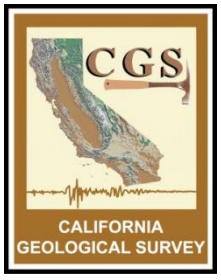
SEISMIC HAZARD ZONE REPORT 124

SEISMIC HAZARD ZONE REPORT FOR THE BRENTWOOD 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

2018



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How to view or obtain Earthquake Zones of Required Investigation

California Geological Survey (CGS) maps of Earthquake Zones of Required Investigation, which include Seismic Hazard Zones, and Earthquake Fault Zones; their related reports, and GIS data are available for download and online viewing on the CGS's Information Warehouse: http://maps.conservation.ca.gov/cgs/informationwarehouse/.

These maps and reports are also available for purchase and reference at the CGS office in Sacramento at the address presented below, or online at: http://www.conservation.ca.gov/cgs/information/publications/Pages/ordering.aspx.

All Earthquake Zones of Required Investigation are available as a WMS service here: https://spatialservices.conservation.ca.gov/arcgis/rest/services/CGS_Earthquake_Hazard_Zones.

This Seismic Hazard Zone Report documents the data and methods used to construct the Seismic Hazard Zone Map for the 7.5-minute quadrangle evaluated for earthquake-induced liquefaction and landslide hazards. The information contained in this report should be particularly helpful to site investigators and local government reviewers of geotechnical reports.

Information regarding the Seismic Hazard Zonation Program with links to the Seismic Hazards Mapping Act and the Alquist-Priolo Earthquake Fault Zoning Act are available on CGS' website: http://www.conservation.ca.gov/cgs/shzp/Pages/Index.aspx.

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Release and Revision History: Seismic Hazard Zone Map and Evaluation Report of the Brentwood Quadrangle, SHZR 124	
August 17, 2017	Preliminary Map Release
January 11, 2018	Official Map Release

EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the map of *Earthquake Zones of Required Investigation* (EZRI) for liquefaction and earthquake-induced landslides (also referred to as *Seismic Hazard Zones*) in the Brentwood 7.5-Minute Quadrangle, Contra Costa County, California. The topographic quadrangle map, which covers approximately 152 square kilometers (~59 square miles) at a scale of 1:24,000 (41.7 mm = 1,000 meters; 1 inch = 2,000 feet), displays the boundaries of the EZRI for liquefaction and earthquake-induced landslides. The area subject to seismic hazard mapping includes the City of Brentwood, parts of the Cities of Oakley and Antioch, unincorporated census-designated places such as Byron and Knightsen, and Contra Costa County and State of California land.

Seismic Hazard Zone 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.

About 102 square kilometers (39 square miles) of land in the Brentwood Quadrangle has been designated EZRI for liquefaction hazard, encompassing much of the Brentwood delta-alluvial plain and most upland alluvial valleys. Borehole logs of test holes drilled in these areas indicate the widespread presence of near-surface soil layers composed of saturated, loose sandy sediments. Geotechnical tests indicate that these soils generally have a moderate to high likelihood of liquefying, given the region is subject to strong ground motion.

The amount of area designated as EZRI for earthquake-induced landsliding within the Brentwood Quadrangle is less than a combined total of 1 square kilometer (.38 square miles). These zones show up on the topographic map as small, discontinuous patches of land concentrated in narrow strips along some of the steeper slopes in the upland, hilly terrain encompassed by the quadrangle.

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 EZRI 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 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 of 1990 (the Act) (Public Resources Code, Chapter 7.8, Division 2) directs the State Geologist to prepare maps that delineate Seismic Hazard Zones, a subset of Earthquake Zones of Required Investigation (EZRI), which include Earthquake Fault 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 these guidelines is online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/documents/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 historic-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/documents/sp118_revised.pdf.

This Seismic Hazard Zone Report summarizes the development of the Seismic Hazard Zone for the Brentwood 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. Ground motion calculations used by CGS exclusively for regional zonation assessments are currently based on the probabilistic seismic hazard analysis (PSHA) model developed by USGS for the 2014 *Update of the United States National Seismic Hazard Maps* (NSHMs).

SECTION 1: EVALUATION REPORT FOR LIQUEFACTION HAZARD

in the

BRENTWOOD 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

by

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DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

INTRODUCTION

Purpose

The Seismic Hazards Mapping Act of 1990 (the Act) (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) (CGS, 2004). The text of this report is available online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/documents/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/documents/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 (SCEC, 1999).

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Brentwood 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 region, 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 for much of the San Francisco Bay region, including areas within the Brentwood 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 borehole 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 historic-high 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 Earthquake Zones of Required Investigation according to criteria adopted by the SMGB (CGS, 2004).

Scope and Limitations

Evaluation for potentially liquefiable soils generally is confined to areas covered by Quaternary (less than about 2.6 million years) sedimentary deposits. Such areas within the Brentwood Quadrangle consist mainly of the Sacramento-San Joaquin Delta-alluvial plain and alluviated valleys. 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.

Seismic Hazard Zones for liquefaction 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 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 Seismic Hazard Zones for liquefaction in the Brentwood Quadrangle.

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Brentwood Quadrangle covers an area of approximately 152 square kilometers (59 square miles) in eastern Contra Costa County, California. The map area spans the boundary between the western portion of the Great Valley Geomorphic Province and the eastern portion of the Coast Ranges Geomorphic Province of California. The center of the quadrangle is about 66 kilometers (41 miles) east-northeast of the City of San Francisco Civic Center and about 74 kilometers (46 miles) south-southwest of the City of Sacramento Civic Center. Approximately 38 square kilometers (15 square miles) of the City of Brentwood occupies the west-central part of the quadrangle, the City of Oakley encompasses an area of approximately 28 square kilometers (~11 square miles) along the northern margin of the map area, and a small section (approximately 4 square kilometers) of the City of Antioch is within the northwest corner of the map area. The remainder of the map area consists of unincorporated census-designated places such as Byron and Knightsen, and Contra Costa County and State of California land.

The quadrangle is situated on the western edge of the Sacramento-San Joaquin Delta. The southwest corner of the study area is characterized by low, gently rolling hills, whereas the rest

of the Brentwood Quadrangle is dominated by the relatively flat Sacramento-San Joaquin Delta-alluvial plain. In the northeast part of the map area, the Sacramento-San Joaquin Delta alluvial plain is dotted with small, low relief, isolated sand dunes. These isolated dunes transition westward into a larger northwest-southeast oriented sand dune plain that occupies the northwest part of the Brentwood Quadrangle. Most of the uninterrupted flatland in the study area is found in the central and southeastern parts of the quadrangle.

Streams within the quadrangle include Marsh Creek, Sand Creek, and Kellogg Creek. Many man-made canals traverse the Brentwood Quadrangle, including the Byron-Bethany Irrigation Canal near the southern boundary of the map area; Main Canal which transports water from Marsh Creek Reservoir to Discovery Bay in the southern half of the map area; and the Contra Costa Canal which follows the northern boundary of the map area and crosses through Antioch, Oakley, and unincorporated county land. Located in the southwest corner of the Brentwood Quadrangle is Marsh Creek Reservoir, a detention basin constructed in the 1960's that holds back water during high rain events, providing flood protection along Marsh Creek for developed areas downstream. Elevations in the map area range from 0 meters (0 feet) in the northeastern corner of the map area, to 138 meters (450 feet) at a hilltop near Marsh Creek Reservoir, in the southwest corner of the map.

Land Use

Land use in the Brentwood Quadrangle historically was dominated by agriculture in valley areas and cattle grazing in the surrounding hills. However, since 2000, Brentwood's population has more than doubled in size, and urban development has increased substantially in both Oakley and Brentwood, mainly as light industrial, shopping centers and home construction that continued to expand in both the flat land and low hills. Nearly one-half of the quadrangle remains undeveloped, consisting primarily of crops, orchards, livestock, and vineyards on the valley floor in the eastern half of the quadrangle, and John Marsh State Park as regional open space in the uplands of the southwest corner of the quadrangle.

The primary transportation route in the study area is California State Route 4, which follows the southern and western quadrangle boundaries and connects the city of Brentwood with the cities of Antioch and Oakley. The Byron Highway crosses the eastern part of the map area and provides access to census-designated place, Byron in the south and census-designated place, Knightsen in the north. Balfour Road trends east-west across the quadrangle connecting State Route 4 with the Byron Highway. Sand Creek Road and Lone Tree Way are major east-west thoroughfares traversing the city of Brentwood. Marsh Creek Road and Walnut Boulevard join Vasco Road near the southern boundary of the quadrangle and are major rural roads connecting the city of Brentwood with outlying communities. Access to undeveloped areas within the quadrangle is primarily by paved county roads and paved and unpaved private roads south and east of the city of Brentwood.

GEOLOGY

Geologic units generally susceptible to liquefaction include latest Pleistocene and Holocene alluvial and fluvial sedimentary deposits and artificial fill. The primary source of geologic mapping used in the evaluation of these materials for the Brentwood Quadrangle is the CGS unpublished preliminary geologic map digital database of the Stockton 30' x 60' Quadrangle (Dawson, 2010). This geologic map was compiled from geologic mapping by Witter and others

(2006), Knudsen and others (2000), Knudsen and Lettis (1997), Graymer and others (1994 and 1996), and Bartow (1985). Other geologic maps and reports reviewed in this investigation include Atwater (1982) and Helley and Graymer (1997). The Quaternary geologic unit nomenclature used by CGS for mapping in the San Francisco Bay Region was adopted from Knudsen and others (2000). Table 1.1 compares stratigraphic nomenclature used by CGS with nomenclature used by several previous studies performed in northern California.

The digital geologic maps covering the Brentwood Quadrangle were combined to form a single, 1:24,000 scale, geologic materials map. CGS staff used DEMs, aerial photos, online imagery, and limited field reconnaissance to modify the Quaternary/bedrock boundary, confirm the location of geologic contacts, map recently modified ground surfaces, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units. Linear structural features such as folds, faults, and anticlines are not included in the geologic materials map. The distribution of Quaternary deposits on the final geologic materials map (summarized on Plate 1.1) was used in combination with other data, discussed below, to evaluate liquefaction susceptibility and develop the Seismic Hazard Zone Map.

Bedrock Units

Although bedrock units are not generally considered subject to liquefaction, they are briefly described in this section because the composition and texture of sediments that accumulate in lowland basins are governed in large part by the lithology of older rocks exposed in surrounding highlands. For additional detail on bedrock exposed in the Brentwood Quadrangle, see Section 2 of this report, Evaluation Report for Earthquake-Induced Landslide Hazard.

Bedrock of the Diablo Range exposed in the Brentwood Quadrangle consists mainly of Cretaceous sedimentary strata of the Great Valley Sequence and Tertiary sedimentary strata (Wentworth and others, 1999). These bedrock units outcrop where they have not been buried beneath Quaternary sediments in the southwest and northwest corners of the quadrangle (Plate 2.1). The Great Valley Sequence exposed in the quadrangle consists of a thick sequence of interbedded sandstone, siltstone, and mudstone, originally deposited on the ocean floor by turbidity currents and subsequently folded, faulted and uplift (Graymer and others, 1994). Tertiary rocks cover about 75% of the Brentwood Quadrangle uplands and consist predominantly of interbedded sandstone and shale, with occasional conglomerate and siltstone intervals.

Both the Cretaceous and Tertiary units are exposed in wide linear outcrops, strike parallel to and form ridges, dip typically to the north or northeast, and become younger toward the northeast. The Great Valley Sequence units typically form moderate to steep sided and often asymmetrical ridges. These ridges are steeper, and often planar and smooth, on the south facing anti-dip slopes, with the dip slope side of the ridges often dissected into spur ridges that are less steep. Generally, the Cretaceous units form a greater proportion of steeper slopes than the Tertiary units. The Tertiary shale and siltstone units in the map area commonly underlie the lower slopes of ridges and knolls and adjacent unalluviated bedrock valley floors. In contrast, the sandstone and conglomerate Tertiary units form low, gently to moderately sloping, rounded to sharp crested ridges.

Quaternary Sedimentary Deposits

Approximately 134 km^2 (52 mi^2) of the Brentwood Quadrangle is covered by Quaternary sediments, of which approximately 129 km^2 (50 mi^2) are latest Pleistocene to Holocene in age. In total, 11 different Quaternary units are mapped in the Brentwood Quadrangle (Plate 1.1). These sedimentary units are summarized in Table 1.1 and discussed below. The liquefaction susceptibility evaluation and development of the Seismic Hazard Zone Map for the quadrangle was based on the distribution of these deposits at a scale of 1:24,000 (Plate 1.1) and analyses of associated geotechnical data as discussed under the Engineering Geology heading of this section.

Old Quaternary Units

Two Pleistocene sedimentary units are exposed in the Brentwood Quadrangle; late Pliocene to early Pleistocene-age alluvium (**QPu**) and latest Pleistocene alluvial fan deposits (**Qpf**). The unnamed late Pliocene to early Pleistocene-age alluvium (**QPu**) consists of undifferentiated sandstone, siltstone, and gravel, and is unrelated to modern drainages. Unit **QPu** forms low knolls and high terraces along the southwestern alluvial plain margin in the southwest quarter of the Brentwood Quadrangle, just north of Marsh Creek Reservoir (Plate 1.1). The unnamed latest Pleistocene alluvial fan unit (**Qpf**) consists of sand, gravel, silt, and clay. This unit is related to modern drainages and forms broad, gently sloping fans and terraces exposed in the southwest quarter of the map area along Kellogg Creek and Marsh Creek (Plate 1.1) Deposits of **Qpf** are distinguished from younger alluvial fan units by higher topographic position, greater degree of dissection, and stronger soil profile development.

Young Quaternary Units

Nearly 85%, of the Brentwood Quadrangle is covered by young Quaternary (latest Pleistocene and Holocene) alluvial sediments and eolian dune sands. One of the most notable surficial units in the Brentwood Quadrangle is the northwest-southeast trending, latest Pleistocene to Holocene, fine grained, very well-sorted eolian dune field (**Qds**) mapped in the northern half of the map area. These eolian sands form a continuous gently rolling dune field in the northwest corner of the quadrangle and isolated low hills across the northeast corner of the map area. They are thought to be associated with latest Pleistocene to early Holocene low sea level stands, during which large volumes of fluvial and glacially derived sediment were blown into dunes (Atwater and others, 1977). Accumulation began after the last interglacial high stand of sea-level began to recede about 70 thousand years ago, continued to form when sea level dropped to its Wisconsin minimum about 18 thousand years ago, and ceased to accumulate after sea level reached its present levels (Helley and Graymer, 1997).

Alluvial fan deposits in the Brentwood Quadrangle are subdivided into three distinct units; alluvial fan (**Qhf**), alluvial fan, fine facies (**Qhff**), and alluvial fan levee (**Qhl**) deposits. These materials were eroded from surrounding hills, then transported and deposited into the inter-ridge valleys, alluvial and delta plains. The coarsest of these units, the alluvial fan deposits (**Qhf**), was deposited by streams emanating from the Marsh Creek and Sand Creek drainages onto the Brentwood alluvial valley floor as debris flows, hyperconcentrated mudflows, and braided stream flows. These deposits include sand, gravel, silt, and clay and decrease in grain size downslope from the fan apex, gradually transition into the fine facies of the alluvial fan (**Qhff**). The alluvial fan, fine facies is mapped as distal alluvial fan deposits and flood plain overbank deposits laid down in very gently sloping portions of the alluvial fan or valley floor. These deposits form the inter-dune valley floor

in the northeastern part of the quadrangle and extend across the delta-alluvial plain. **Qhff** is the finest grained of the three alluvial fan units, consisting primarily of clay and silt, with interbedded lobes of coarser alluvium (sand and occasional gravel). The Holocene alluvial fan levee deposits (**Qhl**) were formed by streams that overtopped their banks and deposited sand, silt, and clay adjacent to the channel. This unit was mapped based on interpretation of topography where levees are identified as long, low ridges oriented down fan.

Two young Quaternary undifferentiated deposits are exposed in the Brentwood Quadrangle; undifferentiated Pleistocene to Holocene alluvium (**Qa**) and undifferentiated Holocene alluvial deposits (**Qha**). Undifferentiated Pleistocene to Holocene alluvium is exposed in only one small valley along the west central boundary of the map. This unit is used where separate fan, basin, and terrace units could not be delineated at the scale of the mapping. The younger undifferentiated alluvial deposits (**Qha**) are mapped in the southwest corner of the Brentwood Quadrangle in the upland valley bottoms of the Marsh Creek and Briones Valley drainages. This unit consists of intercalated sand, silt, and gravel, with little to no dissection.

Late Holocene (modern) surficial deposits in the Brentwood Quadrangle include Holocene to modern channel deposits (**Qhc**) consisting of unconsolidated sand and gravel recently transported within active channels. Young landslides are present in the area (**Qls**), but are not shown on Plate 1.1 (see Section 2 of this report for occurrences and descriptions).

Geologic Structure

The structural framework of the Brentwood Quadrangle is governed by a series of sub-parallel, generally northwest-striking faults ranging in age from Mesozoic to present (Wentworth and others, 1999). Movement on these faults has resulted in the current transpressional tectonic regime, characterized by horizontal northeast-southwest maximum compression, that has uplifted Mount Diablo and folded the surrounding rocks over the last 4 million years into the Mount Diablo Anticline (Schemmann, Unruh and Moores, 2007). The uplands of the Brentwood Quadrangle are on the northeast flank of the Mount Diablo anticline (Unruh and others, 2007).

A number of faults cross the Brentwood quadrangle, including the Antioch Fault which crosses into the southwestern part of the Brentwood Quadrangle at Dry Creek from the adjacent-to-the-west Antioch South quadrangle. The Quaternary aged (<2.6 my) Antioch Fault is mapped as extending only about 0.2 miles into the quadrangle and is well constrained where in bedrock and inferred in alluvium (Bryant and Cluett, 2002). This fault appears to extend to the south, crossing Briones Valley just west of the Marsh Creek Reservoir where it is mapped as pre-Quaternary aged (Dawson, 2010; Graymer, and others, 1994). The north-south trending Sherman Island Fault and Midland Fault Zone are mapped as crossing bedrock and alluvium in the western half and southeastern corner of the Brentwood Quadrangle, respectively (Bryant and Cluett, 2002; Dawson, 2010; Schemmann and others, 2007). These faults are mapped as pre-Quaternary aged and are well constrained where in bedrock and inferred in alluvium. Several other unnamed, north-south trending, apparently pre-Quaternary faults are mapped crossing bedrock in the southwest corner of the quadrangle (Bryant and Cluett, 2002; Dawson, 2010; and Graymer and others, 1994). No active faults are mapped in the Brentwood Quadrangle by the California Geological Survey under the Alquist-Priolo Earthquake Fault Zoning Act.

Table 1.1. Correlation chart of Quaternary stratigraphic nomenclature used in previous studies. CGS has adopted the nomenclature of Knudsen and others (2000) for Quaternary mapping in the San Francisco Bay Region.

Geologic Unit	CGS GIS Database	Helley & Graymer (1997)	Knudsen & Others (2000)	Atwater (1982)
Artificial Stream Channel	ac	Qhasc	ac	
Artificial Fill	af	af	af	
Holocene to Modern Stream Channel Deposits	Qhc	Qhsc	Qhc	
Holocene Alluvial Fan Levee Deposits	Qhl	Qhl	Qhl	Qymc
Holocene Alluvial Deposits - Undifferentiated	Qha	Qhaf	Qha	Qymc
Holocene Alluvial Fan Deposits	Qhf	Qhaf	Qhf	Qymc
Holocene Alluvial Fan Deposits, Fine Facies	Qhff	Qhb	Qhff	Qymc
Latest Pleistocene to Holocene Dune Sand	Qds	Qds	Qds	Qm2e
Pleistocene to Holocene Undifferentiated Alluvium	Qa	Qpaf	Qa	Qymc
Latest Pleistocene Alluvial Fan Deposits	Qpf	Qpaf	Qpf	Qomc
Late Pliocene to Early Pleistocene Sandstone, Siltstone, and Gravel - Undifferentiated	QPu	QTu	br	Qomc
Pre-Quaternary deposits and bedrock	br	br	br	TKb

ENGINEERING GEOLOGY

As stated above, soils generally susceptible to liquefaction are late Quaternary alluvial and fluvial sedimentary deposits and non-engineered artificial fill. Deposits that contain saturated loose sandy and silty soils are the most susceptible to liquefaction. Lithologic descriptions and soil test results reported in geotechnical borehole logs provide valuable information regarding subsurface geology, groundwater levels, and the engineering characteristics of sedimentary deposits.

Historic-High Groundwater Mapping

Saturated soil conditions are required for liquefaction to occur, and the susceptibility of a soil to liquefaction varies with the depth to groundwater. Saturation reduces the effective normal stress of near-surface sediment, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). CGS compiles and interprets current and historical groundwater 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 groundwater 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 groundwater level based on historical groundwater data. CGS constructs regional contour maps that depict these anticipated historic-high groundwater levels in areas where groundwater is either currently near-surface or could return to near-surface levels within a land-use planning interval of 50 years.

Groundwater Data

The study area is located within the northwestern-most part of the California Department of Water Resources (DWR) designated San Joaquin Valley Groundwater Basin, Tracy Subbasin (Groundwater Subbasin Number 5-22.15), and is included in the San Joaquin River Hydrologic Region (DWR, 2003). Watersheds within the Brentwood Quadrangle include the Lower Marsh Creek, Upper Marsh Creek, Lower Kellogg Creek, Upper Kellogg Creek, Dutch Slough – Big Break, and the Markley Canyon – San Joaquin River watersheds (USGS, 2015). For this study, groundwater mapping was performed for the valley and flatland regions of these watersheds that are subject to liquefaction zonation in order estimate depths to saturated materials.

Groundwater conditions were evaluated based on first encountered water levels noted in geotechnical boring logs, online groundwater databases, groundwater monitoring reports, and water well drilling logs. Geotechnical borehole logs were acquired from planning departments at the cities of Brentwood, Oakley, and Antioch, and the California Department of Transportation (CalTrans). Additional water level data were collected from the State Water Resources Control Board (SWRCB), California Department of Water Resources (DWR), the United States Geological Survey (USGS), and local water districts and agencies.

Groundwater data from all available records were spatially and temporally evaluated in a GIS database to constrain the estimate of historically shallowest groundwater for the project area. CGS created a highest historic-high groundwater surface map for the northwestern most part of the Tracy Subbasin based on available well records and data from previous hydrologic studies. The historic-high groundwater map was modified, where warranted, with input from current ground-surface water, such as active creeks, recharge ponds, detention basins, other water impoundments, and reservoirs. The depth to groundwater contours depicted on Plate 1.2 do not represent present-day conditions, as usually presented on typical groundwater contour maps, but rather the historic-high groundwater elevation surface levels for the northwestern part of the Tracy Subbasin in the Brentwood Quadrangle.

Water level data evaluated in this study represents more than 1400 groundwater measurements (Plate 1.2) collected from the 1960’s through the present, with most records representing conditions of the early 1990’s through the 2000’s. Review of hydrographs of wells in the map area

indicate that, except for seasonal variation resulting from recharge and pumping, the majority of water levels in wells have remained relatively stable over at least the last 10 years (DWR, 2003).

Groundwater Levels

Water-bearing materials in the northwestern-most part of the Tracy Subbasin include continental deposits of late Tertiary to Quaternary age, flood-basin deposits, and Pleistocene to Holocene alluvium (DWR, 2003). Groundwater levels in these deposits are strongly influenced by natural groundwater recharge resulting from direct precipitation and annual runoff in creeks and streams (DWR, 2003; USGS, 2015). Artificial sources of groundwater recharge often locally affect groundwater levels and result from canal seepage, irrigation return flows, urban landscaping runoff, agricultural tail water, slow leakage from detention basins, and releases of treated water. This groundwater generally flows northeasterly across the study area, from the foothills of Mount Diablo, southwest of the map area, towards the San Joaquin River Delta along the northern and eastern boundaries of the study area.

Historic-high groundwater depths in the Brentwood Quadrangle vary from 0 feet in the northeastern corner of the map area to greater than 40 feet in the southwest and northwest corners. The depth to groundwater in the northeastern corner of the Brentwood Quadrangle is strongly influenced by its proximity to San Joaquin River Delta channels and sloughs that border the northern and eastern quadrangle boundaries. Water level measurements in this area indicate groundwater has been at 0 to 5 feet below ground surface for the last 40 years. For this reason, the northeast part of the quadrangle has been assigned a historic-high groundwater depth of 0 feet below ground surface.

Depth to groundwater in the northwest part of the Brentwood Quadrangle is influenced by the northwest-southeast trending Antioch Dune Field. The eolian sands (**Qds**) that comprise the Antioch Dune Field are well sorted, highly permeable and lack extensive confining units (Cain and others, 2003). These characteristics, which limit water retention, coupled with variable topographic relief of the sand dunes, result in historic-high groundwater levels that vary from 20 feet to more than 40 feet below ground surface. Similar to the eolian dune sands, the upper 100 feet of the Marsh Creek Alluvial fan in the southwest part of the map area contain no extensive confining units and consists of thick packages of sand and gravel with thin, discontinuous beds of clay and silt, limiting water retention (LHSC, 1999; 2012). Historic-high groundwater levels below the surface of the alluvial fan ranges between 20 and 50 feet deep, where the greatest depths are measured near the apex of the alluvial fan.

In the winter of 1955-1956 Marsh Creek, Sand Creek, and Kellogg Creek experienced several severe floods that inundated low-lying areas adjacent to the waterways with as much as 4,900 acres of water to a depth of four feet (Eastern Contra Costa Soil Conservation Service and others, 1959). The areas inundated during these large flood events have been assigned historic-high groundwater levels of less than 10 feet. Areas where the historic-high groundwater levels are not well constrained with sufficient borehole or water well measurements often occur in the upland alluvial valleys and in canyons. These areas are assigned a value of less than 10 feet because they tend to trap and accumulate heavy runoff and near-surface groundwater derived from surrounding highlands.

Soil Testing

For this investigation, borehole logs were collected from the files of the City of Brentwood, City of Antioch, City of Oakley, and CalTrans. Borehole logs that report the results of downhole standard penetration tests (SPT) in alluvial materials are of particular value in liquefaction evaluations because the standard penetration test provides a standardized measure of the penetration resistance of soil and, therefore, is commonly used as an index of soil density. For this reason, SPT results are also a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and commonly by the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material (see Liquefaction Analysis in Part II of this report). SPT is an in-field test that is based on counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil. The driving force is provided by dropping a 140-pound hammer weight a distance of 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (American Society for Testing and Materials, 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, if reliable conversions can be made. The actual and converted SPT blow counts are normalized to a common reference, effective-overburden pressure of one 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 $(N_1)_{60}$. Geotechnical borehole logs provide information on lithologic and engineering characteristics of Quaternary deposits the study area. The characteristics reported in Table 1.2 summarize conditions in the Brentwood Quadrangle.

Data from a total of 770 borehole logs were entered into the CGS geotechnical GIS database and evaluated during the course of this study. Of the 770 geotechnical borehole logs analyzed in this study (Plate 1.1), most included blow-count data from SPTs or from penetration tests that allow reasonable blow count conversions to SPT-equivalent values. Few of the borehole logs collected, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal analysis using the Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using either recorded density, moisture, and sieve test values or using averaged test values of similar materials.

The Seed-Idriss Simplified Procedure for liquefaction evaluation was developed primarily for clean sand and silty sand. As described above, results depend greatly on accurate evaluation of in-situ soil density as measured by the number of soil penetration blow counts using an SPT sampler. However, borehole logs show that Holocene alluvial layers containing gravel are present in the subsurface of the Brentwood alluvial plain. In the past, gravel and gravelly materials were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravel has, in fact, been reported during earthquakes and recent laboratory studies have confirmed the phenomenon (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 artificially high. They are likely to lead to over-estimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where blow counts appear to have been affected by gravel content, correlations are made with boreholes in the same unit where the tests do not appear to have been affected by gravel content.

Table 1.2. Liquefaction susceptibility of Quaternary units in the Brentwood Quadrangle.

Geologic Map Unit	Age	Sediment/Material Type	Consistency	Liquefaction Susceptibility*
ac, af	Late Holocene	Sand, silt, gravel, concrete	Loose to dense	Yes
Qhc	Holocene	Sand, gravel, cobbles, clay, silt	Loose	Yes
Qhl	Holocene	Sand, silt, clay	Loose	Yes
Qha	Holocene	Sand, gravel, silt	Loose to medium dense	Yes
Qhf	Holocene	Sand, gravel, silt, clay	Medium dense to dense	Yes
Qhff	Holocene	Silt, clay, sand, gravel	Loose to medium dense	Yes
Qds	Holocene and latest Pleistocene	Sand	Loose to dense	Yes
Qa	Holocene to Pleistocene	Sand, silt, gravel	Loose to dense	Yes
QPu, Qpf	Late Pliocene and Pleistocene	Gravel, sand, silt, clay	Dense to very dense	No
*When saturated				

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 California State Mining and Geology Board (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 sediment's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment.

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not 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 historical occurrences and geologic maps, cross-sections, geotechnical test data, geomorphology, and groundwater hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historic-high 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. CGS's qualitative relations among susceptibility, geologic map unit, and depth to groundwater are summarized in Table 1.2.

In the Brentwood Quadrangle, most Holocene materials in areas where ground-water levels are within 20 feet of the ground surface are highly susceptible to liquefaction. Such Holocene deposits include stream channel (**Qhc**), alluvium (**Qha**, **Qa**), alluvial fan (**Qhl**, **Qhf**, **Qhff**), and eolian dune sands (**Qds**). Where groundwater levels exceed 20 feet deep, the liquefaction susceptibility of units **Qds**, **Qha**, and **Qhl** is reduced to low due to an abrupt increase in unit density (**Qds**) or an increase in clay content (**Qhf** & **Qhl**) below 20 feet. Pleistocene and older deposits (**QPu**, **Qpf**) within the study area are characterized by a high relative density and thus a low susceptibility to liquefaction.

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 analysis (PSHA) model developed by USGS (Petersen and others, 2014; 2015) for the 2014 Update of the United States National Seismic Hazard Maps (NSHMs). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance probability level. CGS calculations incorporate additional programming that modifies probabilistic PGA by a scaling factor that is a function of magnitude at a post-PSHA step. Calculation of the scaling factor is based on binned magnitude-distance deaggregation and is weighted by the contribution of each earthquake-distance bin to the total shaking hazard. 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 LOP values are then used to calculate cyclic stress ratio (CSR), the seismic load imposed on a soil column at a particular site. A more detailed description of the development of ground shaking opportunity data and parameters used in liquefaction hazard zoning can be found in Section 3 of this report.

LIQUEFACTION ANALYSIS

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using an in-house developed computer program based on 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 pseudo PGA-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.

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 11,700 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 (11,700 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 Earthquake 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 Seismic Hazard Zones for liquefaction. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Brentwood Quadrangle.

Areas of Past Liquefaction

There is no documentation of historical surface liquefaction or paleoseismic liquefaction occurrences in the Brentwood Quadrangle.

Artificial Fills

Non-engineered fill placements are often composed of uncompacted, silty or sandy material and, therefore, are generally considered to have a high potential for liquefaction when saturated. No significant placements of non-engineered artificial fill were identified in the study area. Conversely, significant amounts of engineered artificial fill, which by definition are designed to resist liquefaction, have been used in the construction of river levees, detention basins, and elevated freeways within the Brentwood Quadrangle. In these areas, seismic hazard zonation for liquefaction does not depend on the fill, but on soil properties and groundwater levels in underlying strata.

Areas with Sufficient Existing Geotechnical Data

Most of the 770 logs evaluated for this study are from boreholes located within the Brentwood delta-alluvial plain. Collectively, the logs provide the level of subsurface information needed to conduct a regional assessment of liquefaction susceptibility with a reasonable level of certainty. Much of surface area of the delta-alluvial plain is covered by Holocene alluvium with a thickness generally greater than 40 feet, which CGS considers to be the maximum depth at which liquefaction can cause damaging ground failure at the surface.

Examination of geotechnical boring logs show that the Sacramento-San Joaquin Delta alluvial plain deposits consist of discontinuous layers of sand, gravel, silt and clay. Analysis of blow count values and other soil property measurements reported in the logs indicate that most of the boreholes penetrated one or more layers of liquefiable material where seismic stress ratio (CSR) is greater than the soils' seismic resistance ratio (CRR). Accordingly, all areas where the identified layers of liquefiable material are saturated within 40 feet of the surface are included in the Seismic Hazard Zone.

The boundary for the Seismic Hazard Zone is defined in part by the contact of Holocene deposits with bedrock and/or late Pleistocene deposits, and extends along base of the foothills that in the southwest and northwest corners of the quadrangle. Liquefaction analysis of boreholes logs in older Quaternary units and Tertiary bedrock units indicated a very low potential for liquefaction. For this reason, these units were not included in the Seismic Hazard Zone within the Brentwood Quadrangle.

Areas with Insufficient Existing Geotechnical Data

In areas with insufficient geotechnical data coverage, Quaternary sedimentary deposits were evaluated for seismic hazard zonation on the basis of geologic factors, groundwater levels, and extrapolation of known soil conditions in adjacent areas. Adequate geotechnical borehole information is lacking for the eastern parts of the Brentwood Quadrangle in areas covered by unincorporated county land. All of the geologic units mapped in the eastern side of the Brentwood Quadrangle extend into parts of the map area with sufficient borehole coverage to adequately assess the liquefaction susceptibility and lithologic character of the units. These units contain varying amounts of loose, granular materials that are saturated because of the presence of near-surface groundwater and proximity to delta channels. Those conditions, along with the ground motions expected to occur in the region, combine to form a sufficient basis for including these areas in the Seismic Hazard Zone for liquefaction.

ACKNOWLEDGMENTS

The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Arne Simonsen, Tamara Leach, Lynne Filson, and Harold Jirousky of Antioch City, Stephanie Butler of Brentwood City, Keith Coggins of Oakley City, Loren Turner of the CalTrans Laboratory, and Kenneth Haseman of California Department of Water Resources arranged access and assisted in retrieving geotechnical data from files maintained by their respective offices. At CGS, Wayne Haydon provided valuable insights on the Bedrock geology of the Brentwood Foothills and groundwater mapping oversight. Ante Mlinarevic facilitated meetings with DWR and DSOD. Terilee McGuire, Bob Moscovitz, Janine Bird, and Kate Thomas of CGS provided GIS operations and database support. Kate Thomas prepared the final Seismic Hazard Zone Map and Janine Bird prepared the graphic displays for this report. Tim McCrink and Mike Silva provided technical review for this report.

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SECTION 2: EVALUATION REPORT FOR EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

BRENTWOOD 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

by

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CALIFORNIA GEOLOGICAL SURVEY

INTRODUCTION

Purpose

The Seismic Hazards Mapping Act of 1990 (the Act) (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/documents/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/documents/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.usc.edu/resources/catalog/hazardmitigation.html.

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 II, summarizes seismic hazard zone mapping for earthquake-induced landslides in the Brentwood 7.5-minute Quadrangle. Section 1, which addresses liquefaction hazard, and Section 3, which addresses earthquake-shaking hazard, complete 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 Brentwood 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 shear-test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area. In areas with insufficient laboratory shear-test data, the Hoek-Brown failure criterion was utilized to estimate geologic material strength.
- Ground motion from the latest USGS probabilistic shaking map were calculated to characterize future earthquake shaking within the mapped area, also referred to as ground-shaking opportunity (see Section 3).

The data collected for this evaluation were processed into a series of geographic information system (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 Seismic Hazard Zone for earthquake-induced landslides 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.

Seismic Hazard Zone maps for earthquake-induced landslides 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 landslide hazard, 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 Brentwood Quadrangle, namely the physiographic, geologic and engineering geology conditions. Part II documents the data and parameters used to evaluate earthquake-induced landslide hazard and to delineate Seismic Hazard Zones for earthquake-induced landslides in the Brentwood Quadrangle.

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Brentwood quadrangle covers an area of approximately 152 square kilometers (59 square miles) in eastern Contra Costa County, California. The center of the quadrangle is about 78 square kilometers (30 miles) east by northeast of downtown Oakland. The quadrangle is at the western edge of the Sacramento-San Joaquin River Delta. Approximately 38 square kilometers (15 square miles) of the City of Brentwood occupies the west-central part of the quadrangle, the City of Oakley encompasses an area of approximately 28 square kilometers (~11 square miles)

along the northern margin of the map area, and a small section (approximately 4 square kilometers) of the City of Antioch is within the northwest corner of the map area. The remainder of the map area consists of unincorporated census-designated places such as Byron and Knightsen, and Contra Costa County and State of California land.

Topography

Approximately 15% of the map area is occupied by uplands of the foothills of the Diablo Range; which is part of the Coast Ranges Geomorphic Province. The axis of the Diablo Range is aligned roughly parallel to the northwest-trending Greenville Fault, which diagonally traverses the range to the west of the study area. The landscape of the uplands consists of parallel ridge and valley topography. The parallel ridges are west by northwest trending, moderately to steeply sloping, smooth to dissected, and separated by flat-floored alluvial valleys. These ridges occur as smooth hills and knolls in the southwest corner of the quadrangle, and as moderately sloping ridges, hills and knolls in the northwest quarter of the quadrangle

The remainder of the map area is occupied by flatlands of the northeast draining alluvial plain and dune fields located on the east side of the Diablo Range and on the western margin of the Sacramento-San Joaquin Delta. The Delta and alluvial plain are both within the Central Valley Geomorphic Province, with the Delta underling the far northeast corner of the quadrangle.

Upland watersheds and flatland streams drain eastward toward the San Joaquin Delta. Major streams in the southwestern uplands include: Deer Creek, Sand Creek and Dry Creek, all of which are tributary to northward flowing Marsh Creek; and the eastern flowing Kellogg Creek, which drains the uplands mostly to the south of the Brentwood Quadrangle.

Land Use

Land use in the Brentwood Quadrangle historically was dominated by agriculture in valley areas and cattle grazing in the surrounding hills. However, in the last several decades urban development has increased substantially in both Oakley and Brentwood, mainly as light industrial, shopping centers and home construction that continued to expand in both the flat land and low hills. Substantial areas of undeveloped, agricultural land remain on the valley floor in the eastern half of the quadrangle, and in the uplands of the John Marsh State park in the southwest corner of the quadrangle.

The primary transportation route in the study area is California State Route 4, which follows the southern and western quadrangle boundaries and connects the city of Brentwood with the cities of Antioch and Oakley. Additional access is provided by a network of paved city or county roads: the west-east tending, from north toward the south, Laurel Road, Lone Tree Way, Sand Creek Way, Balfour Road and Marsh Creek Road; and the north-south trending, from west to east, Jeffery Way, Brentwood Way, Walnut Boulevard and Byron Highway. There is also a network of private roads, fire roads and trails in undeveloped areas.

GEOLOGY

The primary source of 1:24,000-scale bedrock geologic mapping used in the slope stability evaluation of the Brentwood Quadrangle was the CGS unpublished preliminary geologic map digital database of the Stockton 30’ x 60’ Quadrangle (Dawson, 2010). The bedrock units in this geologic map were compiled from geologic mapping by Graymer and others (1994;1996). The

bedrock unit nomenclature that is used in this report parallels that adopted by CGS during the compilation of the Stockton 30' x 60' Quadrangle. Bedrock units are described in detail in this section. Surficial geologic units are briefly described here and are discussed in more detail in Section 1, of this report.

The digital geologic maps covering the Brentwood Quadrangle were combined to form a single, 1:24,000 scale, geologic materials map (summarized on Plate 2.1). CGS staff used DEMs, aerial photos, online imagery, and limited field reconnaissance to modify the Quaternary/bedrock boundary, confirm the location of geologic contacts, map recently modified ground surfaces, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units. Landslide deposits were deleted from the map so that the distribution of bedrock formations and the newly created landslide inventory would exist on separate layers for the hazard analysis. Young alluvial valleys were added or modified by CGS geologists in some areas to refine the map and ensure continuity of geologic mapping with adjacent quadrangles. Linear structural features such as folds, faults, and anticlines are not included in the geologic materials map. In addition, the relationship of the rock units to the development and abundance of landslides was noted. The distribution of bedrock deposits on the final geologic materials map was used in combination with other data, discussed below, to evaluate landslide susceptibility and develop the Seismic Hazard Zone Map for the Brentwood Quadrangle.

Bedrock Units

The bedrock geology of Contra Costa County has been divided by Graymer and others (1994) into six individual stratigraphic assemblages, each lying within a discrete, fault-bounded block. The concept of individual fault-bounded stratigraphic assemblages in the San Francisco Bay Area was introduced by Jones and Curtis (1991) and then defined further by Graymer and others (1994). These investigators believe that the individual stratigraphic assemblages originated in separate depositional basins or in different parts of large basins that were later juxtaposed by large offsets on strike-slip and dip-slip faults during Tertiary time.

In Contra Costa County, the oldest rocks exposed in the fault-bounded assemblages belong to two slightly to highly deformed Mesozoic rock complexes: the Jurassic Coast Range Ophiolite and overlying Cretaceous Great Valley Sequence, and the Jurassic to Cretaceous Franciscan Complex (Graymer and others, 1994). The Coast Range Ophiolite and Franciscan Complex are not exposed in the Brentwood quadrangle, but along with the Great Valley Sequence, underlie the younger units exposed in this study area. The Great Valley Sequence is exposed in the quadrangle and consists of a thick sequence of interbedded sandstone and shale originally deposited on the ocean floor by turbidity currents and subsequently folded, faulted and uplift (Graymer and others, 1994).

An angular unconformity forms the boundary between underlying Cretaceous Great Valley Sequence units and Tertiary marine strata (Graymer and others, 1994). The following is a summary of bedrock map units exposed in the Brentwood Quadrangle based on Graymer and others (1994) and Dawson (2010).

Assemblage VI

Assemblage VI underlies the entire Brentwood Quadrangle. Mesozoic and Tertiary rocks of this assemblage outcrop where they have not been buried beneath Quaternary sediments in the far southwest and northwest corners of the quadrangle (Plate 2.1). These rocks are expressed in

narrow to wide linear outcrops that strike parallel to, and in some areas, form linear ridges. They typically dip to the north or northeast and become younger to the northeast.

Mesozoic rock units cover about 25% of the uplands and consist of the Late Cretaceous Great Valley Sequence, divided into the following units, from south to north and oldest to youngest: Unit D (**Kd**); Unit D, interbeds (**Kds**); Unit E, Lower Member (**Kel**), Unit E, Lower Member, Interbeds (**Kels**); Unit E, Upper Member (**Keu**); and Deer Valley Sandstone (**Kdv**). Units **Kd**, **Kel** and **Kels**, and the Deer Valley Sandstone (**Kdv**), typically form moderate to steep sided and often asymmetrical ridges. These ridges are steeper and often planar and smooth, on the south facing anti-dip slopes, with the dip slope side of the ridges often dissected into spur ridges that are less steep. Generally, the Mesozoic units form a greater proportion of steeper slopes than the Tertiary units. The Great Valley Sequence unit **Keu** tends to form unalluviated, bedrock valley floors, and adjacent small short knolls.

Unit D of the Great Valley Sequence is divided into a sandstone unit (**Kd**) and interbedded shale member (**Kds**). The sandstone unit occurs as thick packages (up to 10 meters) of medium to coarse grained, light gray, clean sandstone with 1 to 2 meters of interbedded siltstone and mudstone. Grains include quartz, feldspar, and biotite. Spherical weathering is common. In places, the clean sandstone is interbedded with fine to medium grained, biotite and muscovite bearing wacke with mudstone rip-up clasts. The shale member occurs in two distinct layers, one being a brown to gray, micaceous mudstone and brown micaceous siltstone and the other a dark gray-brown to dark gray, massive, foraminifera-rich, siliceous mudstone.

Unit E of the Great Valley Sequence occurs as a series of low relief hills on the north side of Briones valley and east side of Marsh Creek. It is divided into a lower member (**Kel**), lower member, interbeds (**Kels**), and an upper member (**Keu**). The lower member is a light gray to gray brown, foraminifera-bearing siltstone and mudstone. The lower member interbeds consist of coarse grained, clean white, fossiliferous, lithic sandstone with frequent iron concretions. Grains in the lower member interbeds include quartz, feldspar, and black lithic grains. Unit E upper member consists of light gray siltstone, interbedded with medium to coarse grained, clean, white and orange, lithic sandstone with many large (as much as 50 cm diameter) iron concretions, and weathers to light orange.

The Late Cretaceous Deer Valley Sandstone (**Kdv**) overlies unit **Keu** and is exposed on a ridge on the north side of Briones Valley and on the east side of the Marsh Creek Reservoir. The Deer Valley sandstone consists of fine- to medium-grained, white to gray, biotite-bearing arkosic sandstone and minor pebbly, cobbly conglomerate. Thin beds of metamorphic and igneous pebbles and layers of thick shelled mollusks are common in the formation. Locally, calcareous sandstone concretions as large as 3 meters in diameter weather as bare, resistant knobs. The Deer Valley Sandstone attains a maximum unit thickness of 240 meters near Kellogg Creek.

Tertiary rocks cover about 75% of the uplands and consist of the following units, from south to north and oldest to youngest: Meganos Formation, Lower Member (**Pema**); Meganos Formation, Shale Member (**Pemc**); Meganos Formation, Sandstone Member (**Pemd**); Meganos Formation, Upper Member (**Peme**); Domingene Formation (**Ed**); Nortonville Shale (**Env**); Neroly Sandstone (**Mnr**); Tulare Formation (**Pth**); Markley Formation (**Emk**); and Markley Formation, Lower member (**Emkl**). The Meganos Formation units **Pema**, **Pemc**, the Nortonville Shale unit **Env**, the Tulare Formation **Pth**, and the Markley Formation unit **Emkl**, tend to form lower slopes of ridges and small short knolls and adjacent unalluviated bedrock valley floors. The Domingene Formation (**Ed**), Neroly Sandstone (**Mnr**), Tehama/Tulare Formation (**Pth**), and

Markley Formation unit **Emkl**, form low, gently sloping rounded ridges and adjacent unalluviated, bedrock valley floors. The Meganos Formation unit **Peme** forms moderately sloping ridges, and the Meganos Formation unit **Pemd** forms sharp crested ridgelines.

The Paleocene Meganos Formation unconformably overlies Great Valley Sequence units in the Brentwood Quadrangle. This formation is divided into a sandstone with basal conglomerate (**Pema**), shale with sandstone interbeds (**Pemc**), sandstone (**Pemd**), and siltstone and silty mudstone (**Peme**). The sandstone with basal conglomerate consists of medium- to coarse-grained, clean, white, distinctly cross bedded, biotite bearing arkosic sandstone. The basal conglomerate locally contains pebbles and blocks composed of white vein quartz, quartzite, chert, limestone, and large angular slabs of sandstone. The shale with sandstone interbeds member occurs as a dark bluish-gray shale with abundant calcite nodules and lenses interbedded with layers of fine to coarse sandstone comprised chiefly of quartz and mica grains with some clay lenses. This member has fairly distinct to indistinct beds, often breaks down into small fragments where mapped as shale, and forms grit and weathers on the surface to rusty brown where mapped as sandstone. The sandstone member is light gray to bluish-gray micaceous sandstone with carbonaceous laminates and a local basal pebble conglomerate. This member is thin bedded to massive and contains nearly 100 feet of cross-bedded eolian sandstone near its top. Locally, the sandstone member contains lenses of calcareous and fossiliferous sandstones. The siltstone and silty mudstone member consists of Greenish-gray to light gray, biotite-rich siltstone and silty mudstone, with abundant plant debris in places.

The four Eocene aged units mapped within the Brentwood Quadrangle are the Eocene Domingene formation (**Ed**); the Nortonville Shale (**Env**); the Markley Formation (**Emk**); and the Markley Formation lower member (**Emkl**). The Domingene Formation overlies and is in fault contact with the Paleocene Meganos Formation. This formation occurs primarily as a light colored, fine- to coarse-grained quartzose sandstone. Locally, the Domingene Formation includes conglomerate with pebbles of quartz, chert, and andesite near base of unit, as well as thin beds of shale. Directly overlying the Domingene formation is the Nortonville shale (**Env**) which is best exposed in the walls of the open-pit Byron Mine near the southern boundary of the quadrangle. The Nortonville shale consists of brown to grayish-green marine mudstone and claystone with minor siltstone and thin beds of fine-grained, quartz-lithic, glauconitic sandstone. sandstone. The Markley Formation (**Emk**) and Markley Formation lower member (**Emkl**) overlie the Nortonville shale. These units consist of white to light-gray quartz-muscovite and quartz lithic sandstone and siltstone (**Emk**) and brownish gray silty shale (**Emkl**). Most areas previously mapped as the Markley Formation lower member have been subjected to extensive grading and development and minimal topographic relief of the member remains.

The Miocene Neroly Sandstone (**Mnr**) overlies the Markley Formation and is only exposed in the map area along a few road cuts on Vasco Road near the Brentwood Quadrangle south-central boundary. This formation consists of blue to blue-gray, fine to coarse-grained, volcanic-rich, shallow marine sandstone, with minor siltstone, shale, tuff and andesite-pebble conglomerate.

The Pliocene Tehama Formation (**Pth**) is the youngest non-Quaternary unit in the map area and it is exposed along the south-central and northwestern Brentwood Quadrangle boundaries. It is a poorly consolidated, non-marine, gray to maroon siltstone, quartz arenite sandstone, tuff, and weakly indurated pebble to cobble conglomerate.

Quaternary Sedimentary Deposits

The flatlands of the Brentwood Quadrangle are covered by Quaternary alluvial sediments and eolian dunes. The alluvial materials were eroded from surrounding hills, then transported and deposited into the inter-ridge valleys and delta-alluvial plains. The Quaternary units in the Brentwood Quadrangle include: late Pliocene and early Pleistocene sandstone, siltstone, and gravel (**QPu**) forming low knolls and high terranes along the southwestern plain margin; latest Pleistocene Alluvial fan deposits (**Qpf**); Holocene alluvial fan deposits (**Qhf**), alluvial fan levee deposits (**Qhl**), and alluvial fan deposits, fine facies (**Qhff**) forming the inter-ridge valleys floor and extending across the plain; Latest Pleistocene to Holocene dune sand (**Qds**) forming a continuous gently rolling dune field in the northwest corner of the quadrangle and isolated low hills and knolls across the northeast corner of the quadrangle; undifferentiated Pleistocene to Holocene alluvium (**Qa**); undifferentiated Holocene alluvial deposits (**Qha**); and late Holocene (modern) channel deposits (**Qhc**) (see Section 1 and Plate 1.1 for descriptions and distribution of Quaternary units).

Geologic Structure

The structural geology of the bedrock uplands of the Brentwood Quadrangle is governed by the geologic processes that created Mount Diablo. This area falls within in a tectonically active region associated with movement of the Mendocino Triple Junction along the boundary of the Pacific and North American plates. The Mendocino Triple Junction passed the latitude of Mount Diablo about 10 million years ago, generating a change from a convergent to a strike slip plate boundary margin. The two plates are currently moving past each other in a right lateral sense at the rate of about 4.8 centimeters per year (Petersen and others, 1996).

In the San Francisco Bay area currently about three-fourths of relative plate movement is accommodated by shearing that is distributed across a broad, complex belt marked by major northwest-trending faults, including the San Andreas, Hayward, and Calaveras, along with many parallel secondary faults such as the Greenville, Green Valley, and San Ramon-Concord. Differential strike-slip movement among these faults locally generates thrust faulting, folding, and related structures throughout this tectonic belt. The current transpressional tectonic regime is characterized by horizontal northeast-southwest maximum compression, which has uplifted Mount Diablo and folded the surrounding rocks over the last 4 million years into the Mount Diablo Anticline; an asymmetric, doubly plunging, southwest-vergent, fault-propagation fold in a restraining stepover between the dextral Greenville and Concord faults, both of which are strike-slip faults of the San Andreas Fault System (Schemmann and others, 2007).

The northwest-southeast trending axis of the Mount Diablo Anticline passes through the core of Mount Diablo and toward the southeast passing about 5 miles to the southwest of the southwest corner of the Brentwood quadrangle. As such, the uplands of the Brentwood Quadrangle are on the northeast flank of the Mount Diablo anticline, a relatively simple northeast-dipping homocline that exposes Cretaceous and Tertiary strata with bedding dips ranging from 20 to 70 degrees, the majority being about 45 degrees (Unruh and others, 2007). In the Brentwood quadrangle, the geologic units typically strike to the west-northwest, northwest and rarely to the west-southwest, with north, northeast or rarely north-northwest dips typically ranging from up to about 40 degrees in the oldest units in the southwest and decreasing in the increasingly younger units toward the northeast to as low as about 12 degrees.

A number of faults cross the Brentwood Quadrangle. The Antioch Fault crosses the western boundary of the southwest quarter of the quadrangle at Dry Creek, from the adjacent-to-the-west Antioch South Quadrangle. The Antioch Fault is mapped as extending only about 0.2 miles into the quadrangle, is Quaternary aged (<2.6 my), and is well constrained where in bedrock and inferred in alluvium (Bryant and Cluett, 2002). This fault appears to extend to the south crossing Briones Valley just west of the Marsh Creek Reservoir where it is mapped as pre-Quaternary aged (Dawson, 2010; Graymer, et al, 1994). The north-south trending Sherman Island Fault and Midland Fault Zone are mapped as crossing bedrock and alluvium in the west half and southeast corner, respectively, of the Brentwood Quadrangle (Bryant and Cluett, 2002; Dawson, 2010; Schemmann and others, 2007). These faults are mapped as pre-Quaternary aged and are well constrained where in bedrock and inferred in alluvium. Several other unnamed, north-south trending, apparently pre-Quaternary aged faults are mapped crossing the bedrock in the southwest corner of the quadrangle (Bryant and Cluett, 2002; Dawson, 2010; Graymer, et al, 1994). No active faults are mapped in the Brentwood Quadrangle by the California Geological Survey under the Alquist-Priolo Earthquake Fault Zoning Act.

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the Brentwood Quadrangle has been prepared through field reconnaissance, a review of previously published landslide mapping, but primarily interpreted from geomorphic analyses of digital stereo imagery employing a GIS-based softcopy photogrammetric system (listed as “Air Photos” in the Reference section). 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. Landslide mapping was not conducted in areas of the uplands where extensive grading was conducted prior to imagery capture, as this grading likely removed the geomorphic evidence of slope instability.

Landslides were mapped at a scale of 1:24,000. For each landslide included on the map, a number of characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable and questionable) and other properties, such as activity, thickness, and associated geologic unit(s). Landslides rated as definite and probable were carried into the landslide zone as described later in this report. Landslides rated as questionable were not carried into the zone map. The completed landslide map was digitized and the attributes were entered into a database. A small-scale version of this landslide inventory is included on Plate 2.1.

Only 26 landslides were identified in the landslide inventory of the uplands of the Brentwood Quadrangle. The distribution and density of landslides mapped in the quadrangle (Plate 2.1) differ among the different geologic units, mainly as a function of areal distribution of various rock types along with variations in rock strength, topography, and structure. Eleven landslides were identified in three of the six Great Valley Sequence units: one landslide in the Unit D-sandstone (**Kd**), five landslides in the Unit E-Siltstone and mudstone, Lower Member (**Kel**); and five landslides in the Deer Valley Sandstone (**Kdv**). Fifteen landslides were identified in five of the twelve Tertiary units: the Meganos Formation units **Pema**, **Pemc** and **Peme**; the Domingene Formation (**Ed**); and the Markley Formation unit **Emk**. Significant portions of the uplands underlain by the Tertiary units have been graded and landslides were not mapped in these areas. Therefore, landslide distribution may be underrepresented in the Tertiary units.

In the Mesozoic and Tertiary units, landslides occur on moderate to steep, dip and strike slopes and are categorized as small to moderately sized earthflows, rock slides and debris slides. In the Tertiary units the mapping identified a greater proportion of dormant rockslides with deep slide planes, a few landslides on anti-dip slopes and a debris flow. In the Mesozoic units the majority of landslides were mapped as shallow historic earthflows and debris slides, with the balance of the landslides mapped as dormant young moderately deep earthflows or as dormant mature deep rockslides. As the dip of strata generally exceeds the slope inclination the dip slope, landslides do not appear to be dip slope failures but rather a primary controlling factor seems to be steep slopes. Additionally, nearly three quarters (19 of 26) of the landslides were mapped as within 300 meters of faults mapped in Dawson (2010) and Graymer, et al, (1994); which suggests faulting may have played a role in slope failures in this area.

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

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above were grouped on the basis of their shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. Shear-strength data for the units identified on the Brentwood Quadrangle geologic map were obtained from the City of Brentwood and City of Oakley (see Appendix A). Shear tests from the adjoining Antioch South, Byron Hot Springs, and nearby Clifton Court Forebay quadrangles were acquired from the City of Antioch, CalTrans, and the Department of Water Resources and used to augment data for several geologic formations for which little shear test information was available within the Brentwood Quadrangle. For geologic units where sufficient shear-strength laboratory data could not be acquired, we applied the Hoek-Brown Failure Criterion (Hoek and others, 2002) to estimate the overall geologic unit strength.

The non-linear Hoek-Brown criterion is a rock mass characterization method which uses equations to relate rock mass classification through a Geological Strength Index (GSI) to the angle of internal friction of a rock mass. This method allows strength assessment based on collected data, mainly discontinuity density, discontinuity condition, and geologic material properties (Hoek and others, 2002; Marinos and others, 2007). The locations of rock and soil samples taken for shear testing and Hoek-Brown data collection locations within the Brentwood Quadrangle are shown on Plate 2.1.

Shear-strength data gathered from the above sources were compiled and averaged for each geologic map unit. Geologic units were grouped according to average angle of internal friction (average phi) and lithologic character. Average (mean or median) phi values for each geologic map unit and corresponding strength groups are summarized in Table 2.1. The average angle of internal friction for each geologic strength group were assigned to the units within that group and used in our slope stability analysis (Table 2.2). A geologic material strength map that provides spatial representation of material strength for use in slope stability analysis was developed based on groupings presented in Tables 2.1 and 2.2.

Table 2.1. Summary of the shear strength statistics for the Brentwood Quadrangle.

BRENTWOOD QUADRANGLE							
SHEAR STRENGTH DATA SUMMARY							
	Formation Name	Number of Tests	Mean/Median Phi (deg)	Mean/Median Group Phi (deg)	Mean/Median Group C (psf)	No Data: Similar Lithology - (Group Phi Used in Analysis)	Phi Values Used in Analysis
GROUP 1	Pema	2	35/35	34/34	117/150		34
	Mnr	18	34/34				
	Ed	3	34/34				
GROUP 2	Qds	5	34/37	32/33	251/84	Kels	32
	Pemd	5	32/32				
	Kdv	1	32/32				
	Kd	10	31/31				
GROUP 3	Qpf	4	29/29	29/28	896/580	Keu	28
	Pth	35	29/29				
	QPu	2	26/26				
GROUP 4	Qh	17	25/25	24/25	697/450	af, Qa, Peme, Kel, Kds	24
	afbm	2	24/24				
	Emk	12	23/25				
GROUP 5	Emsu	2	18/18	18/18	516/516	Env	18
	Pemc	1	18/18				
Formation name abbreviations from Dawson (2010)							

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 Seismic Hazard Zone for earthquake-induced landslides. 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 typically collect and compile shear strength data considered representative of existing landslides within the quadrangle if available. 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, strength parameters applicable to existing landslide planes were not available in or around the Brentwood Quadrangle, so the strength parameters for existing landslides is not included in Table 2.1.

Table 2.2. Summary of shear strength groups for the Brentwood Quadrangle.

SHEAR STRENGTH GROUPS FOR THE BRENTWOOD QUADRANGLE				
GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**	**GROUP 5**
Ed **Mnr** **Pema**	**Qds** **Pemd** **Kdv** **Kd** **Kels**	**Qpf** **QPu** **Pth** **Keu**	**af** **afbm** **Qa** **Qh** **Emk** **Peme** **Kel** **Kds**	**Emsu** **Env** **Pemc**

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 latest USGS probabilistic seismic hazard analysis (PSHA) model, 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 2010 DEM was obtained from Contra Costa County (http://www.co.contra-costa.ca.us/1827/Web-GIS) for the Brentwood Quadrangle. This terrain data presents point spacing of 3 meters and elevations at 1-meter horizontal accuracy and 15-cm RMSE vertical accuracy. A slope gradient map was derived from the DEM using a third-order, finite-difference, center-weighted algorithm after 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 USGS probabilistic seismic hazard analysis (PSHA) model for the 2014 Update of the United States National Seismic Hazard Maps (NSHM) (Petersen and others, 2014; 2015). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance level. Raster versions of the PSHA PGA and Modal Magnitude maps for the Brentwood Quadrangle were calculated from the statewide model and applied in the Newmark displacement calculations, as described below. A more detailed description of the development of the ground shaking opportunity data and parameters used in the preparation of the Seismic Hazard Zone for earthquake-induced landslides can be found in Section 3 of this report.

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

Earthquake-induced landslide hazard potential is derived by combining the material strength and slope maps 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 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 was 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

Seismic Hazard Zones for earthquake-induced landslides were delineated using criteria adopted by the California State Mining and Geology Board (CGS, 2004). Under these criteria, these 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 Seismic Hazard Zones. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Brentwood 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 Seismic Hazard Zone.

Hazard Potential Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), the Seismic Hazard Zone for earthquake-induced landslides encompasses 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 1 square kilometer (.38 square miles) of the study area lying within the earthquake-induced landslide Seismic Hazard Zone for the Brentwood Quadrangle.

ACKNOWLEDGMENTS

The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Arne Simonsen, Tamara Leach, Lynne Filson, and Harold Jirousky of Antioch City, Stephanie Butler of Brentwood City, Keith Coggins of Oakley City, Loren Turner of the CalTrans Laboratory, and Kenneth Haseman of California Department of Water Resources arranged access and assisted in retrieving geotechnical data from files maintained by their respective offices. At CGS, Florante Perez provided guidance during landslide displacement calculations. Ante Mlinarevic facilitated meetings with DWR and DSOD. Terilee McGuire, Bob Moscovitz, Janine Bird, and Kate Thomas of CGS provided GIS operations and database support. Kate Thomas prepared the final Seismic Hazard Zone Map and Janine Bird prepared the graphic displays for this report. Tim McCrink and Mike Silva provided technical review for this report.

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Air Photos and Imagery

Google Earth Pro DigitalGlobe, 1-m resolution, 2006, covering Brentwood Quadrangle.

North West Geomatics Ltd. and Fugro Earthdata, Inc., 2005, digital stereo imagery flown for the USDA National Agriculture Imagery Program (NAIP); Image Lines L106131823 and L106131840 flown 6/13/2005; approximate ground sample distance (GSD; aka pixel dimension) 0.81 to 0.87 meters.

Lidar DEM, 3-m resolution, 2010, covering Contra Costa County (http://www.co.contra-costa.ca.us/1827/Web-GIS) for the Brentwood Quadrangle. Lidar flight company not published. Approximate ground point spacing distance 3 meters, and elevations at 1-meter horizontal accuracy, and 15cm RMSE vertical accuracy.

APPENDIX A: SOURCES OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City of Brentwood	18
City of Oakley	5
Hoek Brown Data Collection	3
Antioch South Quadrangle	54
Byron Hot Springs Quadrangle	6
Clifton Court Forebay Quadrangle	23
Total Number of Shear Tests	109

SECTION 3: GROUND SHAKING ASSESSMENT

for the

BRENTWOOD 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

using the

2014 Probabilistic Seismic Hazard Assessment Model

by

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/documents/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/documents/sp117.pdf.

This section of the evaluation report summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Site-specific ground motions can be calculated using U.S. Geological Survey (USGS) Unified Hazard Tool available online at: https://earthquake.usgs.gov/hazards/interactive/.

This section and Sections 1 and 2, which address liquefaction and earthquake-induced landslide hazards, respectively, 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 website: http://conservation.ca.gov/CGS/shzp.

PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL

Probabilistic ground motions are calculated using the USGS probabilistic seismic hazard analysis (PSHA) model for the 2014 Update of the United States National Seismic Hazard Maps (NSHM) (Petersen and others, 2014; 2015). This model replaces ground-motion models of Petersen and others (2008), Frankel and others (2002), Cao and others (2003), and Petersen and others (1996) used in previous official Seismic Hazard Zone maps. Like previous models, the 2014 USGS PSHA model utilizes the best available science, models and data, and is the product of an extensive effort to obtain consensus within the scientific and engineering communities regarding earthquake sources and ground motions. In California, two earthquake source models control ground motion hazards, namely version three of the Uniform California Earthquake Rupture Forecast Model (UCERF3) (Field and others, 2013; 2014) and the Cascadia Subduction Zone model (Frankel and others, 2014). For shallow crustal earthquakes, ground motions are calculated using the Next Generation Attenuation Relations for Western U.S. (NGA-West2) developed from a Pacific Earthquake Engineering Research Center ground motion research project (Bozorgnia and others, 2014). The NGA-West2 includes five ground motion attenuation equations (GMPEs): Abrahamson and others (2014), Boore and others (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014), and Idriss (2014). For subduction zone earthquakes and earthquakes of other deep sources, GMPEs developed specifically for such sources are used, including Atkinson and Boore (2003) global model, Zhao and others (2006), Atkinson and Macias (2009), and BC Hydro (Addo and others, 2012).

In PSHA, ground motion hazards from potential earthquakes of all magnitudes and distances on all potential seismic sources are integrated. GMPEs are used to calculate shaking level from each earthquake based on earthquake magnitude, rupture distance, type of fault rupture (strike-slip, reverse, normal, or subduction), and other parameters such as time-average shear-wave velocity in the upper 30 m beneath a site (V_{S30}). In previous applications, a uniform firm-rock site condition was assumed in PSHA calculation and, in a separate post-PSHA step, National Earthquake Hazard Reduction Program (NEHRP) amplification factors were applied to adjust all sites to a uniform alluvial soil condition to approximately account for the effect of site condition on ground motion amplitude. In the current application, site effect is directly incorporated in PSHA via GMPE scaling. Specifically, V_{S30} is built into GMPEs as one of the repressors and, therefore, it is an input parameter in PSHA calculation. V_{S30} value at each grid point is assigned based on a geology and topography based V_{S30} map for California developed by Wills and others (2015). The statewide V_{S30} map consists of fifteen V_{S30} groups with group mean V_{S30} value ranging from 176 m/s to 733 m/s. It is to be noted that these values are not determined from site-specific velocity data. Some group values have considerable uncertainties as indicated by a coefficient of variation ranging from 11% in Quaternary (Pleistocene) sand deposits to 55% in crystalline rocks.

For zoning purpose, ground motions are calculated at each grid point of a 0.005-degree grid (approximately 500-m spacing) that adequately covers the entire quadrangle. V_{S30} map and grid points in the Brentwood Quadrangle are depicted in Plate 3.1. For site investigations, it is strongly recommended that V_{S30} be determined from site-specific shear wave velocity profile data.

PSHA provides more comprehensive characterizations of ground motion hazards compared to traditional scenario-based analysis by integrating hazards from all earthquakes above a certain magnitude threshold. However, many applications of seismic hazard analyses, including

liquefaction and induced landslide hazard mapping analyses, still rely on scenario earthquakes or some aspects of scenario earthquakes. Deaggregation enables identification of the most significant scenario or scenarios in terms of magnitude and distance pair. Deaggregation is often performed for a particular site, a chosen ground motion parameter (such as peak ground acceleration or PGA), and a predefined exceedance probability level (i.e., hazard level). Like in previous regulatory zone maps, ground motion hazard level for liquefaction and landslide hazard zoning is 10% exceedance probability in 50 years or 475-year return period.

Probabilistic ground motion calculation and hazard deaggregation are performed using a new USGS hazard codebase, nshmp-haz version 1.0.0, a Java library developed in support of the USGS NSHM project. The Java code library is hosted in GitHub and is publically available at: https://github.com/usgs/nshmp-haz/releases/tag/v1.0.0). It is also the codebase that support USGS web-based site-specific ground motions calculator, the Unified Hazard Tool (https://earthquake.usgs.gov/hazards/interactive/). The source model used for the published 2014 NSHMs is adopted in its entirety. The 2014 source model is also hosted in GitHub and publically available at: https://github.com/usgs/nshmp-model-cous-2014/.

APPLICATION TO LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENT

The current CGS liquefaction hazard analysis approach requires PGA be scaled by an earthquake magnitude weighting factor (MWF) to incorporate a magnitude-correlated duration effect (California Geological Survey, 2004; 2008). The MWF-scaled PGA is referred to as pseudo-PGA and is used as Liquefaction Opportunity (see Section 1 of this report). MWF calculation is straight forward for a scenario earthquake. In PSHA, however, earthquakes of different magnitudes and distances contribute differently to the total hazard at a chosen probabilistic PGA level. The CGS approach to MWF calculation is based on binned magnitude-distance deaggregation. An MWF is calculated for each magnitude-distance bin and is weighted by the contribution of that magnitude-distance bin to the total hazard. The total MWF is the sum of probabilistic hazard-weighted MWFs from all magnitude-distance bins. 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 PGA, 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).

The current CGS landslide hazard analysis approach requires the probabilistic PGA and a predominant earthquake magnitude 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. The predominant earthquake magnitude is chosen to be the modal magnitude from deaggregation.

Pseudo-PGA and probabilistic PGA at grid points are depicted in Plates 3.2 and 3.3, respectively. Modal magnitude is depicted in Plate 3.4. The values of PGA and pseudo-PGA generally increase from northeast corner of the quadrangle to southwest corner. Ground motion hazards in the Brentwood Quadrangle are controlled by the Greenville Fault Zone in the southern and central parts of the quadrangle and by the Great Valley Fault in the northern part. Other fault sources that contribute to ground motion hazards include the Calaveras Fault, Hayward Fault,

Concord Fault, San Andreas Fault, Mount Diablo thrust fault, and Clayton Fault. Background (gridded) seismicity contributes significantly to ground motion hazards, particularly in the northern part of the quadrangle. Modal magnitude generally reflects the magnitudes of earthquakes that these contributing seismic sources are capable of producing. Ground motion distribution also is affected by subsurface geology. In general, expected PGA is higher where there are softer Quaternary sediments (lower V_{S30} values) and lower where there are harder Tertiary and Cretaceous rocks (higher V_{S30} values). The table below summarizes ranges of PGA, pseudo PGA, modal magnitude, and V_{S30} values expected in the quadrangle.

PGA (g)	Pseudo-PGA (g)	Modal Magnitude	V_{S30} (m/s)
0.37 to 0.49	0.24 to 0.34	6.1 to 7.1	228 to 503

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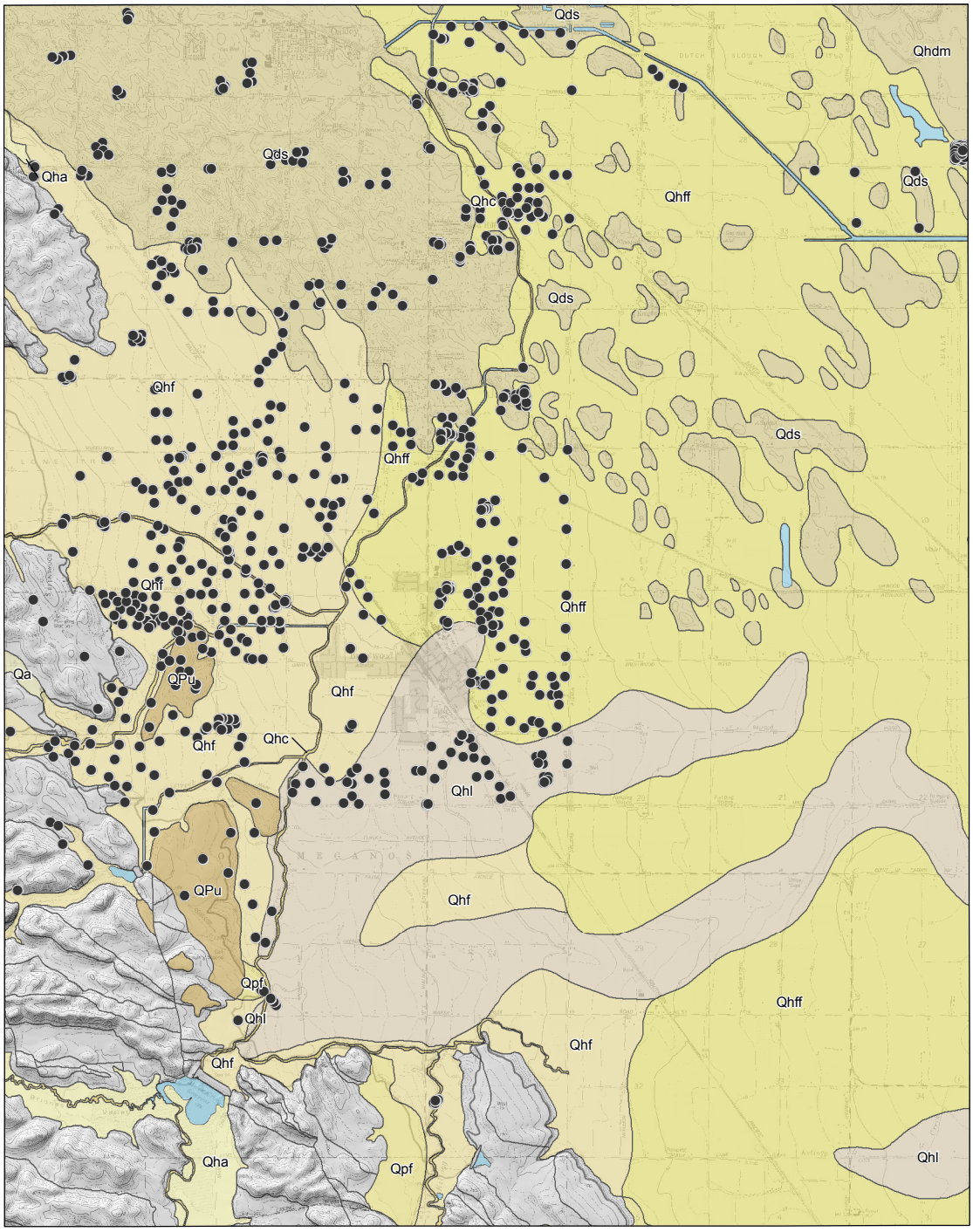


Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

N

1 0.5 0 1 2 Miles

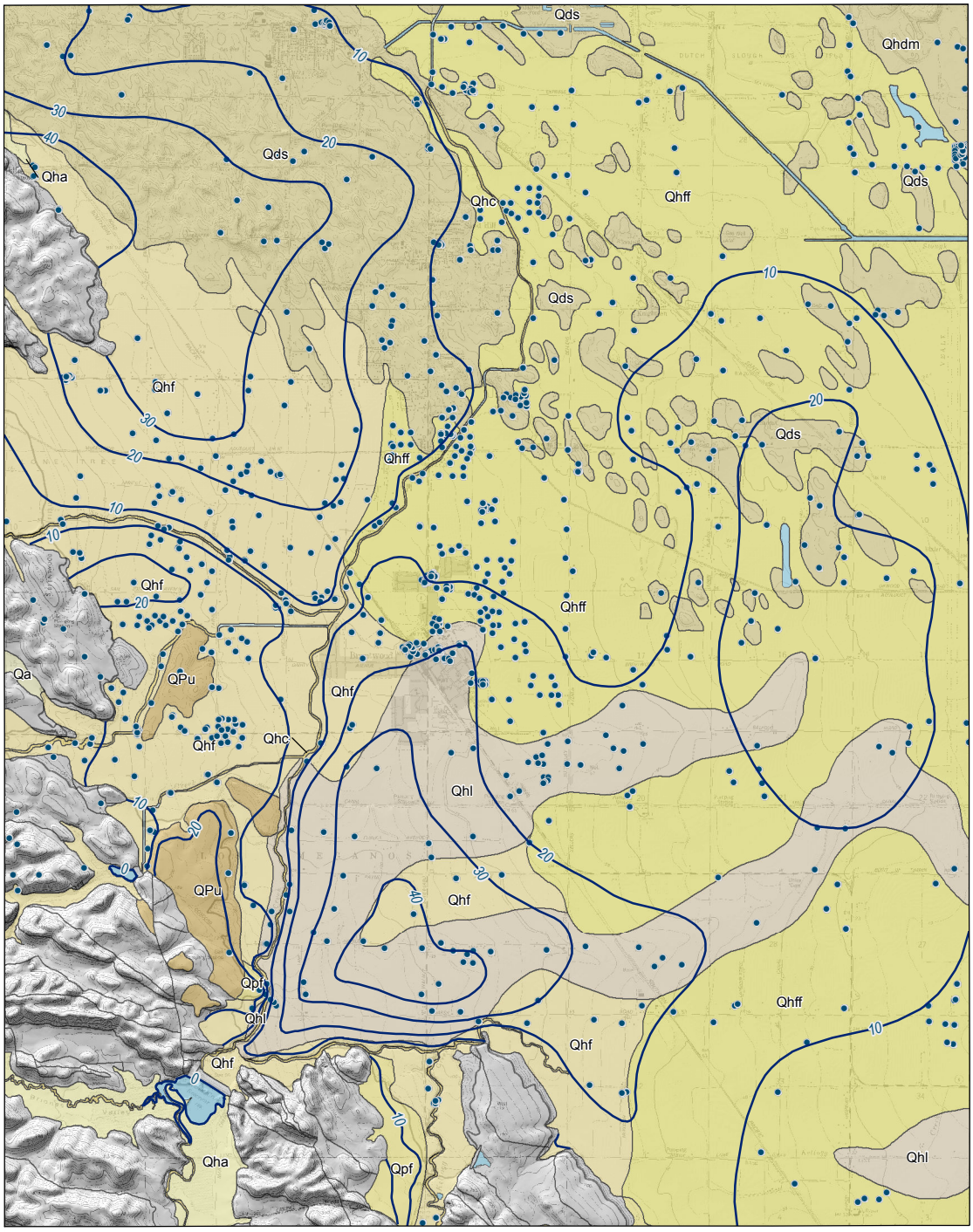
5,000 2,500 0 5,000 10,000 Feet

1 0.5 0 1 2 Kilometers

See "Geology" in Section 1 of report for descriptions of units.
Pre-Quaternary bedrock units shown without color.

● Geotechnical boring used in liquefaction evaluation

Plate 1.1 Quaternary Geologic Materials Map and Locations of Boreholes Used in Evaluating Liquefaction Hazard, Brentwood Quadrangle, California.



Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

N

1 0.5 0 1 2 Miles

5,000 2,500 0 5,000 10,000 Feet

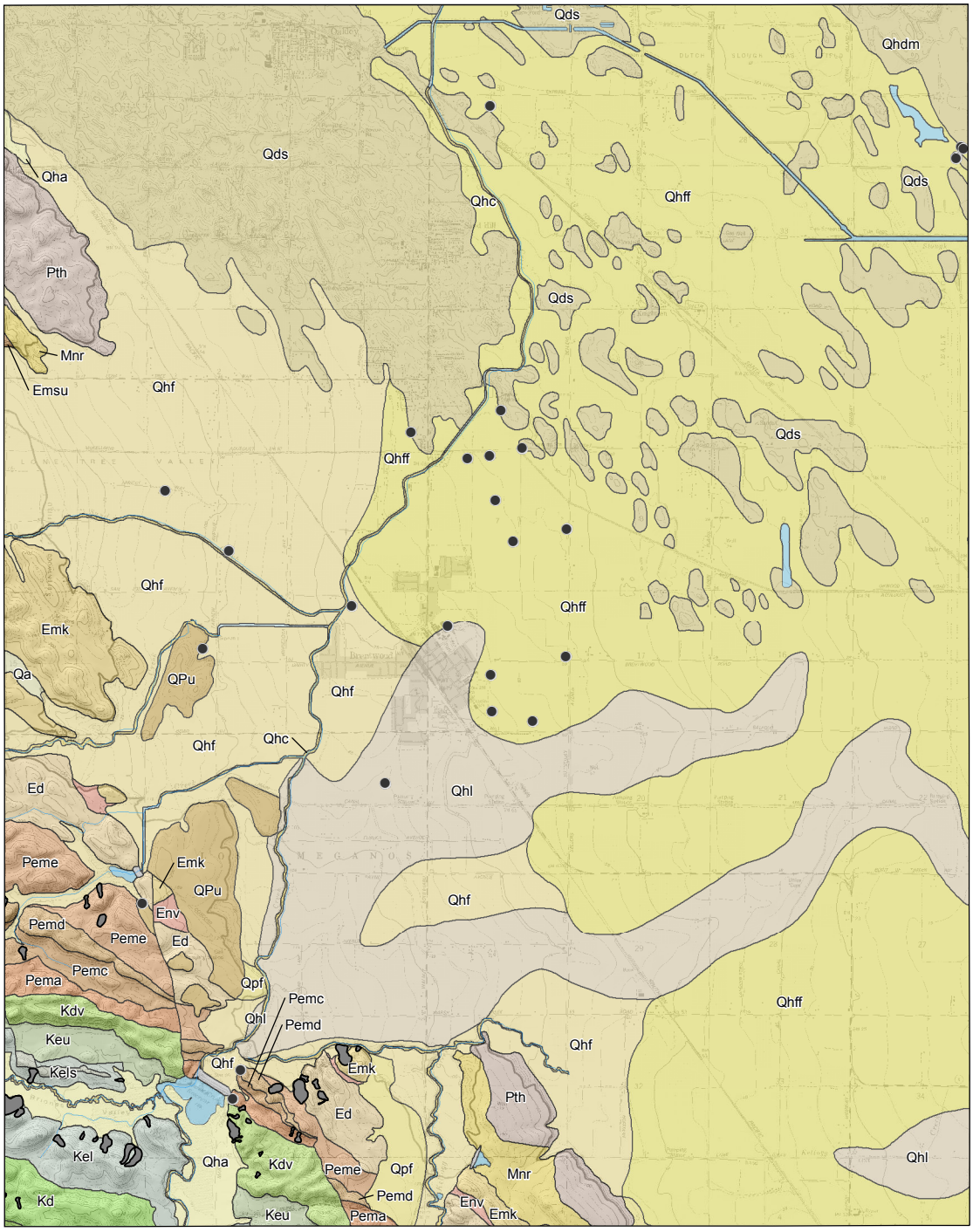
1 0.5 0 1 2 Kilometers

See "Geology" in Section 1 of report for descriptions of units.
Pre-Quaternary bedrock units shown without color.

• Groundwater measurement location

—10— Depth to groundwater (in feet)

Plate 1.2 Depth to Historic-High Groundwater levels in Quaternary Alluvial Deposits and Groundwater Measurement Locations, Brentwood Quadrangle, California.



Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

N

1 0.5 0 1 2 Miles

5,000 2,500 0 5,000 10,000 Feet

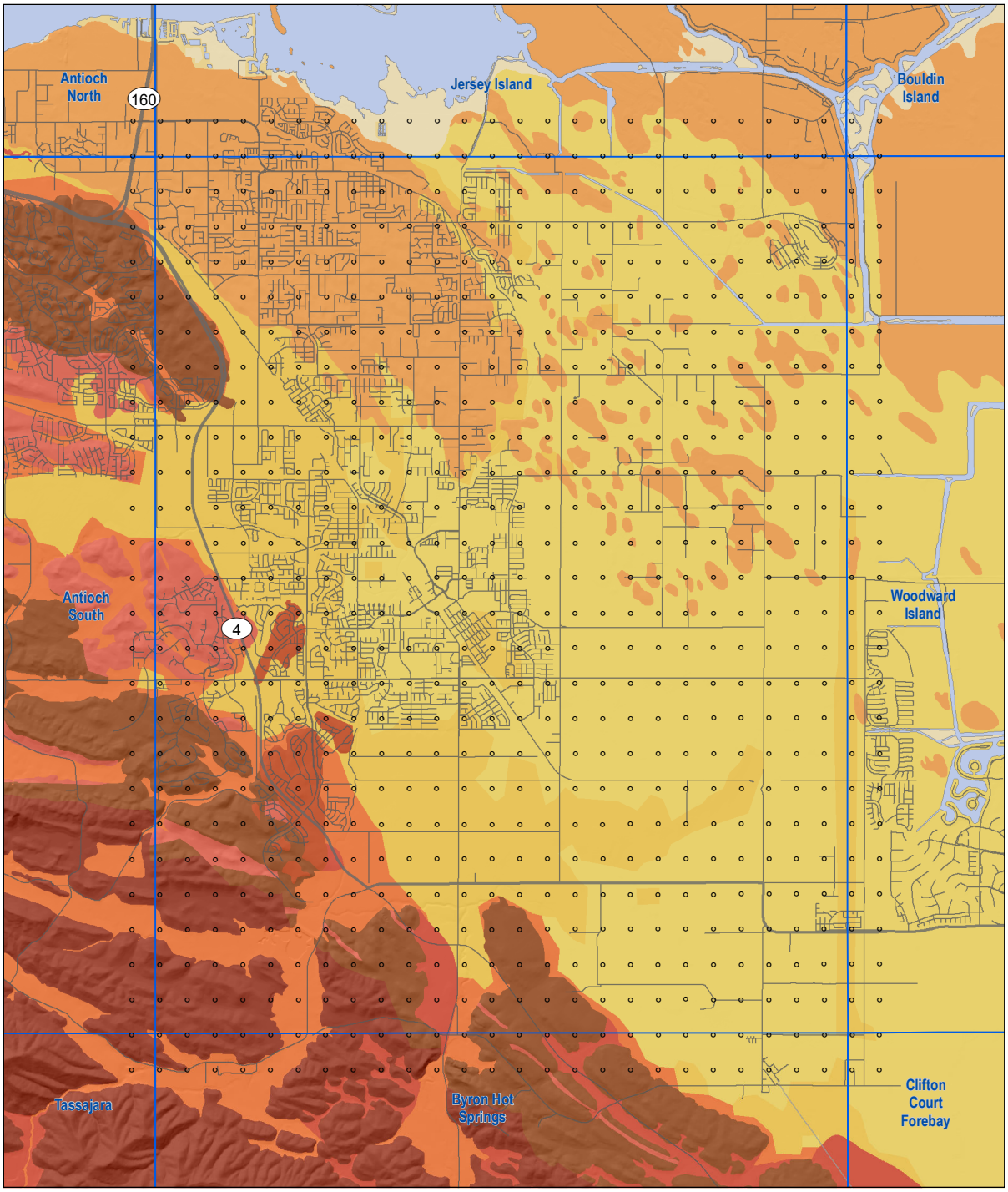
1 0.5 0 1 2 Kilometers

See "Geology" in Section 2 of report for descriptions of units.

Shear test sample location

Landslide

Plate 2.1 Geologic Materials and Landslide Inventory Map with Locations of Shear Test Samples Used in Evaluating Landslide Hazard, Brentwood Quadrangle, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

N

1 0.5 0 1 2 Miles

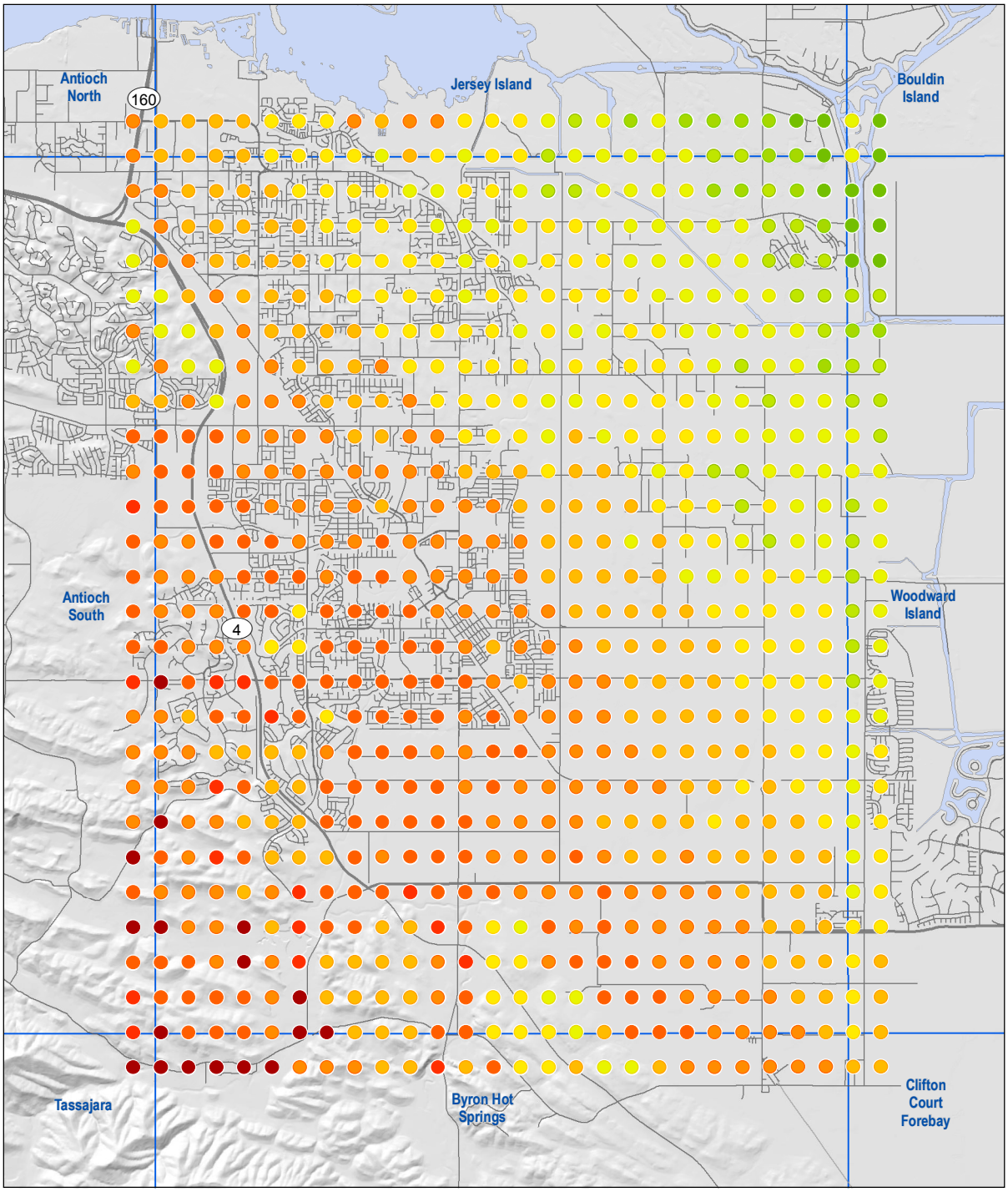
5,000 2,500 0 5,000 10,000 Feet

1 0.5 0 1 2 Kilometers

Shear wave velocity of upper 30 meters

503 (Kss)	308 (Qs)
468 (Tss)	294 (Qal2)
444 (QT)	228 (Qal1)
387 (Qoa)	226 (af/Qi)
385 (Tsh)	176 (Qi)
352 (Qal3)	water

Plate 3.1 Map of Vs30 groups and corresponding geologic units extracted from the state-wide Vs30 map developed by Wills and others (2015), Brentwood Quadrangle and surrounding area, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

N

1 0.5 0 1 2 Miles

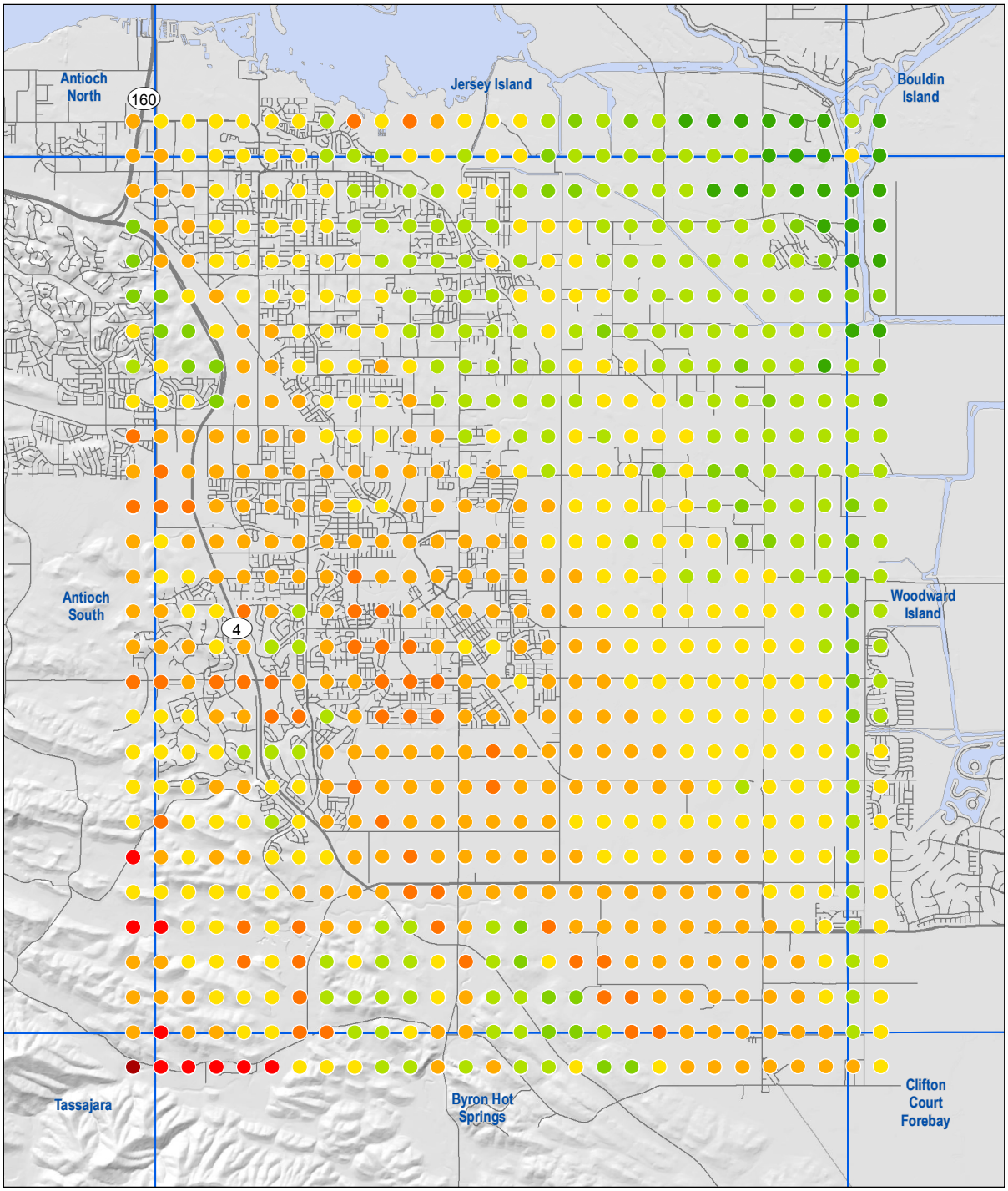
5,000 2,500 0 5,000 10,000 Feet

1 0.5 0 1 2 Kilometers

Pseudo-PGA (g)
10% in 50 yrs

0.32 - 0.35	0.26 - 0.27
0.31 - 0.32	0.25 - 0.26
0.30 - 0.31	0.24 - 0.25
0.29 - 0.30	0.23 - 0.24
0.28 - 0.29	0.22 - 0.23
0.27 - 0.28	0.20 - 0.22

Plate 3.2 Pseudo-PGA for liquefaction hazard mapping analysis, Brentwood Quadrangle and surrounding area, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

1 0.5 0 1 2 Miles

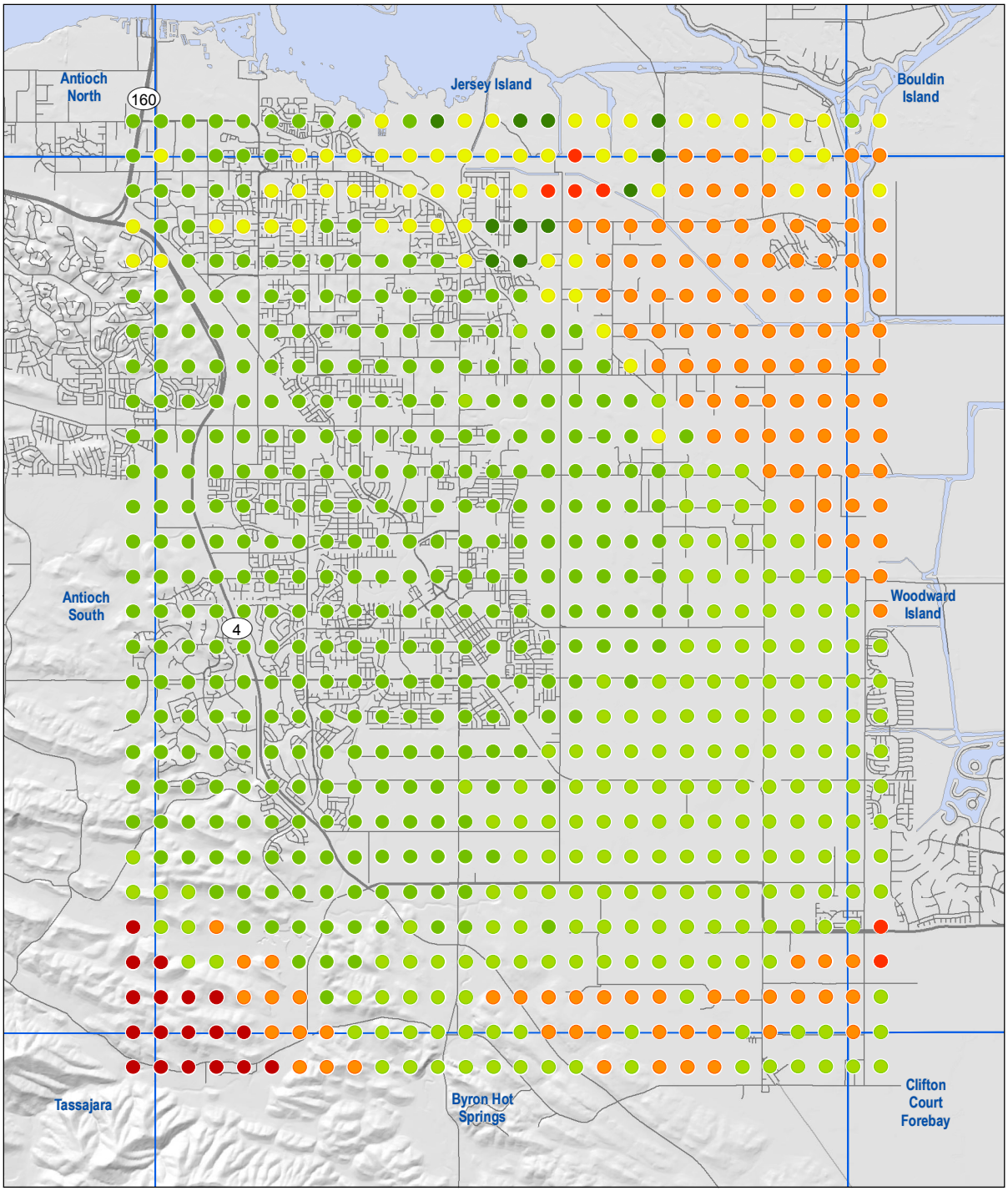
5,000 2,500 0 5,000 10,000 Feet

1 0.5 0 1 2 Kilometers

Probabilistic PGA (g)
10% in 50 yrs

0.51 - 0.52	0.43 - 0.44
0.49 - 0.50	0.41 - 0.42
0.47 - 0.48	0.39 - 0.40
0.45 - 0.46	0.36 - 0.38

Plate 3.3 Probabilistic peak ground acceleration for landslide hazard mapping analysis, Brentwood Quadrangle and sur-rounding area, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

BRENTWOOD QUADRANGLE

1 0.5 0 1 2 Miles

5,000 2,500 0 5,000 10,000 Feet

1 0.5 0 1 2 Kilometers

Modal Magnitude (g)
10% in 50 yrs

7.06 - 7.20	6.46 - 6.60
6.91 - 7.05	6.31 - 6.45
6.76 - 6.90	6.16 - 6.30
6.61 - 6.75	6.14 - 6.15

Plate 3.4 Modal magnitude for landslide hazard mapping analysis, Brentwood Quadrangle and surrounding area, California.