 9%; Other 18% | H | M | L | VL |
| **Qht** | Holocene stream terrace deposits | 0 | n/a | H | H | M | VL |
| **Qha** | Holocene alluvial deposits, undifferentiated | 154 | CL 50%; SM 17%; ML 14% SC 10; SW 8%; Other 1% | M | M | L | VL |
| **Qf** | Late Pleistocene to Holocene alluvial fan deposits | 271 | CL 49%; SP 18%; SM 14%; GC 7%; ML 5%; Other 7% | M | L | L | VL |
| **Qt** | Late Pleistocene to Holocene strear terrace deposits | 0 | n/a | H | H | M | VL |
| **Qa** | Late Pleistocene to Holocene alluvial deposits, undifferentiated | 0 | n/a | M | L | L | VL |
| **Qpf** | Late Pleistocene alluvial fan deposits | 2266 | CL 53%; SC 8%; SM 6%; SI 5%; SW 5%; Other 23% | L | L | VL | VL |
| **Qpt** | Late Pleistocene stream terrace deposits | 0 | n/a | L | L | VL | VL |
| **Qpa** | Late Pleistocene alluvial deposits, undifferentiated | 3 | SM 100% | L | L | VL | VL |
| **Qof** | Early to middle Pleistocene alluvial fan deposits | 60 | CL 65%; SC 22%; ML 6%; Other 7% | L | VL | VL | VL |
| **B** | Bedrock | n/a | n/a [4] | VL | VL | VL | VL |

**Table 1.3 Liquefaction Susceptibility for Quaternary Map Units in the Palo Alto Quadrangle**. Relative susceptibility of deposits to liquefaction as a function of material type and ground-water depth within that deposit. VH = very high, H = high, M = moderate, L = low, and VL = very low to none.

(1) Susceptibility assignments are specific to the materials within the Palo Alto 7.5-Minute Quadrangle.
(2) Based on the Simplified Procedure (Seed and Idriss, 1971; Youd and Idriss, 1997) and a small number of borehole analyses for some units.
(3) The liquefaction susceptibility of artificial fill ranges widely, depending largely on the nature of the fill, its age, and whether it was compacted during emplacement.
(4) n/a = not applicable

## Quantitative Liquefaction Analysis

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997; Youd and others, 2001). Using the Seed-Idriss Simplified Procedure one can calculate soil resistance to liquefaction, expressed in terms of cyclic resistance ratio (CRR), based on SPT results, ground-water level, soil density, moisture content, soil type, and sample depth. CRR values are then compared to calculated earthquake-generated shear stresses expressed in terms of cyclic stress ratio (CSR). The Seed-Idriss Simplified Procedure requires normalizing earthquake loading to a M7.5 event for the liquefaction analysis. To accomplish this, CGS's analysis uses the Idriss magnitude-scaling factor (MSF) (Youd and Idriss, 1997). It is convenient to think in terms of a factor of safety (FS) relative to liquefaction, where: FS = (CRR / CSR) * MSF. FS, therefore, is a quantitative measure of liquefaction potential. CGS uses a factor of safety of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil. While an FS of 1.0 is considered the "trigger" for liquefaction, for a site specific analysis an FS of as much as 1.5 may be appropriate depending on the vulnerability of the site and related structures.

The CGS liquefaction analysis program calculates an FS for each geotechnical sample where blow counts were collected. Typically, multiple samples are collected for each borehole. The program then independently calculates an FS for each non-clay layer that includes at least one penetration test using the minimum $(N_1)_{60}$ value for that layer. The minimum FS value of the layers penetrated by the borehole is used to evaluate the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data.

Of the 264 geotechnical borehole logs reviewed in this study (Plate 1.2), 253 include blow-count data from SPTs or from penetration tests that allow reasonable blow count translations to SPT-equivalent values. Non-SPT values, such as those resulting from the use of 2-inch or 2½-inch inside-diameter ring samplers, were translated to SPT-equivalent values if reasonable factors could be used in conversion calculations. The reliability of the SPT-equivalent values varies, therefore, they are weighted and used in a more qualitative manner. Few borehole logs, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or using averaged test values of similar materials.

The Seed-Idriss Simplified Procedure for liquefaction evaluation was developed primarily for clean sand and silty sand. As described above, results depend greatly on accurate evaluation of in-situ soil density as measured by the number of soil penetration blow counts using an SPT sampler. In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and recent laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995). SPT-derived density measurements in gravelly soils are unreliable and generally too high. They are likely to lead to overestimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N values appear to have been affected by gravel content, correlations were made with boreholes in the same unit where the N values do not appear to have been affected by gravel content.

## LIQUEFACTION ZONES OF REQUIRED INVESTIGATION

### Criteria for Zoning

Areas underlain by materials susceptible to liquefaction during an earthquake were included in liquefaction zones of required investigation using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (DOC, 2004). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following:

1. Areas known to have experienced liquefaction during historical earthquakes

2. All areas of uncompacted artificial fill that are saturated, nearly saturated, or may be expected to become saturated

3. Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable

4. Areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard. Within such areas, zones may be delineated by geologic criteria as follows:

   a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; or

   b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; or

   c) Areas containing soil deposits of latest Pleistocene age (11,000 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

Application of these criteria allows compilation of liquefaction zones of required investigation, which are useful for preliminary evaluations, general land-use planning and delineation of special studies zones (Youd, 1991).

## Areas of Past Liquefaction

Knudsen and others (2000) compiled ground failure data from Tinsley and others (1998) and Youd and Hoose (1978) for earthquakes in the San Francisco Bay region. Tinsley and others (1998) compiled observations of evidence for liquefaction for the 1989 Loma Prieta earthquake. Youd and Hoose (1978) compiled them for earlier earthquakes, including 1868 Hayward and 1906 San Francisco earthquakes. The Knudsen and others (2000) digital database differs from earlier compilation efforts in that the observations were located on a 1:24,000-scale base map versus the smaller- scale base maps used in the earlier publications. Sites were reevaluated and some single sites were broken into two or more where the greater base-map scale allowed.

In the Palo Alto Quadrangle, Youd and Hoose (1978) compiled four instances of ground failure recorded following the 1906 earthquake. One of the incidents occurred in Holocene alluvial fan deposits (Qhf), two incidents occurred in Holocene levee deposits (Qhl), and one incident occurred in Bay mud deposits (Qhbm, afbm). The report by Lawson and others (1908) of earthquake-induced ground failure in Qhf deposits occurred in the vicinity of an area formerly referred to as “Meyer Place on the west side of San Francisquito Creek”, but which currently is known as the vicinity of Olive Street and Oakdell Drive in the City of Menlo Park (site 143). Lawson and others (1908) report “…a crack about 1.5 inches wide ran for 20 feet along the edge of the county road parallel to and just above the creek, showing a half-inch vertical displacement, the lower side lying next to the creek. This crack appears to be due to the starting [sic] of the filled ground of which the road is partly made”. The two reports of earthquake-induced ground failure in Qhl occurred in the same general area (site 143). In addition to ground cracks, lateral spread was observed where “Water-pipes along the road leading from the reservoir toward Menlo Park had been pulled apart” (Lawson and others, 1908). Finally, Youd and Hoose (1978) includes a report by Gilbert and others (1907), noting the absence of earthquake-induced ground failure in Bay mud deposits in the northeast corner of the Palo Alto Quadrangle, in the vicinity of the Dumbarton Bridge (site 144). Gilbert and others (1907) report “Some subaqueous pipe lines crossing the bay seem not to have been injured”.

In the Palo Alto Quadrangle all but one instance of recorded earthquake-induced ground failure fall within the liquefaction Zone of Required Investigation. In particular, is it not clear whether or not features associated with Site 143 (Lawson and others, 1908), categorized as “miscellaneous ground cracks”, and described as “cracks and fissures that on the basis of published descriptions cannot be related to tectonic faulting, landslides or ground settlement” (Youd and Hoose, 1978) are related to liquefaction. Further, although there are many reports of earthquake-induced ground failure following the 1906 earthquake, some features are not well documented. Youd and Hoose caution that “Most post-earthquake investigative efforts were applied to assessing the extent of structural and other damage or tracing out ruptured faults; hence notations concerning ground failures are commonly of incidental nature”.

## Artificial Fills

In the Palo Alto Quadrangle, artificial fill areas large enough to show at the scale of mapping consist of engineered fill for flood control levees and elevated freeways, as well as small, isolated bodies of fill typically associated with small-scale construction projects, such as singlefamily homes. Since these fills are considered to be properly engineered, zoning for liquefaction in such areas depends on soil conditions in underlying strata. Small bodies of artificial fill located along stream channels are included in the zone of required investigation because stream channel deposits are commonly coarse grained, loose, and likely to be saturated. However, small bodies of artificial fill located in upland canyon areas are not included in the zone of required investigation, because although they may be coarse grained and loose, they typically are not saturated, and thus are not susceptible to liquefaction.

The San Francisco Bay is defined by an active margin that has been, and continues to be, modified by both natural processes and human activities. Witter and others (2006) reviewed historical maps of the San Francisco Bay shoreline and tidal marshes to map the extent of artificial fill overlying Bay Mud (afbm) that has been placed since the 1850's. These bodies of artificial fill historically have been particularly susceptible to liquefaction. In the Palo Alto Quadrangle artificial fill over Bay Mud deposits primarily occur in narrow linear deposits parallel to the shoreline of San Francisco Bay. Larger, isolated bodies of afbm are found at the north end of Willow Road in East Palo Alto, and, north of the intersection of Marsh Road and Highway 101 near Bayfront Park in Menlo Park. A larger body of afbm is located in Redwood City, defined roughly by the intersection of Industrial Road and Center Street near the northwest corner of the quadrangle, just south of Veterans Boulevard to the south, Chestnut street in the east, and, by a channel associated with a salt evaporation pond to the north. Each of these areas is included in the zone of required investigation.

**Areas with Sufficient Existing Geotechnical Data**

Borehole logs that include penetration test data and sufficiently detailed lithologic descriptions were used to evaluate liquefaction potential. In the Holocene alluvial deposits that cover approximately half of the Palo Alto Quadrangle, approximately 94 of the borehole logs that were analyzed using the Seed-Idriss Simplified Procedure contain sediment layers that may liquefy under the expected earthquake loading. These areas containing saturated potentially liquefiable material are included in the zone of required investigation.

There is sufficient geotechnical data for the northern portion of the Palo Alto Quadrangle, north of the Santa Cruz Mountains to be able to evaluate the liquefaction potential of subsurface deposits. Much of the Holocene sediment in the northern portion of the Palo Alto Quadrangle is underlain at shallow depths by sediment interpreted as Latest Pleistocene alluvial fan (Qpf). The Late Pleistocene sediment primarily is composed of clay and silt, with grayish-brown, fine to medium grained, gravels. The boundary for the zone of required investigation that runs through the northern portion of the Palo Alto Quadrangle is defined by the surface projection of the contact between ground water and the base of Holocene alluvial fan deposits. Holocene deposits in the central portion of the northern Palo Alto Quadrangle are not saturated and, therefore, this area is not included within the zone of required investigation. A narrow, northeast-trending band of Latest Holocene alluvial fan levee (Qhly) deposits in the eastern central portion of the map area, adjacent to the downstream end of San Francisquito Creek, is included in the zone of required investigation because these deposits are young, loose, granular and saturated, and therefore, susceptible to liquefaction.

### Areas with Insufficient Existing Geotechnical Data

Adequate geotechnical borehole information is lacking for the Santa Cruz Mountains portion of the south and southwestern regions of the Palo Alto Quadrangle. In addition, adequate geotechnical borehole information for artificial and modern stream channel deposits (ac and Qhc) generally is lacking. Holocene sediment deposited in upland creeks and canyons of the Santa Cruz Mountains includes Holocene basin (Qhb), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht), and undifferentiated Holocene alluvium (Qha) deposits. Artificial fill and modern stream channel deposits (af and Qhc) also occur along upland creeks and canyons, as well as in urban areas where natural drainages are modified to control run-off. All of these Holocene to late Holocene deposits are likely to contain loose, granular material that is saturated because of the proximity of active stream channels. In the Palo Alto Quadrangle, ground water and forecast ground motions are sufficiently high to include these Holocene units within the liquefaction zone of required investigation.

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# SECTION 2

# Earthquake-Induced Landslide Zones of Required Investigation in the Palo Alto 7.5-Minute Quadrangle

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## PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use seismic hazard zone maps prepared by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997). The text of this report is on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf.

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing landslide hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee in 1998 under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of landslide analysis, evaluation, and mitigation techniques (SCEC, 2002). This text is also on the Internet at: http://www.scec.org/

This section of the evaluation report summarizes seismic hazard zone mapping for earthquake-induced landslides in the Palo Alto 7.5-minute Quadrangle. Section 1 (addressing liquefaction) and Section 3 (addressing earthquake shaking), complete the report, which is one of a series that summarizes the preparation of seismic hazard zone maps within the state (Smith, 1996). Additional information on seismic hazard zone mapping in California can be accessed on the California Geological Survey's Internet page: http://www.consrv.ca.gov/CGS/index.htm

## BACKGROUND

Landslides triggered by earthquakes historically have been a significant cause of earthquake damage. In California, large earthquakes such as the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes triggered landslides that were responsible for destroying or damaging numerous structures, blocking major transportation corridors, and damaging life-line infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, areas underlain by loose, weak soils, and areas on or adjacent to existing landslide deposits. These geologic and terrain conditions exist in many parts of California, including numerous hillside areas that have already been developed or are likely to be developed in the future. The opportunity for strong earthquake ground shaking is high in many parts of California because of the presence of numerous active faults. The combination of these factors constitutes a significant seismic hazard throughout much of California, including the hillside areas of the Palo Alto Quadrangle.

## METHODS SUMMARY

The mapping of earthquake-induced landslide hazard zones presented in this report is based on the best available terrain, geologic, geotechnical, and seismological data. If unavailable or significantly outdated, new forms of these data were compiled or generated specifically for this project. The following were collected or generated for this evaluation:

- Digital terrain data were used to provide an up-to-date representation of slope gradient and slope aspect in the study area
- Geologic mapping was used to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether triggered by earthquakes or not, was prepared
- Geotechnical laboratory test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area

- Seismological data in the form of CGS probabilistic shaking maps and catalogs of strong-motion records were used to characterize future earthquake shaking within the mapped area

The data collected for this evaluation were processed into a series of GIS layers using commercially available software. A slope stability analysis was performed using the Newmark method of analysis (Newmark, 1965), resulting in a map of landslide hazard potential. The earthquake-induced landslide hazard zone was derived from the landslide hazard potential map according to criteria developed in a CGS pilot study (McCrink and Real, 1996; McCrink, 2001) and adopted by the State Mining and Geology Board (DOC, 2000).

## SCOPE AND LIMITATIONS

The methodology used to make this map is based on earthquake ground-shaking estimates, geologic material-strength characteristics and slope gradient. These data are gathered from a variety of outside sources. Although the selection of data used in this evaluation was rigorous, the quality of the data is variable. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data gathered from outside sources.

Earthquake-induced landslide zone maps are intended to prompt more detailed, site-specific geotechnical investigations as required by the Act. As such, these zone maps identify areas where the potential for earthquake-induced landslides is relatively high. Due to limitations in methodology, it should be noted that these zone maps do not necessarily capture all potential earthquake-induced landslide hazards. Earthquake-induced ground failures that are not addressed by this map include those associated with ridge-top spreading and shattered ridges. It should also be noted that no attempt has been made to map potential run-out areas of triggered landslides. It is possible that such run-out areas may extend beyond the zone boundaries. The potential for ground failure resulting from liquefaction-induced lateral spreading of alluvial materials, considered by some to be a form of landsliding, is not specifically addressed by the earthquake-induced landslide zone or this report. See Section 1, Liquefaction Evaluation Report for the Palo Alto Quadrangle, for more information on the delineation of liquefaction zones.

The remainder of this report describes in more detail the mapping data and processes used to prepare the earthquake-induced landslide zone map for the Palo Alto Quadrangle. The information is presented in two parts. Part I covers physiographic, geologic and engineering geologic conditions in the study area. Part II covers the preparation of landslide hazard potential and landslide zone maps.

# PART I

## PHYSIOGRAPHY

The Palo Alto 7.5-Minute Quadrangle southwest of the San Francisco Bay covers approximately 59 square miles in San Mateo, Santa Clara and Santa Cruz counties. Approximately 61 percent of the map area lies in San Mateo County in the western extent of the quadrangle and includes a portion of the city of Portola Valley. Approximately 36 percent of the map area lies in Santa Clara County in the northern and eastern extent of the quadrangle and includes portions of the cities of Palo Alto and Los Altos Hills. Approximately 3 percent of the map area lies in unincorporated Santa Cruz County in the southeast corner of the quadrangle. This report addresses earthquake-induced landslide zones only for those parts of the map that lie within San Mateo and Santa Clara counties.

The map area straddles the crest of the northwest-trending Santa Cruz Mountains in the Coast Range geomorphic province. The axis of the Santa Cruz Mountains and several broad-crested ridges are aligned roughly parallel to the prominent northwest trending San Andreas Rift zone, which bisects the quadrangle from the northwest to the southeast. Numerous creeks and small streams originate in the Santa Cruz Mountains and drain the quadrangle. Among the larger drainage systems in the map area are Pescadero, Peters, Mindego, and Alpine creeks flowing west toward the Pacific Ocean, and Los Trancos, Stevens, Adobe, Permanente and Big Green Moose creeks flowing east toward San Francisco Bay. Elevations within the zoned portions of the map area range from 240 feet in the northeast corner of the quadrangle to 2675 feet on Monte Bello Ridge just east of the center of the quadrangle.

With the exception of the city of Portola Valley in the northwest corner of the map, the entire portion of San Mateo County on the Palo Alto Quadrangle is unincorporated. Development in hill slope areas in San Mateo County favors low density residential structures. The cities of Los Altos Hills and Palo Alto occupy the northern portion of Santa Clara County in the Palo Alto Quadrangle. A substantial portion of the undeveloped land in the Palo Alto Quadrangle in both San Mateo and Santa Clara Counties is parkland managed by California State Parks, Santa Clara County, San Mateo County, and the Midpeninsula Regional Open Space District.

Major transportation routes in the Palo Alto Quadrangle include State Highway 280 which runs through the northeast corner of the quadrangle, State Highway 35 (Skyline Boulevard) which runs from the northwest corner to the southeast corner of the quadrangle, and State Highway 84 (Woodside Road east of Skyline Blvd. and La Honda Road west of Skyline Blvd.) which runs from the northeast corner to the southwest corner of the quadrangle. Additional access within the quadrangle is provided by a network of county roads and private roads in developed areas and by fire roads and trails in undeveloped land.

### Digital Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. An accurate slope gradient calculation begins with an up-to-date map representation of the earth's surface in the form of a digital topographic map. Within the Palo Alto Quadrangle, a Level 2 digital elevation model (DEM) was obtained from the USGS (U.S. Geological Survey, 1993). This DEM was prepared from the 7.5-minute quadrangle topographic contours generated from 1955 aerial photographs by photogrammetric methods and from planetable surveys. The DEM has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy.

In addition, due to significant topographic change from grading activity at the limestone quarry in the Permanente Creek drainage, a DEM obtained from an airborne interferometric radar platform was used to update the topography in this area (Intermap, 1998). This DEM was acquired in 1998 and has a vertical accuracy of approximately 2 meters. Because radar DEMs are prone to creating false topography where tall buildings, metal structures, or trees are present, the final hazard zone map was checked for potential errors and corrected where necessary. The area where the radar DEM was used is shown on Plate 2.1.

A slope map was made from the DEMs using a third-order, finite difference, center-weighted algorithm (Horn, 1981). The DEMs were also used to make a slope aspect map. The manner in which the slope and aspect maps were used to prepare the zone map will be described in subsequent sections of this report.

## GEOLOGY

The primary source of bedrock geologic mapping used in this slope stability evaluation was obtained from U.S. Geological Survey Open File Report OF-98-348 (Brabb and others, 1998). Geologic Mapping of Quaternary surficial deposits was derived from recently completed maps of the nine-county San Francisco Bay Area (Knudsen and others, 2000) obtained from the U.S. Geological Survey in digital form. Surficial geology is discussed in detail in Section 1 of this report.

CGS geologists modified the above digital geologic maps in the following ways. Landslide deposits were deleted from the bedrock geologic map and a new landslide inventory map was prepared (discussed later) so that the distribution of bedrock formations and the landslide inventory would exist on separate GIS layers for the hazard analysis. CGS geologists merged the bedrock and Quaternary geologic map databases, and contacts between bedrock and surficial units were revised to better conform to the topographic contours of the U.S.G.S. 7.5-minute quadrangle. Air-photo interpretation and field reconnaissance were performed to assist in adjusting contacts between bedrock and surficial geologic units and to review geologic unit lithology and geologic structure.

The geology of the Palo Alto 30 x 60-minute Quadrangle has been divided into ten individual stratigraphic assemblages that lie within a series of fault-bounded bedrock structural blocks (Brabb and others, 1998). Each stratigraphic assemblage differs from its neighbors in depositional and deformational history. Five of these stratigraphic assemblages extend into the Palo Alto Quadrangle (Brabb and others, 1998). The Butano Ridge Assemblage is found in the southwest corner of the map area and is separated from the Palo Alto assemblage by the Butano Fault. The Palo Alto Assemblage, which occupies the largest percentage of the Palo Alto Quadrangle covers most of the south and west portions of the map area. The Palo Alto Assemblage is separated from the Sky Londa and Portola Valley assemblages in the north by the Woodhaven Fault, and from the Woodside Assemblage in the north east by the San Andreas Fault. The Sky Londa and Portola Valley assemblages are separated by the Pilarcitos Fault, and the Portola Valley and Woodside assemblages are separated by the San Andreas Fault.

Bedrock units exposed in the five assemblages in the Palo Alto Quadrangle consists of the following Tertiary formations from oldest to youngest: Whiskey Hill Formation (Tw), Butano Sandstone (Tb), San Lorenzo Formation (Tsl), Vaqueros Formation (Tvq), Mindego Basalt (Tmb), Lambert Shale (Tla), Monterey Formation ™, Purisima Formation (Tp), Merced Formation (QTm) and Santa Clara Formation (QTsc). The following detailed descriptions of the assemblages and their rock units are from Brabb and others (1998).

### *Butano Ridge Assemblage*

The Butano Ridge Assemblage consists of lower Eocene and upper Eocene and Oligocene marine sedimentary rocks. The Tertiary rocks overlie a Mesozoic basement complex of granitic to gabbroic intrusive rocks and high-grade metamorphic rocks of the Salinian complex along an angular unconformity. The basement complex rocks are not exposed in the Palo Alto Quadrangle. The Tertiary units of the Butano Ridge assemblage, exposed in the Palo Alto Quadrangle, are discussed below.

Butano Sandstone (Tb) of middle and lower Eocene age consists of thin to very thick beds of fine- to very coarse-grained sandstone. Sandstone is interbedded with mudstone and shale layers that typically make up 10 to 40 percent of the unit.

The San Lorenzo Formation (Tsl) of Oligocene and upper and middle Eocene age consists of shale, mudstone and siltstone with local interbeds of sandstone. In the Butano Ridge Assemblage of the Palo Alto Quadrangle, the San Lorenzo Formation includes the Rices Mudstone Member (Tsrm) of Oligocene and upper Eocene age. This unit is an unbedded mudstone and siltstone with some laminated shale, and spheroidal weathering; elongate carbonate concretions are common.

### *Mindego Hill Assemblage*

The Mindego Hill Assemblage consists of Eocene through Pliocene marine sedimentary rocks and basalt. The Tertiary rocks overlie a Mesozoic basement complex of granitic to gabbroic intrusive rocks and high-grade metamorphic rocks of the Salinian Complex. The basement complex rocks are not exposed in the Palo Alto Quadrangle. The Tertiary units of the Mindego Hill assemblage, exposed in the Palo Alto Quadrangle, are discussed below.

The oldest rocks in the Midego Hill Assemblage in the Palo Alto Quadrangle are unnamed sedimentary rocks (Tu) of Eocene (?) age consisting of mudstone, shale and argillite with minor sandstone. The Butano Sandstone (Tb) includes a separate unit of uncertain affinity that is mapped as conglomerate of the lower member of the formation (Tblc?). This unit consists of thick to very thick beds of sandy pebble conglomerate.

The San Lorenzo Formation (Tsl) of Oligocene and upper and middle Eocene age consists of shale, mudstone and siltstone with local interbeds of sandstone. The Vaqueros Sandstone (Tvq) of Oligocene to lower Miocene age consists of fine- to medium-grained and, locally, coarse-grained arkosic sandstone with interbedded mudstone and shale.

The Mindego Basalt and related volcanic rocks (Tmb) of Miocene and/or Oligocene age consist of both extrusive and intrusive volcanic rocks. Extrusive rocks primarily are basaltic flow breccias with lesser amounts of tuff, pillow lavas and flows. Intrusive rocks consist of medium to coarsely crystalline basaltic rocks.

The Lambert Shale (Tla) of Oligocene to lower Miocene age consists primarily of moderately well cemented mudstone, siltstone and claystone, but does include some sandstone beds. The Lambert Shale and San Lorenzo Formation, Undivided (Tlsl) of lower Miocene, and middle and upper Eocene consists of mudstone, siltstone, and shale. Although the Lambert shale is generally more siliceous than the San Lorenzo Formation, the units are indistinguishable without fossils when they are found out of stratigraphic sequence.

The Monterey Formation ™ of middle Miocene age consists of porcelaneous mudstone and shale, impure diatomite, calcareous claystone with small amounts of sandstone and siltstone near the base.

The Purisima Formation (Tp) of Pliocene and upper Miocene age consists primarily of sandstone, siltstone, and mudstone, and may also include porcelaneous shale and mudstone, chert, silty mudstone and volcanic ash. Within the Mindego Hill Assemblage, the Purisima Formation also includes the Tahana Member (Tptm) of Pliocene and upper Miocene age. The Tahana Member consists of medium- to very fine-grained sandstone and siltstone, with some silty mudstone.

The Santa Clara Formation (QTsc) of lower Pleistocene and upper Pliocene age consists of poorly indurated conglomerate, sandstone, and mudstone in irregular and lenticular beds.

***Sky Londa Assemblage***

The Sky Londa Assemblage includes a sequence of Tertiary (Lower Eocene through Miocene and/or Oligocene) rocks that unconformably overlies a composite Mesozoic basement consisting of the Franciscan Complex and the Coast Range Ophiolite. During the Late Cretaceous or Early Tertiary the Franciscan Complex was subducted beneath the Coast Range Ophiolite and the contact between the two is everywhere faulted as a consequence. The Tertiary units of the Sky Londa assemblage, exposed in the Palo Alto Quadrangle are discussed below.

Within the Sky Londa Assemblage the Butano Sandstone (Tb) includes the lower Eocene Shale in Butano Sandstone (Tbs), consisting of clay shale, mudstone, siltstone and minor thin interbeds of sandstone.

The San Lorenzo Formation (Tsl) of Oligocene and upper and middle Eocene age consists of shale, mudstone and siltstone with local interbeds of sandstone. In the Sky Londa Assemblage, the San Lorenzo Formation also includes the Twobar Shale Member (Tstw) of middle and upper Eocene age consisting of laminated shale with some mudstone.

The Sky Londa Assemblage contains Mindego Basalt and related volcanic rocks (Tmb) with similar characteristics to those found in the Mindego Hill Assemblage.

***Portola Valley Assemblage***

The Portola Valley Assemblage consists of middle and lower Eocene, and upper Miocene through lower Pleistocene marine sediments. These Tertiary rocks are believed to be underlain by the Mesozoic Franciscan Complex everywhere east of the Pilarcitos Fault. A minor amount of Franciscan Complex Serpentinite (sp) of Cretaceous and/or Jurassic age is exposed in the Portola Valley assemblage. The Tertiary units of the Portola Valley Assemblage, exposed in the Palo Alto Quadrangle are discussed below.

The Whiskey Hill Formation (Tw) of middle and lower Eocene age consists of coarse-grained arkosic sandstone, with silty claystone, glauconitic sandstone and tuffaceous siltstone. The Purisima Formation (Tp) of Pliocene and upper Miocene age consists primarily of sandstone, siltstone, and mudstone, and may also include porcelaneous shale, chert, silty mudstone and volcanic ash.

The Santa Clara Formation (QTsc) of lower Pleistocene and upper Pliocene age consists of poorly indurated conglomerate, sandstone, and mudstone in irregular and lenticular beds. The portion of the Portola Valley Assemblage exposed in the vicinity of Coal Mine Ridge, south of Portola Valley, includes conglomerate with boulders as long as 1 meter derived from an older conglomerate.  In addition, some claystone and siltstone beds on Coal Mine Ridge contain carbonized wood fragments as large as 60 cm in diameter.

### *Woodside Assemblage*

The Woodside Assemblage includes a sequence of middle and lower Eocene and Miocene rocks that unconformably overlies a composite Mesozoic basement consisting of Franciscan Complex, Coast Range Ophiolite, and Great Valley Sequence. Franciscan Complex rocks are exposed in the east and southeast parts of the quadrangle along the northeast side of the San Andreas Fault. Coast Range Ophiolite rocks are exposed in small quantities enclosed by Franciscan Complex rocks. Great Valley Sequence rocks are not exposed in the map area. Tertiary marine and non-marine rocks of the Woodside Assemblage are exposed primarily in the northeast portion of the Palo Alto Quadrangle.

Several distinct units of the Franciscan Complex are mapped in the Palo Alto Quadrangle. Sheared rock or melange (fsr) consists of sandstone, siltstone, and shale that has been extensively sheared but locally contains resistant blocks of relatively unsheared rock. Greenstone (fg) consists of basaltic flows, pillow lavas, breccias, tuffs and minor related intrusive rocks. Chert (fc) consists of thin to thick layers and commonly is rhythmically interbedded with thin shale layers. Limestone (fpl) is fine to coarsely crystalline and crops out in lenticular bodies usually associated with greenstone. Sandstone (fss) consists of fine- to coarse-grained graywacke with interbedded siltstone and shale.

One lithology of the Coast Range Ophiolite is mapped in the Palo Alto Quadrangle. Serpentinite (sp) is exposed in small fault-bounded bodies enclosed by Franciscan rocks. Serpentinite is extensively to slightly sheared and contains some altered ultramafic rock.

The Monterey Formation ™ of middle Miocene age consists of porcelaneous mudstone and shale, impure diatomite, calcareous claystone with small amounts of sandstone and siltstone near the base. Unnamed marine sandstone and shale (Tmsu) of upper Miocene age consists of fine- to medium-grained sandstone with some siliceous mudstone and shale.

The Santa Clara Formation (QTsc) of upper Pliocene to lower Pleistocene age consists of non-marine, poorly indurated conglomerate, sandstone and mudstone in lenticular beds.

## Structural Geology

The stratigraphic assemblages of the Santa Cruz Mountains were deposited and deformed in separate depositional basins. Later, these stratigraphic assemblages were truncated and juxtaposed against one another by a complex system of Tertiary and Quaternary strike-slip and dip-slip faults.

The most prominent fault in the map area is the San Andreas Fault, which juxtaposes the Mindego Hill and Sky Londa assemblages on the southwest against the Woodside and Portola Valley assemblages on the northeast. The San Andreas Fault is a right-lateral strike-slip fault with an estimated 35 km of displacement in the last 8 million years (Brabb and others, 1998). The San Andreas Fault includes many individual fault strands in a zone that ranges in width from several hundred to more than a thousand feet. Some of the individual fault strands ruptured during the 1906 earthquake.

The Pilarcitos fault juxtaposes the Sky Londa Assemblage against the Portola Valley Assemblage. It is interpreted as not active during the Holocene (Bortugno and others, 1991), and is believed to be an abandoned strike-slip segment to the Pacific-North American transform Plate boundary (McLaughlin and others, 1996).

The Berrocal Fault has a component of reverse or thrust offset, and displaces rocks of the Woodside assemblage northeast of the San Andreas Fault zone. The Berrocal Fault forms a prominent east-west topographic lineament in the northeast corner of the map area and juxtaposes rocks of the Franciscan Complex (KJf) against rocks of the Plio-Pleistocene Santa Clara Formation (QTsc). Sorg and McLaughlin (1975) report that the Franciscan rocks on the southwest side of the fault have been uplifted and displaced laterally to the northwest.

The Woodhaven Fault is located in the north-west portion of the quadrangle. It is not considered an active fault, but it is a structural boundary between the Mindego Hill and the Sky Londa assemblages.

**Landslide Inventory**

As a part of the geologic data compilation, an inventory of existing landslides in the Palo Alto Quadrangle was prepared by field reconnaissance, analysis of stereo-paired aerial photographs and a review of previously published landslide mapping. Landslides were mapped at a scale of 1:24,000. For each landslide included on the map a number of characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable and questionable) and other properties, such as activity, thickness, and associated geologic unit(s). Landslides rated as definite and probable were carried into the landslide zoning as described later in this report. Landslides rated as questionable were not carried into the slope stability analysis due to the uncertainty of their existence. The completed landslide map was scanned, digitized, and the attributes were compiled in a database. A version of this landslide inventory is included with Plate 2.1.

In general, landslides are concentrated in the western half of the Palo Alto Quadrangle, southwest of the San Andreas Fault. Many of the slides in the Palo Alto Quadrangle cut across numerous geologic units, however, the majority of landslides occur on slopes underlain by a combination of the Lambert Shale (Tla) and Santa Clara (QTsc) and Mindego Basalt (Tmb) Formations. In the northwest corner of the quadrangle this inventory includes landslides mapped for the town of Portola Valley by Rodine (unpublished, 1973) and William Cotton and Associates (1978). Modifications to these inventories include removal of slides that are too small to be discernable at the scale of this investigation, removal of areas susceptible to landsliding and areas where only portions of landslides are mapped.

Large, old, deep-seated bedrock landslide complexes are common. Examples are found in the vicinity of Rogers Gulch and Mindego Hill near the center of the quadrangle and along the ridge separating Evans and Peters creeks. Shallow earth and debris slides are also abundant in the Palo Alto Quadrangle and often develop within coherent blocks of larger and older landslides.

Because it is not within the scope of the Act to review and monitor grading practices to ensure past slope failures have been properly mitigated, all documented slope failures, whether or not surface expression currently exists, are included in the landslide inventory.

***Earthquake-Induced Historical Landsliding***

Youd and Hoose (1978) compiled observations of landslides and related ground failure from the 1906 earthquake, and Knudsen and others (2000) have completed a digital compilation of data from this earlier source. This digital database differs from earlier compilation efforts in that the observations were located on a 1:24,000 scale base map versus the smaller-scale base maps used in Youd and Hoose (1978). Sites were reevaluated and some single sites were broken into two or more where the greater base map detail allowed. These sites of past landslide-related ground failure occurrences are shown on Plate 2.1. Although detailed descriptions are recorded, maps of the exact location and extent of any of the ground failures that resulted from the 1906 earthquake do not exist and therefore none of the ground failures described in Youd and Hoose (1978) are included in the land slide inventory for the Palo Alto Quadrangle.

Within the Palo Alto Quadrangle, Youd and Hoose (1978) compiled nine accounts of earthquake-induced landsliding reported by Lawson and others (1908) following the 1906 earthquake. Descriptions of ground failure include: 1) streambank landsliding including rotational slumps and soil falls, 2) hillside landslides including rotational slumps, block glides, debris avalanches and rockfalls, and 3) ground cracks not clearly associated with landslides, lateral spreads, settlement or primary fault movements (Youd and Hoose, 1978). Ground failures are described in numerous formations, however the majority occur in sediments of Tertiary age including, from oldest to youngest: Whiskey Hill Formation (Tw), Butano Sandstone (Tb), Vaqueros Formation (Tvq), Mindego Basalt (Tmb), and the Purisima Formation (Tp).

Streambank failures are noted along Stevens Creek at the southeast margin of the Palo Alto Quadrangle. Hillside landslides are described at several locations throughout the quadrangle. Isolated instances of hillside landslides are noted at the western margin of the quadrangle along Woodruff Creek in the vicinity of Langley Hill as well as Alpine Creek. Further isolated instanced of hillside landslides are noted at the south end of the quadrangle in Pescadero Creek, in the central portion of the quadrangle along Skyline Boulevard east of Lambert Creek, and in the northeast portion of the quadrangle in the vicinity of Elephant Mountain and south of Adobe Creek where “…large blocks of rock are reported to have rolled down the slopes" (Youd and Hoose, 1978). Widespread instances of hillside landslides and ground cracks are reported along Page Mill Road and Alpine Road along the northern boundary of the quadrangle.

## ENGINEERING GEOLOGY

### Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above were ranked and grouped on the basis of their shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. Shear-strength data for the units identified on the Palo Alto Quadrangle geologic map were obtained from the San Mateo County Department of Public Works, the Town of Portola Valley, the Town of Los Altos Hills, and Cotton, Shire, and Associates, Inc. (see Appendix A). The locations of rock and soil samples taken for shear testing within the Palo Alto Quadrangle are shown on Plate 2.1. Geologic material strength information from the adjoining Cupertino and Castle Rock Ridge quadrangles was used for several geologic formations for which little or no shear test information was available within the Palo Alto Quadrangle. One possibly significant difference in material strength values between the units in the Cupertino Quadrangle and those used in the Palo Alto Quadrangle was the strength value for the bedrock unit fsr (called fm, Franciscan Melange, in the Cupertino and Castle Rock Ridge quadrangles). Based on observations in the field, this unit appears to be similar in strength and landslide potential to the Franciscan Greenstone (fg) and, therefore, was grouped with fg in Shear Strength Group 3; this also corresponds closely with the value given to the melange unit in the Castle Rock Ridge Quadrangle (31 degrees).

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped on the basis of average angle of internal friction (average phi) and lithologic character. Average (mean or median) phi values for each geologic map unit and corresponding strength groups are summarized in Table 2.1. For each geologic strength group (Table 2.2) in the map area, the average shear strength value was assigned and used in our slope stability analysis. A geologic material strength map was made based on the groupings presented in Table 2.1 and Table 2.2, and this map provides a spatial representation of material strength for use in the slope stability analysis. A number of geologic map units were subdivided further, as discussed below.

### Adverse Bedding Conditions

Adverse bedding conditions are an important consideration in slope stability analyses. Adverse bedding conditions occur where the dip direction of bedded sedimentary rocks is roughly the same as the slope aspect, and where the dip magnitude is less than the slope gradient. Under these conditions, landslides can slip along bedding surfaces due to a lack of lateral support.

To account for adverse bedding in our slope stability evaluation, we used geologic structural data in combination with digital terrain data to identify areas with potentially adverse bedding, using methods similar to those of Brabb (1983). The structural data, strike and dip measurements and fold axes derived from the geologic map database, were used to categorize areas of common bedding dip direction and magnitude. The dip direction was then compared to the slope aspect and, if the same, the dip magnitude and slope gradient categories were compared. The area was marked as a potential adverse bedding area if the dip magnitude category was less than or equal to the slope gradient category, but greater than 25% (4:1 slope).

According to Wentworth, et al. (1985), the Tp, Tptm, Tmsu, Tvq, Tsl, Tlsl, and Tw formations are considered potentially susceptible to slope failure where adverse bedding exists. Therefore, these formations were subdivided based on shear strength differences between coarse-grained (higher strength) and fine-grained (lower strength) lithologies. Shear strength values for the fine- and coarse-grained lithologies were then applied to areas of favorable and adverse bedding orientation, which were determined from structural and terrain data as discussed above. It was assumed that coarse-grained material (higher strength) dominates where bedding dips into a slope (favorable bedding) while fine-grained (lower strength) material dominates where adverse bedding occurs. The geologic material strength map was modified by assigning the lower, fine-grained shear strength values to areas where potential adverse bedding conditions were identified. The favorable and adverse bedding shear strength parameters for Tp, Tptm, Tmsu, Tvq, Tsl, Tlsl, and Tw are included in Table 2.1.

**Existing Landslides**

As discussed later in this report, the criteria for landslide zone mapping state that all existing landslides that are mapped as definite or probable are automatically included in the landslide zone of required investigation. Therefore, an evaluation of shear strength parameters for existing landslides is not necessary for the preparation of the zone map. However, in the interest of completeness for the material strength map, to provide relevant material strength information to project plan reviewers, and to allow for future revisions of our zone mapping procedures, we have collected and compiled shear strength data considered representative of existing landslides within the quadrangle.

The strength characteristics of existing landslides (Qls) must be based on tests of the materials along the landslide slip surface. Ideally, shear tests of slip surfaces formed in each mapped geologic unit would be used. However, this amount of information is rarely available. We collect and compile primarily “residual” strength parameters from laboratory tests of slip surface materials tested in direct shear or ring shear test equipment. Back-calculated strength parameters, if the calculations appear to have been performed appropriately, have also been included in our compilation.

Within the Palo Alto Quadrangle, 13 direct shear tests of landslide slip surface materials were obtained, and the results are summarized in Table 2.1.

**PALO ALTO QUADRANGLE**
**SHEAR STRENGTH GROUPS**

| | Formation Name | Number Tests | Mean/Median Phi (deg) | Mean/Median Group Phi (deg) | Mean/Median Group C (psf) | No Data: Similar Lithology | Phi Values Used in Stability Analyses |
|---|---|---|---|---|---|---|---|
| GROUP 1 | Tld(fbc) | 8 | 36/37 | 34/35 | 659/500 | | 34 |
| | Tws(fbc) | 1 | 35/35 | | | Tp(fbc) | |
| | Tw(fbc) | 171 | 34/34 | | | Tpm, Tb | |
| | | | | | | fl, fm | |
| | | | | | | fmm, fpl | |
| | | | | | | fs, fss | |
| | | | | | | fu | |
| GROUP 2 | Qht | 10 | 31/30 | 29/29 | 706/650 | | 29 |
| | QTsc | 137 | 29/28 | | | Qf | |
| | fg | 43 | 29/29 | | | Qpt | |
| | fc | 16 | 30/30 | | | Qpoaf | |
| | sp | 9 | 30/29 | | | Qt | |
| | | | | | | QTm | |
| | | | | | | Tlad | |
| | | | | | | Ksh | |
| | | | | | | Kshu | |
| | | | | | | KJf | |
| GROUP 3 | af | 26 | 25/25 | 26/26 | 594/500 | | 26 |
| | Qhc | 6 | 27/27 | | | afbm | |
| | Qpaf | 6 | 26/28 | | | alf | |
| | Qpa | 4 | 26/32 | | | ac | |
| | Tld(abc) | 5 | 27/25 | | | Qhb | |
| | | | | | | Qhbm | |
| | | | | | | Tp(abc) | |
| | | | | | | Tm(fbc) | |
| GROUP 4 | Qa | 7 | 21/25 | 22/21 | 773/700 | | 22 |
| | Qhf | 58 | 22/21 | | | Qhf1 | |
| | Qhl | 27 | 21/20 | | | Qhf2 | |
| | Qha | 30 | 23/23 | | | Qhff | |
| | Qof | 35 | 23/23 | | | Qhl1 | |
| | Tm(abc) | 2 | 23/23 | | | Qhl2 | |
| | Tw(abc) | 268 | 22/21 | | | | |
| | Tws(abc) | 6 | 21/17 | | | | |
| GROUP 5 | Qls | 4 | 16/17 | 16/17 | 503/515 | | 16 |

**abc = adverse bedding condition, fine-grained material strength**

**fbc = favorable bedding condition, coarse-grained material strength**

**Formation name abbreviations from Brabb and others (1988) and Knudsen and others (2000)**

**Table 2.1. Summary of the Shear Strength Statistics for the Palo Alto Quadrangle.**

| SHEAR STRENGTH GROUPS FOR THE PALO ALTO 7.5-MINUTE QUADRANGLE | | | | |
|---|---|---|---|---|
| **GROUP 1** | **GROUP 2** | **GROUP 3** | **GROUP 4** | **GROUP 5** |
| Tb | Tp(fbc) | Qt | af, Qha | Qls |
| Tblc | Tptm(fbc) | QTm | Qhay, Qhc | |
| fss | Tmsu(fbc) | QTsc | Qpf, Qa | |
| fc | Tvq(fbc) | Tlsl(fbc) | Tp(abc) | |
| fpl | Tw(fbc) | Tmb | Tptm(abc) | |
| fsr | sp | Tsl(fbc) | Tm, Tmsu(abc) | |
| | | Tu | Tla, Tlsl(abc) | |
| | | fg | Tvq(abc), Tsl(abc) | |
| | | fsr | Tsrm, Tstw | |
| | | | Tbs, Tw(abc) | |

**Table 2.2. Summary of Shear Strength Groups for the Palo Alto Quadrangle.**

# PART II

# EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

## Design Strong-Motion Record

To evaluate earthquake-induced landslide hazard potential in the study area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. The Newmark method analyzes dynamic slope stability by calculating the cumulative down-slope displacement for a given earthquake strong-motion time history. As implemented for the preparation of earthquake-induced landslide zones, the Newmark method necessitates the selection of a design earthquake strong-motion record to provide the "ground shaking opportunity." For the Palo Alto Quadrangle, selection of a strong motion record was based on an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA). The parameters were estimated from maps prepared by CGS for a 10% probability of being exceeded in 50 years (Petersen and others, 1996). The parameters used in the record selection are:

| | |
|---|---|
| Modal Magnitude: | 7.9 |
| Modal Distance: | 2.5 to 10.5km |
| PGA: | 0.6 to 1.0g |

The strong-motion record selected for the slope stability analysis in the Palo Alto Quadrangle was the Southern California Edison Lucerne record from the 1992 magnitude 7.3 Landers, California, earthquake was used because it was the closest fit to the above criteria. This record had a source to recording site distance of 1.1 km and a peak ground acceleration (PGA) of 0.80g. Although the modal distance and magnitude from the Lucerne record do not fall within the range or are not the same as the probabilistic parameters, this record was considered to be sufficiently conservative to be used in the stability analyses. The selected strong-motion record was not scaled or otherwise modified prior to its use in the analysis.

## Displacement Calculation

The design strong-motion record was used to develop a relationship between landslide displacement and yield acceleration ($a_y$), defined as the earthquake horizontal ground acceleration above which landslide displacements take place. This relationship was prepared by integrating the design strong-motion record twice for a given acceleration value to find the corresponding displacement, and the process was repeated for a range of acceleration values (Jibson, 1993). The resulting curve in Figure 2.1 represents the full spectrum of displacements that can be expected for the design strong-motion record. This curve provides the required link between anticipated earthquake shaking and estimates of displacement for different combinations of geologic materials and slope gradient, as described in the Slope Stability Analysis section below.

The amount of displacement predicted by the Newmark analysis provides an indication of the relative amount of damage that could be caused by earthquake-induced landsliding. Displacements of 30, 15 and 5 cm were used as criteria for rating levels of earthquake-induced landslide hazard potential based on the work of Youd (1980), Wilson and Keefer (1983), and a CGS pilot study for earthquake-induced landslides (McCrink and Real, 1996; McCrink, 2001). Applied to the curve in Figure 2.1, these displacements correspond to threshold yield accelerations of 0.142, 0.182 and 0.243g. Because these yield acceleration values are derived from the design strong-motion record, they represent the ground shaking opportunity thresholds that are significant in the Palo Alto Quadrangle.

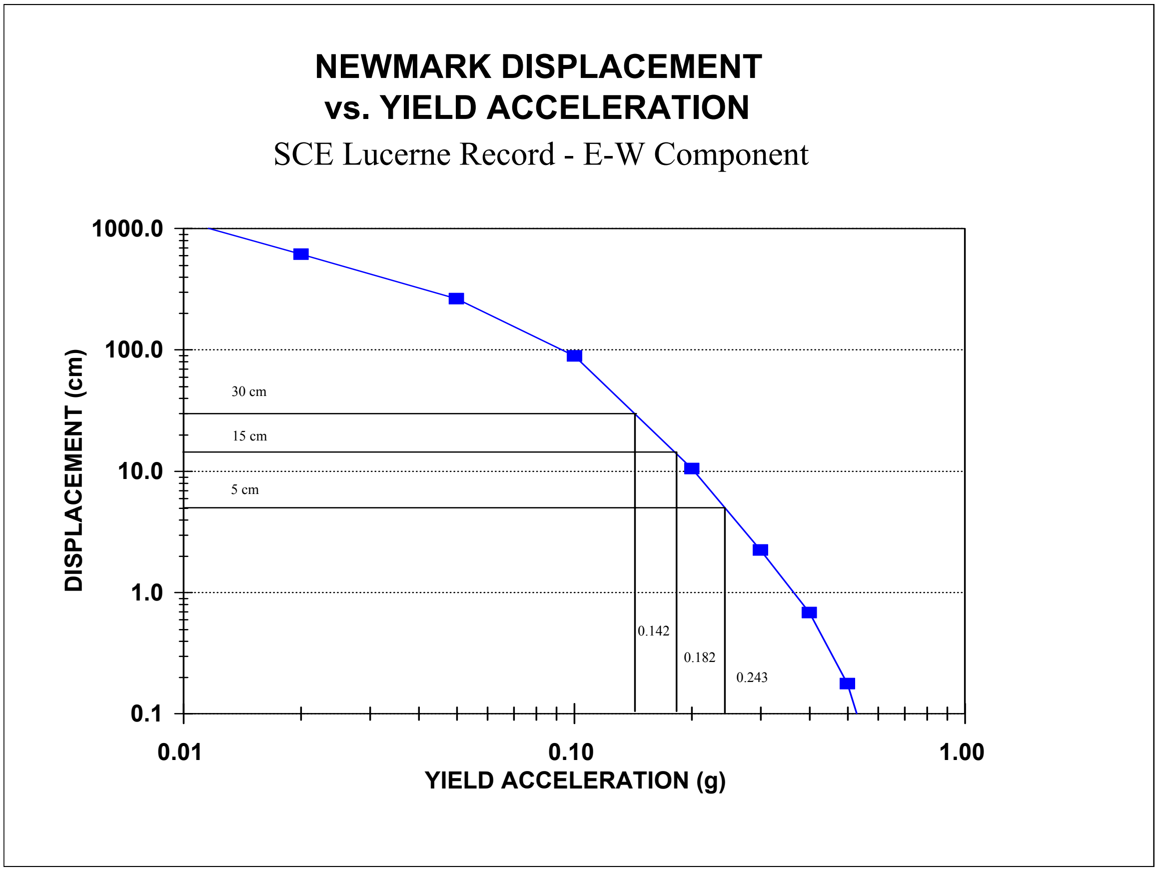


**Figure 2.1. Yield Acceleration vs. Newmark Displacement for the Southern California Edison Lucerne Record.**

**Slope Stability Analysis**

A slope stability analysis was performed for each geologic material strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration from Newmark's equation: $a_y = ( FS - 1 )g \sin \alpha$

where **FS** is the Factor of Safety, **g** is the acceleration due to gravity, and $\alpha$ is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite slope failure $\alpha$ is the same as the slope angle.

The yield accelerations resulting from Newmark's equations represent the susceptibility to earthquake-induced failure of each geologic material strength group for a range of slope gradients. Based on the relationship between yield acceleration and Newmark displacement shown in Figure 2.1, hazard potentials were assigned as follows:

1. If the calculated yield acceleration was less than 0.142g, Newmark displacement greater than 30 cm is indicated, and a HIGH hazard potential was assigned.

2. If the calculated yield acceleration fell between 0.142g and 0.182g, Newmark displacement between 15 cm and 30 cm is indicated, and a MODERATE hazard potential was assigned.

3. If the calculated yield acceleration fell between 0.182g and 0.243g, Newmark displacement between 5 cm and 15 cm is indicated, and a LOW hazard potential was assigned.

4. If the calculated yield acceleration was greater than 0.243g, Newmark displacement of less than 5 cm is indicated, and a VERY LOW potential was assigned.

Table 2.3 summarizes the results of the stability analyses. The earthquake-induced landslide hazard potential map was prepared by combining the geologic material-strength map and the slope map according to this table.

| PALO ALTO QUADRANGLE HAZARD POTENTIAL MATRIX | | | | |
|---|---|---|---|---|
| Geologic Material Strength Group (Average Phi) | HAZARD POTENTIAL (% Slope) | | | |
| | Very Low | Low | Moderate | High |
| **1 (36)** | 0 to 46% | 47 to 52% | 53 to 57% | > 57% |
| **2 (33)** | 0 to 39% | 40 to 46% | 47 to 49% | > 49% |
| **3 (30)** | 0 to 31% | 32 to 37% | 38 to 42% | > 42% |
| **4 (25)** | 0 to 22% | 23 to 27% | 28 to 31% | > 31% |
| **5 (16)** | - | 0 to 2% | 3 to 8% | > 8% |

**Table 2.3. Hazard Potential Matrix for Earthquake-Induced Landslides in the Palo Alto Quadrangle**. Values in the table show the range of slope gradient (expressed as percent slope) corresponding to calculated Newmark displacement ranges from the design earthquake for each material strength group.

## EARTHQUAKE-INDUCED LANDSLIDE HAZARD ZONE

### Criteria for Zoning

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (DOC, 2000). Under these criteria, earthquake-induced landslide hazard zones are defined as areas that meet one or both of the following conditions:

1. Areas that have been identified as having experienced landslide movement in the past, including all mappable landslide deposits and source areas as well as any landslide that is known to have been triggered by historic earthquake activity.

2. Areas where the geologic and geotechnical data and analyses indicate that the earth materials may be susceptible to earthquake-induced slope failure.

These conditions are discussed in further detail in the following sections.

## Existing Landslides

Existing landslides typically consist of disrupted soils and rock materials that are generally weaker than adjacent undisturbed rock and soil materials. Previous studies indicate that existing landslides can be reactivated by earthquake movements (Keefer, 1984). Earthquake-triggered movement of existing landslides is most pronounced in steep head scarp areas and at the toe of existing landslide deposits. Although reactivation of deep-seated landslide deposits is less common (Keefer, 1984), a significant number of deep-seated landslide movements have occurred during, or soon after, several recent earthquakes. Based on these observations, all existing landslides with a definite or probable confidence rating are included within the earthquake-induced landslide hazard zone.

## Geologic and Geotechnical Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), it has been concluded that earthquake-induced landslide hazard zones should encompass all areas that have a High, Moderate or Low level of hazard potential (see Table 2.3). This would include all areas where the analyses indicate earthquake displacements of 5 centimeters or greater. Areas with a Very Low hazard potential, indicating less than 5 centimeters displacement, are excluded from the zone.

As summarized in Table 2.3, all areas characterized by the following geologic strength group and slope gradient conditions are included in the earthquake-induced landslide hazard zone:

1. Geologic Strength Group 5 is included in the zone for all slope gradients. (Note: The only geologic unit included in Geologic Strength Group 5 is Qls, existing landslides. They have been included or excluded from the landslide zones on the basis of the criteria described in the previous section)

2. Geologic Strength Group 4 is included for all slopes steeper than 22 percent.

3. Geologic Strength Group 3 is included for all slopes steeper than 31 percent.

4. Geologic Strength Group 2 is included for all slopes steeper than 39 percent.

5. Geologic Strength Group 1 is included for all slopes greater than 46 percent.

This results in about 64 percent of the quadrangle lying within the earthquake-induced landslide hazard zone for the Palo Alto Quadrangle.

## ACKNOWLEDGMENTS

The authors would like to thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project. Geologic material strength data were collected with the assistance of Jay Mazzetta (San Mateo County), Leslie Lambert (Town of Portola Valley), and Ted Sayre (Cotton, Shires, and Associates, Inc.). Ted Sayre and John Wallace of Cotton, Shires and Associates provided helpful review comments to the landslide inventory.

At CGS, Kent Aue, Cathy Slater, and Mark Wiegers helped collect shear strength data for the Palo Alto Quadrangle as well as surrounding quadrangles. Ellen Sander digitized borehole locations and entered shear test data into the database. Terilee McGuire, Lee Wallinder, and Bob Moscovitz provided GIS support. Barbara Wanish prepared the final landslide hazard zone maps and the graphic displays for this report.

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## AIR PHOTOS

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# APPENDIX A
# SOURCE OF ROCK STRENGTH DATA

| SOURCE | NUMBER OF TESTS SELECTED |
|---|---|
| San Mateo County Public Works | 104 |
| Town of Portola Valley | 102 |
| Cotton, Shire, and Associates, Inc. | 70 |
| Total Number of Shear Tests | 276 |

# SECTION 3

# Potential Ground Shaking in the Palo Alto 7.5-Minute Quadrangle

**By**

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## PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the Seismic Hazard Zone Maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997); also available on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

This section of the evaluation report summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included are ground motion and related maps, a brief overview on how these maps were prepared, precautionary notes concerning their use, and related references. The maps provided herein are presented at a scale of approximately 1:150,000 (scale bar provided on maps), and show the full 7.5-minute quadrangle and portions of the adjacent eight quadrangles.

They can be used to assist in the specification of earthquake loading conditions ***for the analysis of ground failure*** according to the "Simple Prescribed Parameter Value" method (SPPV) described in the site investigation guidelines (DOC, 1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard.

This section and Sections 1 and 2 (addressing liquefaction and earthquake-induced landslide hazards) constitute a report series that summarizes development of seismic hazard zone maps in the state. Additional information on seismic hazard zone mapping in California can be accessed on CGS's Internet homepage: http://www.conservation.ca.gov/CGS/index.htm

## EARTHQUAKE HAZARD MODEL

The estimated ground shaking is derived from the statewide probabilistic seismic hazard evaluation released cooperatively by the California Department of Conservation, California Geological Survey, and the U.S. Geological Survey (Petersen and others, 1996). That report documents an extensive 3-year effort to obtain consensus within the scientific community regarding fault parameters that characterize the seismic hazard in California. Fault sources included in the model were evaluated for long-term slip rate, maximum earthquake magnitude, and rupture geometry. These fault parameters, along with historical seismicity, were used to estimate return times of moderate to large earthquakes that contribute to the hazard.

The ground shaking levels are estimated for each of the sources included in the seismic source model using attenuation relations that relate earthquake shaking with magnitude, distance from the earthquake, and type of fault rupture (strike-slip, reverse, normal, or subduction). The published hazard evaluation of Petersen and others (1996) only considers uniform firm-rock site conditions. In this report, however, we extend the hazard analysis to include the hazard of exceeding peak horizontal ground acceleration (PGA) at 10 percent probability of exceedance in 50 years on spatially uniform conditions of rock, soft rock, and alluvium. These soil and rock conditions approximately correspond to site categories defined in Chapter 16 of the Uniform Building Code (ICBO, 1997), which are commonly found in California. We use the attenuation relations of Boore and others (1997), Campbell (1997), Sadigh and others (1997), and Youngs and others (1997) to calculate the ground motions.

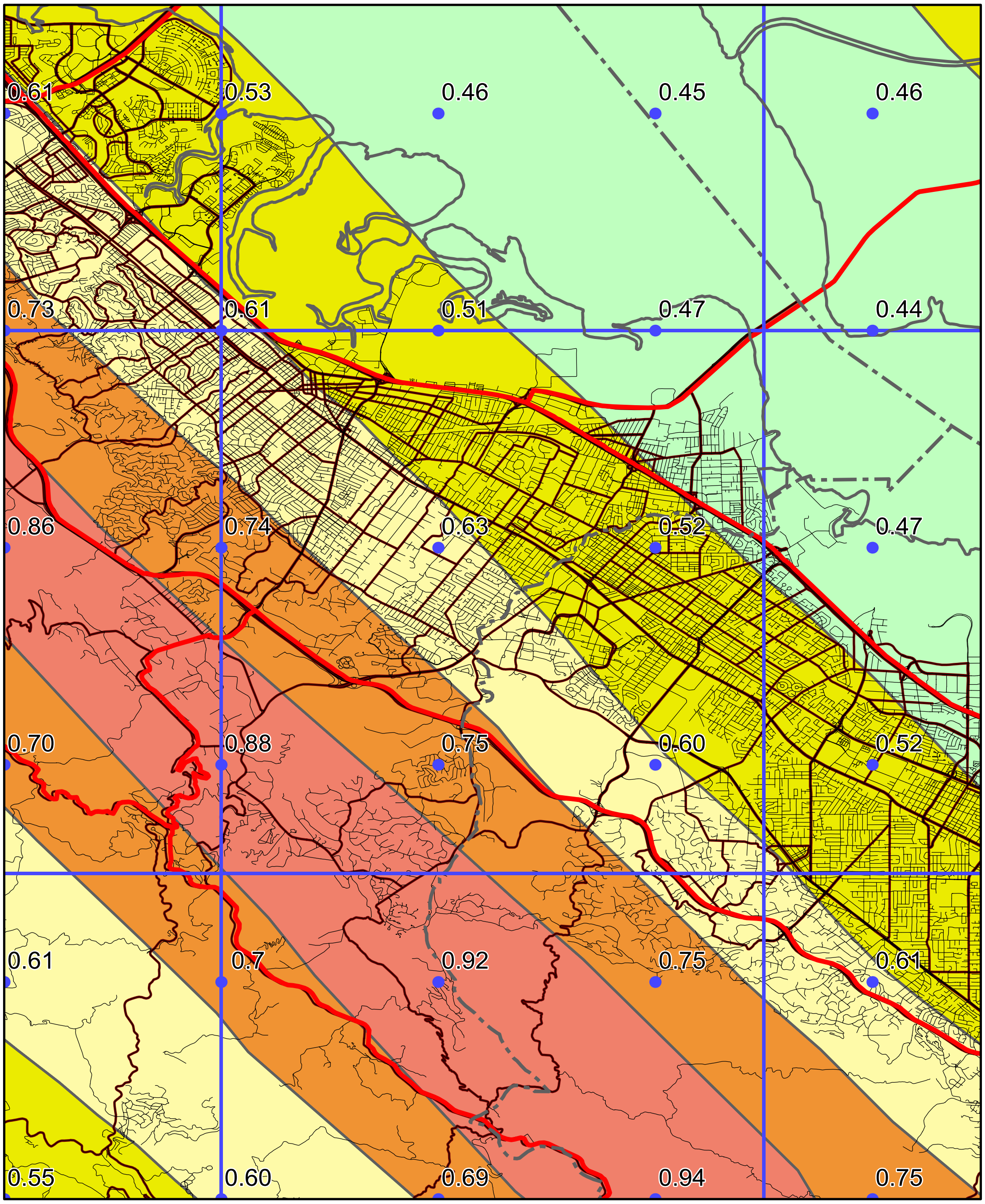
The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figures 3.1 through 3.3 show the hazard for PGA at 10 percent probability of exceedance in 50 years assuming the entire map area is firm rock, soft rock, or alluvial site conditions respectively. The sites where the hazard is calculated are represented as dots and ground motion contours as shaded regions. The quadrangle of interest is outlined by bold lines and centered on the map. Portions of the eight

PALO ALTO 7.5-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

*10% EXCEEDENCE IN 50 YEARS PEAK GROUND ACCELERATION (g)*

1998

**FIRM ROCK CONDITIONS**




Base map from GDT

Department of Conservation
California Geological Survey

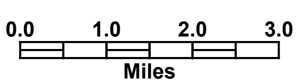
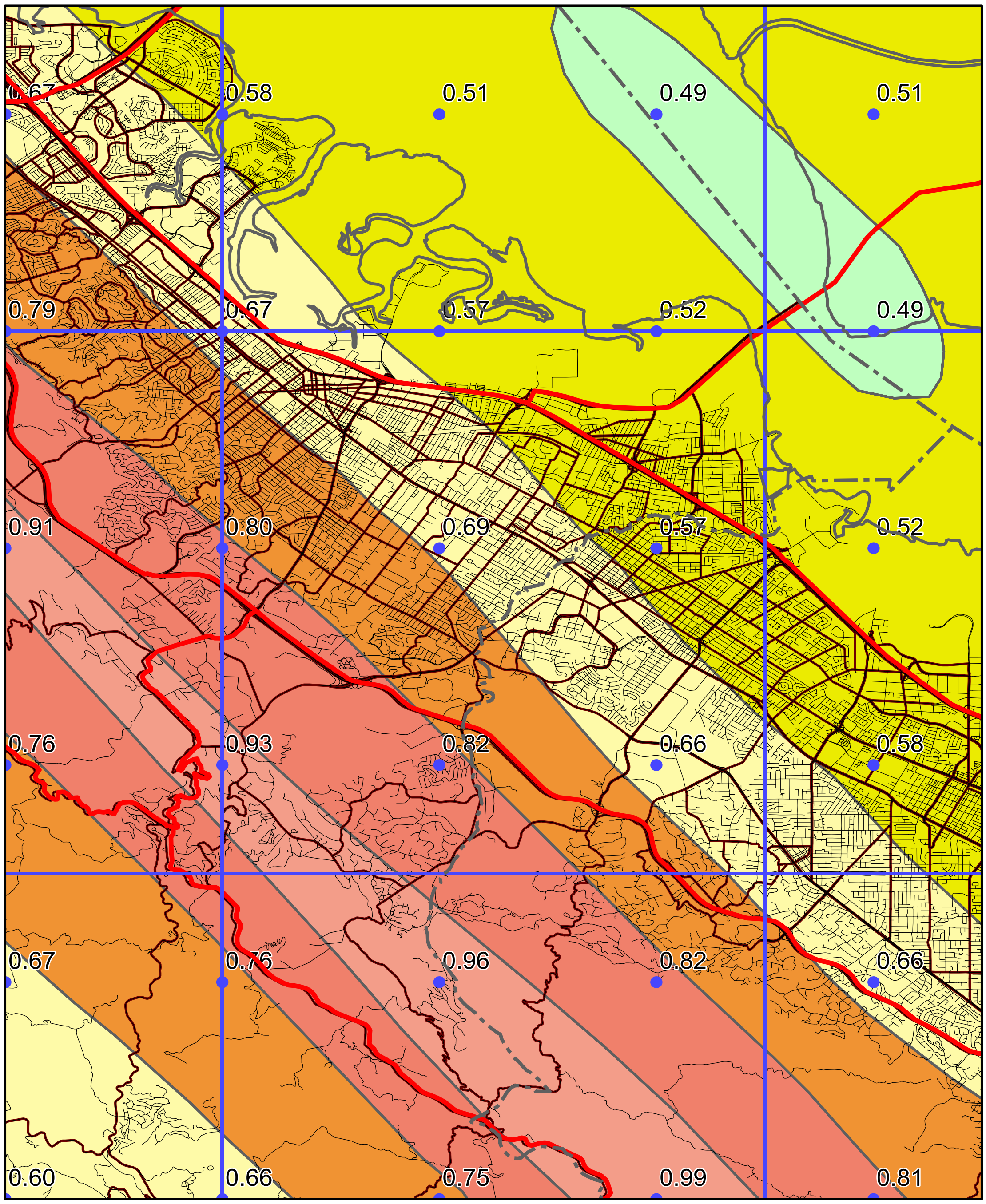



Figure 3.1

PALO ALTO .5-MINUTE QUADRANGLE AND PORTIONS OF
ADJACENT QUADRANGLES

*10% EXCEEDENCE IN 50 YEARS PEAK GROUND ACCELERATION (g)*
1998

**SOFT ROCK CONDITIONS**




Base map from GDT

0.0 1.0 2.0 3.0
Miles

Department of Conservation
California Geological Survey

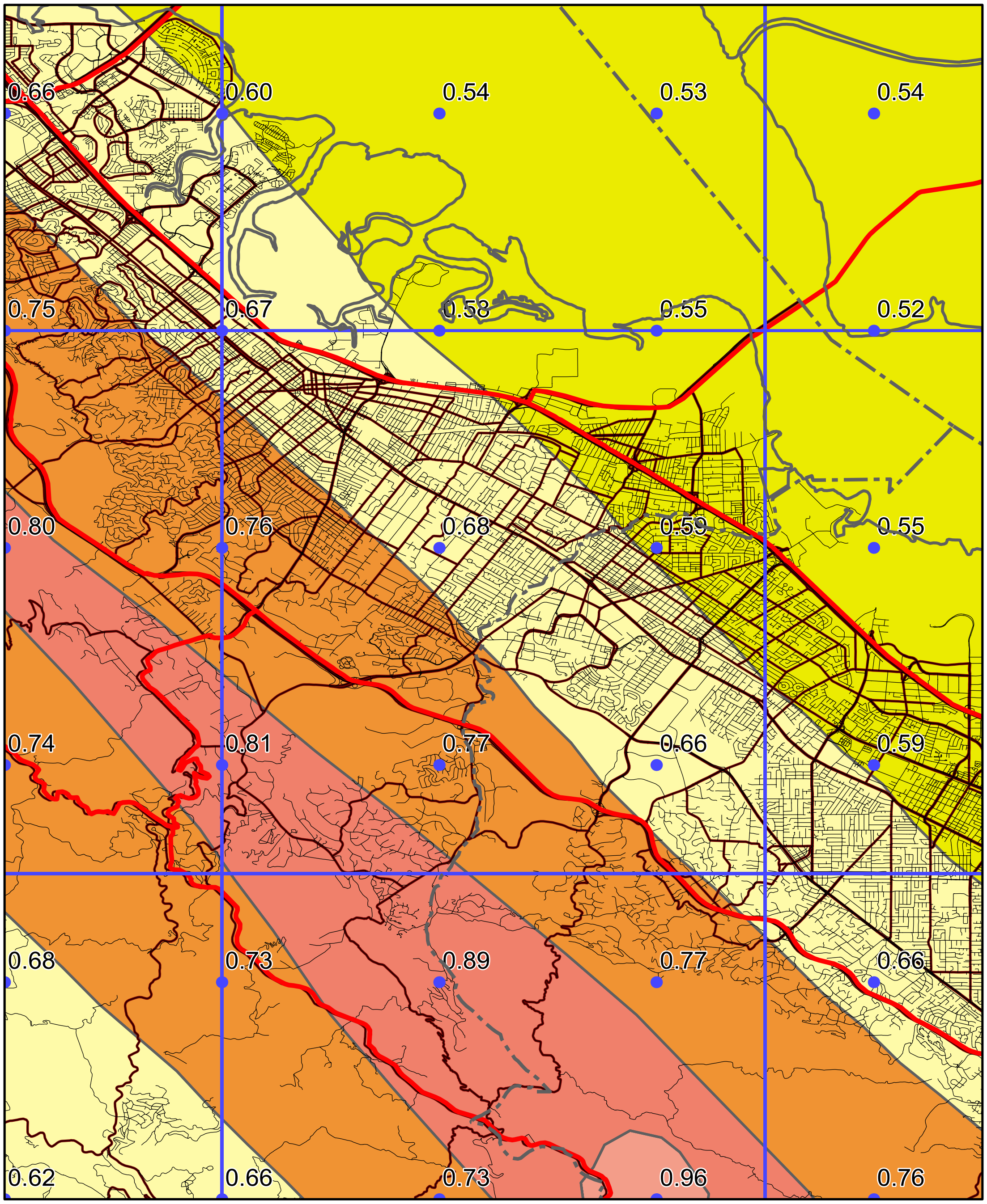
Figure 3.2

PALO ALTO 7.5-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

*10% EXCEEDENCE IN 50 YEARS PEAK GROUND ACCELERATION (g)*

1998

**ALLUVIUM CONDITIONS**




Base map from GDT

0.0 1.0 2.0 3.0

Miles

Department of Conservation
California Geological Survey

Figure 3.3

adjacent quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating ground motion values by selecting the map that matches the actual site conditions, and interpolating from the calculated values of PGA rather than the contours, since the points are more accurate.

## APPLICATIONS FOR LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENTS

Deaggregation of the seismic hazard identifies the contribution of each of the earthquakes (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (see Cramer and Petersen, 1996). The map in Figure 3.4 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10 percent probability of exceedance in 50 years on alluvial site conditions (*predominant earthquake*). This information gives a rationale for selecting a seismic record or ground motion level in evaluating ground failure. However, it is important to keep in mind that more than one earthquake may contribute significantly to the hazard at a site, and those events can have markedly different magnitudes and distances. For liquefaction hazard the predominant earthquake magnitude from Figure 3.4 and PGA from Figure 3.3 (alluvium conditions) can be used with the Youd and Idriss (1997) approach to estimate cyclic stress ratio demand. For landslide hazard the predominant earthquake magnitude and distance can be used to select a seismic record that is consistent with the hazard for calculating the Newmark displacement (Wilson and Keefer, 1983). When selecting the predominant earthquake magnitude and distance, it is advisable to consider the range of values in the vicinity of the site and perform the ground failure analysis accordingly. This would yield a range in ground failure hazard from which recommendations appropriate to the specific project can be made. Grid values for predominant earthquake magnitude and distance should **not** be interpolated at the site location, because these parameters are not continuous functions.

A preferred method of using the probabilistic seismic hazard model and the “simplified Seed-Idriss method” of assessing liquefaction hazard is to apply magnitude scaling probabilistically while calculating peak ground acceleration for alluvium. The result is a “magnitude-weighted” ground motion (liquefaction opportunity) map that can be used directly in the calculation of the cyclic stress ratio threshold for liquefaction and for estimating the factor of safety against liquefaction (Youd and Idriss, 1997). This can provide a better estimate of liquefaction hazard than use of predominate magnitude described above, because all magnitudes contributing to the estimate are used to weight the probabilistic calculation of peak ground acceleration (Real and others, 2000). Thus, large distant earthquakes that occur less frequently but contribute *more* to the liquefaction hazard are appropriately accounted for.

Figure 3.5 shows the magnitude-weighted alluvial PGA based on Idriss’ weighting function (Youd and Idriss, 1997). It is important to note that the values obtained from this map are pseudo-accelerations and should be used in the formula for factor of safety without any magnitude-scaling (a factor of 1) applied.

## USE AND LIMITATIONS

The statewide map of seismic hazard has been developed using regional information and is ***not appropriate for site specific structural design applications***. Use of the ground motion maps prepared at larger scale is limited to estimating earthquake loading conditions for preliminary assessment of ground failure at a specific location. We recommend consideration of site-specific analyses before deciding on the sole use of these maps for several reasons.

1. The seismogenic sources used to generate the peak ground accelerations were digitized from the 1:750,000-scale fault activity map of Jennings (1994). Uncertainties in fault location are estimated to be about 1 to 2 kilometers (Petersen and others, 1996). Therefore, differences in the location of calculated hazard values may also differ by a similar amount. At a specific location, however, the log-linear attenuation of ground motion with distance renders hazard estimates less sensitive to uncertainties in source location.

2. The hazard was calculated on a grid at sites separated by about 5 km (0.05 degrees). Therefore, the calculated hazard may be located a couple kilometers away from the site. We have provided shaded contours on the maps to indicate regional trends of the hazard model. However, the contours only show regional trends that may not be apparent from points on a single map. Differences of up to 2 km have been observed between contours and individual ground acceleration values. *We recommend that the user interpolate PGA between the grid point values rather than simply using the shaded contours*.

3. Uncertainties in the hazard values have been estimated to be about +/- 50 percent of the ground motion value at two standard deviations (Cramer and others, 1996).

4. Not all active faults in California are included in this model. For example, faults that do not have documented slip rates are not included in the source model. Scientific research may identify active faults that have not been previously recognized. Therefore, future versions of the hazard model may include other faults and omit faults that are currently considered.

5. A map of the predominant earthquake magnitude and distance is provided from the deaggregation of the probabilistic seismic hazard model. However, it is important to recognize that a site may have more than one earthquake that contributes significantly to the hazard. Therefore, in some cases earthquakes other than the predominant earthquake should also be considered.

PALO ALTO 7.5-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

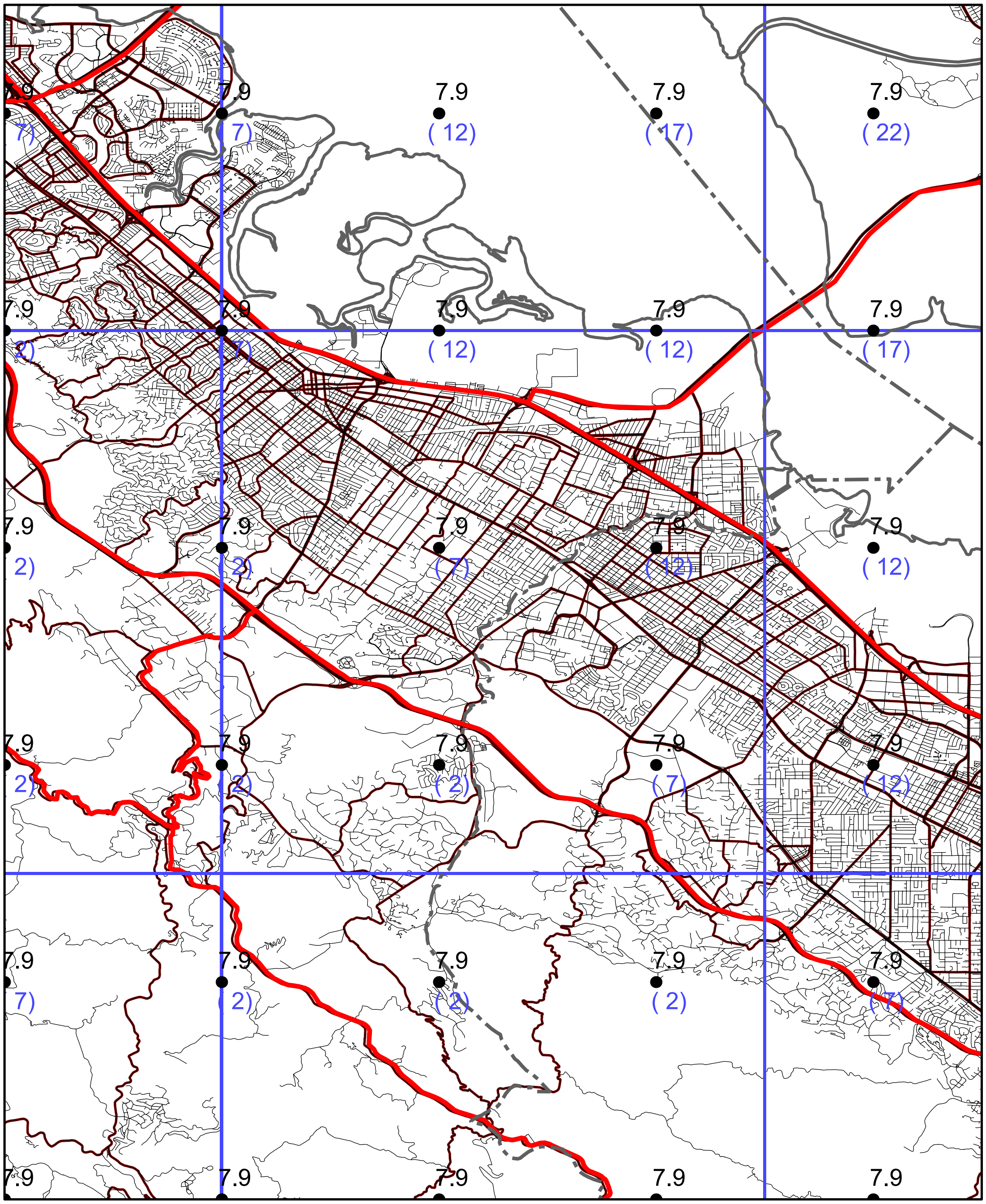
*10% EXCEEDENCE IN 50 YEARS PEAK GROUND ACCELERATION*

1998

**PREDOMINANT EARTHQUAKE**

**Magnitude (Mw)**

**[Distance (km)]**




Base map from GDT

0.0 1.0 2.0 3.0 Miles

Kilometers 0.0 1.0 2.0 3.0

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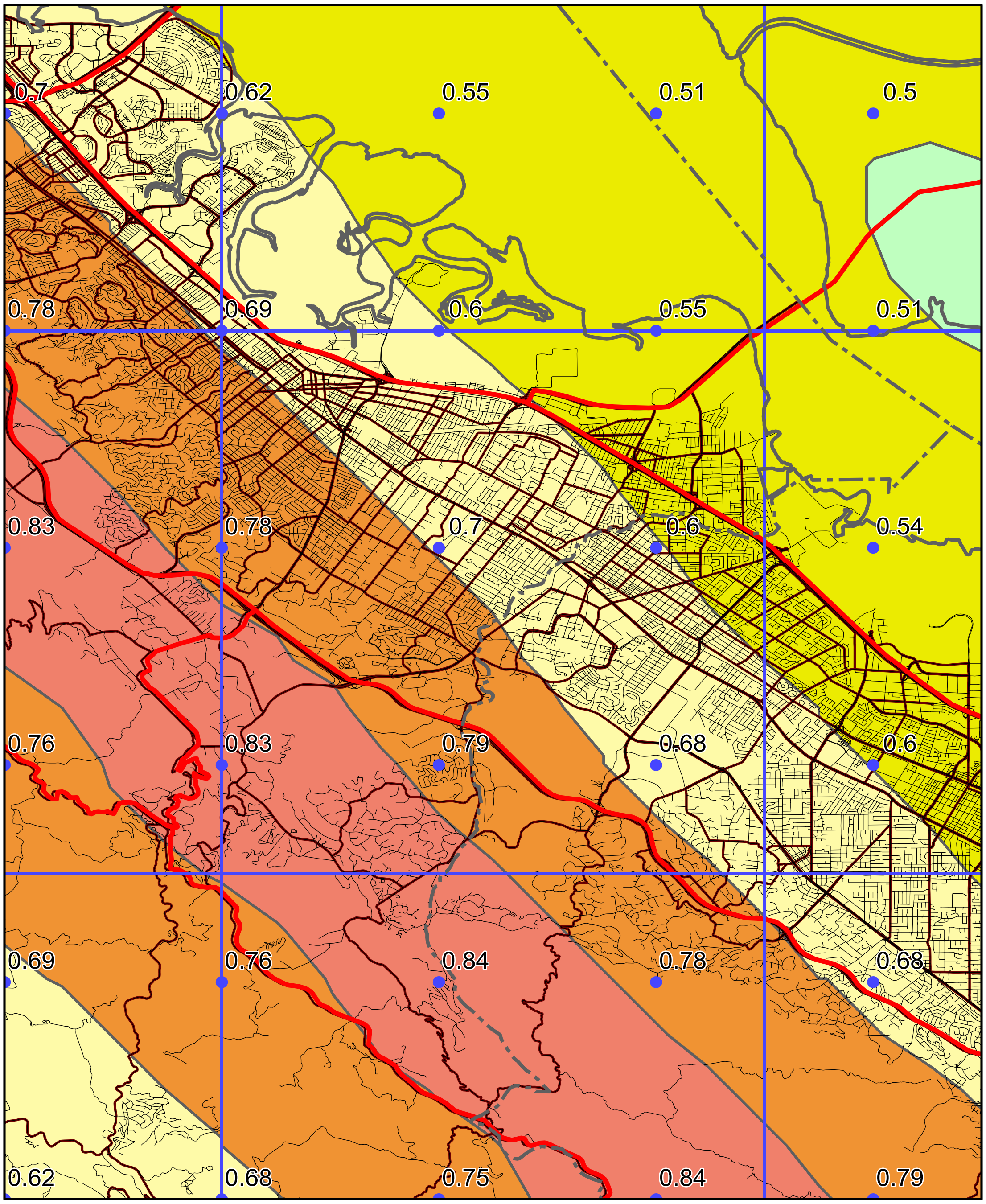
Figure 3.4

PALO ALTO 7.5-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

*10% EXCEEDENCE IN 50 YEARS MAGNITUDE WEIGHTED PSEUDO-PEAK ACCELERATION (g)*

1998

**LIQUEFACTION OPPORTUNITY**




Base map from GDT

0.0 1.0 2.0 3.0
Miles

Department of Conservation
California Geological Survey

Figure 3.5

Because of its simplicity, it is likely that the SPPV method (DOC, 1997) will be widely used to estimate earthquake shaking loading conditions for the evaluation of ground failure hazards. It should be kept in mind that ground motions at a given distance from an earthquake will vary depending on site-specific characteristics such as geology, soil properties, and topography, which may not have been adequately accounted for in the regional hazard analysis. Although this variance is represented to some degree by the recorded ground motions that form the basis of the hazard model used to produce Figures 3.1, 3.2, and 3.3, extreme deviations can occur. More sophisticated methods that take into account other factors that may be present at the site (site amplification, basin effects, near source effects, etc.) should be employed as warranted. The decision to use the SPPV method with ground motions derived from Figures 3.1, 3.2, or 3.3 should be based on careful consideration of the above limitations, the geotechnical and seismological aspects of the project setting, and the "importance" or sensitivity of the proposed building with regard to occupant safety.

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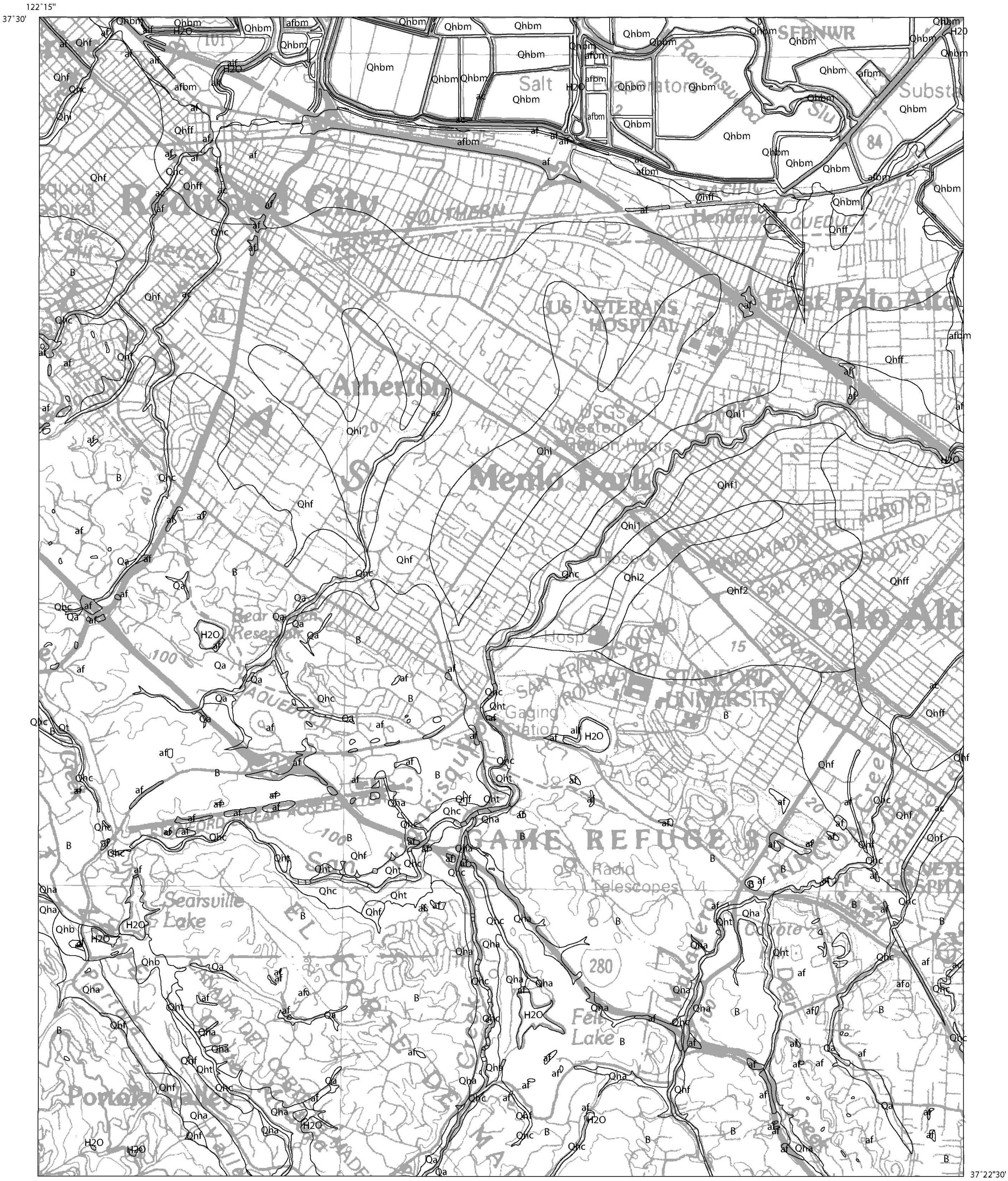



Base map enlarged from U.S.G.S. 30 x 60-minute series

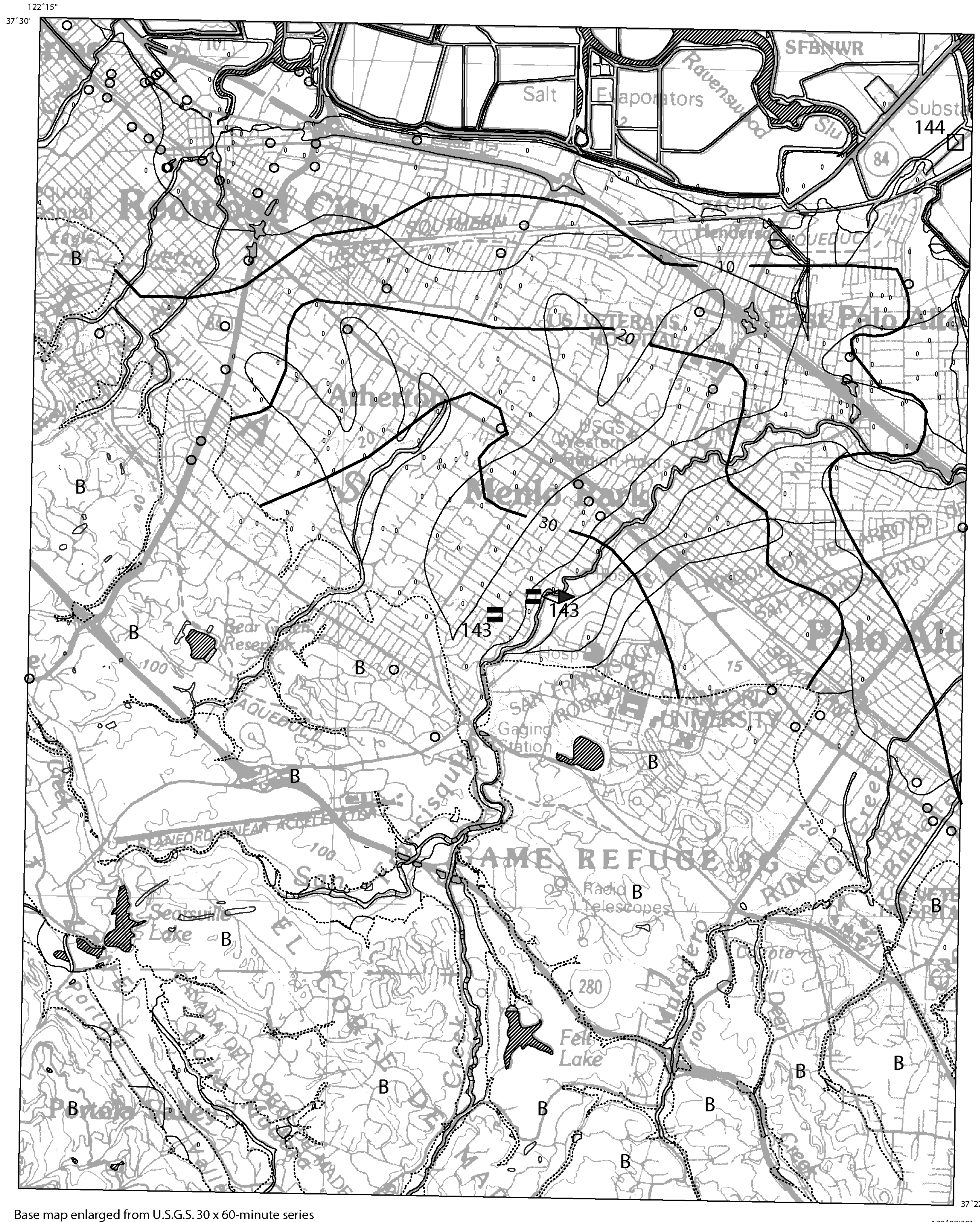
PALO ALTO QUADRANGLE

SCALE

N

B = Pre-Quaternary bedrock.
See "Geology" in Section 1 of report for descriptions of units.

Plate 1.1 Quaternary Geologic Map of the Palo Alto 7.5-Minute quadrangle (modified from Witter and others [2006] )




Base map enlarged from U.S.G.S. 30 x 60-minute series
Historical Ground Failures (From Knudsen and others, 2000)

PALO ALTO QUADRANGLE

SCALE

1 0.5 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 0.5 0 1 KILOMETER

Water Body

☐ Absence of ground failure noted

Ground cracks not clearly associated with landslide, lateral spread, settlement, or primary movement

Lateral spread

B Bedrock

Bedrock- Quaternary boundary

152 Number assigned to ground failure site (adapted from Youd and Hoose, 1978; and Tinsley and others,1998; by Knudsen and others, 2000)

—10— Depth to ground water, in feet

○ Geotechnical borings used in liquefaction evaluation

Ground-water level data provided by the State Water Resources Control Board.

Plate 1.2 Depth to historically high ground water, and locations of boreholes used in this study, Palo Alto 7.5-minute Quadrangle, California

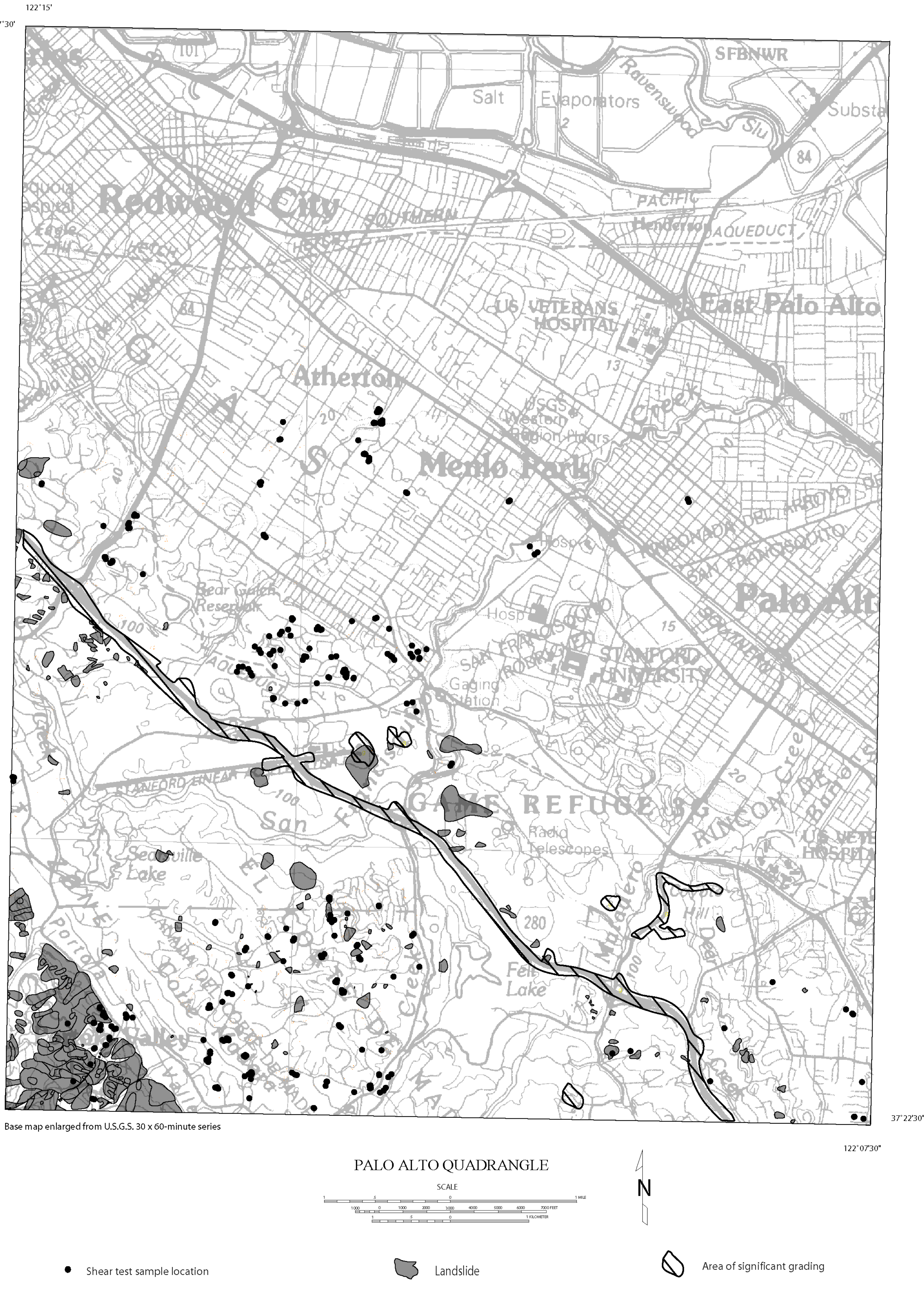



Plate 2.1 Landslide inventory, shear test sample locations, and areas of significant grading, Palo Alto 7.5-Minute Quadrangle, California.