SEISMIC HAZARD ZONE REPORT 130

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

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EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the map of *Seismic Hazard Zones* (a subset of *Earthquake Zones of Required Investigation* (EZRI) which include Earthquake Fault Zones) for the Clayton 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 mapped area includes the City of Clayton, part of the City of Concord, a very small part of the City of Pittsburg and City of Walnut Creek, and unincorporated Contra Costa County.

This Seismic Hazard Zone Report describes the development of the Seismic Hazard Zone for the Clayton 7.5-Minute Quadrangle. The process of zonation for liquefaction hazard involves evaluation of earthquake loading, Quaternary geologic maps, groundwater level records, and subsurface geotechnical data. The process of zonation for earthquake-induced landslide hazard incorporates evaluation 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 the United States Geological Survey (USGS) for the 2018 *Update of the United States National Seismic Hazard Maps*.

About 28 square kilometers (11 square miles) of land in the Clayton Quadrangle has been designated as EZRI for liquefaction, encompassing most of the Clayton Valley, and major drainages such as Mt. Diablo, Pine, and Kirker Creeks. Some alluvial deposits on the Pittsburg-Antioch Plain in the northeastern part of the map area are also zoned. The 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 have a moderate to high likelihood of liquefying, given that the region is subject to strong ground motion.

The amount of area designated as EZRI for earthquake-induced landslides within the Clayton Quadrangle is approximately 63 square kilometers (24 square miles). These zones are prominent around Mt. Diablo and on the side slopes of many moderate to steep ridges in the map area and generally increase in frequency and size towards the southern and northeastern parts of the Clayton 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.

INTRODUCTION

The California Seismic Hazards Mapping Program

The Seismic Hazards Mapping Act of 1990 (the Act) (Public Resources Code, Division 2, Chapter 7.8) directs the State Geologist to prepare maps that delineate Seismic Hazard Zones for liquefaction, earthquake-induced landslides, tsunami inundation, and other ground failures. These are a subset of Earthquake Zones of Required Investigation (EZRI), which also include Earthquake Fault Zones. The California Geological Survey (CGS) prepares EZRI following guidelines prepared by the California State Mining and Geology Board (SMGB). For liquefaction and landslide hazard zone delineation, the SMGB established the Seismic Hazard Mapping Act Advisory Committee to develop guidelines and criteria for the preparation of seismic hazard zones in the state. The committee's recommendations are published in CGS Special Publication 118, which is available on online at: http://www.conservation.ca.gov/cgs/publications/sp118.

The purpose of the Act is to reduce the threat to public health and safety 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. State-of-the-practice evaluation and mitigation of seismic hazards are conducted under guidelines published in CGS Special Publication 117A, which are available online at: http://www.conservation.ca.gov/cgs/publications/sp117a.

Following the initial release of Special Publication 117 in 1997, local government agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction and landslide hazards. These agencies convened two independent committees, one for liquefaction and one for landslides, to provide more detailed procedures for implementing Special Publication 117 guidelines. The reports produced by these committees were published under the auspices of the Southern California Earthquake Center (SCEC) and are available online at: http://www-scec.usc.edu/resources/catalog/hazardmitigation.html. Special Publication 117 was revised in 2008 as Special Publication 117A.

Methodology and Organization of this Report

Delineating liquefaction and landslide hazard zones requires the collection, compilation, and analysis of multiple types of digital data. These data include geologic maps, ground water measurements, subsurface and laboratory geotechnical tests, elevation (terrain) maps, and probabilistic ground motion estimates. The data are processed into a series of geographic information system (GIS) layers using commercially available and open-source software, which are used as input for the delineation of hazard zones.

Earthquake Zones of Required Investigation (EZRI) for liquefaction and earthquake-induced landslides share many input datasets. Section 1 of this report describes the geographic, geologic, and hydrologic characteristics of the Clayton Quadrangle and laboratory tests used to categorize geologic materials within the quadrangle according to their susceptibility to liquefaction and/or landslide failure. Section 2 describes the development of the earthquake shaking parameters used in the liquefaction and landslide hazard analyses, provides map plates of the spatial distribution of key ground motion parameters, and summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential in the Clayton Quadrangle. Sections 3 and 4 summarize the analyses and criteria used to delineate liquefaction and earthquake-induced landslide hazard zones, respectively, in the Clayton Quadrangle.

Scope and Limitations

Seismic Hazard Zones for liquefaction and earthquake-induced landslides are intended to prompt more detailed, site-specific geotechnical investigations. Due to scale and other limitations inherent in these zones, they should not be used as a substitute for site-specific geologic or geotechnical investigations required under Chapters 7.5 and 7.8 of Division 2 of the California Public Resources Code. Site-specific geologic/geotechnical investigations are the best way to determine if these hazards could affect structures or facilities at a project site.

The zones described in this report identify areas where the potential for ground failure related to liquefaction and earthquake-induced landslides is relatively high. Liquefaction and landslides may occur outside the delineated zones in future earthquakes, but the majority of the occurrences should be within zoned areas. Conversely, not all of the area within a hazard zone will experience damaging ground failure in future earthquakes. The analyses used to delineate liquefaction and earthquake-induced landslide zones cannot predict the amount or direction of liquefaction- or landslide-related ground displacements, or the amount of damage to structures or facilities that may result from such displacements. Because of this limitation, it is possible that run-out areas during future earthquakes could extend beyond zone boundaries.

Other earthquake-induced ground failures that are not specifically addressed in the analyses conducted for the Clayton Quadrangle include those associated with soft clay deformation, non-liquefaction-related settlement, ridge-top spreading, and shattered ridges. In addition, this report does not address the potential for ground failure related to precipitation-induced landslides, including debris flows.

Although data used in this evaluation was selected using rigorous criteria, 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.

Accessing Earthquake Zones of Required Investigation Maps, Reports, and GIS Data

CGS EZRI, including Seismic Hazard Zones and Earthquake Fault Zones, their related reports and GIS data, are available for download and/or online viewing on the CGS Information Warehouse: http://maps.conservation.ca.gov/cgs/informationwarehouse/.

Alternatively, EZRI are available as a web map service (WMS) and feature service here: https://gis.conservation.ca.gov/server/rest/services/CGS_Earthquake_Hazard_Zones.

EZRI are also available on a statewide parcel base, which can be useful for initial Natural Hazards Disclosure determinations, by using the California Earthquake Hazards Zone Application (EQ Zapp): https://maps.conservation.ca.gov/cgs/EQZApp/app/.

EZRI maps and reports are also available for purchase at the CGS Sacramento office at the address presented below, or online at: http://www.conservation.ca.gov/cgs/publications.

Publications and Information Office
801 K Street, MS 14-34
Sacramento, CA 95814-3531
(916) 445-5716

Information regarding the Seismic Hazard Zonation Program is available on the CGS website: http://www.conservation.ca.gov/cgs/shp.

SECTION 1: GEOGRAPHY, GEOLOGY AND ENGINEERING GEOLOGY

of the

CLAYTON 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

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Purpose of this Section

Preparing Earthquake Zones of Required Investigation (EZRI) for liquefaction and earthquake-induced landslides requires many input datasets and complex analyses. The purpose of Section 1 of the Seismic Hazard Zone Report is to describe the overall geologic and geographic setting of the Clayton Quadrangle and then discuss the collection, processing, and analyses of primary geologic and engineering geologic data that were used to delineate EZRI.

GEOGRAPHY

Location

The Clayton Quadrangle covers an area of approximately 152 square kilometers (59 square miles) in central Contra Costa County, California. The center of the quadrangle is about 32 kilometers (20 miles) northeast of the City of Oakland and about 80 kilometers (50 miles) southwest of the City of Sacramento. The City of Clayton is entirely within the quadrangle, occupying approximately 10 square kilometers (4 square miles) of land. Approximately 35 square kilometers (14 square miles) of the City of Concord occupies the northwestern part of the quadrangle, the City of Walnut Creek encompasses a small area of approximately 4 square kilometers (1.5 square miles) in the western part of the map area, and the City of Pittsburg occupies 3 square kilometers (1 square mile) of land along the northern quadrangle boundary. Mt. Diablo State Park covers roughly 34 square kilometers (13 square miles) in the southern third of the study area. In the west-central part of the map area, Black Diamond Mines Regional Preserve occupies approximately 13 square kilometers (5 square miles) and Clayton Ranch encompasses a 1 square kilometer (0.4 square miles). The Concord Naval Weapons Station covers 12.5 square kilometers (5 square miles) of land in the northwestern corner of the map area. The remainder of the map area consists of unincorporated census-designated communities, and Contra Costa County and State of California land.

The map area is situated on the northern flank of Mt. Diablo, located south of the Sacramento-San Joaquin Delta. Elevations in the map area generally increase towards the southeast and range from 27 meters (88 feet) in the northwestern part of the map area along Diablo Creek, to 1173 meters (3850 feet) at the summit of Mt. Diablo in the south-central part of the quadrangle. Approximately three-quarters of the quadrangle consists of the foothills and uplands of the Diablo Range; both part of the Coast Ranges Geomorphic Province. Topography in the northeastern quarter of the quadrangle and along the southern border of the map area is characterized by northwest-southeast trending, gentle to moderately steep, rounded ridges separated by narrow valleys. The south-central part of the map area hosts the steep to very steep-sided peaks of the Diablo Range, including Mt. Diablo, Eagle Peak, and North Peak. The flat-floored Clayton Valley trends through the central and northwestern part of the map area, extending from the base of Mt. Diablo to the City of Concord in the northwest. Flatlands associated with the Pittsburg-Antioch alluvial plain and the Ygnacio Valley occur in the very northeast corner and along the southwestern boundary of the quadrangle, respectively.

In the central and northwestern part of the study area, the drainages of Mt. Diablo Creek, Galindo Creek, Donner Creek, Irish Canyon, and several unnamed tributary streams drain Mt. Diablo and flow northwesterly towards the Ygnacio Valley and into Suisun Bay. Along the northern part of the map area, Kirker Creek, Lawlor Ravine, and Willow Creek all flow north towards the Pittsburg-Antioch alluvial plain and eventually into the San Joaquin River. In the southwestern corner of the map area, Arroyo Del Cerro, Little Pine Creek, and Pine Creek all drain westward towards Walnut Creek and the Ygnacio Valley.

The Clayton Canal and Contra Costa Canal traverse the northern part of the Clayton Quadrangle. In the northwestern part of the map area, the Clayton Canal flows parallel to Mt. Diablo Creek through the Concord Naval Weapons Station. The Contra Costa Canal briefly enters the northwestern corner of the quadrangle from east to west and transports water from Rock Slough in the Sacramento-San Joaquin Delta in the east to Martinez in the west (CCWD, 2009). These canals provide water for agricultural, industrial, and municipal uses in the Bay Area.

Land Use

Land use in the northern and western parts of the Clayton Quadrangle historically was dominated by agriculture in valley areas and cattle grazing in the surrounding low-lying hills. In the 1850's, coal was discovered in the hills northeast of Clayton, which formed the first substantial industry aside from farming in the area. In the 1920's, underground mining for sand began near the townships of Nortonville and Somersville in the northeastern part of the map area and continued until 1949 when increasing foreign competition led to the abandonment of the sand mines in the map area. The coal and sand mines in the Clayton Quadrangle are now closed due to various hazards, and much of the former mining land is used for ranching or has been set aside as open space. The only active mining operations in the quadrangle are at the Clayton Quarry in the southern part of the map area, where diabase is mined for aggregate resources.

In the last several decades, urban development has increased substantially in the Clayton Valley, mainly as shopping centers and home construction as the City of Clayton has expanded into both flatland areas and some of the surrounding foothills. Additional substantial growth in the northeastern corner of the study area has occurred over the last two-decades in the City of Pittsburg, where development is occurring on low-lying hills mainly as residential communities.

Since 1990, the population of Clayton has nearly doubled in size with development largely occurring to the northwest and southeast of the city center. Today, more than three-quarters of the quadrangle remains undeveloped. The uplands in the eastern half and southern third of the map area are included in two large parks operated by the State of California and the East Bay Regional Park District: Mt. Diablo State Park and Black Diamond Mines Regional Preserve. Substantial areas of undeveloped, recreational and agricultural land remain in the uplands of the northeastern corner and south-central parts of the quadrangle.

The primary transportation route in the study area is Kirker Pass Road/Ygnacio Valley Road, which trends northeast-southwest across the northwestern part of the map area, connecting Highway 4 in the City of Pittsburg with Interstate 680 in Walnut Creek. Clayton Road and Concord Blvd are northwest-southeast trending thoroughfares that traverse the suburbs of the Cities of Clayton and Concord. Marsh Creek Road trends northwest-southeast across the east central part of the map area and connects the City of Clayton with State Route 4 near the City of Brentwood to the east of the map area. Treat Blvd and Willow Pass Road are northeast-southwest trending thoroughfares connecting the cites of Clayton and Concord with the City of Walnut Creek. Access to undeveloped areas within the quadrangle is primarily by paved county roads and paved and unpaved roads in Mt. Diablo State Park.

Digital Terrain Data

A digital representation of the earth's surface is a key component in delineating liquefaction and earthquake-induced landslide hazards. Within the Clayton Quadrangle, digital topography in the form of a lidar-derived digital elevation model was obtained from Contra Costa County (http://www.co.contra-costa.ca.us/4475/Maps-and-Data). This terrain data was collected in 2010 and presents elevations at a point spacing of 3 meters and elevations at 1-meter horizontal accuracy and 15-cm RMSE vertical accuracy.

For liquefaction hazard analyses, surface elevations derived from the Contra Costa County DEM are differenced with historic-high ground water elevations to derive a "depth to water" map. In alluvial areas, the depth value obtained was combined with geologic data from boreholes and used in liquefaction calculations.

For earthquake-induced landslide hazard analyses, slope gradient and slope aspect are calculated using the slope applications built into commercially available GIS software. Both parameters are calculated using a third-order, finite difference, center-weighted algorithm based on Horn (1981), as documented in Burrough and McDonnell (1998). The slope gradient is combined with the geologic material strength map to calculate yield acceleration, a measure of susceptibility to earthquake slope failure as described in Section 4 of this report.

GEOLOGY

The primary source of geologic information used in the evaluation of liquefaction and earthquake-induced landslide hazards in the Clayton 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).

Digital geologic maps covering the Clayton Quadrangle and adjacent areas 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. Landslide deposits were deleted from the geologic 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 that did not form a geologic boundary were removed. The distribution of Quaternary and bedrock deposits on the final geologic materials map was used, in combination with other data, to evaluate liquefaction and landslide susceptibility and develop the Seismic Hazard Zone Map.

The following map unit names and descriptions of geologic units exposed in the study area are taken primarily from Dawson (2010). The Quaternary geologic unit nomenclature used by CGS for mapping in the San Francisco Bay Region was adopted from Knudsen and others (2000).

Bedrock Units

The bedrock geology of Contra Costa County has been divided by Graymer and others (1994) into six individual stratigraphic assemblages (I – VI), 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. Stratigraphic Assemblage VI underlies the entire Clayton Quadrangle (Graymer and others, 1994).

In eastern and central Contra Costa County, the oldest rocks exposed in the fault-bounded assemblage belong to two slightly to highly deformed Mesozoic rock complexes: The Franciscan Complex, and the overlying Cretaceous Great Valley Sequence (Graymer and others, 1994). Rocks of the Franciscan Complex exposed in the map area are composed of sheared and metamorphosed mudstone, siltstone, sandstone, greywacke, conglomerate, chert, and minor pillow basalt, which represent Jurassic oceanic crust and pelagic deposits overlain by Late Jurassic to Late Cretaceous turbidities (Graymer and others, 1994). The Great Valley Sequence exposed in the quadrangle 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).

In the study area, Mesozoic and Tertiary rocks of Assemblage VI outcrop where they have not been buried beneath Quaternary sediments. 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.

The following is a summary of bedrock map units exposed in the Clayton Quadrangle based on Dawson (2010).

Mesozoic Units

Mesozoic rock units underlie about 60 percent of the uplands and comprise most of the bedrock in the southern half of the Clayton Quadrangle. The oldest units mapped in the Clayton Quadrangle belong to five Franciscan Complex rock units in the southeastern part of the map area. These five units make up the core of Mt. Diablo and consist of highly sheared blocks and lenses of basalt and chert (**fbc);** mélange of metamorphic rocks including glaucophane and other schistose rocks in a sheared sandstone and shale matrix (**fm**); sandstone, shale, and metagraywacke (**fss**); silica carbonate rocks, formed by the alteration of serpentinite (**sc**); and serpentinite and massive harzburgite (**sp**). On the flanks of Mt. Diablo, a northeast-southwest trending band of unit **sp** unconformably separates units **fm** and **fbc** in the southeastern part of the map area from Great Valley Sequence units **Jpb**, **Jdb**, **KJk** and **Ka** to the northwest.

The Great Valley Sequence, Coast Range Ophiolite units **Jdb** and **Jpb** are the oldest of 11 Great Valley Sequence units mapped in the study area. These units are mapped on the northwest side of Mt. Diablo and consist of diabase, mainly sills, dikes, and screens of pillow basalt (**Jdb**); and pillow basalt, basalt breccia, and minor diabase (**Jpb**). Units **Jdp** and **Jpb** are in unconformable contact with the Upper Jurassic Knoxville Formation. The Knoxville Formation is primarily mapped along the upper reaches of Galindo Creek in the southwestern part of the map area and consists of shale with thin sandstone interbeds. Overlying the Knoxville Formation are 5 unnamed members of the Great Valley Sequence, referred to as Units A-E.

Unit A (**Ka**) of the Great Valley Sequence conformably overlies the Knoxville Formation and consists of siltstone and mudstone with minor sandstone. It forms a series of gently rolling hills in the southeast part of the map area along Mt. Diablo Creek and near the southwestern boundary of the quadrangle, near the eastern limits of the City of Walnut Creek. Unit B (**Kb**) of the Great Valley Sequence consists of interbedded sandstone and shale, forms a series of ridges and low hills, and is exposed along Keller Ridge and Irish Canyon in the east-central part of the map area. Great Valley Sequence Unit C is mapped in conformable contact with and to the north of unit **Kb** in the east-central part of the map area, where it is divided into a shale and siltstone member (**Kcu**), and a sandstone member (**Kcus**). Mapped to the north of Unit C is Great Valley Sequence Unit D, which is divided into a sandstone unit (**Kd**) and interbedded shale member (**Kds**). Unit E of the Great Valley Sequence (**Kel**) is the youngest Mesozoic rock formation in the Clayton Quadrangle and consists of siltstone and mudstone. Unnamed Great Valley Sequence sedimentary rocks (**Ku**) are mapped along Little Pine Creek in the southwestern corner of the Clayton Quadrangle. This unit is comprised of massive to distinctly bedded, coarse to fine grained graywacke and lithic wacke, siltstone and mudstone.

Tertiary Units

Tertiary bedrock units are exposed along a northwest-southeast trending band in the northern part of the map area and in a small area along the southwestern corner of the quadrangle. These bedrock units consist of a series of sandstone and shale formations that range from Eocene to Pliocene in age. Along the northeastern and southwestern quadrangle boundaries, these bedrock units form moderately steep slopes with narrow, generally north-south trending valleys and drainages. However, in the very northeastern corner of the map area and in the northwest part of the Quadrangle near the Cities of Clayton and Concord, these units have been subjected to extensive grading and development and minimal topographic expression of the units remain.

The oldest Tertiary unit exposed in the Clayton Quadrangle is the Paleocene Meganos Formation. The Meganos formation forms a series of valleys, linear ridges, and low-lying hills in the east-central part of the map area. Locally, the Meganos Formation is divided into 5 units: a sandstone with basal conglomerate (**Pema**), shale (**Pemc**), shale with sandstone interbeds (**Pemcs**), and an unnamed sandstone (**Pemzl**) and interbedded siltstone and shale member (**Pemzu**). The Paleocene Meganos Formation is in fault contact with the overlying Eocene Domengine Formation (**Ed**).

The Domengine Formation (**Ed**) is a distinctly light colored, fine to coarse-grained sandstone, and locally includes conglomerate lenses and thin beds of shale. The Nortonville Shale (**Env**) conformably overlies the Domengine Formation in the east-central part of the map area and consists of marine claystone with minor siltstone and thin beds of fine-grained, glauconitic sandstone. The Nortonville Shale is conformably overlain by the Markley Formation (**Emk**), which is the most prominent unit in the Clayton Quadrangle, covering approximately 17 percent of the study area. The Markley Formation is exposed in the northern half of the quadrangle and is divided into sandstone with shale (**Emk**), minor siltstone subunit (**Eml)**, and a black shale and sandstone unit known as the Sidney Flat Member (**Ems**). Pliocene age hypabyssal basalt dikes and sills (**Pb**) intrude unit **Emk** on the north side of the Clayton Valley, east of Concord. These deposits dot the landscape and form low relief hills.

The Oligocene Kirker Tuff unconformably overlies the Upper Member of the Markley Formation. The Kirker Tuff is divided into two units: a white, pumiceous tuff unit (**Okt**); and tuffaceous sandstone, conglomerate and siltstone (**Oks**). Locally, **Okt** and **Oks** form moderately steep side slopes below ridges of late Miocene Cierbo Sandstone (**Mc**) and Miocene Neroly Sandstone (**Mnr**). The Kirker Tuff units are in conformable contact with the overlying Miocene Cierbo Sandstone, which consists of a moderately consolidated, fine- to coarse-grained marine sandstone. Locally, this marine sandstone is in conformable contact with the overlying Miocene Neroly Formation unit **Mnr**. The Neroly Sandstone (**Mnr**), consists of blue to gray, fine to coarse-grained, volcanic-rich, shallow marine sandstone, with minor gray and brown siltstone, shale, tuff and pebble conglomerate layers.

Miocene silicic volcanic rocks (**Msv**), consisting of andesite porphyry stocks, dikes and sills, are exposed in a small area along the southeastern boundary of the quadrangle. This unit forms low rolling hills and is the only Tertiary unit mapped in southeastern part of the study area.

The Pliocene Lawlor Tuff (**Plt**) unconformably overlies the Miocene Neroly Formation in the northern part of the map area. Unit **Plt** consists of a basal pumice-fall unit and an upper, unwelded pumice-ash-flow. It has an Ar/Ar age of 4.83 ± 0.04 Ma and was derived from the Sonoma Volcanics. Stratigraphically above the Pliocene Lawlor Tuff is the Pliocene Tehama Formation (**Pth**). The Tehama Formation is a poorly consolidated, non-marine, gray to maroon siltstone, quartz arenite sandstone, tuff, and weakly indurated pebble to cobble conglomerate.

Quaternary Sedimentary Deposits

Approximately 38 square kilometers (15 square miles) of the Clayton Quadrangle is covered by Quaternary sediments, of which approximately 31 square kilometers (12 square miles) are

Pleistocene or older in age. In total, 13 different Quaternary units are mapped in the Clayton 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); analyses of associated geotechnical data are discussed under the Engineering Geology heading of this section. Structural features such as faults are not presented on the plate.

Old Quaternary Units

Older Quaternary (Pliocene to Pleistocene) deposits cover approximately 20 percent of the Clayton Quadrangle. These deposits are divided into five geologic units: late Pliocene to early Pleistocene-age alluvium (**QPu**), early to late Pleistocene alluvial fan deposits (**Qof**), early to late Pleistocene undifferentiated alluvium (**Qoa**), latest Pleistocene alluvial fan deposits (**Qpf**), and late Pleistocene undifferentiated alluvium (**Qpa**). The unnamed late Pliocene to early Pleistocene-age alluvium (**QPu**) consists of undifferentiated sandstone, siltstone, and gravel, and is unrelated to modern drainages. This unit forms low knolls in the northwestern corner of the quadrangle in the vicinity of the Concord Naval Weapons Station (Plate 1.1). Early to late Pleistocene alluvial fan deposits (**Qof**) consist of sand, gravel, silt and clay that was deposited by streams emanating from mountain canyons on to alluvial valley floors or alluvial plains as debris flows, hyperconcentrated mudflows, or braided stream flows. Deposits mapped within the early to late Pleistocene undifferentiated alluvium unit (**Qoa**) consist of sand, silt, clay, and gravel and can include alluvial fan, stream terrace, and channel deposits. This unit includes deposits that were shed off the flanks of Mt. Diablo and are moderately to extremely dissected with little or no one of the original geomorphic expression preserved. Because of the age of these older Pleistocene deposits, the streams responsible for deposition may have evolved and no longer be readily evident in today's topography. The Pleistocene alluvial fan unit (**Qpf**) consists of sand, gravel, silt, and clay. These alluvial fans developed at the mouths of modern drainages and form broad, gently sloping fans and terraces. This map unit covers much of the Clayton Valley alluvial plain in the northwestern part of the map area and along the southwestern quadrangle boundary (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. Unit **Qpf** differs from unit **Qoa** and **Qof** in that some original fan surface morphology is preserved. Pleistocene undifferentiated alluvium (**Qpa**) is primarily mapped in upland alluvial valleys in the central part of the map area and along drainages in the northeastern part of the quadrangle. Unit **Qpa** is mapped on gently sloping to level surfaces where latest Pleistocene age is indicated by depth of stream incision, development of soils, and lack of historical flooding. These undifferentiated alluvial deposits consist of intercalated sand, silt, and gravel that are poorly to moderately sorted and are mapped where separate fan, basin, and terrace units could not be delineated at the mapping scale.

Young Quaternary Units

Young Quaternary (latest Pleistocene to Holocene) alluvial sediments cover approximately 4 percent of the Clayton Quadrangle. These deposits are subdivided into eight distinct units: alluvial fan (**Qhf**), stream channel (**Qhc**), stream terrace (**Qhty** and **Qht**), undifferentiated alluvial deposits (**Qha** and **Qa**), and artificial fill (**af** and **ac**). These materials were eroded from surrounding hills, then transported and deposited into the inter-ridge valleys and alluvial plains.

The latest Pleistocene to Holocene alluvial fan deposits (**Qhf**) were deposited by streams emanating from Mt. Diablo Creek, Kirker, Galindo Creek, Pine Creek, and several tributary streams that drain Mt. Diablo and flow northwesterly towards the Ygnacio Valley and into Suisun Bay. These deposits include sand, gravel, silt, and clay and decrease in grain size downslope from the fan apex. Late Holocene to modern stream channel deposits (**Qhc**) consist of unconsolidated sand and gravel recently transported within active channels. Stream terrace deposits (**Qht** and **Qhty**) are mapped along Mt. Diablo Creek in the central part of the quadrangle. These units were deposited in point bar and overbank settings and are as much as 10 meters above the historic flood plain, but mostly undissected by later erosion. Stream terrace deposits include sand, gravel, silt, and minor clay, and are moderately to well sorted and moderately to well bedded. The latest Pleistocene to Holocene undifferentiated alluvial deposits (**Qha** and **Qa**) are mapped primarily along the upper reaches of Kirker Creek in the northeastern and central part of the study area. These units typically form the upland inter-ridge valley floors of Kirker Creek and Galindo tributary drainages and consist of intercalated sand, silt, and gravel, with little to no dissection. Units **Qha** and **Qa** are used where separate fan, basin, and terrace units could not be delineated at the scale of the mapping.

Late Holocene artificial fill (**af**) and artificial channels (**ac**) are deposits of sand, gravel, silt, and clay resulting from human activity and are mapped in the central part of the map area, in and around the cities of Concord and Clayton. These units include engineered and non-engineered fill and are chiefly related to residential, industrial, commercial, and water conveyance system development projects. Although areas with fills have been mapped, not all fills are represented in the study area.

Young landslides (**Qls**) are present in the area and are shown on Plate 1.2 (see the Existing Landslides section for occurrences and descriptions).

Table 1.1 Quaternary units mapped in the Clayton Quadrangle.

Map Unit	Environment of Deposition	Age
ac	Artificial Stream Channel	Historical
af	Artificial Fill	Historical
Qhty	Stream Terrace	Latest Holocene
Qhc	Stream Channel	Holocene
Qha	Undifferentiated Alluvium	Holocene
Qhf	Alluvial Fan	Holocene
Qht	Stream Terrace	Holocene
Qa	Undifferentiated Alluvium	Pleistocene to Holocene
Qpf	Alluvial Fan	Latest Pleistocene
Qpa	Undifferentiated Alluvium	Latest Pleistocene
Qof	Alluvial Fan	Pleistocene
Qoa	Undifferentiated Alluvium	Pleistocene
QPu	Undifferentiated Alluvium	Latest Pliocene to Pleistocene

Geologic Structure

The structural framework of the Clayton 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, about three-fourths of this relative movement is accommodated by shearing 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. In the current transpressional tectonic regime, characterized by a horizontal northeast-southwest maximum compression direction, differential strike-slip movement along these faults locally generates thrust faulting and folding. This has resulted in the uplift of Mount Diablo, and folded the surrounding rocks over the last 4 million years into the Mount Diablo Anticline (Schemmann and others, 2007).

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

Several faults cross the Clayton Quadrangle. The northwest-southeast trending Greenville Fault Zone, Clayton Section is mapped as crossing bedrock and alluvium in the southwestern and central parts of the quadrangle (Bryant and Cluett, 2002; Dawson, 2010; Schemmann and others, 2007). This fault is mapped as pre-Holocene (>11,700 years), and is well constrained where in bedrock and inferred in alluvium. The Holocene aged Ygnacio Valley Section of the Concord Fault is mapped as extending about 1.5 miles into the southwestern part of the quadrangle, and is well constrained where in bedrock and approximately located in alluvium (USGS, 2020a). The Concord fault has been determined to be sufficiently active and well defined, such that it has met the criteria for zoning under the Alquist-Priolo Earthquake Fault Zoning Act. Several other unnamed, well constrained, variably oriented, apparently pre-Quaternary age faults are mapped in the bedrock in the southern part of the quadrangle in the vicinity of Mt. Diablo (Graymer and others, 1994; Dawson, 2010; USGS, 2020).

Existing Landslides

As a part of the geologic data compilation, an inventory of existing landslides in the Clayton Quadrangle has been prepared through field reconnaissance and review of previously published landslide mapping, but primarily from geomorphic analyses of lidar-derived topography and digital stereo imagery employing a GIS-based softcopy photogrammetric system (listed in the

"Air Photos" section of 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 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 upland areas where extensive grading was conducted prior to imagery capture, as this grading likely removed the geomorphic evidence of slope instability (Plate 1.2).

For each landslide included on the map, several characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable, or questionable) and other properties, such as activity, thickness, and associated geologic unit(s). The completed landslide map was digitized, and the attributes were entered into a database. Landslides rated as definite or probable were carried into the landslide zone as described in Section 4. A small-scale version of this landslide inventory is included on Plate 1.2.

A total of 548 landslides were identified in the landslide inventory, covering about 17 percent of the uplands of the Clayton Quadrangle, or approximately 25 square kilometers (10 square miles). There are no historic landslides in the Clayton Quadrangle. All landslides in the inventory are instead classified as dormant-young or dormant-mature, consisting of 461 rock slides, 271 earth flows, 58 debris fans, 34 debris slides, and 4 debris flows. As the dip of strata generally exceeds the slope inclination, dip-slope landslides are not common. Rather, a primary controlling factor seems to be the differing geologic units and steepness of slopes. Landslides appear to occur where slopes are steeper with higher relief, and generally increase in size and frequency from west to east in the map area. Additionally, there does not appear to be a clustering of landslides near faults mapped in the USGS active faults database (USGS, 2020) or in Graymer and others, (1994), suggesting faulting has not played a significant role in slope failures in this area.

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

ENGINEERING GEOLOGY

Historic-High Groundwater Mapping

Liquefaction occurs only in saturated soil conditions, and the susceptibility of a soil to liquefaction varies with the depth to groundwater. 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 a high groundwater level based on historical groundwater data. 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, CGS constructs regional contour maps that depict highest historical depths to groundwater surface. Plate 1.3 depicts contours reflecting the historic-high depth to groundwater surface within the Clayton Quadrangle.

Groundwater Basins

The majority of the study area is located within the California Department of Water Resources (CDWR) designated Clayton Valley Groundwater Basin, and its associated highland area known as the Clayton Valley Highlands. The remainder of the quadrangle is located within the Pittsburg

Plain and Ygnacio Valley groundwater basins and their associated highlands (Plate 1.3). For this study, groundwater mapping was performed for the valley and flatland regions of these groundwater basins that are subject to liquefaction zonation in order to estimate depths to saturated materials.

Water-bearing units in the Clayton Valley Groundwater Basin primarily consist of recent to older alluvium valley fill deposits. The deposits are generally unconsolidated Quaternary alluvium and semi-consolidated Tertiary-Quaternary deposits with interbedded lenses of clays, sands, and gravels (CDWR, 2003). Groundwater levels in these deposits are strongly influenced by natural groundwater recharge resulting from percolation from direct precipitation, mountain-front runoff, and from creeks and streams (USGS, 2015). Artificial sources of groundwater recharge often affect local groundwater levels and result from canal seepage, irrigation return flows, urban landscape irrigation, agricultural irrigation, septic tanks, slow leakage from detention basins, or releases of treated water.

Aquifers in the Clayton Valley and Ygnacio Valley groundwater basins are hydrologically connected to Suisun Bay, and the Pittsburg Plain Groundwater Basin is hydrologically connected to the San Joaquin River (CDWR, 2003). There are limited data regarding the occurrence and movement of groundwater in the basins. However, groundwater gradients within the alluvial flatlands and upland valleys were evaluated as part of this study, and they are generally consistent with natural topographic gradients to the northwest towards Suisun Bay in the Clayton Valley and Ygnacio Valley groundwater basins, and to the north towards the San Joaquin River in the Pittsburg Plain Groundwater Basin.

Groundwater Data

Groundwater conditions in the Clayton Quadrangle were evaluated using depth to groundwater levels noted in geotechnical boring logs, online groundwater databases, groundwater monitoring reports, and water well drilling logs. Geotechnical borehole logs for this study were acquired from planning departments at the cities of Clayton, Concord, Pittsburg, Antioch, and the California Department of Transportation (CDOT, 2020). Additional water level data were collected from the State Water Resources Control Board (CWRCB, 2020a; 2020b), California Department of Water Resources (CDWR, 2020a; 2020b), the United States Geological Survey (USGS, 2020b), and local water districts and agencies.

Water level data evaluated in this study represent more than 360 groundwater measurements (Plate 1.3) collected from the 1950’s through the present, with most records representing conditions of the past twenty years. Review of hydrographs of wells in the Clayton Valley Groundwater Basin indicates that groundwater levels have shown a slight gradual decline over the period of record (CDWR, 2003). Ygnacio Valley Ground Basin water level records indicate that the groundwater levels have also declined over the period of record. Hydrographs from DWR well data in the Pittsburg Plain Groundwater Basin indicate that groundwater levels in this area have remained fairly stable over the period of record, with the exception of static water level drops and subsequent recovery associated with the 1976-1977 and 1987-1992 drought periods (CDWR, 2003).

Groundwater data from all available records were spatially and temporally evaluated in a geographic information system (GIS) database to constrain the estimate of historically shallowest groundwater for the project area. CGS created a historic-high groundwater elevation surface map for the alluvial valleys and flatlands of the Clayton Valley, Ygnacio Valley, and Pittsburg Plain groundwater basins based on available well records and data from previous groundwater studies. Our highest historical groundwater elevation surface was compared with the existing ground-surface elevation, and consideration was given to active creeks, recharge ponds, detention basins, water impoundments, and reservoirs. The depth to groundwater contours depicted on Plate 1.3 do not represent present-day conditions, as usually presented on typical groundwater contour maps, but rather the historic-high depths to groundwater in the Clayton Quadrangle.

Groundwater Levels

Historic-high groundwater depths in the Clayton Quadrangle vary from less than 10 feet along streams, reservoirs, and in upland alluvial valleys to greater than 50 feet below older Quaternary deposits in the northwestern part of the map area. Most of the water-bearing materials in the Clayton Quadrangle are located in the northwest-southeast trending Clayton Valley in the west and central parts of the map area. Historic-high groundwater levels below the surface of the Pleistocene alluvial fans deposits (**Qpf**) range from less than 10 feet to 30 feet deep, where the greatest depths are typically measured near the apex of alluvial fans and gradually shallow towards the streams and foothills that flank the valley. Some of the older alluvial deposits (**Qof**) have been dissected by active stream channels where shallow groundwater conditions, within 10 feet of the ground surface, were noted.

The remainder of the quadrangle is characterized by upland alluvial valleys and canyons, including Mt. Diablo Creek, Kirker Creek, Pine Creek, where sufficient borehole or water well measurements are lacking, and the historic-high groundwater level could not be well constrained. The deposits in the upland alluvial valleys are typically thin, consist of sand, gravel, clay, and tend to trap and accumulate heavy runoff and near-surface groundwater. As such, these areas were assigned a historical-high groundwater value of less than 10 feet, unless otherwise noted.

Geologic Material Testing

Liquefaction Hazard Zoning: In-Situ Penetration Resistance

Of particular value in liquefaction evaluations are logs that report the results of downhole standard penetration tests in alluvial materials. The Standard Penetration Test (SPT) provides a standardized measure of the penetration resistance of geologic deposits and is used as an index of soil density. For this reason, SPT results are a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material. The SPT is an in-field test based on counting the number of blows required to drive a standard split-spoon sampler (1.375-inch inside diameter) one foot into the soil. The driving force is provided by dropping a 140-pound hammer weight 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (ASTM, 2004). Recorded blow counts for non-SPT geotechnical sampling, where the sampler diameter, hammer weight or drop distance differs from that specified for an SPT (ASTM D1586), are converted to SPT-equivalent blow counts if reliable conversions can be made. The actual and converted SPT blow counts are normalized to a common-reference, effective-overburden pressure of 1 atmosphere (approximately 1 ton per square foot) and a hammer efficiency of 60 percent using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$. Geotechnical borehole logs provided information on lithologic and engineering characteristics of Quaternary deposits within the study area.

For liquefaction hazard zoning in the Clayton Quadrangle, borehole logs were collected from the files of the City of Concord, City of Clayton, City of Pittsburg, and CalTrans (CDOT, 2018). Data from a total of 149 borehole logs were entered into the CGS geotechnical GIS database and analyzed. Of the 149 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.

Landslide Hazard Zoning: Laboratory Shear Strength

To evaluate the stability of geologic materials susceptible to landslide failure under earthquake conditions, the bedrock map units described above were ranked and grouped based on 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 Clayton Quadrangle geologic map were obtained from the City of Concord, City of Clayton, City of Pittsburg, and CalTrans (CDOT, 2020). The locations of rock and soil samples taken for shear testing within the Clayton Quadrangle are shown on Plate 1.2. Shear tests from neighboring quadrangles (Antioch North, Honker Bay, Clayton, Brentwood, Clifton Court Forebay, and Richmond) were used to augment data for several geologic formations for which little or no shear test information was available within the Clayton Quadrangle (see Appendix A at the end of this Section). For geologic units where sufficient shear-strength laboratory data could not be acquired, field measurements of Geologic Strength Index (GSI) (Marinos and others, 2007) were collected and the Hoek-Brown Failure Criterion (Hoek and others, 2002) was used to estimate the overall geologic unit strength.

The non-linear Hoek-Brown Failure Criterion is a rock mass characterization method which uses equations to relate rock mass classification of the 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 laboratory shear testing and GSI field measurements within the Clayton Quadrangle are shown on Plate 1.2.

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped based on average angle of internal friction (average phi) and lithologic character. Mean and median phi values for each geologic map unit and corresponding strength groups are summarized in Table 1.2. For each geologic strength group (Table 1.3) in the map area, the mean shear strength value was assigned and used in our slope stability analysis. A geologic material strength map was made based on the groupings presented in Table 1.2 and Table 1.3, and this map provides a spatial representation of material strength for use in the slope stability analysis.

As discussed later in this report, the criteria for landslide zone mapping state that all existing landslides 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 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. Where available, we collect and compile primarily “residual” strength parameters from laboratory tests of slip surface materials tested in direct shear or ring shear test equipment. For the Clayton Quadrangle, strength parameters applicable to existing landslide planes were not available and are not included in Table 1.3.

Table 1.2. Summary of the shear strength statistics for the Clayton Quadrangle.

	Formation Name	Number of Tests	Mean/Median Phi (deg)	Mean/Median Group Phi (deg)	Mean/Median Group Cohesion (psf)	No Data: Similar Lithology	Phi Values Used in Stability Analysis
GROUP 1	Plt	13	37/38	37 / 38	1225 / 1225	Okt, Jpb, Fss, Fbc, Msv, Pb	37
GROUP 2	Ed	45	34 / 35	33 / 34	928 / 650	Pema, Pemcs, Pemzl	33
	Mnr	42	34 / 35				
	Jdb	13	33 / 32				
	Kb	4	32 / 32				
	Kcus	2	32 / 32				
	Mc	16	32 / 34				
	Kd	10	31 / 30				
	Emk	42	30 / 29				
GROUP 3	Pth	37	29 / 28	28 / 27	870 / 660	Kds, Kel, Qoa*, Eml	28
	KJk	12	28 / 27				
	Oks	6	28 / 32				
	Qpa*	30	28 / 26				
	Kcu	1	28 / 28				
	Ku	18	27 / 25				
	Pemzu	2	26 / 26				
GROUP 4	Qha*	44	25 / 25	25 / 25	648 / 500		25
	af*	2	24 / 24				
	Qa	3	25 / 29				
GROUP 5	Ka	2	21 / 21	19 / 18	939 / 800	sc, sp	19
	fm	9	21 / 19				
	Pemc	1	18 / 18				
	Env	9	17 / 18				
	Ems	5	17 / 15				

*Unit af includes af, ac; Qha includes Qha, Qhc, Qhf, Qht, Qhty, gq; Qpa includes Qpa, Qpf, Qpt, & Qpu; Qoa includes Qoa, Qof

Table 1.3. Summary of shear strength statistics for the Clayton Quadrangle

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
Plt	Ed	Pth	Qha	Ka
Okt	Mnr	KJk	af	fm
Jpb	Jdb	Oks	Qa	Pemc
Fss	Kb	Qpa		Env
Fbc	Kcus	Kcu		Ems
Msv	Mc	Ku		sc
Pb	Kd	Pemzu		sp
	Emk	Kds		
	Pema	Kel		
	Pemcs	Qoa		
	Pemzl	Eml		

REFERENCES

American Society for Testing and Materials, 2004, Standard test method for penetration test and split-barrel sampling of soils, Test Method D1586-99, *in* Annual Book of ASTM Standards, v. 4.08.

Atwater, B.F., 1982, Geologic maps of the Sacramento-San Joaquin Delta, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1401, scale 1:24,000.

Bartow, J.A., 1985, Map showing Tertiary stratigraphy and structure of the northern San Joaquin Valley, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1761, 2 sheets, scale 1:250,000.

Bryant, W.A., and Cluett, S.E., compilers, 2002, Quaternary fault and fold database of the United States: U.S. Geological website, http://earthquakes.usgs.gov/regional/qfaults.

Burrough, P.A., and McDonnell, R.A., 1998, Principles of Geographical Information Systems: Oxford University Press, New York, 190 pages

California Department of Transportation (CDOT), 2020, GeoDOG, Digital Archive of Geotechnical Data, https://geodog.dot.ca.gov/ (January, 2020).

California Department of Water Resources (CDWR), 2003, California's Groundwater, Bulletin 118, Update 2003, https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Bulletin-118/Files/Statewide-Reports/Bulletin_118_Update_2003.pdf.

California Department of Water Resources (CDWR), 2020a, California Statewide Groundwater Elevation Monitoring (CASGEM) Program, https://water.ca.gov/Programs/Groundwater-Management/Groundwater-Elevation-Monitoring--CASGEM, (May, 2020).

California Department of Water Resources (CDWR), 2020b, Groundwater Level Data, Water Data Library, http://www.water.ca.gov/waterdatalibrary (May, 2020).

California Water Resources Control Board (CWRCB), 2020a, California Protection Agency, GeoTracker database, http://geotracker.waterboards.ca.gov (May 2020).

California Water Resources Control Board (CWRCB), 2020b, California Protection Agency, GeoTracker Groundwater Ambient Monitoring & Assessment (GAMA) database, http://geotracker.waterboards.ca.gov/gama (May 2020).

Contra Costa Water District (CCWD), 2009, Los Vaqueros Reservoir Expansion Project – Draft EIS/EIR, https://www.ccwater.com/DocumentCenter/View/3257/20-Background

Dawson, T., 2010, Preliminary Geologic Map of the Stockton 30'x 60' Quadrangle, California; California Geological Survey, unpublished.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1994, Preliminary geologic map emphasizing bedrock formations in Contra Costa County, California: A digital database: U.S. Geological Survey Open-File Report 94-622.

Graymer, R.W., Jones, D.L., and Brabb, E. E., 1996, Preliminary geologic map emphasizing bedrock formations in Alameda County, California: A digital database: U.S. Geological Survey Open-File Report 96-252, scale 1:100,000 (1:750,000 digital version).

Helley, E.J., Graymer, R. W., 1997, Quaternary geology of Alameda County, and parts of Contra Costa, Santa Clara, San Mateo, San Francisco, Stanislaus, and San Joaquin Counties, California: A digital database: U. S. Geological Survey Open-File Report 97-97, 13 pp., https://pubs.usgs.gov/of/1997/0097/

Hoek. E., Caranza-Torres, C.T., and Corkum, B., 2002, Hoek–Brown failure criterion—2002 edition *in* Bawden, H.R., Bawden, W., Curran, J., and Telesnicki, M., *editors*, Proceedings of the Fifth North American Rock Mechanics Symposium (NARMS-TAC), University of Toronto Press, Toronto, pp 267–273.

Horn, B.K.P., 1981, Hill shading and the reflectance map: Proceedings of the IEEE, v. 69, no. 1, p.14-47.

Jones, D.L. and Curtis, G.H., 1991, Guide to the geology of the Berkeley Hills, central Coast Ranges, California, *in* Sloan, Doris, and Wagner, D.L., *editors*, Geologic excursions in Northern California: San Francisco to the Sierra Nevada: California Division of Mines and Geology Special Publication 109, p. 63-74.

Knudsen, K.L., and Lettis, W.R., 1997, Preliminary maps showing Quaternary geology of twenty 7.5- minute quadrangles, eastern Stockton, California, 1:100,000 quadrangle: National Earthquake Hazards Reduction Program, U.S. Geological Survey, Final Technical Report , Award #1434-94-G- 2499.

Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000, Description of mapping of quaternary deposits and liquefaction susceptibility, nine-county San Francisco Bay region, California: U.S. Geological Survey Open-File Report 00-444.

Marinos, P., Marinos, V., and Hoek, E., 2007, Geological Strength Index (GSI). A characterization tool for assessing engineering properties for rock masses *in* Olalla, C., Perucho, A., and Romana, M., *editors*, proceedings of the ISRM workshop W1: Madrid, Spain 2007: Taylor & Francis, p.13-21.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A., and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology Open-File Report 96-08; also U.S. Geological Survey Open-File Report 96-706, 33p.

Schemmann, K., Unruh, J.R., and Moores, E.M., 2007, Kinematics of Franciscan Complex exhumation: New insights from the geology of Mount Diablo, California: Geological Society of America Bulletin, v. 120; no. 5/6; p. 543–555.

Seed, H.B., and Idriss, I.M., 1982, Ground motions and soil liquefaction during earthquakes: Monograph Series, Earthquake Engineering Research Institute, Berkeley, California, 134 p.

Seed, H.B., Tokimatsu, K., Harder, L.F., and Chung, R.M., 1985, Influence of SPT procedures in soil liquefaction resistance evaluations: Journal of Geotechnical Engineering, ASCE, v. 111, no. 12, p. 1,425-1,445.

Unruh, J.R., Dumitru, T.A. and Sawyer, T.L., 2007, Coupling of early Tertiary extension in the Great Valley forearc basin with blueschist exhumation in the underlying Franciscan accretionary wedge at Mount Diablo, California: Geological Society of America Bulletin, v. 119; no. 11/12; p. 1347–1367.

United States Geological Survey (USGS), 2015, National Watershed Boundary Dataset (WBDHU12) for Contra Costa County, California. Available online at: https://nhd.usgs.gov/wbd.html.

U.S. Geological Survey and California Geological Survey, Quaternary fault and fold database for the United States, accessed June 26, 2020b, at: https://www.usgs.gov/natural-hazards/earthquake-hazards/faults (June, 2020)

U.S. Geological Survey (USGS), 2020a, National Water Information System data available on the World Wide Web (Water Data for the Nation), http://waterdata.usgs.gov/nwis/ (May, 2020)

Witter, R.C., Knudsen, K.L, Sowers, J.M., Wentworth, C.M., Koehler, R.D., Randolph, C.E., Brooks, S.K., and Gans, K.D., 2006, Maps of Quaternary deposits and liquefaction susceptibility in the central San Francisco Bay region, California: U.S. Geological Survey Open-File Report 2006-1037, http://pubs.usgs.gov/of/2006/1037/.

Air Photos and Imagery Used

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 L1061840 flown 6/13/2005, and L106302247 flown 6/30/2005; approximate ground sample distance (GSD; aka pixel dimension) 0.81 to 0.87 meters.

USDA, CIV 284-41 through CIV 284-51, Dated 7-31-39; CIV 342-50 through CIV 342-54, and CIV 342-95 through CIV 342-109, Dated 6-9-40, approximate scale 1:20,000.

USDA, CIV 20G-65 through CIV 20G-70, Dated 4-10-50, approximate scale 1:20,000.

WAC Corporation, Inc., Flight Number WAC-85CA; Photos 14-52 through 14-55, Dated 4-13-85; and 7-203 through 7-205, Dated 4-3-85, approximate scale 1:20,000.

WAC Corporation, Inc., Flight Number WAC-97CA; Photos 13-56 through 13-60, Dated 4-25-97, approximate scale 1:20,000.

WAC Corporation, Inc., Flight Number WAC-C-99CA, Photos 7-87 through 7-88, 7-143 through 7-151, 7-211 through 7–215, Dated 4-14-99; and 8-22 through 8-24, Dated 4-15-99, approximate scale 1:20,000.

APPENDIX A: Sources of Rock Strength Data

SOURCE	NUMBER OF TESTS SELECTED
City of Clayton	27
GSI Data Collection	39
Antioch South Quadrangle	104
Honker Bay Quadrangle	60
Hayward Quadrangle	34
Livermore Quadrangle	24
Clifton Court Forebay Quadrangle	23
Walnut Creek Quadrangle	11
Dublin Quadrangle	9
Brentwood Quadrangle	8
Antioch North Quadrangle	6
Byron Hot Springs Quadrangle	4
Richmond Quadrangle	4
Total Number of Shear Tests	353

SECTION 2: GROUND MOTION ASSESSMENT

for the

CLAYTON 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

using the

2018 NATIONAL SEISMIC HAZARD MODEL

by

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P.G. 8598

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

This section of the Seismic Hazard Zone Report presents an assessment of shaking hazards from earthquakes in the Clayton Quadrangle. It includes an explanation of the probabilistic seismic hazard analysis model from which ground motion parameters are derived, and how these parameters are used to delineate liquefaction and earthquake-induced landslide zones.

PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL

Probabilistic ground motions are calculated using the United States Geological Survey (USGS) probabilistic seismic hazard analysis (PSHA) model for the 2018 Update of the National Seismic Hazard Maps (NSHMs) (Petersen and others, 2020). This model replaces ground-motion models of Petersen and others (2015, 2014, and 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 2018 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 used in the 2018 update of the NSHMs includes four ground motion models (GMMs): Abrahamson and others (2014), Boore and others (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014). For subduction zone earthquakes and earthquakes of other deep sources, GMMs developed specifically for such sources are used, including the 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. GMMs are used to calculate the 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 CGS seismic hazards mapping applications prior to 2017, 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 GMM scaling. Specifically, V_{S30} is built into GMMs as one of the predictor variables and, therefore, it is an input parameter in the 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} values 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 Clayton Quadrangle are depicted in Plate 2.1. For site investigation, 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). As in previous regulatory zone maps, the 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 USGS hazard codebase, nshmp-haz version 1.3.0, a Java library developed in support of the USGS NSHM project. The Java code library is hosted in GitHub and is publicly available at: https://github.com/usgs/nshmp-haz/. This codebase also supports the 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 2018 NSHMs is adopted in its entirety. The 2018 source model is also hosted in GitHub and is publicly available at: https://github.com/usgs/nshm-cous-2018.

APPLICATION TO LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENT

The current CGS liquefaction hazard analysis approach requires that 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 3 of this report). The 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. At each location, 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 4 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 2.2 and 2.3, respectively. Modal magnitude is depicted in Plate 2.4. Ground motion generally increases from the northeast corner to the southwest corner as distance to the Concord fault and Calaveras fault zone decreases, and is the highest in the vicinity of the Concord fault. Shaking hazards are controlled predominantly by the Concord fault with increasing contribution from the Calaveras fault toward southwest, except in the northeast corner of the quadrangle where the top contributor is the Great Valley fault zone. Other sources that contribute to shaking hazards include the Greenville fault, Great Valley fault zone, Clayton fault, Franklin fault, Hayward fault, Mount Diablo Thrust fault, Los Medanos fault, and background (gridded) seismicity. Modal magnitudes (Plate 2.4) reflects the magnitudes of earthquakes that these controlling fault sources are capable of producing. Ground motion distribution is controlled by proximity to these faults and is affected by subsurface geology. In general, when fault distances are similar, expected PGA is higher where there are softer Quaternary sediments (lower V_{S30} values) and lower where there are harder volcanic and crystalline rocks (higher V_{S30} values). The table below summarizes ranges of PGA, pseudo-PGA, modal magnitude, and V_{S30} values expected in the quadrangle.

Table 2.1. Summary of ground motion parameters used for liquefaction and earthquake-induced landslide analyses.

PGA (g)	Pseudo-PGA (g)	Modal Magnitude	V_{S30} (m/s)
0.41 to 0.62	0.34 to 0.54	6.28 to 6.50	228 to 733

REFERENCES

Abrahamson, N.A., Silva, W.J., and Kamai, R., 2014, Summary of the ASK14 ground motion relation for active crustal regions: Earthquake Spectra, vol. 30, p. 1025–1055.

Addo, K., Abrahamson, N., and Youngs, R. (BC Hydro), 2012, Probabilistic seismic hazard analysis (PSHA) model—Ground motion characterization (GMC) model: Report E658, published by BC Hydro.

Atkinson, G.M., and Macias, M., 2009, Predicted ground motions for great interface earthquakes in the Cascadia subduction zone: Bulletin of the Seismological Society of America, vol. 99, p. 1,552–1,578.

Boore, D.M., Stewart, J.P., Seyhan, E., and Atkinson, G.M., 2014. NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes: Earthquake Spectra, vol. 30, p. 1057–1085.

Bozorgnia Y., Abrahamson, N.A., Atik, L.A., Dawson T.D., and others, 2014, NGA-West2 Research Project: Earthquake Spectra, vol 30, no. 3, p. 973 –987, DOI: 10.1193/072113EQS209M.

Campbell, K.W., and Bozorgnia, Y., 2014, NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra: Earthquake Spectra, vol. 30, p. 1087–1115.

California Geological Survey, 2008, Guidelines for evaluating and mitigating seismic hazards in California: California Geological Survey Special Publication 117a, 98 p. Available on-line at: http://www.conservation.ca.gov/cgs/publications/sp117a.

California Geological Survey, 2004, Recommended criteria for delineating seismic hazard zones in California: California Geological Survey Special Publication 118, 12 p. Available on-line at: http://www.conservation.ca.gov/cgs/publications/sp118.

Cao, T., Bryant, W.A., Rowshandel, B., Branum, D. and Wills, C.J., 2003, The Revised 2002 California Probabilistic Seismic Hazard Maps. California Geological Survey, Online Report: http://www.conservation.ca.gov/cgs/Documents/PSHA/2002%20California%20Hazard%20Maps.pdf.

Chiou, B.S.-J., and Youngs, R.R., 2014. Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra: Earthquake Spectra, vol. 30, p. 1117–1153.

Field, E.H., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher,W.R., Weldon, II, R.J., and Zeng, Y., 2013, Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3)—The Time-Independent Model, U.S. Geological Survey Open-File Report 2013–1165, California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, 97 pp., available at http://pubs.usgs.gov/of/2013/1165/.

Field, E.H., Arrowsmith, R.J., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, II, R.J., and Zeng, Y., 2014, Uniform California earthquake rupture forecast, Version 3 (UCERF3) —The time independent model: Bulletin of Seismological Society of America, vol. 104, p. 1122–1180.

Frankel, A.D., Petersen, M.D., Muller, C.S., Haller, K.M., Wheeler, R.L., Layendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: U.S. Geological Survey, Open-File Report 02-420, 33 p.

Frankel, A., Chen, R., Petersen, M., Moschetti, M., and Sherrod, B., 2014, 2014 Update of the Pacific Northwest Portion of the U.S. National Seismic Hazard Maps: Earthquake Spectra, vol. 31, no. S1, p. S131–S148, DOI: 10.1193/111314EQS193M.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A. and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology Open-File Report 96-08; also U.S. Geological Survey Open-File Report 96-706, 33 p.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States National Seismic Hazard Maps: U.S. Geol. Survey Open-File Report 2008-1XXX, 60p.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps, U.S. Geol. Survey. Open-File Rept. 2014-1091, 243 pp., doi: 10.3133/ofr20141091.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2015, The 2014 United States national seismic hazard model: Earthquake Spectra, vol. 31, no. S1, p. S1–S30, doi: 10.1193/120814EQS210M.

Petersen, M.D., Shumway, A.M., Powers, P.M., Mueller, C.S., Haller, K.M., Moschetti, M.P, Frankel, A.D., Rezaeian, S., McNamara, D.E., Luco, N., Boyd, O.S., Rukstales, K.S., Jaiswal, K.S., Thompson, E.M., Hoover, S.M., Clayton, B.S., Field, E.H., and Zeng, Y., 2020, The 2018 updated of the US National Seismic Hazard Model: Overview of model and implications: Earthquake Spectra, vol. 36, no. 1, p. 5–41, doi: 10.1177/8755293019878199.

Real, C.R., Petersen, M.D., McCrink, T.P. and Cramer, C.H., 2000, Seismic Hazard Deaggregation in zoning earthquake-induced ground failures in southern California: Proceedings of the Sixth International Conference on Seismic Zonation, November 12-15, Palm Springs, California, EERI, Oakland, CA.

Wills, C.J., Gutierrez, C.I., Perez, F.G., and Branum, D.M., 2015, A next-generation V_{S30} map for California based on geology and topography: Bulletin of Seismological Society of America, vol. 105, no. 6, p. 3083–3091, doi: 10.1785/0120150105.

Zhao, J.X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H.K., Somerville, P.G., Fukushima, Y.A, and Fukushima, Y., 2006, Attenuation relations of strong ground motion in Japan using site classification based on predominant period: Bulletin of the Seismological Society of America, v. 96, p. 898–913.

SECTION 3: EVALUATION OF LIQUEFACTION HAZARD

in the

CLAYTON 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

by

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DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

This Section of the Seismic Hazard Zone Report summarizes the analyses and criteria used to delineate liquefaction hazard zones in the Clayton Quadrangle.

ZONING 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 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, density, compaction, cementation, saturation, and depth from the surface govern the degree of resistance to liquefaction. Some of these properties can be correlated to a deposit's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment.

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may, however, 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 of liquefaction, 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 characteristics of surficial deposits, liquefaction susceptibility maps are often similar to Quaternary geologic maps, varying depending on local groundwater levels. Generalized correlations between susceptibility, geologic map unit, and depth to ground water are summarized in Table 3.1.

Table 3.1. Liquefaction Susceptibility of Quaternary units in the Clayton Quadrangle.

Geologic Map Unit	Age	Sediment/Material Type	Consistency	Susceptible?*
ac, af	Late Holocene	Sand, silt, gravel, concrete	Loose to dense	Yes
Qhc	Holocene	Sand, gravel, cobbles, clay, silt	Loose	Yes
Qha	Holocene	Sand, gravel, silt	Loose to medium dense	Yes
Qhf, Qht, Qhty	Holocene	Sand, gravel, silt, clay	Loose to medium dense	Yes
Qa	Holocene to Pleistocene	Sand, silt, gravel	Loose to dense	Yes
Qpa	Latest Pleistocene	Sand, silt, gravel	Dense	Not Likely
Qpf	Latest Pleistocene	Gravel, sand, silt, clay	Dense to very dense	Not Likely below a depth of 30 feet
Qoa	Early to Late Pleistocene	Sand, silt, clay, gravel	Dense to very dense	Not Likely
Qof	Early to Late Pleistocene	Sand, gravel, silt, clay	Dense to very dense	Not Likely
QPu	Pliocene to Pleistocene	Sandstone, siltstone, gravel	Dense to very dense	Not Likely

*When saturated

Ground Motion for Liquefaction Opportunity

Ground motion calculations used by CGS for regional liquefaction zonation assessments are based on the probabilistic seismic hazard analysis (PSHA) model developed by the United States

Geological Survey (USGS) (Petersen and others, 2020) for the 2018 Update of the National Seismic Hazard Maps (NSHM). The model calculates ground motion in terms of peak horizontal ground acceleration (PGA) at a 10 percent in 50 years exceedance probability level. For liquefaction analysis, CGS modifies probabilistic PGA by a scaling factor that is a function of magnitude. Calculation of the scaling factor is based on binned magnitude-distance deaggregation of seismic source contribution to total shaking. 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 the effects of large, infrequent, distant earthquakes, as well as smaller, more frequent, nearby events are appropriately accounted for (Real and others, 2000). These weighted, pseudo-PGA ground motion values are used to calculate the seismic load imposed on a soil column, expressed as the cyclic stress ratio (CSR). A more detailed description of the development of ground shaking opportunity data and parameters used in liquefaction hazard zoning can be found in Section 2 of this report.

Liquefaction Analysis

CGS performs a 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). The calculations and correction factors used in the program are taken directly from the equations in Youd and others (2001).

The program calculates the liquefaction potential of each non-clay soil layer encountered at a test-drilling site that includes at least one SPT. CGS defines soil layers with a factor of safety (FS) relative to liquefaction hazard of 1.0 or less as potentially liquefiable. The FS is defined as the ratio of cyclic resistance ratio (CRR), which reflects the resistance to liquefaction of the soil layer, to cyclic stress ratio (CSR), which represents the seismic load on the layer. Input parameters for calculation of CRR include SPT results, groundwater level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The CSR is calculated using the pseudo-PGA provided in the ground motion analysis.

The FS is calculated for each layer in the soil column at a given borehole. The minimum FS value of all the layers penetrated by the borehole determines the liquefaction potential for that borehole location. CGS geologists use the results of this analysis, the groundwater analysis, and geologic conditions to determine the final liquefaction hazard zone.

Liquefaction Zoning Criteria

Areas underlain by materials potentially subject 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 other special study zones (Youd, 1991).

Delineation of Liquefaction Hazard Zones

Upon completion of the liquefaction hazard evaluation within the Clayton Quadrangle, CGS applied the above criteria to its findings in order to delineate Seismic Hazard Zones for liquefaction. Based on the evaluation, about 28 square kilometers (11 square miles) of the quadrangle are included in the Seismic Hazard Zone for liquefaction. The zones encompass much of the Clayton Valley, as well as most of the upland alluvial valleys including Mt. Diablo Creek, Pine Creek, and Kirker Creek.

Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Clayton Quadrangle.

Areas of Past Liquefaction

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

Artificial Fills

Artificial fill areas in the Clayton Quadrangle large enough to show at the scale of project mapping (1:24,000) have been used in the construction of river levees, detention basins, and elevated freeways within the Clayton 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

CGS collected 149 borehole logs that included penetration and associated geotechnical test data required to quantitatively analyze liquefaction potential. Most of the logs evaluated for this study are from boreholes located within the Clayton Valley and Mt. Diablo Creek alluvial valley in the central part of the map area. Analysis of blow count values and other soil property measurements reported in these logs indicate that most of the boreholes in the younger Quaternary units penetrated one or more layers of material that may liquefy under expected earthquake loading. These deposits include stream channel (**Qhc**) and stream terrace deposits (**Qhty** and **Qht**), alluvial fans (**Qhf**), and undifferentiated alluvium (**Qha** and **Qa**). 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.

In general, liquefaction analysis of boreholes in older Quaternary units indicate a low potential for liquefaction. However, in a few locations on the Clayton Valley floor in the northwestern part of the map area, borehole logs penetrating older Quaternary alluvium indicated the presence of potentially liquefiable material in the upper 30 feet of some Pleistocene fans (**Qpf**). In these areas, Seismic Hazard Zones were extended into older Quaternary units where saturated within the upper 30 feet of the subsurface. The boundary for the Seismic Hazard Zone is defined in part by the contact of young Quaternary deposits with bedrock and/or old Quaternary deposits, extending along the base of the foothills in the central and northern part of the map area and into the upland alluvial valleys.

Areas with Insufficient Existing Geotechnical Data

In areas with insufficient geotechnical data coverage, Quaternary sedimentary deposits were evaluated for seismic hazard zonation based on geologic factors, groundwater levels, and extrapolation of known soil conditions in adjacent areas. Adequate geotechnical borehole information is lacking for upland alluvial valleys in the foothills of Mt. Diablo. The Quaternary units mapped in the upland alluvial valleys typically contain varying amounts of loose, granular materials that are saturated because of the presence of near-surface groundwater following rainfall events and proximity to streams. 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.

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The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Mindy Gentry of the City of Clayton, Mary Lehman of the City of Concord, and Alfredo Hurtado of the City of Pittsburg. At CGS, Christopher Tran and Edward Southwick assisted with geotechnical data collection efforts. Terilee McGuire, Bob Moskovitz, Janine Bird, and Kate Thomas 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 Erik Frost provided technical review for this report.

REFERENCES

California Geological Survey, 2004, Recommended criteria for delineating seismic hazard zones in California: California Geological Survey Special Publication 118, 12 p. Available on-line at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp118_revised.pdf.

National Research Council, 1985, Liquefaction of soils during earthquakes: National Research Council Special Publication, Committee on Earthquake Engineering, National Academy Press, Washington, D.C., 240 p.

Petersen, M.D., Shumway, A.M., Powers, P.M., Mueller, C.S., Haller, K.M., Moschetti, M.P, Frankel, A.D., Rezaeian, S., McNamara, D.E., Luco, N., Boyd, O.S., Rukstales, K.S., Jaiswal, K.S., Thompson, E.M., Hoover, S.M., Clayton, B.S., Field, E.H., and Zeng, Y., 2020, The 2018 updated of the US National Seismic Hazard Model: Overview of model and implications: Earthquake Spectra, vol. 36, no. 1, p. 5–41, doi: 10.1177/8755293019878199.

Real, C.R., Petersen, M.D., McCrink, T.P., and Cramer, C.H., 2000, Seismic Hazard Deaggregation in zoning earthquake-induced ground failures in southern California: Proceedings of the Sixth International Conference on Seismic Zonation, November 12-15, Palm Springs, California, EERI, Oakland, CA.

Seed, H.B., and Idriss, I.M., 1971, Simplified procedure for evaluating soil liquefaction potential: Journal of the Soil Mechanics and Foundations Division of ASCE, v. 97: SM9, p. 1,249-1,273.

Seed, H.B., Idriss, I.M., and Arango, I., 1983, Evaluation of liquefaction potential using field performance data: Journal of Geotechnical Engineering, v. 109, no. 3, p. 458-482.

Seed, H.B., Tokimatsu, K., Harder, L.F., and Chung, R.M., 1985, Influence of SPT procedures in soil liquefaction resistance evaluations: Journal of Geotechnical Engineering, ASCE, v. 111, no. 12, p. 1,425-1,445.

Seed, R.B., and Harder, L.F., 1990, SPT-based analysis of cyclic pore pressure generation and undrained residual strength: Proceedings of the H. Bolton Seed Memorial Symposium, v. 2, p. 351-376.

Tinsley, J.C., Youd, T.L., Perkins, D.M., and Chen, A.T.F., 1985, Evaluating liquefaction potential, in Ziony, J.I., editor, Evaluating earthquake hazards in the Los Angeles region — An earth science perspective: U.S. Geological Survey Professional Paper 1360, p. 263-316.

Youd, T.L., 1991, Mapping of earthquake-induced liquefaction for seismic zonation: Earthquake Engineering Research Institute, Proceedings, Fourth International Conference on Seismic Zonation, v. 1, p. 111-138.

Youd, T.L., and Idriss, I.M., 1997, *editors*, Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils: National Center for Earthquake Engineering Research Technical Report NCEER-97-0022, 276 p.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder, L.F. Jr., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcusson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, K.H., 2001, Liquefaction resistance of soils; Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils: Journal of Geotechnical and Geoenvironmental Engineering, October 2001, p. 817-833.

Youd, T.L., and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering, v. 104, p. 433-446.

SECTION 4: EVALUATION OF EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

CLAYTON 7.5-MINUTE QUADRANGLE, RIVERSIDE COUNTY, CALIFORNIA

by

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CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

This Section of the Seismic Hazard Zone Report presents the analyses and criteria used to delineate of earthquake-induced landslide hazard zones in the Clayton Quadrangle.

ZONING 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 motion parameters are calculated using the United States Geological Survey (USGS) National Seismic Hazard 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 1.3). Preparation of a slope gradient (**β**) map is discussed in Section 1.

Ground Motion for Landslide Hazard Assessment

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 2018 Update of the National Seismic Hazard Maps (Petersen and others, 2020). The model is set to calculate ground motion hazard in terms of peak horizontal ground acceleration (PGA) at a 10 percent in 50 years exceedance probability level. Raster versions of the PSHA PGA and Modal Magnitude maps for the Clayton 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 ground motion parameters used in preparation of the Seismic Hazard Zone for earthquake-induced landslides can be found in Section 2 of this report.

Earthquake-Induced Landslide Hazard Potential

Earthquake-induced landslide hazard potential is derived by combining the susceptibility map (a_y) with the ground motion 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).

Earthquake-Induced Landslide Zoning Criteria

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 Earthquake-Induced Landslide Hazard Zones

Upon completion of the earthquake-induced landslide hazard evaluation within the Clayton Quadrangle, CGS applied the above criteria to its findings to delineate Earthquake Zones of Required Investigation for earthquake-induced landslides. Based on our evaluation, about 63 square kilometers (24 square miles) of the quadrangle are included in the Seismic Hazard Zone for landslides. These zones are prominent on the side slopes of many moderate to steep ridges in the map area and generally increase in frequency and size towards the southern and northeastern parts of the Clayton Quadrangle. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Clayton 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 mapped landslides with a definite or probable confidence rating are included within the Seismic Hazard Zone. Mapping and categorization of existing landslides is discussed in further detail in Section 1.

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 encompass all areas that have calculated Newmark displacements of 5 centimeters or greater.

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The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Mindy Gentry of the City of Clayton, Mary Lehman of the City of Concord, and Alfredo Hurtado of the City of Pittsburg. At CGS, Wayne Haydon provided valuable insights on the Bedrock geology of the Clayton Quadrangle. Christopher Tran and Edward Southwick assisted with geotechnical data collection efforts. Terilee McGuire, Bob Moskovitz, Janine Bird, and Kate Thomas 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 Erik Frost provided technical review for this report

REFERENCES

California Geological Survey, 2004, Recommended criteria for delineating seismic hazard zones in California: California Geological Survey Special Publication 118, 12 p. Available on-line at: http://www.conservation.ca.gov/cgs/publications/sp118.

Jibson, R.W., 2007, Regression models for estimating coseismic landslide displacement: Engineering Geology, vol. 91, issue 2-4, p. 209-218.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, no. 4, p. 406-421.

McCrink, T.P., 2001, Mapping earthquake-induced landslide hazards in Santa Cruz County *in* Ferriz, H., and Anderson, R., *editors*, Engineering geology practice in northern California: California Geological Survey Bulletin 210 / Association of Engineering Geologists Special Publication 12, p. 77-94.

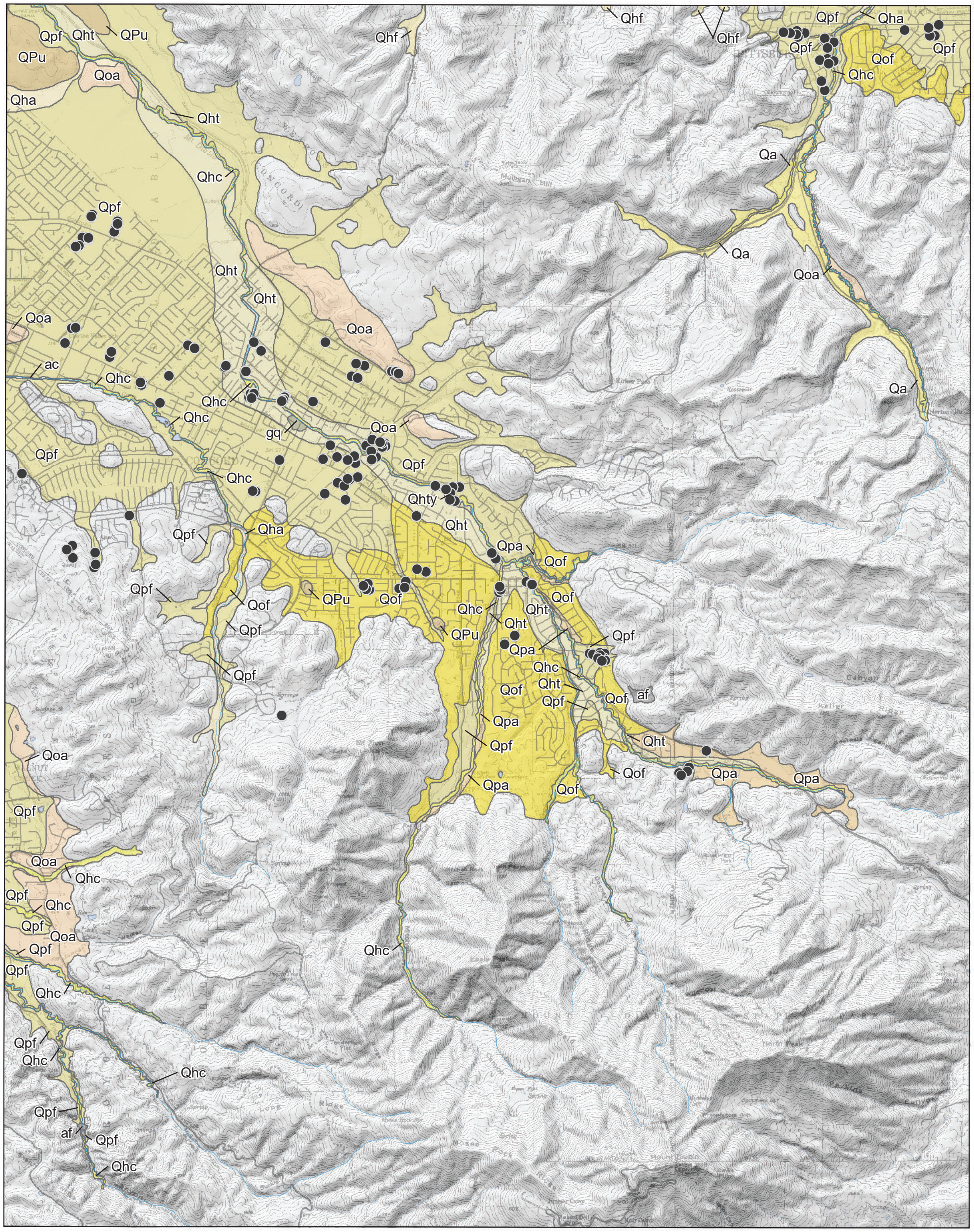
McCrink, T.P., and Real, C.R., 1996, Evaluation of the Newmark method for mapping earthquake-induced landslide hazards in the Laurel 7-1/2 minute Quadrangle, Santa Cruz County, California: California Division of Mines and Geology Final Technical Report for U.S. Geological Survey Contract 143-93-G-2334, U.S. Geological Survey, Reston, Virginia, 31 p.

Newmark, N.M., 1965, Effects of earthquakes on dams and embankments: Geotechnique, v. 15, no. 2, p. 139-160.

Petersen, M.D., Shumway, A.M., Powers, P.M., Mueller, C.S., Haller, K.M., Moschetti, M.P, Frankel, A.D., Rezaeian, S., McNamara, D.E., Luco, N., Boyd, O.S., Rukstales, K.S., Jaiswal, K.S., Thompson, E.M., Hoover, S.M., Clayton, B.S., Field, E.H., and Zeng, Y., 2020, The 2018 updated of the US National Seismic Hazard Model: Overview of model and implications: Earthquake Spectra, vol. 36, no. 1, p. 5–41, doi: 10.1177/8755293019878199.

Wilson, R.C., and Keefer, D.K., 1983, Dynamic analysis of a slope failure from the 1979 Coyote Lake, California, earthquake: Bulletin of the Seismological Society of America, v. 73, p. 863-877

Youd, T.L., 1980, Ground failure displacement and earthquake damage to buildings: American Society of Civil Engineers Conference on Civil Engineering and Nuclear Power, 2d, Knoxville, Tennessee, 1980, v. 2, p. 7-6-2 to 7-6-26.



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

CLAYTON QUADRANGLE

N

1 0.5 0 1 2 Miles

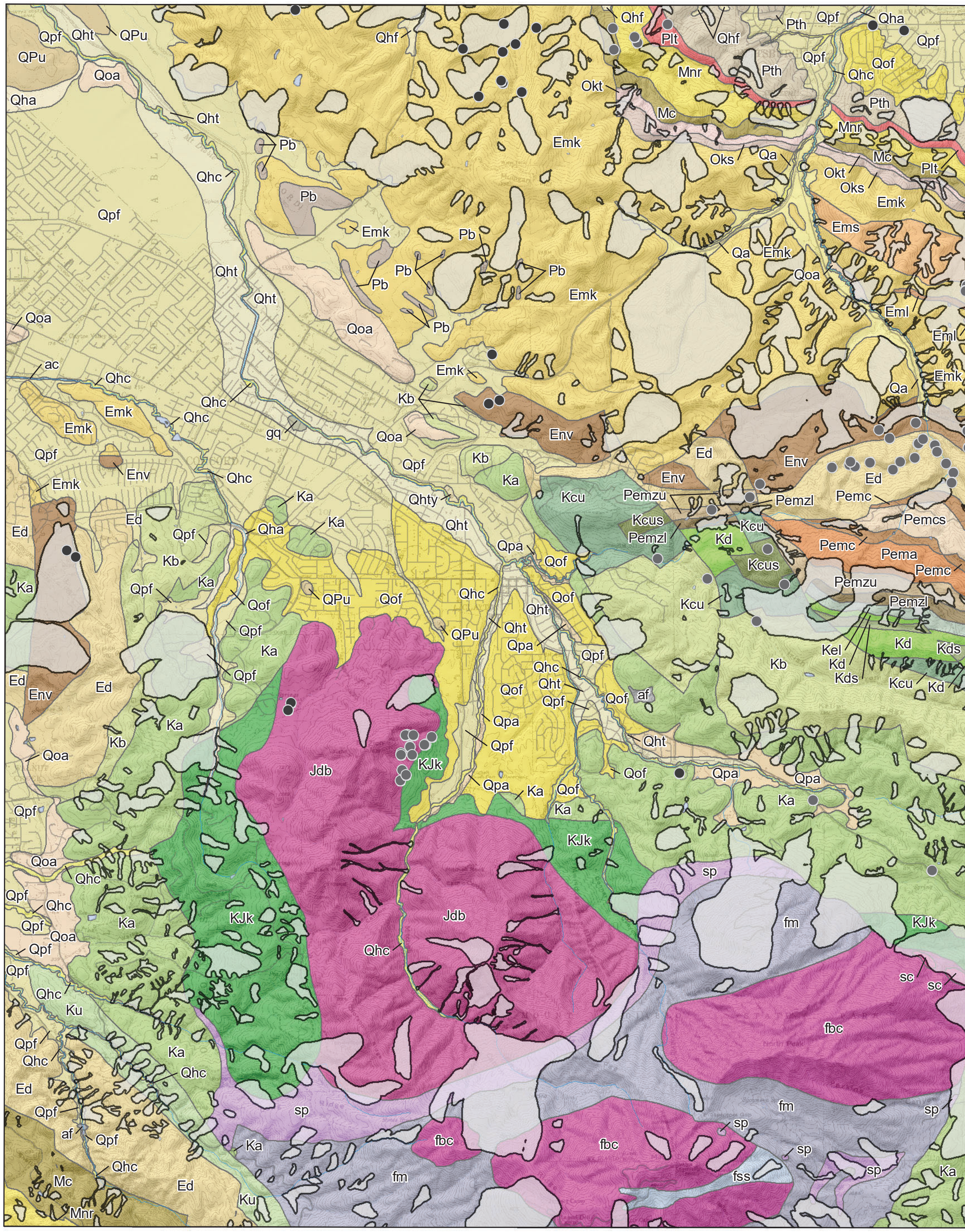
5,000 2,500 0 5,000 10,000 Feet

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, Clayton Quadrangle, California.



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

CLAYTON QUADRANGLE

N

1 0.5 0 1 2 Miles

4,900 2,450 0 4,900 9,800 Feet

1 0.5 0 1 2 Kilometers

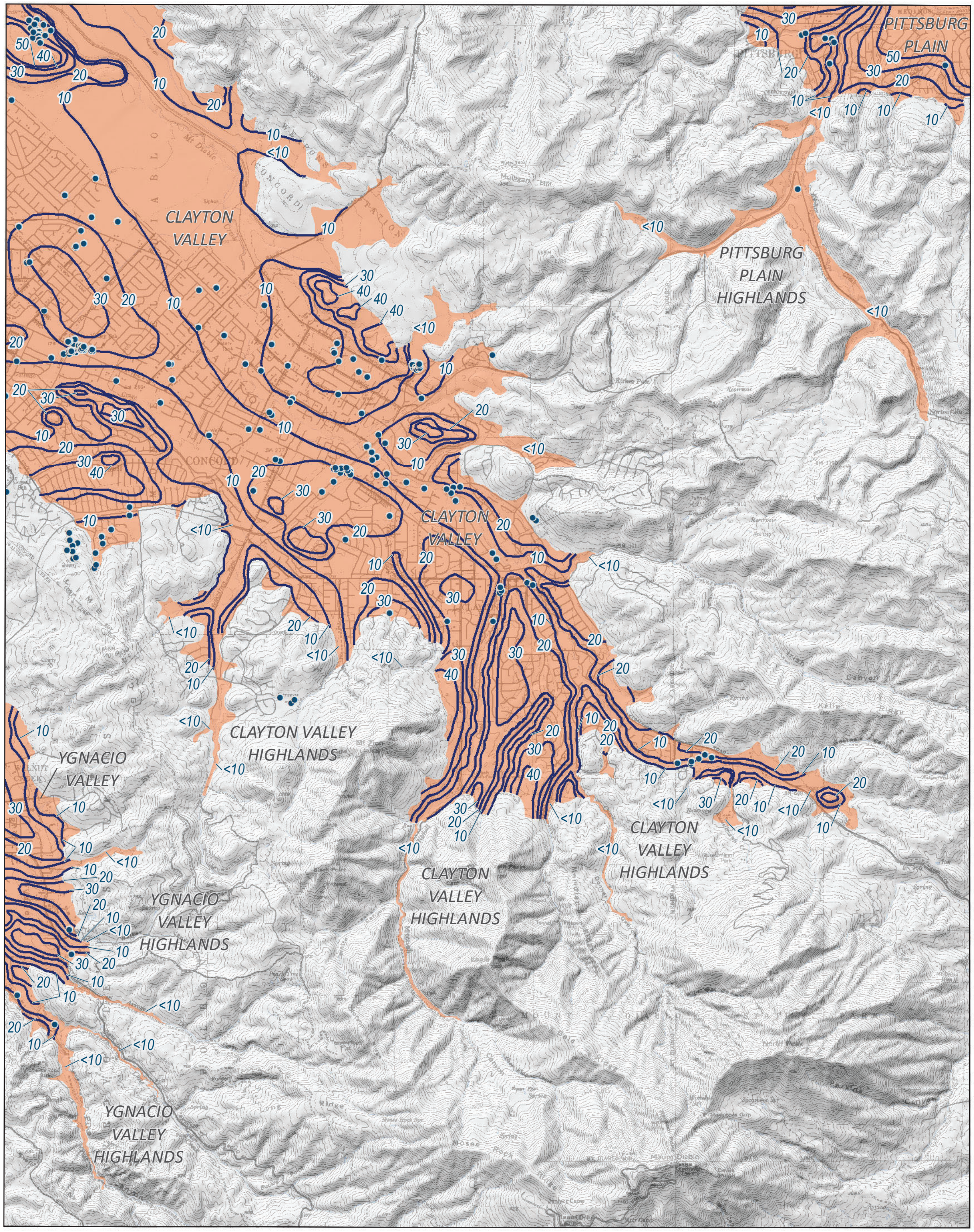
See "Geology" in Section 1 of report for descriptions of units.

Shear test sample location

GSI measurement location

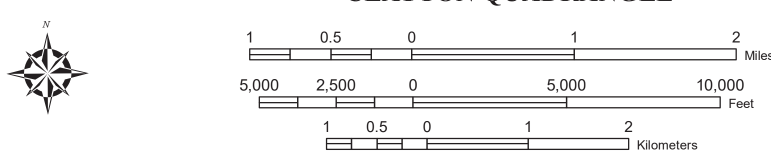
Landslide

Plate 1.2 Geologic materials and landslide inventory map with locations of shear test samples and Geologic Strength Index (GSI) measurements used in evaluating landslide hazard, Clayton Quadrangle, California.



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

CLAYTON QUADRANGLE



- Groundwater measurement location
- Depth to historic-high groundwater (in feet)
- Groundwater basin limits

Plate 1.3 Groundwater basins, depth to historic-high groundwater levels, and groundwater data points, Clayton Quadrangle, California. Department of Water Resources (DWR) groundwater basin boundaries were modified to match revised Quaternary mapping.

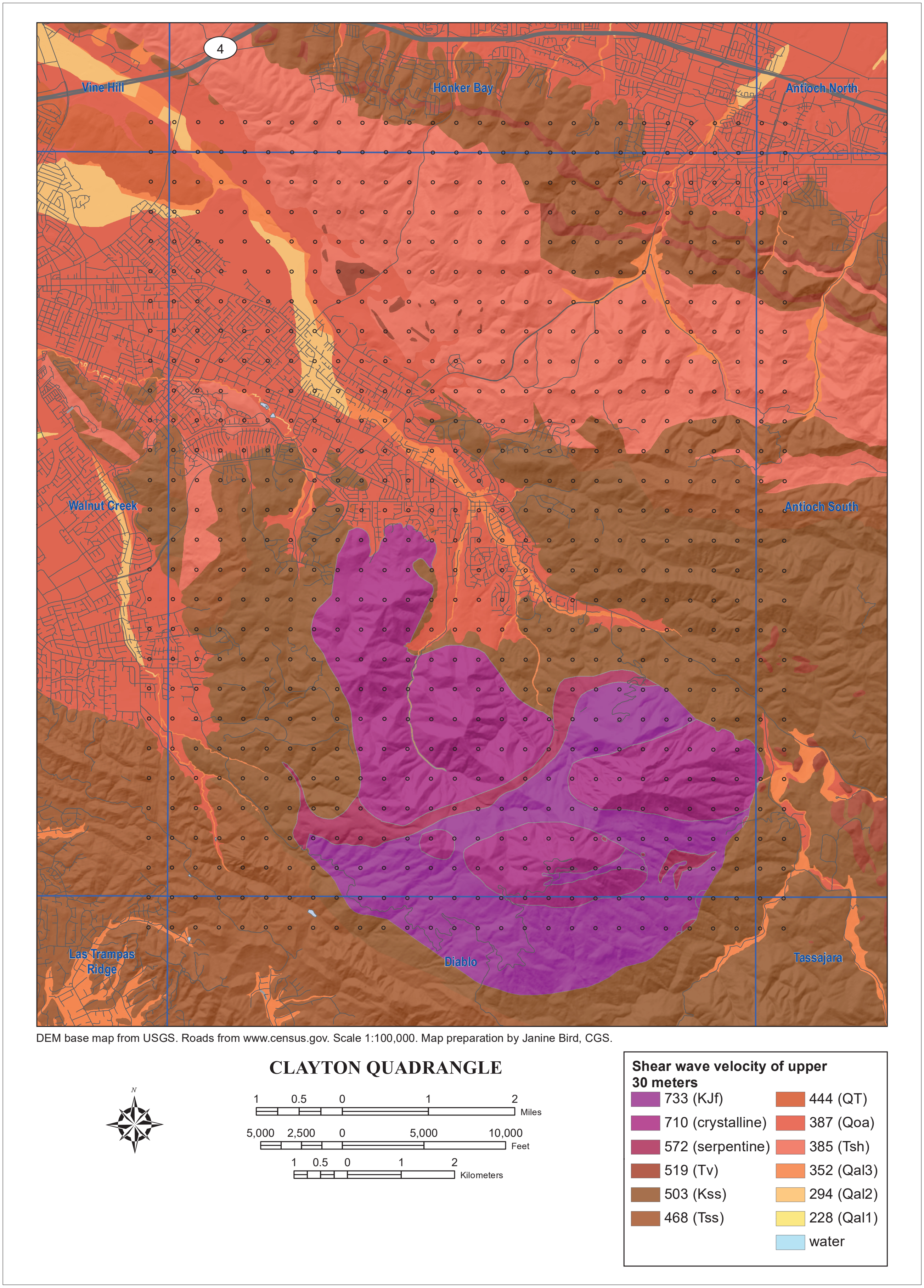


Plate 2.1 Map of V_{S30} groups and corresponding geologic units extracted from the state-wide V_{S30} map developed by Wills and others (2015), Clayton Quadrangle and surrounding area, California.

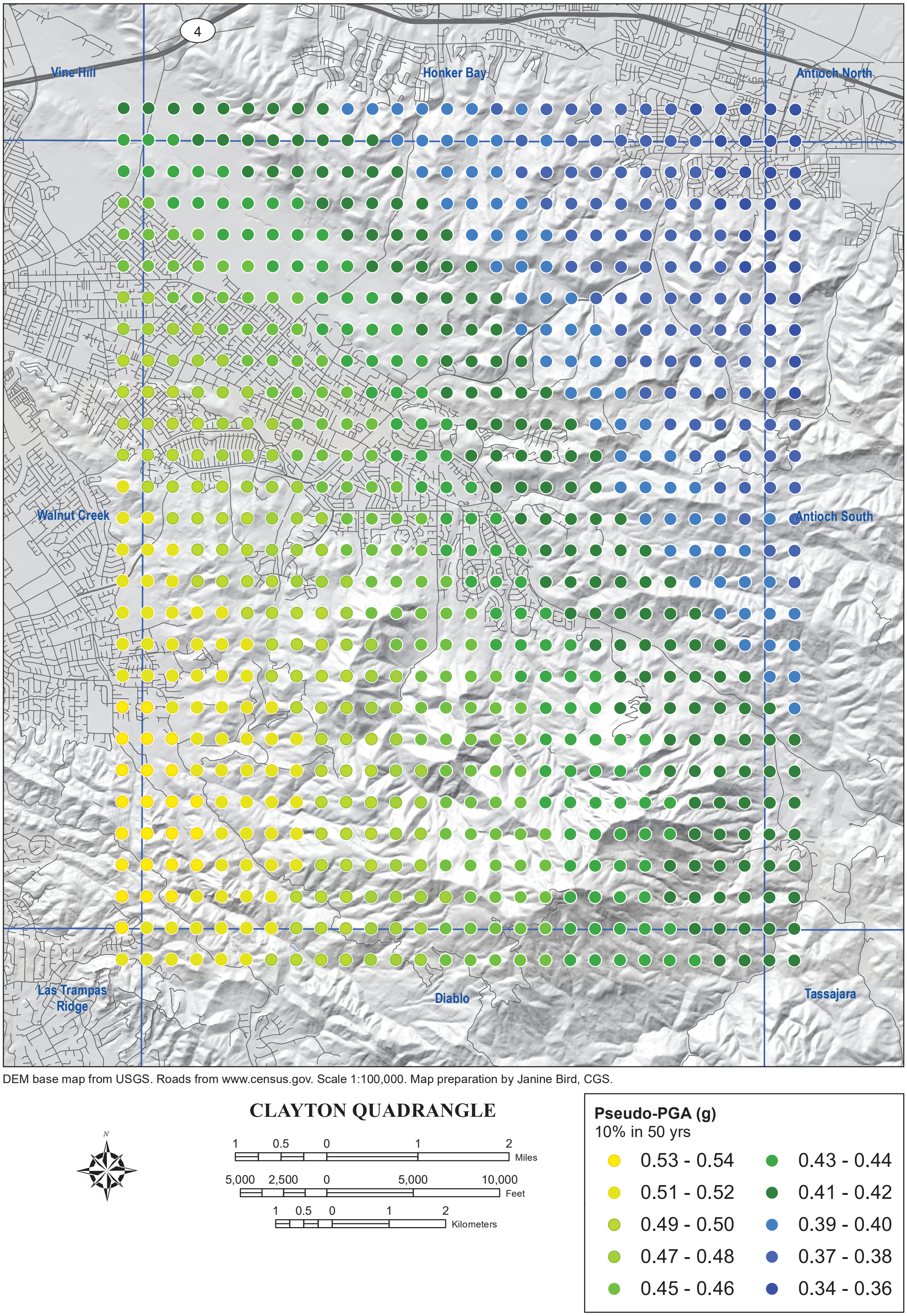
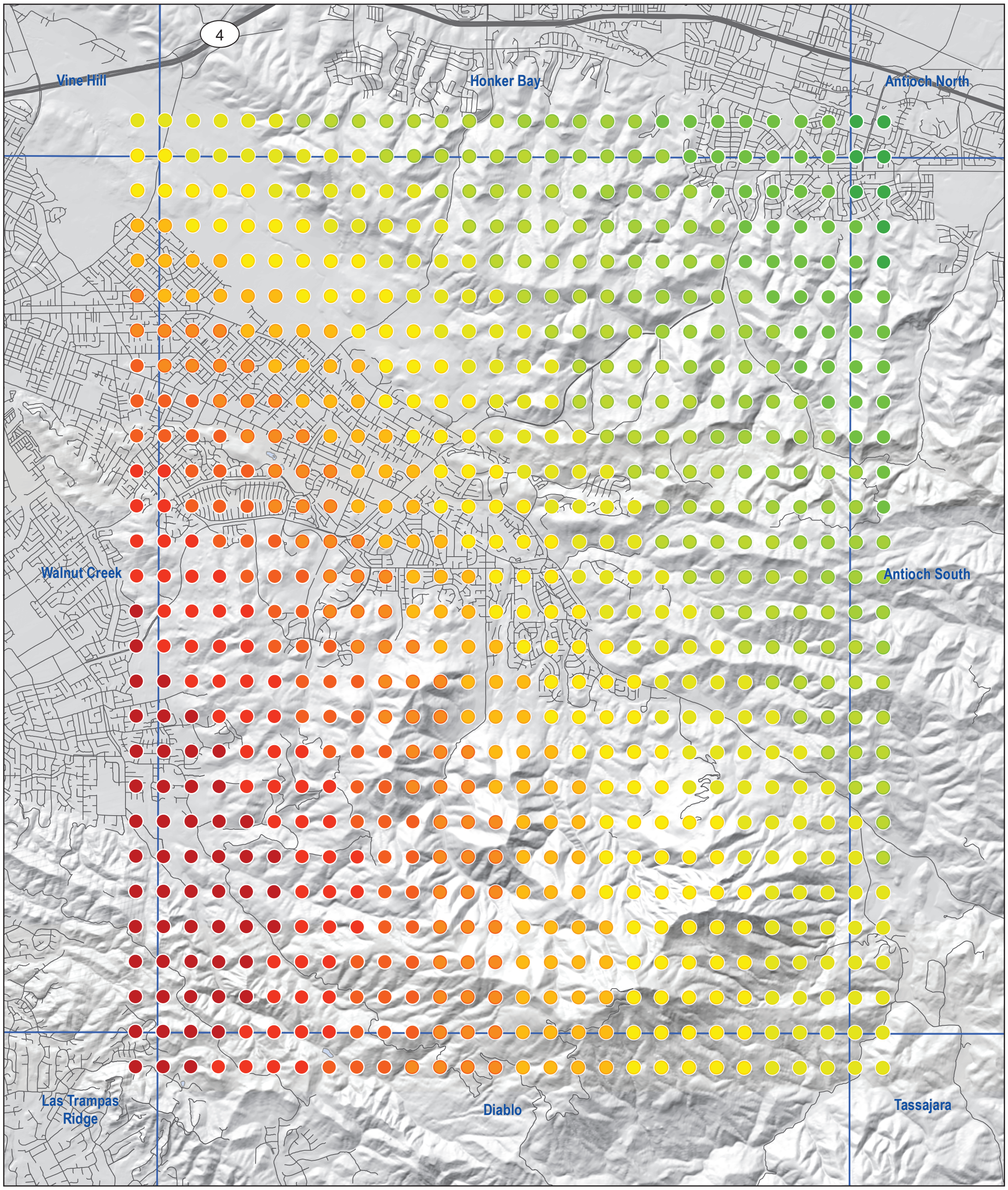


Plate 2.2 Pseudo-PGA for liquefaction hazard mapping analysis, Clayton Quadrangle and surrounding area, California.



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

CLAYTON 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

Probabilistic PGA (g)
10% in 50 yrs

- 0.61 - 0.62
- 0.59 - 0.60
- 0.57 - 0.58
- 0.55 - 0.56
- 0.53 - 0.54
- 0.51 - 0.52
- 0.49 - 0.50
- 0.47 - 0.48
- 0.45 - 0.46
- 0.43 - 0.44
- 0.41 - 0.42

Plate 2.3 Probabilistic peak ground acceleration for landslide hazard mapping analysis, Clayton Quadrangle and surrounding area, California.

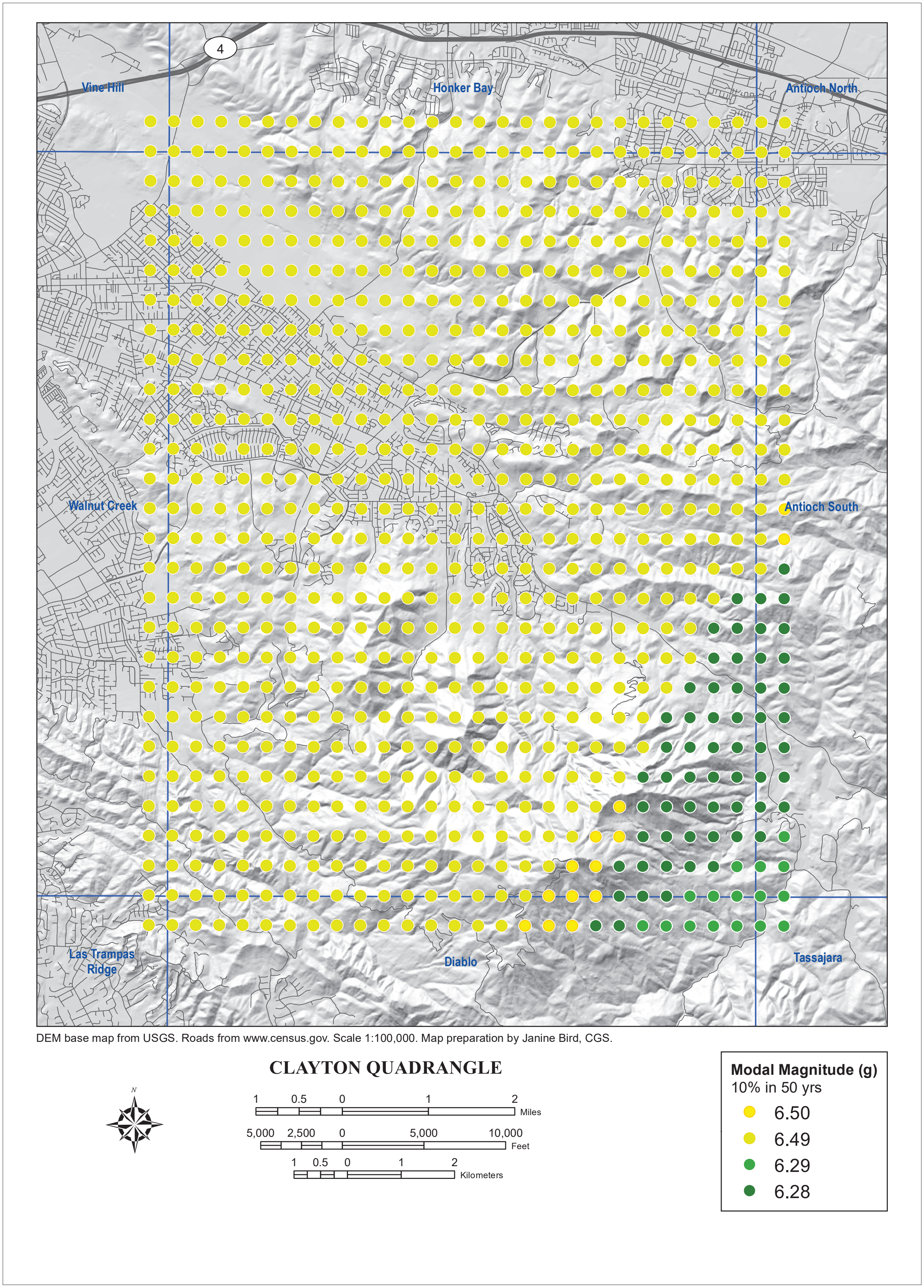


Plate 2.4 Modal magnitude for landslide hazard mapping analysis, Clayton Quadrangle and surrounding area, California.