SEISMIC HAZARD ZONE REPORT FOR THE LICK OBSERVATORY 7.5-MINUTE QUADRANGLE, SANTA CLARA COUNTY, CALIFORNIA

2012

DEPARTMENT OF CONSERVATION
California Geological Survey

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How to view or obtain Seismic Hazard Zone maps

Seismic Hazard Zone Maps, Seismic Hazard Zone Reports, and related information are available on the California Geological Survey's (CGS) Internet page: http://www.consrv.ca.gov/cgs/shzp/Pages/Index.aspx.

The maps and reports are also available for reference at CGS offices in Sacramento, Menlo Park, and Los Angeles at the addresses presented below.

The *Seismic Hazard Zone Report* documents the methods and data used to construct the *Seismic Hazard Zone Map* for each 7.5-minute quadrangle evaluated by CGS. The information should be particularly helpful to site investigators and local government reviewers of geotechnical reports.

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10/26/2012	Official Zone Map Release

EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the Lick Observatory 7.5-Minute Quadrangle, Santa Clara County, California. The topographic quadrangle map, which covers approximately 155 square kilometers (~60 square miles) at a scale of 1:24,000 (41.7 mm = 1,000 meters; 1 inch = 2,000 feet), displays the boundaries of preliminary *Zones of Required Investigation* for liquefaction and earthquake-induced landslides. The area subject to seismic hazard mapping includes part of the City of San Jose and the remaining area is unincorporated Santa Clara County. The map designates *Zones of Required Investigation* for liquefaction and earthquake-induced landslides only for the southwestern half of the quadrangle because mountainous terrain and projected land use in the northeastern half make urbanization unlikely.

Zones for liquefaction hazard within the Lick Observatory Quadrangle are generally limited to a few narrow canyon bottoms and stream valleys, such as Halls and San Felipe valleys, and where stream drainages enter Evergreen Valley along the western edge of the quadrangle. Zones for earthquake-induced landslides, however, cover much of the mapped southwest half of the quadrangle because of the predominance of existing landslides and steep slopes underlain by low strength rock.

Seismic hazard maps are prepared by the California Geological Survey (CGS) using geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information analyzed in these studies includes topography, surface and subsurface geology, borehole log data, recorded groundwater levels, existing landslide features, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. Earthquake ground shaking 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. Calculations used in the seismic hazard evaluation of the Lick Observatory Quadrangle were based on an earthquake of Moment Magnitude range of 6.2 to 7.1 with a Modal Distance range of 3 to 14 kilometers.

City, county, and state agencies are required by the California Seismic Hazards Mapping Act to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold building permits for sites being developed within *Zones of Required Investigation* until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans. Guidelines for such investigation can be found at http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf. The Act also requires sellers of real property within these zones to disclose that fact at the time such property is sold.

THE CALIFORNIA SEISMIC HAZARDS MAPPING PROGRAM

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the State Geologist to prepare maps that delineate seismic hazard zones. The purpose of the Act is to reduce the threat to public 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) (California Geological Survey, 2008). The text of this report is online at: http://www.conservation.ca.gov/cgs/shzp/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, the 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 California Geological Survey (CGS) Special Publication 118, were revised in 2004. They provide detailed standards for mapping regional liquefaction and landslide hazards. The Act also directed the State Geologist 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 groundwater 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 online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp118_revised.pdf.

This Seismic Hazard Zone Report summarizes the development of the *Preliminary Seismic Hazard Zone Map* for the Lick Observatory 7.5-Minute Quadrangle. The process of zonation for liquefaction hazard involves an evaluation of Quaternary geologic maps, groundwater level records, and subsurface geotechnical data. The process of zonation for earthquake-induced landslide hazard incorporates evaluations of earthquake loading, existing landslides, slope gradient, rock strength, and geologic structure. A statewide *Earthquake Shaking Potential Map*, based on probabilistic seismic hazard analysis (PSHA), has been prepared so that uniformly generated ground motion parameters (peak ground acceleration, mode magnitude, mode distance) are applied to all CGS liquefaction and earthquake-induced landslide hazard assessments.

SECTION 1: EVALUATION REPORT FOR LIQUEFACTION HAZARD

in the

LICK OBSERVATORY 7.5-MINUTE QUADRANGLE, SANTA CLARA COUNTY, CALIFORNIA

by

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DEPARTMENT OF CONSERVATION
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INTRODUCTION

Purpose

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California State Geologist to compile maps that identify *Seismic Hazard Zones* consistent with requirements and priorities established by the California State Mining and Geology Board (SMGB) (California Geological Survey, 2004). The text of this report is available online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp118_revised.pdf. The Act requires that site-specific geotechnical investigations be performed for most urban development projects situated within seismic hazard zones before lead agencies can issue the building permit. The Act also requires sellers of real property within these zones to disclose that fact at the time such property is sold. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California SMGB (California Geological Survey, 2008). The text of this report is online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf.

Following the release of the SMGB Guidelines, local government agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazard. 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 (Southern California Earthquake Center, 1999). This text is also online at: http://www.scec.org/.

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Lick Observatory 7.5-Minute Quadrangle. Section 2 (addressing earthquake-induced landslide hazard) and Section 3 (addressing ground shaking potential) complete the evaluation report, which is one of a series that summarizes seismic hazard zone mapping by California Geological Survey (CGS) in developing areas of the state where there is potential for strong ground motion (Smith, 1996). Additional information on seismic hazards zone mapping in California can be accessed on CGS's web page: http://www.conservation.ca.gov/cgs/shzp/

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 40 feet of the ground surface. These geological and groundwater 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, including areas within the Lick Observatory Quadrangle.

Methodology

CGS's evaluation of liquefaction potential and preparation of seismic hazard zone maps require the collection, compilation, and analysis of various geotechnical information and map data. The data are processed into a series of geographic information system (GIS) layers using commercially available software. In brief, project geologists complete the following principal tasks to generate a seismic hazard zone map for liquefaction potential:

- Compile digital geologic maps to delineate the spatial distribution of Quaternary sedimentary deposits.
- Collect geotechnical borehole log data from public agencies and engineering geologic consultants.
- Enter boring log data into the GIS.
- Generate digital cross sections to evaluate the vertical and lateral extent of Quaternary deposits and their lithologic and engineering properties.
- Evaluate and digitize historically highest groundwater levels in areas containing Quaternary deposits.
- Characterize expected earthquake ground motion, also referred to as ground-shaking opportunity (see Section 3 of this report).
- Perform quantitative analyses of geotechnical and ground motion data to assess the liquefaction potential of Quaternary deposits.
- Synthesize, analyze, and interpret above data to create maps delineating *Zones of Required Investigation* according to criteria adopted by the SMGB (CGS, 2004).

Scope and Limitations

Evaluation for potentially liquefiable soils is confined to areas covered by Quaternary (less than about 1.6 million years) sedimentary deposits. Such areas within the Lick Observatory Quadrangle consist mainly of alluviated valleys, floodplains, and canyons. CGS's liquefaction hazard evaluations are based on information on earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and groundwater depth, which is gathered from various sources. 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 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 groundwater, 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.

This section of the report is presented in two parts. Part I addresses the geographic and geologic setting of the study area while Part II documents the data and parameters used to evaluate liquefaction hazard and to delineate *Zones of Required Investigation* in the Lick Observatory 7.5-Minute Quadrangle.

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Lick Observatory Quadrangle covers an area of approximately 155 square kilometers (60 square miles) in east-central Santa Clara County. The map area is within the central portion of the Coast Ranges Geomorphic Province of California. The center of the quadrangle is about 97 kilometers (60 miles) southeast of the City of San Francisco and about 24 kilometers (15 miles) east of the City of San Jose. Small fingers of the City of San Jose are within the southwest part of the map area and the remainder of the area is unincorporated Santa Clara County land. This evaluation report, and the accompanying Seismic Hazard Map that it describes, address only the southwest half of the quadrangle. Approximately 78 square kilometers (30 square miles) of area covering the northeast half of the quadrangle was not evaluated for zoning because of the low likelihood of large-scale or significant development in the near future.

The study area is dominated by rugged, mountainous terrain of the northwest-trending Diablo Range that occupies the central region of California's Coast Ranges Geomorphic Province. Less than 8 square kilometers (~3 square miles) of flatland exist in the entire quadrangle, most of which is found in Halls Valley, San Felipe Valley, and two small embayments of Evergreen Valley, which is a sub-basin of the Santa Clara Valley. Major perennial streams within the quadrangle include San Felipe, Thomson, Sulfur, and Smith Creeks, along with Arroyo Aguague. Elevations in the map area range from slightly less than 159 meters (520 feet) above mean sea level in Evergreen Valley, to a little over 1332 meters (4,370 feet) on Copernicus Peak, in the northeastern quadrant of the map.

Land Use

Small fingers of the City of San Jose cover about 8.8 square kilometers (3.4 square miles) of land along the southwest margin of the Lick Observatory Quadrangle. However, home development within this part of the city is concentrated in about 2.5 square kilometers (1 square mile) within Evergreen Valley. The remainder of the quadrangle encompasses unincorporated, generally undeveloped county land. The Lick Observatory complex, which occupies the top of Mt. Hamilton, lies outside of the quadrangle area subject to zone mapping. Joseph D. Grant County Park occupies the north-central portion of the quadrangle within the study area.

The primary transportation route in the study area is Mt. Hamilton Road (State Highway 130), which traverses the quadrangle from the northwest to Lick Observatory on Mt. Hamilton and continuing to the east as San Antonio Valley Road. Quimby Road joins Mt. Hamilton Road from the southwest at Joseph D. Grant County Park. San Felipe Road traverses the southwest corner of the quadrangle, and also provides access north into San Felipe Valley. Access to rural areas within the quadrangle is primarily by unpaved and private roads.

GEOLOGY

Geologic units susceptible to liquefaction generally are late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. To evaluate the areal and vertical distribution of Quaternary deposits in the Lick Observatory Quadrangle, geologic maps of the San Francisco Bay Area showing Quaternary deposits (Knudsen and others, 2000), bedrock units (Wentworth and others, 1999), and geology along the Calaveras Fault (Witter and others, 2003) were obtained from the U.S. Geological Survey in digital form. The GIS maps and layers covering the Lick Observatory Quadrangle were combined, with minor modifications along the bedrock/Quaternary contact, to form a single, 1:24,000-scale *geologic materials map* that displays map unit polygons only (*i.e.* no faults, fold axes, or point data). 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 prepare the Seismic Hazard Zone Map.

Air photos and limited field reconnaissance were used to validate minor modifications to bedrock/Quaternary contacts and to confirm the location of geologic contacts, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units.

Bedrock Units

Bedrock of the Diablo Range exposed in the Lick Observatory Quadrangle consists mainly of Cretaceous sedimentary strata of the Great Valley Sequence, rocks of the Franciscan Complex, serpentine-dominant rock units of the Coast Range Ophiolite, and Tertiary sedimentary strata (Wentworth and others, 1999). Bedrock units mapped in the Diablo Range are grouped by Wentworth and others (1999) and McLaughlin and others (2001) into distinct fault-bounded, elongate blocks that generally parallel the northwest-trending structural grain of the range. Four of these blocks, the Silver Creek, Coyote, Alum Rock, and Mt Hamilton blocks, are identified in the study area by Wentworth and others (1999).

The Silver Creek Block is exposed in the Yerba Buena Hills in the southwest corner of the Lick Observatory Quadrangle. Locally, rock exposures within this structural block are comprised primarily of serpentine of the Coast Range Ophiolite and the Plio-Pleistocene Packwood Gravel, along with small, isolated outcrops of Pliocene Silver Creek Gravel. Across the fault boundary to the east, and which in the study area occupies most of the lower west flank of the Diablo Range, lies the Alum Rock Block. This structural block is comprised of Cretaceous units, mainly sandstone and siltstone of the Great Valley Sequence, along with Miocene sandstone, siltstone, and shale of the Clairmont and Briones formations. The Coyote Block lies east of the Alum Rock Block only in the southern part of the quadrangle because it pinches out where the Madrone Springs Fault converges with the Calaveras Fault in the vicinity of San Felipe Valley. Locally, the Coyote block is characterized by Cretaceous sedimentary rocks of the Great Valley Sequence, along with brown-weathering mudstone of Eocene age and sandstone, siltstone, and shale of the Miocene Clairmont and Briones formations. East of the Calaveras Fault, more than half of the area within the bounds of the quadrangle is underlain by metamorphic rocks of the Mount Hamilton Block. These are mainly Jurassic-Cretaceous rocks assigned to various units of the Franciscan complex, which are exposed in the core of the Diablo Range. However, only a narrow band along the western boundary of the Mt Hamilton Block lies within the Lick Observatory Quadrangle.

More detailed descriptions of bedrock units exposed in the Lick Observatory Quadrangle are presented in Section 2 of this report: Earthquake-Induced Landslides. Refer to Wentworth and others (1999) for a regional geologic map showing bedrock units.

Quaternary Sedimentary Deposits

In total, Knudsen and others (2000) and Witter and others (2003) identify 15 Quaternary map units in the Lick Observatory Quadrangle (Plate 1.1). The Quaternary geologic mapping methods used are described in Knudsen and others (2000), which consist of interpretation of topographic maps, aerial photographs, and soil surveys, as well as compiled published and unpublished geologic maps. They 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 Knudsen and others (2000) and the CGS GIS database with nomenclature used by several previous studies performed in northern California.

Only about 5 percent of the ground surface within the Lick Observatory Quadrangle is mapped as sedimentary deposits of Quaternary age. The most notable areas covered by such deposits are

Halls Valley, San Felipe Valley, and the southeastern margin of Evergreen Valley. Sediment deposited in these alluviated flatlands is derived from local bedrock sources, given the small-scale watersheds present in the Lick Observatory quadrangle. Bedrock in the southwest half of the quadrangle consists primarily of sandstone, siltstone, shale, and gravel. When eroded, much of the material from these rock units breaks down into clastic sediment that is transported short distances down San Felipe Creek, Thompson Creek, Arroyo Aguague, and their tributary creeks as channel deposits (Qhc) and then deposited in the local valleys as generally coarse-grained alluvial (Qha), basin (Qhb), and alluvial fan (Qhf) deposits. Along the creeks, Holocene and latest Holocene stream terrace deposits (Qht and Qhty) are inset into bedrock, undifferentiated alluvial deposits (Qha), and alluvial fan deposits (Qhf). One such Holocene alluvial fan deposit (Qhf) has developed where Thompson Creek canyon opens out onto Evergreen Valley on the southwest margin of the quadrangle. Just to the north of this fan, a latest Pleistocene to Holocene alluvial fan deposit (Qpf) has developed at the base of the foothills. Some stream terrace deposits of latest Pleistocene age (Qpt) and older Quaternary alluvial fan (Qpf, Oof) and undifferentiated older alluvium (Qoa) have been identified along San Felipe Creek along and to either side of the Calaveras Fault.

Structural Geology

The structural framework of the Diablo Range is governed by a series of sub-parallel, generally northwest-trending faults ranging in age from Mesozoic (Coast Range Fault) to present time (Calaveras Fault) (Wentworth and others, 1999). The study area is within the active San Andreas Fault system, which 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 is located about 23 km (13.5 miles) southwest of the southwestern corner of the quadrangle. The Calaveras Fault extends through the quadrangle diagonally from the southeast quadrant through the northwest quadrant and represents the source for the greatest potential ground motions to the study area. Notably, movement along the Calaveras Fault in 1984 produced the magnitude 6.2 Morgan Hill Earthquake. The epicenter of this event was located within the study area, 1.6 km (1 mile) southwest of the Smith Creek Ranger Station, and surface manifestations of liquefaction were reported roughly 17 km (~10 miles) south of the Lick Observatory Quadrangle southern boundary. The Calaveras Fault has also “adopted” and incorporated the older Madrone Springs Fault in the south part of the quadrangle (Page, 1999). As shown on Plate 1.1, the southern terminus of the active Hayward Fault also lies within the study area. Other named faults in the study area include the Silver Creek, Evergreen, and Quimby (Plate 1.1).

UNIT	Knudsen and others (2000)	Helley and others (1994)	Helley and others (1979)	Wentworth and others (1999)	CGS GIS Database
artificial fill	af			af	af
modern stream channel deposits	Qhc	Qhsc	Qhsc	Qhc	Qhc
latest Holocene stream terrace deposits	Qhty				Qhty
Holocene basin deposits	Qhb	Qhb		Qhb	Qhb
Holocene alluvial fan deposits	Qhf	Qhaf, Qhfp	Qham, Qhac	Qhf, Qhfp	Qhf
Holocene stream terrace deposits	Qht	Qhfp		Qht	Qht
Holocene alluvium, undifferentiated	Qha			Qha	Qha
Latest Pleistocene to Holocene stream terrace deposits	Qt				Qt
Latest Pleistocene to Holocene basin deposits	Qb			Qt	
latest Pleistocene to Holocene alluvial fan deposits	Qf				Qf
latest Pleistocene to Holocene alluvium, undifferentiated	Qa			Qa	Qa
latest Pleistocene alluvium, undifferentiated	Qpa	Qpaf	Qpa		Qpa
latest Pleistocene alluvial fan deposits	Qpf	Qpaf		Qpf	Qpf
latest Pleistocene stream terrace deposits	Qpt				Qpt
early to middle Pleistocene alluvial fan deposits	Qof		Qof		Qof?
early to middle Pleistocene undifferentiated alluvial deposits	Qoa		Qpea, Qpmc	Qoa	Qoa
Bedrock	br	Br			br

Table 1.1. Correlation of Quaternary Stratigraphic Nomenclatures Used in Previous Studies. CGS has adopted the nomenclature of Knudsen and others (2000) for Quaternary mapping in the San Francisco Bay Region.

ENGINEERING GEOLOGY

As stated above, soils susceptible to liquefaction are mainly late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. 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. Unfortunately, few borehole logs containing useful geotechnical information were found during the course of this study, which is not surprising given the small combined area (less than 8 square kilometers) of mostly undeveloped land covered by Quaternary surficial deposits within the quadrangle.

Of particular value in liquefaction evaluations, when adequate borehole data are available, 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 are commonly 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 at the bottom of a borehole at chosen intervals while drilling. 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 (ASTM) 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 (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 $(N_1)_{60}$. CGS enters the $(N_1)_{60}$ values and other geotechnical information recorded in borehole logs into its database and applies it to computer generated quantitative analysis in order to evaluate liquefaction potential using a procedure developed by Seed and Idriss (1971).

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 40 feet.

Natural hydrologic processes and human activities can cause ground water levels to fluctuate over 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. Plate 1.2 depicts areas characterized by present or anticipated shallow ground water within the Lick Observatory Quadrangle.

Ground water conditions are evaluated in the valley regions of areas subject to liquefaction zonation in order to estimate depths to saturated materials. These evaluations are based on first-encountered water noted in borehole and water well logs acquired from agencies such as the California Department of Water Resources, planning departments, and water districts. The depths to first-encountered unconfined ground water are plotted onto a map of the project area to constrain the estimate of historically shallowest ground water.

Although there are few water well and borehole logs available in the 8 square kilometers of flatland within the Lick Observatory Quadrangle, previous Seismic Hazard Zonation studies for liquefaction conducted by CGS in the Santa Clara Valley region indicate that ground water is currently at or near historical high levels (*e.g.* Clahan and others, 2000; Bott, 2004). Clahan and others (2000) indicated that most of Evergreen Valley, whose southern end extends into the Lick Observatory Quadrangle, is characterized by shallow ground water (<40 feet). Historical ground water levels in the alluviated stream valley and lowland areas within the foothills of the Diablo Range, such as Halls and San Felipe valleys, are commonly shallow, often within 5 to 10 feet of the surface during the wet seasons. Shallow ground water conditions commonly exist in these types of depositional environments because they tend to trap and accumulate heavy runoff and near-surface ground water derived from surrounding highlands.

PART II: LIQUEFACTION HAZARD ASSESSMENT

MAPPING TECHNIQUES

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. When this occurs, 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, whereas liquefaction opportunity is a function of potential seismic ground shaking intensity.

The method applied in this study to evaluate liquefaction potential is similar to that Tinsley and others (1985) used to map liquefaction hazards in the Los Angeles region. These investigators, in turn, applied a combination of the techniques developed by Seed and others (1983) and Youd and Perkins (1978). CGS's method combines geotechnical analyses, geologic and hydrologic mapping, and probabilistic earthquake shaking estimates employing criteria adopted by the SMGB (CGS, 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 from the surface govern the degree of resistance to liquefaction. Some of these properties can be correlated to a deposit'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 specifically addressed in this investigation. Soil characteristics that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. In summary, soils that lack resistance (susceptible soils) typically are saturated, loose, and granular. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross-sections, geotechnical test data, geomorphology, and groundwater hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to groundwater are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on observable similarities between soil units, liquefaction susceptibility maps typically are often similar to Quaternary geologic maps, depending on local groundwater levels.

In the general area of Santa Clara Valley, most Holocene materials in areas where ground-water levels are within 30 feet of the ground surface have susceptibility assignments of high (H) to very high (VH). Such Holocene deposits in the Lick Observatory Quadrangle include stream channel (Qhc), stream terrace (Qhty, Qht, Qt), alluvium (Qha), some alluvial fan (Qhf) along San Felipe Creek, and some basin (Qhb) deposits within major drainages. Late Pleistocene to Holocene alluvial fan deposits (Qf) and Holocene alluvial fan deposits (Qhf) developed along the base of Diablo Range foothills are both assigned a low susceptibility in the Lick Observatory Quadrangle because these deposits, as indicated in Table 1.3 of Clahan and others (2000) are characterized by high clay. All Pleistocene and older deposits (Qoa, Qof) within the study area are assigned to the low (L) susceptibility category.

GROUND SHAKING OPPORTUNITY

Ground shaking opportunity is a calculated measure of the intensity and duration of strong ground motion normally expressed in terms of *peak horizontal ground acceleration* (PGA). Ground motion calculations used by CGS exclusively for regional liquefaction zonation assessments are currently based on the *Probabilistic Seismic Hazard Assessment (PSHA) Model* developed by the USGS for the 2008 Update of the United States National Seismic Hazard Maps (Petersen and others, 2008). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance level. CGS calculations incorporate additional programming that modifies probabilistic PGA by a scaling factor that is a function of magnitude and is weighted by each earthquake's estimated ground shaking contribution. The result is a magnitude-weighted, pseudo-PGA that CGS refers to as *Liquefaction Opportunity* (LOP). This approach provides an improved estimate of liquefaction hazard in a probabilistic sense, ensuring that large, infrequent, distant earthquakes, as well as smaller, more frequent, nearby events are appropriately accounted for (Real and others, 2000). These firm-rock LOP values are adjusted to alluvium site conditions (Site Class D) by applying the NEHRP corrections (FEMA, 1994; Table 3.1), and are then used to calculate cyclic stress ratio (CSR), the seismic load imposed on a soil column at a particular site.

LIQUEFACTION ANALYSIS

As mentioned in the Engineering Geology section of this report, few borehole logs containing useful geotechnical information were found during the course of this study. However, when borehole logs with adequate geotechnical soil-test data are available, 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; Idriss and Boulanger, 2008). The procedure first calculates the resistance to liquefaction of each soil layer penetrated at a test-drilling site, expressed in terms of cyclic resistance ratio (CRR). The calculations are based on standard penetration test (SPT) results, groundwater level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The procedure then estimates the factor of safety relative to liquefaction hazard for each of the soil layers logged at the site by dividing their calculated CRR by the LOP-derived CSR described in the previous section.

CGS uses a factor of safety (FS) of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil layers. The 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 determine the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data. In addition to FS, consideration is given to the proximity to stream channels, which accounts in a general way for factors such as sloping ground or free face that contribute to severity of liquefaction-related ground deformation.

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. However, many of the Holocene alluvial deposits in the study area contain a significant amount of gravel. In the past, gravelly soils were considered not to be susceptible to liquefaction because it was presumed that the high permeability of these soils 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.

ZONATION CRITERIA: LIQUEFACTION

Areas underlain by materials susceptible to liquefaction during an earthquake are included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (CGS, 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 the above criteria allows compilation of *Zones of Required Investigation* for liquefaction hazard, which are useful for preliminary evaluations, general land-use planning and delineation of special studies zones (Youd, 1991).

DELINEATION OF SEISMIC HAZARD ZONES: LIQUEFACTION

Upon completion of a liquefaction hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings in order to delineate *Zones of Required Investigation*. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone map for the Lick Observatory Quadrangle.

Areas of Past Liquefaction

Documented observations of historical liquefaction are not recorded for the area encompassed by the Lick Observatory Quadrangle, nor has evidence of paleoseismic liquefaction been reported.

Artificial Fills

Artificial fill areas in the Lick Observatory Quadrangle large enough to show at the scale of project mapping (1:24,000) consist of probable non-engineered fill material used for construction of several embankments around a small, shallow reservoir in Halls Valley and along a short segment of a nearby ridge top, unpaved road. Non-engineered fills are commonly loose and uncompacted, and the material varies in size and type. The reservoir embankment is included within a *Zone of Required Investigation*.

Areas with Sufficient Existing Geotechnical Data

Borehole logs that included penetration and associated geotechnical test data required to quantitatively analyze liquefaction potential of young Quaternary sedimentary deposits were not found during the data collection phase of this study. However, CGS did collect several useful logs of borings located on older Quaternary deposits that indicate low potential for liquefaction, which is characteristic of Pleistocene sediments.

Areas with Insufficient Existing Geotechnical Data

Quaternary sedimentary deposits mapped in the Lick Observatory Quadrangle were evaluated for seismic hazard zonation on the basis of geologic factors, few boring logs, extrapolation of known soil conditions in adjacent areas, and limited fieldwork. Based on the evaluation, about 3.4 square kilometers (1.3 square miles) of the approximately 8 square kilometers (3 square miles) of combined flatland in the quadrangle are designated *Zones of Required Investigation*. The zones encompass most of Halls Valley (119 hectare; 293 acres), San Felipe Valley (187 hectare; 462 acres), and several segments of land within and adjacent to local creeks. The remaining 5 square kilometers (~2 square miles) or so of flatland not included in the zones are clay-rich or older alluvial fan deposits along the southeastern margin of Evergreen Valley.

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SECTION 2: EVALUATION REPORT FOR EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

LICK OBSERVATORY 7.5-MINUTE QUADRANGLE, SANTA CLARA COUNTY, CALIFORNIA

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INTRODUCTION

Purpose

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California State Geologist to compile maps that identify *Seismic Hazard Zones* consistent with requirements and priorities established by the California State Mining and Geology Board (SMGB) (California Geological Survey, 2004). The text of this report is available online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp118_revised.pdf. The Act requires that site-specific geotechnical investigations be performed for most urban development projects situated within seismic hazard zones before lead agencies can issue the building permit. The Act also requires sellers of real property within these zones to disclose that fact at the time such property is sold. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California SMGB (California Geological Survey, 2008). The text of this report is online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf.

Following the release of the SMGB Guidelines, local government agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazard. 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 (Southern California Earthquake Center, 2002). This text is also online at: http://www.scec.org/

This report is one of a series that summarizes the preparation of seismic hazard zone maps within the state (Smith, 1996). This particular part of the report, Section 2, summarizes seismic hazard zone mapping for earthquake-induced landslides in the Lick Observatory 7.5-minute Quadrangle. Section 1, which addresses liquefaction hazard, and Section 3, which addresses earthquake-shaking hazard, completes the report. Additional information on seismic hazard zone mapping in California can be accessed online at: http://www.conservation.ca.gov/cgs/shzp/.

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 lifeline infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, sloped 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 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 upland areas within the Lick Observatory Quadrangle.

Methodology

The delineation 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 collected or generated to provide an up-to-date representation of slope gradient and slope aspect in the study area.
- Geologic mapping was compiled to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether or not triggered by earthquakes, 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 compiled and 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 (Newmark, 1965), in order to generate a map showing 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 subsequently adopted by the SMGB (CGS, 2004).

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 run out areas 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.

This section of the report is presented in two parts. Part I addresses the natural setting of the area covered by the Lick Observatory Quadrangle, namely the physiographic, geologic and engineering geology conditions. Part II covers the preparation of landslide hazard potential and landslide zone maps.

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Lick Observatory Quadrangle covers an area of approximately 155 square kilometers (60 square miles) in east-central Santa Clara County. The map area is within the central portion of the Coast Ranges Geomorphic Province of California. The center of the quadrangle is about 97 kilometers (60 miles) southeast of the City of San Francisco and about 24 kilometers (15 miles) east of the City of San Jose. Small fingers of the City of San Jose are within the southwest part of the map area and the remainder of the area is unincorporated Santa Clara County land. This evaluation report, and the accompanying Seismic Hazard Map that it describes, address only the southwest half of the quadrangle. Approximately 78 square kilometers (30 square miles) of area covering the northeast half of the quadrangle was not evaluated for zoning because of the low likelihood of significant development in the near future.

The study area is dominated by rugged, mountainous terrain of the northwest-trending Diablo Range that occupies the central region of California’s Coast Ranges Geomorphic Province. Less than 8 square kilometers (~3 square miles) of flatland exist in the entire quadrangle, most of which is found in Halls Valley, San Felipe Valley, and two small embayments of Evergreen Valley, which is a sub-basin of the Santa Clara Valley. Major perennial streams within the quadrangle include San Felipe, Thomson, Sulfur, and Smith Creeks, along with Arroyo Aguague.

Land Use

Most of the Lick Observatory Quadrangle is sparsely developed mountainous terrain. Current land uses include limited suburban residential developments, a golf course, farm and ranch land, parkland, Halls Valley Lake (a private reservoir), and the Lick Observatory facility located on Mt. Hamilton. Residential development is primarily confined to the foothills and valleys along the western edge of the map. Joseph D. Grant County Park occupies the north-central portion of the quadrangle.

The primary transportation route is Mt. Hamilton Road (State Highway 130), which traverses the northern half of the quadrangle from the northwest to Lick Observatory on Mt. Hamilton, where it then continues to the east as San Antonio Valley Road. Quimby Road joins Mt. Hamilton Road from the southwest in Joseph D. Grant County Park. San Felipe Road traverses the southwest corner of the quadrangle, and also provides access north into the San Felipe Valley. Access to rural areas within the quadrangle is primarily by unpaved and private roads.

Topography

The Lick Observatory Quadrangle is characterized by mountainous and hilly terrain of the southwestern flank of the Diablo Range. Major topographic features in the map area include steep and rugged mountains in the northeast near Mt. Hamilton and Lick Observatory, northwest-trending, steeply to moderately sloping ridges and foothills in the west and southwest, and the intermountain valleys, and Halls and San Felipe valleys, which lie along the Calaveras Fault zone and divide the quadrangle diagonally from northwest to southeast. The southern end of Evergreen Valley, an extension of the Santa Clara Valley, lies along the western edge of the map. Elevations in the map area range from slightly less than 159 meters (520 feet) above mean sea level in Evergreen Valley, to a little over 1332 meters (4,370 feet) on Copernicus Peak, in the northeastern quadrant of the map.

Moderately sloping foothills in the western map area, between Masters Hill and Mt. Misery, are cut by numerous streams that flow westward into Santa Clara Valley. In the southwestern corner of the map, Thompson Creek and Silver Creek flow northwest through Evergreen Valley and Silver Creek Valley into Santa Clara Valley. In the northwest, Arroyo Aguague emanates from slopes north and east of Halls Valley and flows to the northwest beyond the map boundary, toward Upper Penitencia Creek and the Santa Clara Valley. Halls Valley drains into San Felipe Creek, which then flows southeastward through the San Felipe Valley and beyond the southern map boundary. Paralleling and west of San Felipe Creek, Las Animas Creek flows southeast out of the mapped area and eventually into Anderson Reservoir. In the northeast quarter of the map area near Mt. Hamilton, deeply incised streams from the mountainous terrain flow northward out of the map area into Arroyo Hondo, via Smith Creek and Isabel Creek.

GEOLOGY

The primary source of bedrock geologic mapping used in this slope stability evaluation was the digital geologic map database of Wentworth and others (1999), which covers the San Jose 30 by 60 minute Quadrangle and includes the Lick Observatory 7.5-minute Quadrangle. Sources of Quaternary surficial geology include Knudsen and others (2000), and Witter and others (2003). Quaternary surficial materials are discussed in more detail in Section 1 of this report and are summarized on Plate 1.1.

CGS geologists merged the Quaternary and bedrock geologic maps to prepare a map suitable for this study. Contacts between surficial and bedrock units were modified in some areas to resolve differences between the maps. Geologic reconnaissance was performed to assist in adjusting contacts and to review the lithology and structure of geologic units within the Lick Observatory Quadrangle. In addition, the relationship of the rock units to the development and abundance of landslides was noted.

Bedrock Units

The geologic maps of Wentworth and others (1999) and McLaughlin and others (2001) identify a number of distinct stratigraphic assemblages that are exposed in fault-bounded, bedrock structural blocks in Santa Clara County. The concept of individual fault-bounded stratigraphic assemblages in the Bay Area was introduced by Jones and Curtis (1991) and further defined by Graymer and others (1994). Individual stratigraphic assemblages are considered to have originated in distinct and separated depositional basins, or within different parts of larger basins, which were later juxtaposed against one another by displacements on Tertiary strike-slip and dip-slip faults. Each fault-bounded stratigraphic assemblage contrasts with its neighbors in depositional and deformational history. Mapping individual stratigraphic assemblages in discrete bedrock structural blocks has been applied to the recent mapping compiled by the U.S. Geological Survey in the Bay Area (for example, Wentworth and others, 1999; McLaughlin and others, 2001).

Of the eight structural blocks identified by Wentworth and others (1999), four are exposed within the Lick Observatory Quadrangle: the Silver Creek Block, the Alum Rock Block, the Coyote Block, and the Mt. Hamilton Block. A fifth block, the New Almaden Block, underlies the Santa Clara Valley and portions of the southwestern flank of the Diablo Range, and is either beneath the other exposed blocks within the quadrangle or is outside the mapped area. The Silver Creek, Alum Rock, and Coyote, blocks are exposed on the southwestern half of the map while the Mount Hamilton block is exposed on the northeastern side of the quadrangle. The following sections describe bedrock units in each of the structural blocks that extend into the Lick Observatory Quadrangle. Discussion of the blocks proceeds from southwest to northeast. Unconsolidated Quaternary deposits overlie the bedrock units on the floor of the Santa Clara Valley and in smaller alluvial areas in Hall’s Valley and San Felipe Valley, and also on some hillside areas. Quaternary geologic units are briefly described here, and are discussed in more detail in Section 1, Liquefaction Evaluation Report.

Silver Creek Block

The Silver Creek Block is exposed in the very southwest corner of the mapped area. Basement rocks of the Silver Creek Block consist of Franciscan melange (fm), and serpentinite of the

Jurassic Coast Range Ophiolite (Jsp). These units include serpentinized harzburgite and dunite, and a unit containing basalt, andesite, dacite, and quartz keratophyre (Jbk), the latter considered to be remnants of island arc volcanic deposits (Wentworth and others, 1999). The Mesozoic basement rocks of the Silver Creek Block structurally underlie and overlie Cretaceous-Jurrassic Knoxville Formation (KJk) and Tertiary (Tsg) strata. All of the rocks are, in turn, unconformably overlain by the Packwood Gravels (QTp) (Wentworth and others, 1999).

Cretaceous-Jurrassic rocks in the Silver Creek Block within the Lick Observatory Quadrangle are limited to a small, fault-bound sliver of Knoxville Formation (KJk) at the junction of Silver Creek and San Felipe roads. Upper Miocene to Pliocene Silver Creek Gravels (Tsg), widely exposed in the hills on the east side of the Santa Clara Valley and at the southwestern corner of the Lick Observatory Quadrangle, appear to be a distinctive component of the Silver Creek Block as this formation is not mapped elsewhere within the study area. These gravels consist of interbedded conglomerate, sandstone, siltstone, tuffaceous sediment, tuff and basalt, and are distinguishable from similar gravels (such as the Packwood Gravels and the Santa Clara Formation) by the presence of interbedded white tuff layers and other volcanic rocks, and by a characteristic clast composition. About 75 percent of the clasts are Franciscan Complex rocks with the remaining 25 percent consisting of volcanic rocks, Claremont Formation siliceous shale and chert, and other Cenozoic rocks (Wentworth and others, 1999).

The Plio-Pleistocene Packwood Gravels (QTp) consist of silty and fine sandy pebble conglomerate, fine silty sandstone, pebbly to fine sandy siltstone, and minor olive-green claystone beds (Wentworth and others, 1999). Numerous non-marine red mudstone beds also are present. Most of the clasts are derived from rocks of the Great Valley Sequence rather than the Franciscan Complex. This unit overlies the Silver Creek Gravels along an angular unconformity (Wentworth and others, 1999).

Alum Rock Block

The Alum Rock Block consists of Cretaceous through Quaternary strata extending through the Lick Observatory Quadrangle along most of the western and southern borders of the map area. The Knoxville Formation (KJk) of Late Jurassic and Early Cretaceous age is the lowermost unit of the Great Valley Sequence, and consists of dark, greenish-gray shale with thin sandstone interbeds. Overlying this formation are the conglomerate (Kbc) and the sandstone and mudstone (Kbs) units of the Cretaceous Berryessa Formation (Wentworth and others, 1999).

The Alum Rock Block includes two Tertiary units, the lowest being the upper and middle Miocene Claremont Formation (Tcc), overlain by the upper Miocene Briones Formation (Tbr). The Claremont Formation (Tcc) consists of distinctive, massive to laminated, gray or brown chert beds as thick as 10 cm, with thin shale partings (Wentworth and others, 1999). The siliceous shale is dark brown to gray, finely laminated, with grains as large as silt. Some of the shale contains abundant foraminifera and fish scales and also contains interbedded lenses of massive, tan, foraminifera-bearing dolomite that weathers to a distinctive yellowish orange color (Wentworth and others, 1999a).

The Briones Formation (Tbr) unconformably overlies the Claremont Formation and consists of fine-grained sandstone and siltstone. Some of the sandstone beds are as thin as 5 to 10 cm, with 2- to 10-cm-thick shale interbeds. These are interbedded with massive, fine-grained sandstone beds as thick as five meters (Wentworth and others, 1999). The middle portion contains indistinctly bedded, white, fine- to coarse-grained sandstone, conglomeratic sandstone, and massive shell-hash conglomerate made up of interlocking mollusk and barnacle shell fragments, with a white calcareous matrix (Wentworth and others, 1999). The upper part consists of distinctly to indistinctly bedded, massive to cross-bedded, fine- to coarse-grained, white sandstone.

Coyote Block

The Coyote Block lies east of the Alum Rock Block only in the southern part of the Lick Observatory Quadrangle, pinching out where the Madrone Springs Fault converges with the Calaveras Fault in the vicinity of San Felipe Valley. The Coyote Block consists of Coast Range Ophiolite rocks overlain by Cretaceous strata of the Great Valley Sequence, and Tertiary strata of the Claremont Formation and the Briones Formation (Wentworth and others, 1999).

The oldest rocks in the map area consist of Cretaceous sandstone, mudstone and conglomerate (Kcu) within the Great Valley Sequence (Wentworth and others, 1999). The sandstone is indistinctly bedded, massive, fine- to coarse-grained biotite-lithic wacke, interbedded with dark brown to dark gray biotite-rich siltstone and dark olive to gray mudstone. Plant debris is locally common, but foraminifera, if present, are poorly preserved. Conglomerate layers contain boulder to pebble clasts of silicic to intermediate volcanic rocks, limestone, metavolcanics and rip-up clasts of mica-rich sandstone (Wentworth and others, 1999).

The oldest Tertiary unit of the Coyote Block in the map area is the Claremont Formation (Tcc) that contains distinct, massive to laminated, gray or brown chert, and siliceous shale (Wentworth and others, 1999). The siliceous shale is dark brown to gray, finely laminated, with grains as large as silt. The upper Miocene Briones Formation (Tbr) unconformably overlies the Claremont Formation. The Briones Formation is predominantly sandstone with conglomeratic sandstone, shell-hash conglomerate containing interlocking mollusk and barnacle shells, and siltstone (Wentworth and others, 1999).

Mount Hamilton Block

The Mount Hamilton Block is exposed in the northeast half of the Lick Observatory Quadrangle, and constitutes the core of the Diablo Range. The Mount Hamilton Block consists mainly of Franciscan rocks with scattered small bodies of serpentinite derived from the Coast Range Ophiolite (Wentworth and others, 1999). The Mount Hamilton Block is further divided into two terranes, the Cretaceous Burnt Hills terrane and the Jurassic Yolla Bolly Terrane, the former not exposed, but the latter extending into the mapped area of the Lick Observatory Quadrangle. In the map area, thin intra-wedge Franciscan melange (fm) occurs within coherent Yolla Bolly terrane rocks. Melange is composed of a matrix of sheared argillite, lithic graywacke, and scarce but diagnostic “green tuff,” with abundant blocks and slabs of greenstone (gs), radiolarian chert (ch), serpentinite (Jsp), and blue schist (bl). The coherent Yolla Bolly terrane rocks (fy2 and fys) are composed of metagraywacke, slaty mudstone, and conglomerate with metamorphic minerals of the blue schist facies (Wentworth and others, 1999).

Geologic Structure

In the Lick Observatory Quadrangle, the Diablo Range, has been warped into an antiformal structure, flanked on the southwest and northeast by Cenozoic units and rocks of the Great

Valley sequence. The bedrock units in the Lick Observatory Quadrangle have undergone a complex structural history and are strongly deformed by faults and folds of various ages. As discussed in the previous section, the bedrock units in the Lick Observatory Quadrangle are separated into a number of separate bedrock structural blocks, each of which has undergone a separate depositional and deformational history (Wentworth and others, 1999; McLaughlin and others, 2001).

Faulting

The oldest fault in this region is the Coast Range Fault, which was formed during Jurassic subduction of Franciscan rocks below the Coast Range Ophiolite. Originally, the sense of displacement across the Coast Range Fault was reverse. However, subsequent attenuation displacements have taken place, associated with Cenozoic uplift and unroofing of Franciscan basement rocks. A small portion of the Coast Range Fault is located at the southwest corner of the quadrangle, where Coast Range Ophiolite is juxtaposed against Franciscan rocks along Silver Creek (Graymer and others, 1995).

Northwest-trending, transpressive and strike-slip faults extend through the study area. The youngest of these is the Calaveras Fault, which is considered to be Holocene Active based on: active seismicity, offset Holocene deposits (observed in exploratory trenches at Lydell Creek north of the map area) and prominent linear geomorphic features observed at many places along the fault (Page, 1999, and Wentworth and others, 1999). The Calaveras Fault extends into the Lick Observatory Quadrangle from the southeast border and continues into adjacent quadrangles northwest of the mapped area. The Calaveras Fault has adopted and incorporated the older Madrone Springs Fault in the southeast corner of the quadrangle (Page, 1999). Other transpressive faults displace Cenozoic rocks, and in some cases, Pleistocene gravels in the mapped area.

Deformational Features

Deformational features differ in each of the bedrock structural blocks in the map area. The Silver Creek Block contains Mesozoic basement rocks that have been thrust over tightly folded Cretaceous and Tertiary strata along the Silver Creek Thrust (Page, 1999, and Wentworth and others, 1999). The Alum Rock Block contains a steeply east-dipping sequence of strata that are repeated by displacements along Tertiary and Quaternary transpressive faults (notably: the Hayward; Quimby, Arroyo Aguague, East Evergreen, and Clayton Faults). Some of these faults displace Pleistocene gravels in the study area (Crittenden, 1951; Page, 1999; Wentworth and others, 1999). The Coyote Block also consists of steeply dipping strata that are cut by reverse and transpressive faults (Page, 1999, and Wentworth and others, 1999). The Mount Hamilton Block, is a massive uplifted block of complexly interleaved Franciscan rocks (Page, 1999; Wentworth and others, 1999).

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the Lick Observatory Quadrangle has been prepared by field reconnaissance, analysis of stereo-paired aerial photographs (listed under Air Photos in the References) and a review of previously published landslide mapping. Landslides in this inventory primarily were interpreted from geomorphic analyses of traditional paper print (1:20,000-scale) air photos viewed with an optical stereoscope, and digital stereo imagery employing a GIS-based softcopy photogrammetric system. The digital imagery has an approximate 0.84 meter pixel dimension that approximates the resolution of 1:30,000- to 1:40,000-scale print imagery. All landslides in this inventory were digitized on the photogrammetric system, which has been estimated to result in features with 6-meter horizontal and 2-meter vertical accuracies.

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 with a definite and probable confidence were incorporated into the landslide zones as described later in this report. Landslides rated as questionable were not carried into the zone mapping analysis due to the uncertainty of their existence. A version of this landslide inventory is included on Plate 2.1.

In this landslide inventory, 362 landslides were mapped, covering about 30% of the upland bedrock portion of the southwest half of the Lick Observatory Quadrangle. Landslide distribution and density (landslides per unit area) corresponds to the type and distribution of bedrock geologic units, the extent and depth of rock weathering, and the intensity of structural deformation and faulting. The majority (greater than 60 percent) of the outcrop area of Franciscan melange rocks has experienced slope failure in the past. Most of the landslides found in these rocks are associated with fault traces and many occur on anti-dip slopes.

The largest landslide complex in the Lick Observatory Quadrangle incorporates Knoxville and Berryessa formation rocks (KJk, and Kbc) in a group of dormant old rock slides covering roughly 500 hectares (1,230 acres) on the east side of Mt. Misery, west of San Felipe Valley. Active traces of the Calaveras Fault traverse the slide masses in this landslide complex. The landslides at the southern half of this complex, formed in Knoxville Formation rocks, appear to have developed along adversely dipping bedding planes. The influence of adverse bedding is less clear, however, for landslides in the northern half of this complex, which are formed in Berryessa Formation.

Other geologic units that have relatively high landslide densities (30 to 40 percent of their outcrop areas) include the Berryessa Sandstone (Kbs), Yolla Bolly Terrane metagraywacke (fys), Claremont Formation (Tcc), and Coast Range Ophiolite serpentinite (Jos). Most of the landslides in these units have faults through the slide body and toe and are on anti-dip slopes. Moderate landslide densities (15 to 20 percent of their outcrop area) were mapped on Knoxville Formation (KJk); Coyote Block Mudstone (Tbmw); and Coast Range Ophiolite Basalt (Jbk). The largest landslides mapped in this unit were two very large (230 acre) dormant mature rockslides both with faults running through the body and at the toe, and both appear to be dip-slope failures. Notably, the Knoxville Formation (KJk) contains the largest number of landslides per unit; 40% of all of the mapped landslides, including about 60% of all mapped historic landslides. Generally, these smaller landslides do not appear to be associated with faults or dip slopes failures. Geologic units with an apparent high resistance to landsliding, as suggested by relatively low landslide density (less than 5 percent of the outcrop area) and relatively small size (less than 8 hectares; 20 acres), include Cretaceous sandstone, mudstone and conglomerate (Kcusm) of the Coyote Block, and Briones Formation (Tbr).

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above are ranked and grouped relative to shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. However, very few shear-strength data were available within the Lick Observatory Quadrangle, so shear tests from adjoining quadrangles were used to provide data for geologic formations within the study area (see Appendix A). Furthermore, the percentage of area affected by landslides for each rock unit, as described above, was also considered in the strength ranking.

Shear-strength data were compiled for each geologic map unit. Geologic units were grouped according to average angle of internal friction (average phi) and/or lithologic character. Average (mean and 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 the slope stability analysis. A geologic material strength map that provides spatial representation of material strength for use in slope stability analysis was developed from the geologic map based on groupings presented in Tables 2.1 and 2.2.

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. For the Lick Observatory Quadrangle, two shear tests of likely landslide slip surface materials from the adjacent Mt. Sizer Quadrangle were used to characterize the strength of existing landslides. The results are summarized in Table 2.1.

LICK OBSERVATORY 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	KJk	5	33/41	33/36	442/600	Kcusm	33
	Tbr	5	34/30				
GROUP 2	Qf	12	30/30	29/28	755/520	bs, ch, gs	29
	QTp	27	29/27			Jbk	
	Tsg	10	28/26			Tbmw	
GROUP 3	af	3	25/24	25/24	704/550	fy2	25
	Jos	55	27/24			fys	
	Kbs	43	24/23				
	Qh[1]	73	23/22				
	Qp[2]	59	25/25				
GROUP 4	fm	41	22/21	22/20	810/750		21
	Kbc	39	23/20				
	Qa	16	19/18				
	Tcc	21	22/20				
GROUP 5	Qls	2	12/12	12/12			12

Formation name abbreviations from Wentworth and others, 1999; Knudsen and others, 2000.

1: Qh includes Qha, Qhb, Qhc, Qhf, Qht, and Qhty

2: Qp includes Qpa, Qpf, Qpt, Qt, Qoa, and Qof

Table 2.1. Summary of the shear strength statistics for the Lick Observatory Quadrangle. A majority of test data came from adjacent quadrangles; see Appendix A.

SHEAR STRENGTH GROUPS FOR THE LICK OBSERVATORY 7.5-MINUTE QUADRANGLE				
GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**	**GROUP 5**
Kcusm	bs, ch	af	fm	Qls
KJk	QTp	fy2, fys	Kbc	
Tbr	Tbmw	Jos	Qa	
	Tsg	Kbs	Tcc	
		Qh, Qp		

Table 2.2. Summary of shear strength groups for the Lick Observatory Quadrangle.

PART II: EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT

MAPPING TECHNIQUES

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 as originally implemented analyzes dynamic slope stability by calculating the cumulative down-slope displacement for a given earthquake strong-motion time history. The double integration of the earthquake acceleration recording to derive displacement considers only accelerations above a threshold value that represents the inertial force required to initiate slope movement (Factor of Safety = 1). This threshold value, called the “yield acceleration,” is a function of the strength of the earth materials and the slope gradient, and therefore represents the susceptibility of a given area to earthquake-induced slope failure.

As implemented for the preparation of earthquake-induced landslide zones, susceptibility is derived by combining a geologic map modified to reflect material strength estimates with a slope gradient map. Ground shaking opportunity is derived from the CGS/USGS statewide probabilistic shaking map, and Newmark displacements are estimated from a regression equation developed by Jibson (2007) that uses susceptibility and ground motion parameters. Displacement thresholds that define earthquake-induced hazard zones are from McCrink and Real (1996) and McCrink (2001).

EARTHQUAKE-INDUCED LANDSLIDE SUSCEPTIBILITY

Earthquake-induced landslide susceptibility, defined here as Newmark's yield acceleration (1965), is a function of the Factor of Safety (FS) and the slope gradient. To derive a Factor of Safety, an infinite-slope failure model under unsaturated slope conditions was assumed. In addition, material strength is characterized by the angle of internal friction (Φ) and cohesion is ignored. As a result of these simplifying assumptions, the calculation of FS becomes

$$FS = \frac{\tan \Phi}{\tan \beta}$$

where **β** is the slope gradient. The yield acceleration (a_y) is then calculated 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 **α** 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 **α** is the same as the slope gradient angle **(β)**.

These calculations are conducted on a GIS by converting the vector (lines, points and polygons) digital geologic map to a raster (regular spaced grid) material strength map that contains the Φ values assigned to the mapped geologic units (Table 2.1). Slope gradient is derived from a digital elevation model (DEM), a raster file of elevation measurements of the study area. A Level-2 DEM was obtained from the U.S. Geological Survey (USGS) for the Lick Observatory Quadrangle. This DEM was prepared from 7.5-minute quadrangle topographic contours based on 1953 aerial photography. It has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy. The slope gradient map was made from the DEM using a third-order, finite-difference, center-weighted algorithm (Horn, 1981).

GROUND SHAKING OPPORTUNITY

Ground shaking opportunity is a calculated measure of the intensity and duration of strong ground motion anticipated to occur. Ground motion calculations used by CGS for regional earthquake-induced landslide zonation assessments are currently based on the *Probabilistic Seismic Hazard Assessment (PSHA) Model* developed by the USGS for the 2008 Update of the United States National Seismic Hazard Maps (Petersen and others, 2008). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance level. For the Lick Observatory Quadrangle as a whole, an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA) are:

Modal Magnitude:	6.2 to 6.4
Modal Distance:	4 to 14 km
PGA:	0.41 to 0.82 g

Raster versions of the PSHA PGA and Modal Magnitude maps for the Lick Observatory Quadrangle were extracted from the statewide map and applied in the Newmark displacement calculations, as described below.

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

Earthquake-induced landslide hazard potential is derived by combining the susceptibility map (a_y) with the ground shaking opportunity maps (PGA and Modal Magnitude) to estimate the amount of permanent displacement that a modeled slope might experience. The permanent slope displacement is estimated using a regression equation developed by Jibson (2007). That equation is:

$$\log D_N = -2.710 + \log\left[\left(1 - \frac{a_y}{PGA}\right)^{2.335}\left(\frac{a_y}{PGA}\right)^{-1.478}\right] + 0.424\boldsymbol{M} \pm 0.454$$

where D_N is Newmark displacement and **M** is modal magnitude. Jibson's (2007) nomenclature for yield acceleration (a_c) and peak ground acceleration (a_{max}) have been replaced here by a_y and PGA, respectively, to be consistent with the nomenclature used in this report.

The above equation is applied using a_y, PGA and Modal Magnitude maps as input, resulting in mean values of Newmark displacement at each grid cell (the standard deviation term at the end of the equation is ignored). 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).

ZONATION CRITERIA: EARTHQUAKE-INDUCED LANDSLIDES

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (CGS, 2004). 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.

DELINEATION OF SEISMIC HAZARD ZONES: EARTHQUAKE-INDUCED LANDSLIDES

Upon completion of an earthquake-induced landslide hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings in order to delineate *Zones of Required Investigation*. Following is a description of the criteria-based factors that governed the construction of the *Seismic Hazard Zone* map for the Lick Observatory Quadrangle.

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 zone of required investigation.

Hazard Potential Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), earthquake-induced landslide hazard zones encompass all areas that have calculated Newmark displacements of 5 centimeters or greater. Areas with less than 5 centimeters of calculated displacement are excluded from the zone. This results in 58 percent of the study area lying within the earthquake-induced landslide hazard zone for the Lick Observatory Quadrangle.

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APPENDIX A: SOURCES OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City of San Jose	17
CGS Environmental Review	4
Santa Clara County Planning	2
San Jose East Quadrangle	207
Calaveras Reservoir Quadrangle	122
Mt. Sizer Quadrangle	29

Mindego Hill Quadrangle	**28**
Total Number of Shear Tests	**409**

SECTION 3: GROUND SHAKING ASSESSMENT

for the

LICK OBSERVATORY 7.5-MINUTE QUADRANGLE, SANTA CLARA COUNTY, CALIFORNIA

using the

2008 Probabilistic Seismic Hazard Assessment Model

by

Charles R. Real
G.P. 968

and

Rui Chen
P.G. 8598

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

INTRODUCTION

Purpose

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California State Geologist to compile maps that identify *Seismic Hazard Zones* consistent with requirements and priorities established by the California State Mining and Geology Board (SMGB) (California Geological Survey, 2004). The text of this report is available online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp118_revised.pdf. The Act requires that site-specific geotechnical investigations be performed for most urban development projects situated within seismic hazard zones before lead agencies can issue the building permit. The Act also requires sellers of real property within these zones to disclose that fact at the time such property is sold. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California SMGB (California Geological Survey, 2008). The text of this report is online at: http://www.conservation.ca.gov/cgs/shzp/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. The site ground motion levels from the 2008 seismic hazard model are available interactively online:

https://geohazards.usgs.gov/deaggint/2008/

This section and Sections 1 and 2, which address 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 the California Geological Survey's Internet page: http://conservation.ca.gov/CGS/shzp.

2008 PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL

The estimated ground shaking is derived using the revised Probabilistic Seismic Hazard Analysis (PSHA) model developed by the U.S. Geological Survey for the 2008 Update of the United States National Seismic Hazard Maps (Petersen and others, 2008). This model replaces the previous ground-motion model of Frankel and others (2002), Cao and others (2003) and Peterson and others (1996) used in previous Official Seismic Hazard Zone Maps. Like the previous model, the 2008 model is the product of an extensive effort to obtain consensus within the scientific and engineering communities 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 2008 model incorporates improvements to the California fault sources, based on new information from the Working Group on California Earthquake Probabilities (Field and others, 2008), and uses ground motion prediction equations from the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation Relation Project (NGA) (Power and others, 2008) .

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 current PSHA model considers only uniform firm-rock site conditions (the boundary between NEHRP site classes B and C with an average shear wave velocity in the upper 30 meters of the earth of 760 m/s. In a separate post-PSHA step, we apply the NEHRP soil profile type D factor for PGA (FEMA, 1994) to adjust for alluvial soil conditions. See Petersen and others (2008) for more details on changes in the new PSHA model.

APPLICATION TO LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENT

Deaggregation of the seismic hazard identifies the contribution of each earthquake source (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (Cramer and Petersen, 1996). This information provides the rationale for selecting a ground motion level for evaluating ground failure potential. For zoning earthquake-induced landslide hazard, the probabilistic peak ground acceleration and predominant earthquake magnitude are used to estimate cumulative Newmark displacement for a given rock strength and slope gradient condition using a regression equation, described more fully in Section 2 of this report.

For purposes of zoning liquefaction hazard, the probabilistic PGA is scaled by a factor of magnitude and is weighted by each earthquake’s estimated ground shaking contribution. The magnitude-dependant function is simply the inverse of the liquefaction threshold-scaling factor recommended by Youd and others (2001). The result is a “magnitude-weighted” ground motion that is then adjusted for NEHRP alluvial conditions and use directly in the calculation of the induced cyclic stress ratio demand and thus the estimate of the factor of safety against liquefaction. Unlike the predominant–earthquake approach described previously, this approach provides an improved estimate of liquefaction hazard in a probabilistic sense. All magnitudes contributing to the hazard estimate are used to weight the probabilistic calculation of peak ground acceleration, effectively causing the cyclic stress ratio liquefaction threshold curves to be scaled probabilistically when computing factor of safety. This procedure ensures that large, distant earthquakes that occur less frequently but contribute *more*, and smaller, more frequent events that contribute *less* to the liquefaction hazard are appropriately accounted for (Real and others, 2000).

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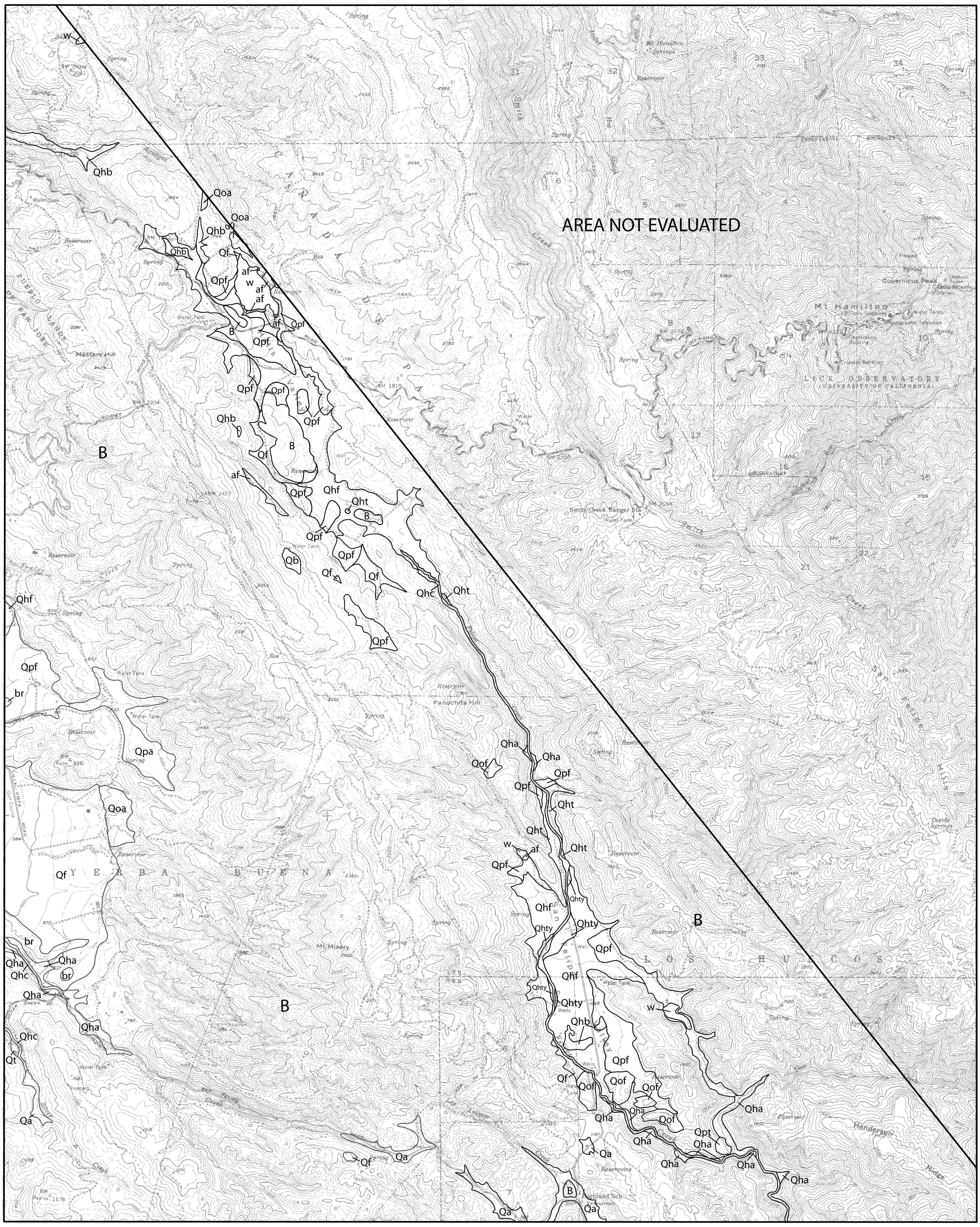
121°45'
37°22'30"



37°15'
121°37'30"

Base U.S.G.S. Lick Observatory 7.5-minute map

LICK OBSERVATORY QUADRANGLE

SCALE

1 MILE
7000 FEET
1 KILOMETER

N

= Witter (unpublished)

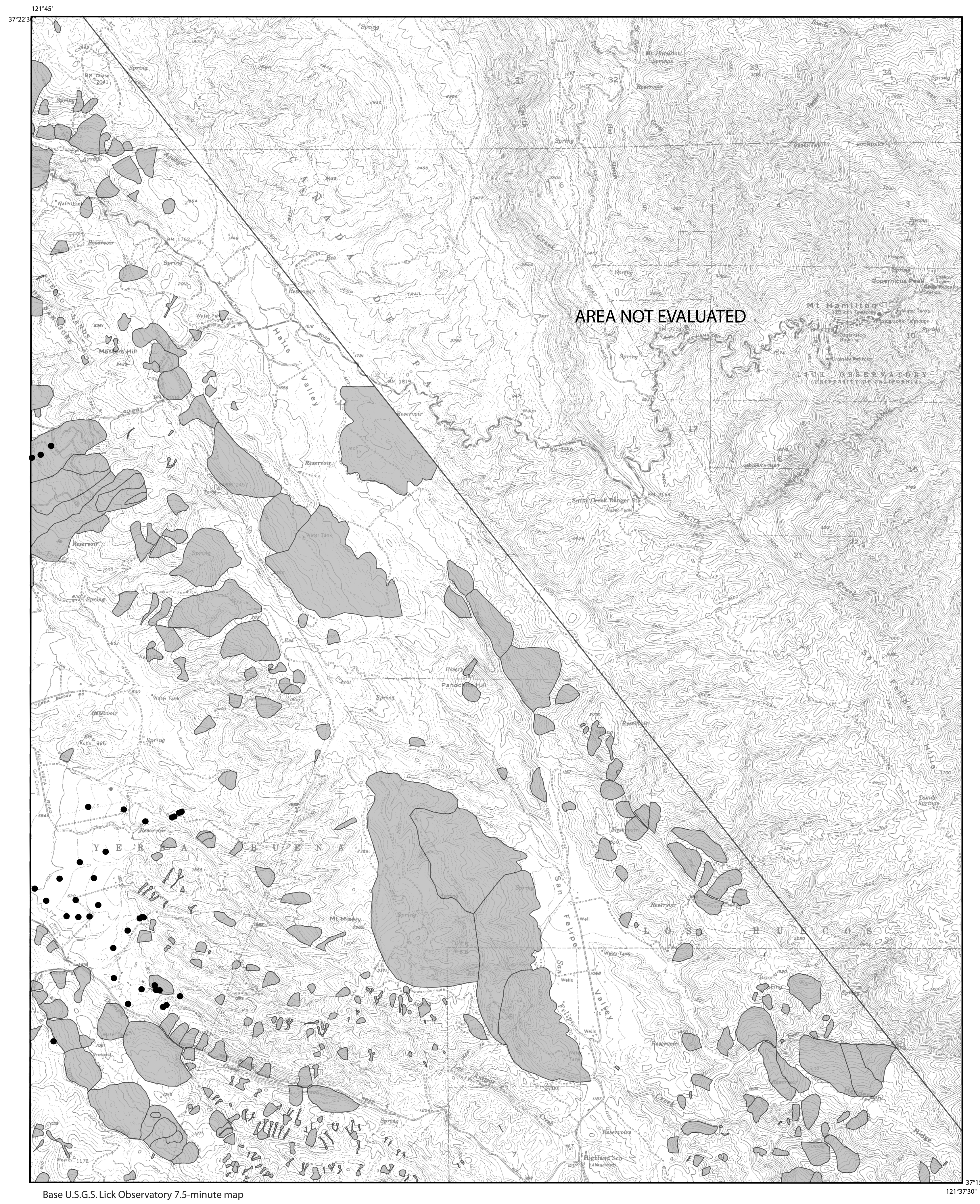
= Knudsen (2000)

B = Pre-Quaternary bedrock.

See "Bedrock and Surficial Geology" in Section 1 of report for descriptions of units.

= Area Not Evaluated

Plate 1.1 Quaternary Geologic Map of the Lick Observatory 7.5-Minute Quadrangle.



Base U.S.G.S. Lick Observatory 7.5-minute map

LICK OBSERVATORY QUADRANGLE

SCALE

1 MILE

7000 FEET

1 KILOMETER

N

● = Geotechnical borings used in landslide evaluation.

Landslide

Plate 2.1 Landslide inventory used in this study of the Lick Observatory 7.5-Minute Quadrangle, California.