SEISMIC HAZARD ZONE REPORT 137

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

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August 24, 2023	Preliminary Map Release
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EXECUTIVE SUMMARY

This report summarizes the sources of information and methods used to prepare the map of *Seismic Hazard Zones* (a subset of *Earthquake Zones of Required Investigation* (EZRI)) for the Diablo 7.5-Minute Quadrangle, Contra Costa County, California. The topographic quadrangle map, which covers approximately 190 square kilometers (~74 square miles) at a scale of 1:24,000 (41.7 mm = 1,000 meters; 1 inch = 2,000 feet), displays the boundaries of the EZRI for liquefaction and earthquake-induced landslides. The area subject to seismic hazard mapping includes the cities of Danville, San Ramon and the unincorporated census designated places of Alamo, Diablo, Blackhawk and Camino Tassajara.

This Seismic Hazard Zone Report describes the development of the Seismic Hazard Zone for the Diablo 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 for the 2018 *Update of the United States National Seismic Hazard Maps*.

About 30 square kilometers (11.6 square miles) of land in the Diablo Quadrangle has been designated EZRI for liquefaction hazard, encompassing much of the San Ramon, Green, Sycamore and Dougherty alluvial valleys and extending along smaller unnamed valleys and canyons dissecting the hills east of Danville and San Ramon. 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 conducted downhole and in labs indicate that these soils generally have a moderate to high likelihood of liquefying, given the level of strong ground motions this region could be subjected to.

About 50 square kilometers (19.4 square miles) of land in the Diablo Quadrangle has been designated EZRI for earthquake-induced landslides, encompassing much of the southern flank of Mount Diablo and including the moderate to steep slopes along Las Trampas Ridge, Pine Ridge, Fossil Ridge, Black Hawk Ridge, and Short Ridge; the Sherburn, Dougherty, and Tassajara hills; and minor unnamed terrain throughout the map area.

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 the 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 Diablo 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 and summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential in the Diablo Quadrangle. Sections 3 and 4 summarize the analyses and criteria used to delineate liquefaction and earthquake-induced landslide hazard zones, respectively, in the Diablo 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 most of the occurrences should be within zoned areas. Conversely, not all 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 Diablo Quadrangle include those associated with soft clay deformation, non-liquefaction-related settlement, ridge-top spreading, and shattered ridges.

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 an interactive web map service (WMS) 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/.

Information on how to purchase EZRI maps and reports is available online at: http://www.conservation.ca.gov/cgs/publications.

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

SECTION 1: GEOGRAPHY GEOLOGY AND ENGINEERING GEOLOGY

of the

DIABLO 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 Diablo 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 Diablo Quadrangle covers an area of approximately 153 square kilometers (59 square miles) in Contra Costa County, California. The center of the quadrangle lies about 42.5 kilometers (26.4 miles) east of the City of San Francisco and about 94 kilometers (58.4 miles) south by southwest of the City of Sacramento. The map encompasses developed areas along the San Ramon Valley and adjoining low lying hills. It includes the cities of Danville and San Ramon as well as the unincorporated census designated places of Alamo, Diablo, Blackhawk and Camino Tassajara. The map also covers undeveloped and protected areas such as the Mount Diablo State Park, the Sycamore Valley Open Space Preserve, the Bishop Ranch Regional preserve, and smaller city parks.

The primary topographic feature of the Diablo Quadrangle is the Mount Diablo range, a fold and thrust belt produced by a compressional domain within the western California transpressional plate boundary. The Mount Diablo range belongs to the Coast Ranges Geomorphic Province.

The northern third of the map area is defined by the southern slopes of Mount Diablo. The highest point of the quadrangle: 1000 meters (3278 feet) is located at its northern boundary. The terrain declines gradually southward to the bottom of Pine Canyon at an altitude of approximately 245 meters (800 feet) where it is bounded by a series of northwest-southeast trending ridges (Pine Ridge, Fossil Ridge, and Black Hawk Ridge) that range from about 300 meters (1000 feet) to 600 meters (2000 feet) in elevation. This terrain is eroded by seasonal and perennial creeks along perpendicular canyons (Dan Cook Canyon, Sycamore Canyon).

The southern two thirds of the map area is defined by another series of northwest-southeast trending ridges and rolling hills (Las Trampas Ridge, Short Ridge, Hemme Hills, Sherburne Hills, Dougherty Hills, and Tassajara Ridge) that range in elevation from about 180 meters (600 feet) to 400 meters (1300 feet), alternating with similarly oriented valleys (Green Valley, Sycamore Valley). This terrain is intersected by the northwest-southeast trending, roughly 15 kilometer wide, San Ramon Valley that cuts through the southwestern corner of the map area, the north-south trending Dougherty Valley, and associated smaller unnamed drainages in the southeastern corner of the map area.

Land Use

Initially inhabited by Ohlone and Miwok Native Americans, the lands in the map area were used for grazing after the arrival of Spanish colonizers in the area in 1776. Farming communities established the first permanent settlements in San Ramon Valley around 1850 and grew slowly. Ranches raised cattle and sheep and farms were planted with orchards and vineyards. The San Ramon Branch Line of the Southern Pacific was built in 1891 and established a connection to Oakland and Stockton allowing for the free movement of crops and people in and out of the area accelerating its development. Agriculture remained the basis of the area's economy for the first half of the 1900s until suburban development began. The I-680 freeway was completed in the mid-1960s and population boomed in the 1970s and 1980s. Today, most of the San Ramon Valley and adjoining Green, Sycamore and Dougherty valleys are developed with residential housing, mixed-use complexes, and some light industry. The urban centers of Danville and San Ramon have been extended eastwards with extensive grading of low-lying hills and the construction of lighter structures in the hill-slope areas. They now cover the majority of the map area. A quarter of the quadrangle remains undeveloped and protected along the slopes of Mount Diablo and some hilly ridge lands throughout the area.

The primary transportation route in the map area is the northwest-trending Interstate 680 that runs along the San Ramon Valley, connecting Danville and San Ramon to Walnut Creek to the north and Dublin and Pleasanton to the south and providing access from the region to the greater bay area. Additional access is provided by a network of city, county, and private roads in the developed areas and by fire roads and trails in undeveloped areas.

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 Diablo Quadrangle, digital topography in the form of a lidar-derived digital elevation model was obtained from Contra Costa County (https://gis.cccounty.us/Downloads/). These lidar data were collected in 2008 and present elevations at a point spacing of 3 meters, with 1-meter horizontal accuracy and 15-centimeter RMSE vertical accuracy.

For liquefaction hazard analyses, surface elevations derived from the DEM are differenced with historical-high ground water elevations to derive a "depth to water" map. In alluvial areas, the depth value obtained is 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. Slope aspect, the compass direction that a slope faces, is used to identify potential adverse geologic bedding conditions and refine the geologic material strength map.

GEOLOGY

The primary source of geologic information used in the evaluation of liquefaction and earthquake-induced landslide hazards in the Diablo Quadrangle is the CGS digital geologic map of the Stockton 30' x 60' Quadrangle (Delattre and others, 2023). This geologic map was compiled from geologic mapping by Witter and others (2006), Knudsen and others (2000), and Graymer and others (1994).

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 unit names and descriptions of bedrock deposits exposed in the study area are taken from Graymer and others (1994) and Delattre and others (2023). The Quaternary geologic unit nomenclature used by CGS for mapping in the San Francisco Bay Region was adopted from Witter and others (2006).

Bedrock Units

The bedrock geology of Contra Costa County has been divided by Graymer and others (1994) into six individual fault-bounded stratigraphic assemblages (I – VI) representing separate depositional basins or different parts of large basins that were later juxtaposed by large offsets on strike-slip and dip-slip faults during Tertiary time. Stratigraphic Assemblages II, V and VI underlie the Diablo Quadrangle and consist of lightly to highly deformed Mesozoic rock complexes: The Franciscan Complex, and the overlying Cretaceous Great Valley Sequence.

Mesozoic Rocks

Rocks of the Franciscan Complex (Jurassic to Upper Cretaceous) are exposed on the southern slopes of Mt. Diablo, at the northern edge of the map area. They represent an ancestral accretionary wedge of Jurassic oceanic crust and pelagic deposits overlain by Late Jurassic to Late Cretaceous turbidities. They consist of basalt and chert (**fbc**), a mélange of metamorphic rocks including glaucophane and other schistose rocks in a sheared sandstone and shale matrix (**KJfm**), and small bodies of serpentinite and harzburgite (**sp**).

The Great Valley Sequence (Cretaceous) is exposed in the northeastern corner of the quadrangle and is dissected by Curry Canyon. It consists of a thick sequence of interbedded sandstone, siltstone, and shale (**Ku**) originally deposited on the ocean floor by turbidity currents that was subsequently folded, faulted, and uplifted forming northwest striking bands at the surface. The Great Valley Sequence is locally divided into siltstone and mudstone with minor sandstone (**Ka**), sandstone interbedded with thin beds of siltstone and mudstone (**Kbs**), sandstone and shale (**Kus**), shale (**Kush**), siltstone with minor shale, claystone and sandstone (**Kslt**).

Cenozoic Units

Tertiary bedrock units rest unconformably on Mesozoic rocks and consist of a series of sandstone and shale formations that range from Eocene to Pliocene in age. They are exposed along northwest-trending banded outcrops forming similarly oriented ridges and valleys.

In the northern third of the map area, Pine Ridge, Fossil Ridge, and Black Hawk Ridge are underlain by the Domengine Formation (Eocene), which is locally divided into siltstone and claystone with minor sandstone and basal conglomerate (**Edl**), fine-grained, white, quartz sandstone (**Edls**) and massive, pebbly, white sandstone (**Edu**); Sobrante Sandstone (**Ms**, Early Miocene), a massive white, medium-grained calcareous quartz sandstone; Cierbo Sandstone (**Mc**, Late Miocene), a light gray, massive to thick-bedded sandstone with abundant marine fossils; the Neroly Formation (**Mnr,** Late Miocene) defined by a blue to gray, fine to coarse-grained, volcanic-rich, shallow marine sandstone, with minor gray and brown siltstone, shale, tuff and pebble conglomerate layers.

Further South and East of San Ramon Valley, Short Ridge, Hemme Hills, Sherburne Hills, Dougherty Hills, and Tassajara Ridge are underlain by the Green Valley and Tassajara formations (**PMgv**, Miocene and Pliocene) which consist of non-marine sandstone, siltstone, and conglomerate and by Livermore gravels (**QPl**, Pleistocene and Pliocene) that consist of poorly to moderately consolidated, indistinctly bedded, cobble conglomerate, gray conglomeratic sandstone, and gray coarse-grained sandstone that can locally include some siltstone and claystone.

In the southwestern corner of the map area, west of the San Ramon Valley, the Las Trampas Ridge is underlain by the Briones Formation (**Mbr**, Late and Middle Miocene), a distinctly to indistinctly bedded, gray and white, fine- to coarse-grained, quartz-lithic sandstone and shell breccia with black and red chert, quartzite, andesite, argillite, siltstone, basalt, felsic tuff, and quartz conglomerate lenses; Unnamed Sedimentary Rocks (**Mus**, Late Miocene) represented by marine and nonmarine conglomerates, sandstones, and siltstones; and the previously described Neroly Formation (**Mnr,** Late Miocene).

Quaternary Sedimentary Deposits

Approximately 31.5 square kilometers (12.2 square miles) of the Diablo Quadrangle is covered by Quaternary sediments and historical artificial materials. In total, nine different units are mapped in the Diablo Quadrangle (Plate 1.1). They are divided into groups based on age, origin, and composition (Table 1.1). The liquefaction susceptibility evaluation and development of the Seismic Hazard Zone Map for the quadrangle is based on the distribution of these deposits at a scale of 1:24,000 (Plate 1.1).

Pleistocene to Holocene alluvial sediments

Alluvial sediments occur along stream channels and adjoining flood prone areas in and at the mouth of San Ramon Valley, Green Valley, Sycamore Valley, Dougherty Valley and other smaller valleys and canyons dissecting elevated terrain throughout the map area. These deposits include undifferentiated alluvium (**Qoa**, Pleistocene; **Qha**, Holocene), alluvial fans (**Qhf**, Holocene), stream channel deposits (**Qhc**, Holocene), alluvial fan levee deposits (**Qhl**, Holocene) and stream terrace deposits (**Qht**, Holocene; **Qhty**, latest Holocene). Alluvial sediments generally consist of poorly to moderately sorted, poorly to well-bedded, loose to dense sand, gravel, silt and clay. Pleistocene age is indicated by depth of stream incision, stronger soil development and lack of historical flooding evidence.

Historical artificial fills

Artificial undifferentiated fill (**af**) is material deposited by human activity and is found throughout the map area. Fill may be engineered or non-engineered material, both of which may occur within the same area on the map. Artificial channel fill (**ac**) is material emplaced in historically active stream channels to re-route water flow.

Table 1.1. Quaternary units mapped in the Diablo 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
Qhl	Alluvial Fan Levee	Holocene
Qoa	Undifferentiated Alluvium	Pleistocene

Geologic Structure

The structural framework of the Diablo Quadrangle is governed by the transform Pacific-North American plate boundary, which accommodates 4.8 centimeters of right-lateral plate motion 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 Concord fault zones.

Plate motion along the transform boundary has resulted in a predominantly transpressional regime in the northern Diablo Range characterized by the maximum horizontal stress axis oriented northeast-southwest. In addition to strike-slip, this stress field results in differential movements among the strike-slip faults that locally generate thrust faulting, folding, and related transpressional structures (Unruh and Lettis, 1998).

In the East Bay Hills, contractional fault and fold features between the Hayward and Calaveras faults are mostly oriented west-northwest, oblique to the more north-northwest trending strike-slip faults, and exhibit a right-stepping, en echelon geometry typical of a dextral shear setting (Unruh and Lettis, 1998). However, the fold axes are oriented more north-northwest near the bounding faults, and the bounding faults display a component of reverse slip, which suggests a component of fault-normal compression in addition to fault-parallel shear.

A similar style prevails in the Diablo Range between the Calaveras and Greenville faults, where a series of west-northwest striking contractional faults and associated folds have been mapped south of Mt. Diablo and informally referred to as the Mt. Diablo fold-and-thrust belt. Compression there is enhanced by a component of fault-parallel compression related to the restraining left step between the Greenville and Concord faults (Unruh and Sawyer, 1995). Rising above this structural domain is the 1173 m peak of Mount Diablo, formed by a strongly asymmetric, doubly plunging, southwest-vergent anticline. Deformation of late Neogene strata in the fold and thrust belt point to Mount Diablo being a relatively young geomorphic feature, with most of its rise above the surrounding landscape taking place since about 4 Ma. More recent studies by Sawyer (2015) support the restraining stepover model for development of the fold-and-thrust belt and suggest the Mt. Diablo blind thrust fault has the highest slip rate of any contractional structure in the San Francisco Bay area and thus presents a significant seismic hazard to the region.

Several Quaternary faults cross the Diablo Quadrangle. The northwest-trending right-lateral strike-slip Calaveras fault marks the western border of San Ramon Valley. It is identified by geomorphic and tonal features in Holocene alluvium and is considered moderately well-defined in the southwestern corner of the map area. As such, it is included in an Alquist Priolo Fault Zone. Its northern end however is largely concealed by landsliding and inferred. An active trace of the fault cannot be traced north of Fountain Spring Court in San Ramon. The northwest-trending right-lateral strike-slip Pleasanton fault is inferred on the eastern border of San Ramon Valley, but it is not considered Holocene active. Several poorly defined thrust fault segments have been mapped south of and parallel to the Sherburne Hills but do not present evidence of Holocene activity.

Adverse Bedding Conditions

Adverse bedding conditions are an important consideration in slope stability analyses. Adverse bedding conditions occur where the dip direction of bedded sedimentary rocks is roughly the same as the slope aspect, and where the dip magnitude is less than the slope gradient. Under these conditions, landslides can slip along bedding surfaces due to a lack of lateral support. To account for adverse bedding in our slope stability evaluation, we used geologic structural data in combination with digital terrain data to identify areas with potentially adverse bedding, using methods similar to those of Brabb (1983). The structural data, strike and dip measurements, and fold axes derived from the geologic map database were used to categorize areas of common bedding dip direction and magnitude. The dip direction was then compared to the slope aspect and, if the same, the dip magnitude and slope gradient categories were compared. The area was marked as a potential adverse bedding area if the dip magnitude category was less than or equal to the slope gradient category, but greater than 25% (4:1 slope).

Existing Landslides

As a part of the geologic data compilation, an inventory of existing landslides in the Diablo Quadrangle has been prepared primarily from geomorphic analyses of lidar-derived elevation data and Google Earth Pro imagery, as well as through field reconnaissance and review of previously published landslide mapping (Davenport, 1985). The lidar dataset consists of bare earth DEM derived hillshade, contour, slope, and other derivative layers. This data was acquired by Contra Costa County in 2008 and meets QL2 accuracy with 4 points per meter pulse density. All landslides in this inventory were digitized in an ArcGIS environment at a resolution of no larger than 1:2,000.

For each landslide included on the map, several characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable, or questionable), 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 zones as described in Section 4. A small-scale version of this landslide inventory is included on Plate 1.2.

A total of 1023 landslides were mapped in the Diablo Quadrangle. There are 541 earth flows, 447 rock slides, 25 debris fans, five debris flows and five debris slides. These landslides have mostly developed on moderate to steep slopes of the southern flank of Mount Diablo, along Las Trampas Ridge, Pine Ridge, Fossil Ridge, Black Hawk Ridge, and Short Ridge; the Sherburn, Dougherty, and Tassajara hills; and minor unnamed terrain throughout the map area.

The largest amount of land covered by landslides occurs mainly in the Green Valley and Tassajara formations (**PMgv**), followed by the Franciscan Complex Mélange (**KJfm**). In terms of area percentage affected by landslides, the bedrock geologic units most susceptible to landsliding are the Franciscan Complex Mélange (**KJfm,** 63%), Basalt and Chert Block in Franciscan Complex (**fbc**, 61%), Domengine Formation Sandstone (**Edls**, 31%), and Great Valley Sequence Siltstone (**Kslt**, 26%), Sandstone (**Kus**, 23%) and Shale (**Ka**, 21%)

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

Historical-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 groundwater basins and contours reflecting historical-high depth to groundwater surface within the Diablo Quadrangle.

Groundwater Basins

The study area lies within the San Francisco Bay hydrologic region and covers the California Department of Water Resources (CDWR, 2003) designated San Ramon Valley Groundwater Basin (number 2-7). The basin is bounded by Pine Ridge, Fossil Ridge, and Blackhawk Ridge on the north, by Las Trampas Ridge on the west, by the Tassajara Hills on the east, and by the Livermore Groundwater Basin on the south. Elevations within the basin in the map area range from 100 meters (350 feet) at the northwestern edge of the San Ramon Valley to nearly 260 meters (850 feet) at the highest alluvial deposits along the southern slopes of Black Hawk Ridge. The East Bridge Green Valley, Green Valley, and Sycamore creeks as well as the Bollinger Canyon creek collect water from the northern half and southwestern corner of the map area respectively. They drain into San Ramon Creek which flows north in San Ramon Valley. The West Bridge Alamo, Alamo, and Coyote creeks collect water from the southeastern quarter of the map area. They drain into South San Ramon Creek, which flows south in San Ramon Valley. Water bearing formations are mainly Quaternary alluvial deposits (**Qhty**, **Qhc**, **Qha**, **Qhf**, **Qht**,, **Qhl**, **Qoa**) and, to a lesser degree, the unconsolidated materials of Tertiary sedimentary units (**PMgv**, **Mbr**, **Mnr**, **Mus**). Aquifer storage coefficients typically indicate unconfined conditions at depths less than 100 feet. Natural recharge occurs by infiltration of water from streams emanating from the upland areas and direct rainfall percolation. Mean annual precipitation in the study area ranges from 17 to 20 inches (CDWR, 2003). The region has a Mediterranean climate with most of the precipitation in the region occurring as rain during the late fall, winter, and early spring.

Groundwater Data

For this study, groundwater conditions were investigated in the alluvial valleys within the Diablo Quadrangle. The evaluation was based on first-encountered, unconfined water noted in geotechnical borehole logs acquired from the planning departments at Contra Costa County and the cities of Danville and San Ramon, and the State Water Resources Control Board on GeoTracker (CWRCB, 2023). These datasets reflect singular water levels from 1970 to present. Additional groundwater measurements were collected from the United States Geological Survey (USGS, 2023). The data collected from this source are generally of higher quality as they consist of monitoring wells with strict measurement protocols and record the evolution of water levels through time on hydrographs. No monitoring wells that are part of the California Department of Water Resources Statewide Groundwater Elevation Monitoring and Water Data Library (CDWR, 2023a and 2023b) are located in the map area.

Water level data evaluated in this study include groundwater measurements from 208 locations (Plate 1.3) collected from the 1970's through the present, with most records representing conditions of the past twenty years. The records reviewed indicate stable groundwater levels over this time period.

Groundwater levels from all available records were spatially and temporally evaluated in a GIS database to constrain the estimate of historically shallowest groundwater for the project area. The historical-high groundwater map was modified, where warranted, with input from current ground surface water, such as active creeks, recharge ponds, detention basins, other water impoundments, and reservoirs. The depth to groundwater contours depicted on Plate 1.3 do not represent conditions at a particular point in time, as usually presented on typical groundwater contour maps, but rather the historical high depth to groundwater anticipated for the Diablo Quadrangle.

Groundwater Levels

Historical-high groundwater depths are shallow (less than 10 feet below the ground surface) along the San Ramon, Green, Sycamore, and Dougherty alluvial valleys, reflecting the presence of surface water in perennial creeks and water recharge conditions from upland areas. As the altitude increases at the groundwater basin boundaries, the depth to measured groundwater typically increases.

Shallow water was also encountered and mapped in alluvium alongside river channels in smaller unnamed valleys and canyons. These materials are seasonally saturated with increased precipitation, heavy runoff, and stream flow.

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 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 Diablo Quadrangle, soils reports were collected from the planning departments at Contra Costa County and the cities of Danville and San Ramon. Additional borehole information was gathered from geotechnical evaluations at school sites reviewed by CGS under contract with the division of the State Architect (DSA). The data were entered into the CGS geotechnical GIS database. After an initial review process and data quality controls, 534 borehole logs were selected for this study.

Of the 534 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, included 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 geologic map units 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. A total of 20 shear tests were collected in the Diablo Quadrangle.

Shear strength data were compiled for each geologic map unit in the Diablo Quadrangle with additional data from adjoining quadrangles (Antioch North, Antioch South, Brentwood, Briones Valley, Byron Hot Springs, Clayton, Honker Bay, Las Trampas Ridge, Richmond, Walnut Creek, see Appendix A). 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 criterion is a rock mass characterization method which uses equations to relate rock mass classification through a Geological Strength Index (GSI) to the angle of internal friction of a rock mass. This method allows strength assessment based on collected data, mainly discontinuity density, discontinuity condition, and geologic material properties (Hoek and others, 2002; Marinos and others, 2007). A total of 36 shear tests were collected in the Diablo Quadrangle. The locations of rock and soil samples taken for shear testing and GSI field measurements (Hoek-Brown) within the study area are shown on Plate 1.2.

Adverse bedding conditions were identified in outcrops of the Green Valley and Tassajara formations (**PMgv**), Unnamed Sedimentary rocks (**Mus**), and areas mapped as Neroly Sandstone (**Mnr**) and Franciscan mélange (**KJfm**). These formations were subdivided based on shear strength differences between coarse-grained (higher strength) and fine-grained (lower strength) lithologies. Shear strength values for the fine- and coarse-grained lithologies were then respectively applied to areas of adverse and favorable bedding orientation as determined from structural and terrain data discussed above.

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 in section 4, 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. Ideally, shear tests of slip surfaces formed in each mapped geologic unit would be used. However, this amount of information is rarely available. We collect and compile primarily “residual” strength parameters from laboratory tests of slip surface materials tested in direct shear or ring shear test equipment. For the Diablo Quadrangle, strength parameters applicable to existing landslide planes were not available and are not included in Table 1.2.

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

	Formation Name	Number of Test	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	Edu	44	35 / 35	35 / 35	3330 / 4886		35
GROUP 2	Mc Kbs Mus(fbc) Mnr(fbc)	4 4 3 36	33 / 35 32 / 32 32 / 30 31 / 32	32 / 32	2128 / 900	fbc	32
GROUP 3	Ms PMgv(fbc) af† Qoa	3 5 5 14	28 / 29 27 / 27 27 / 25 26 / 28	27 / 28	767 / 820	Ku‖	27
GROUP 4	KJfm(fbc) Qha‡ Mbr	1 5 3	25 / 25 24 / 26 23 / 22	24 / 25	596 / 655		24
GROUP 5	Ka Ed§	5 4	21 / 23 19 / 18	20 / 22	325 / 477	sp Kush Mnr(abc) Mus(abc) PMgv(abc) KJfm(abc)	20

* cohesion values only reported based on lab data, if available.
† af includes af, ac
‡ Qha includes Qha, Qhty, Qhc, Qhf, Qht, Qhl
§ Ed includes Edl, Edls
‖ Ku includes Ku, Kslt, Kus

Table 1.3. Summary of shear strength groups for the Diablo Quadrangle, Contra Costa County.

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
Edu	Mc	Ms	KJfm(fbc)	sp
	Kbs	PMgv(fbc)	Qha	Ka
	Mnr(fbc)	af	Mbr	Kush
	Mus(fbc)	Qoa		Edl
	fbc	Ku		Mnr(abc)
				Mus(abc)
				PMgv(abc)
				KJfm(abc)

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Imagery

Lidar Hillshade derived from the 1.5 m Lidar Digital Terrain Model (2008), source of illumination: 45° sun angle, and 90° and 315° sun azimuths.

APPENDIX A: SOURCES OF ROCK STRENGTH DATA

SOURCE	NUMBER OF LAB TESTS SELECTED	NUMBER OF HOEK-BROWN TESTS SELECTED
Diablo Quadrangle	20	10
Antioch South Quadrangle	10	46
Walnut Creek Quadrangle	10	3
Honker Bay Quadrangle	5	3
Clayton Quadrangle	3	22
Byron Hot Springs Quadrangle	0	2
Briones Valley Quadrangle	0	1
Richmond Quadrangle	0	1
Total Number of Tests	48	88

SECTION 2: GROUND MOTION ASSESSMENT

for the

DIABLO 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 earthquake shaking hazards in the Diablo 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 hazard 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 (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-averaged shear-wave velocity in the upper 30 meters 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 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. The V_{S30} value at each location is assigned from 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 landslide zoning purposes, ground motions are calculated at each grid point of a 0.005-degree grid (approximately 500-meter spacing) that adequately covers the entire quadrangle. A V_{S30} map and grid points in the project area are depicted in Plate 2.1. For liquefaction zoning purposes, ground motions are calculated at each boring location. 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 CGS' liquefaction and earthquake-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 earthquake-induced 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 EARTHQUAKE-INDUCED 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 earthquake-induced 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 decreases from the west to east as distance from the Calaveras fault zone increases. Shaking hazards are controlled predominantly by the northern section of the Calaveras fault, with localized contribution from the Mount Diablo thrust fault. Other sources that contribute to shaking hazards include the Hayward fault, Greenville fault, Concord fault and background (gridded) seismicity. Modal magnitudes (Plate 2.4) reflect the magnitudes of earthquakes that the Calaveras fault zone is capable of producing. Ground motion distribution is controlled by proximity to these faults and is affected by subsurface geology. Topographic effects on ground motion are not considered in our analysis at this time. 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)
0.49 – 0.71	0.42 – 0.60	6.31 – 7.29	176 – 733

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SECTION 3: EVALUATION OF LIQUEFACTION HAZARD

in the

DIABLO 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

by

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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 Diablo 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 geologic mapping, geotechnical assessment of soils, hydrogeological and historical groundwater analyses, and probabilistic earthquake ground motions 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, compaction, cementation, saturation, and depth from the surface govern the degree of resistance to liquefaction. Some of these properties can be correlated to a deposit's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment.

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not specifically addressed in this investigation. Soil characteristics that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. In summary, soils that lack resistance (susceptible soils) typically are saturated, loose, and granular. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's inventory of areas containing soils susceptible to liquefaction begins with evaluation of 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 historical-high depths to groundwater are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on observable similarities between soil units, liquefaction susceptibility maps typically are often similar to Quaternary geologic maps, depending on local groundwater levels. CGS's qualitative relations among susceptibility, geologic map unit, and depth to ground water are summarized in Table 3.1.

Table 3.1. Liquefaction susceptibility of Quaternary units in the Diablo Quadrangle.

Geologic Map Unit	Age	Sediment/Material Type	Consistency	Liquefaction Susceptibility*
ac, af	Historical	Sand, silt, gravel, clay, cobbles, concrete	Loose to dense	Variable
Qhc	Holocene	Sand, gravel, cobbles, silt, clay	Loose	Very High
Qhty, Qht	Latest Holocene to Holocene	Sand, gravel, silt, clay	Loose to dense	High
Qhl	Holocene	Sand, silt, clay	Loose	High
Qha,	Holocene	Gravel, sand, silt, clay	Loose to dense	High
Qhf,	Holocene	Gravel, sand, silt, clay	Loose to dense	High
Qoa	Pleistocene	Sand, gravel, silt, clay	Dense to very dense	Low

*When saturated

In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and recent laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995). SPT-derived density measurements in gravelly soils are unreliable and generally too high. They are likely to lead to overestimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N values appear to have been affected by gravel content, correlations were made with boreholes in the same unit where the N values do not appear to have been affected by gravel content.

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 United States National Seismic Hazard Maps. 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-Idris 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 susceptible to liquefaction during an earthquake are included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (CGS, 2004). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following:

1) Areas known to have experienced liquefaction during historical earthquakes.
2) All areas of uncompacted artificial fill that are saturated, nearly saturated, or may be expected to become saturated.
3) Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable.
4) Areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard. Within such areas, zones may be delineated by geologic criteria as follows:
   a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes, and estuaries), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; or
   b) Areas containing soil deposits of Holocene age (less than 11,700 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; or
   c) Areas containing soil deposits of latest Pleistocene age (11,700 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

Application of the above criteria allows compilation of Earthquake Zones of Required Investigation for liquefaction hazard, which are useful for preliminary evaluations, general land-use planning and delineation of special studies zones (Youd, 1991).

Delineation of Liquefaction Hazard Zones

Upon completion of a liquefaction hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings to delineate Seismic Hazard Zones for liquefaction. Based on the evaluation, about 20 square kilometers (8 square miles) of the quadrangle are included in the Seismic Hazard Zone for liquefaction. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Diablo Quadrangle.

Areas of Past Liquefaction

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

Artificial Fills

Artificial fill areas in the Diablo Quadrangle large enough to show at the scale of project mapping (1:24,000) consist of engineered fill for river channels and levees, detention basins, elevated freeways, as well as isolated bodies of fill typically associated with construction projects of various sizes. Zoning for liquefaction in artificial fills depends on soil properties and groundwater conditions in underlying strata.

Areas with Sufficient Existing Geotechnical Data

The majority of the borehole logs evaluated for liquefaction potential using the Seed-Idriss Simplified Procedure are located in developed areas in the San Ramon, Green, Sycamore and Dougherty valleys. Analysis of blow count values and other soil property measurements reported in the logs indicate that most of the boreholes situated in Holocene deposits penetrate saturated layers of loose sand, gravel, and silt that may liquefy under the expected earthquake loading. These deposits include modern stream channel deposits (**Qhc**), Holocene stream terrace deposits (**Qhty, Qht**), Holocene alluvial fan levee deposits (**Qhl**), Holocene undifferentiated alluvial sediments (**Qha**) and Holocene alluvial fan deposits (**Qhf**) mapped along and adjacent to the downstream end of creeks.

Certain areas in Dougherty Valley mapped as Holocene undifferentiated alluvial sediments (**Qha**), Holocene stream terrace deposits (**Qht**) and Holocene alluvial fan deposits (**Qhf**) have been extensively graded and the subsurface geology recorded in the boring logs consists of consolidated fill materials that are not liquefiable according to the Seed-Idriss Simplified Procedure. The Pleistocene undifferentiated alluvial sediments (**Qoa**) mapped at the eastern end of Norris Canyon are also characterized by high density conditions that are resistant to liquefaction under the expected loading.

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 the Green and Sycamore alluvial valleys and smaller unnamed connected valleys and canyons. The Quaternary units mapped in these areas 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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SECTION 4: EVALUATION OF EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

DIABLO 7.5-MINUTE QUADRANGLE, CONTRA COSTA COUNTY, CALIFORNIA

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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 Diablo 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 in an ArcGIS environment 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 1.2). 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 United States 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 Diablo 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 $\boldsymbol{M}$ 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 an earthquake-induced landslide hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings in order to delineate Earthquake Zones of Required Investigation for earthquake-induced landslides. Based on the evaluation, about 50 square kilometers (19.4 square miles) of the quadrangle are included in the Seismic Hazard Zone for earthquake-induced landslides. It encompasses much of the southern flank of Mount Diablo and includes the moderate to steep slopes along Las Trampas Ridge, Pine Ridge, Fossil Ridge, Black Hawk Ridge, and Short Ridge; the Sherburn, Dougherty, and Tassajara hills; and minor unnamed terrain throughout the map area. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Diablo Quadrangle.

Existing Landslides

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

Hazard Zone. 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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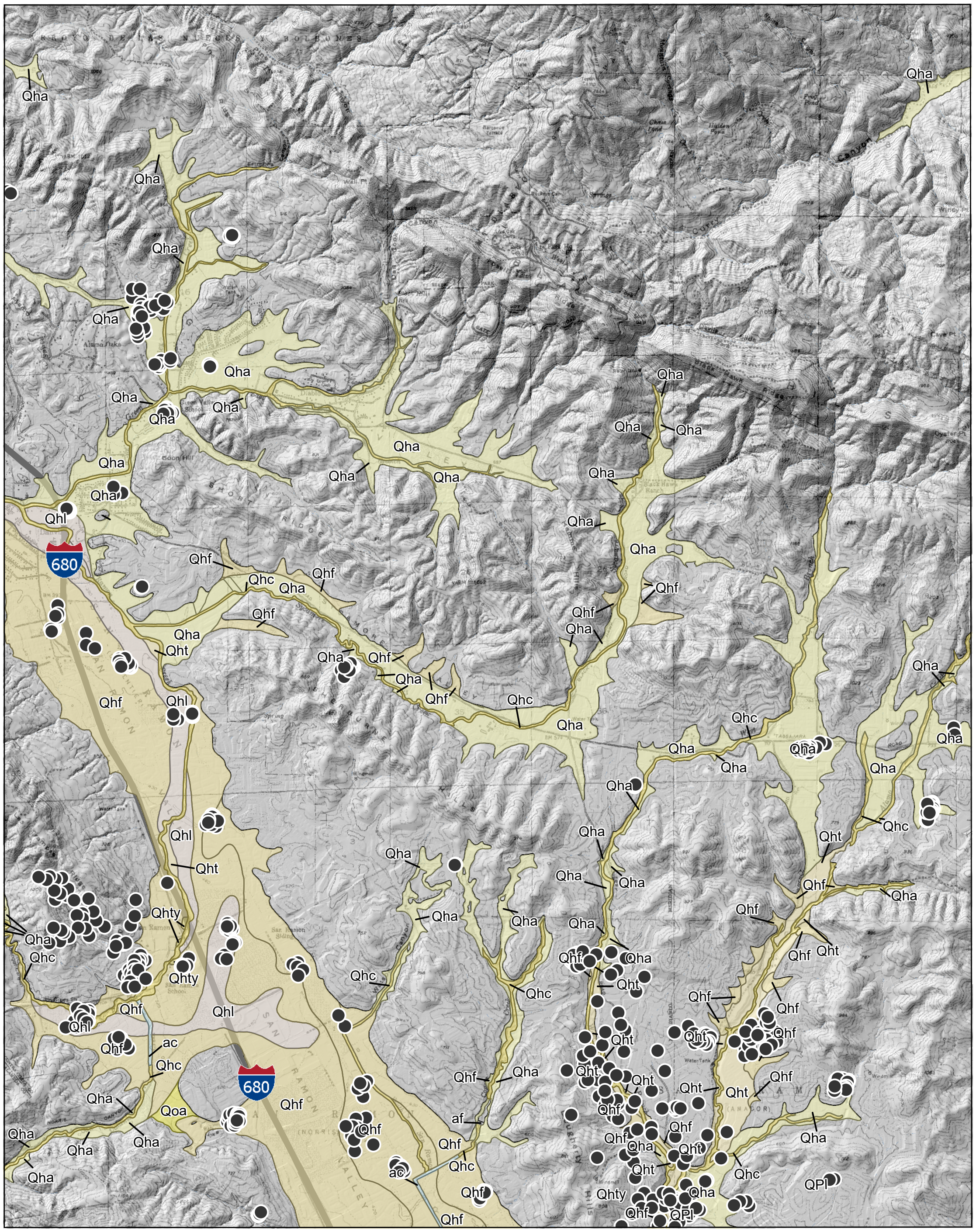
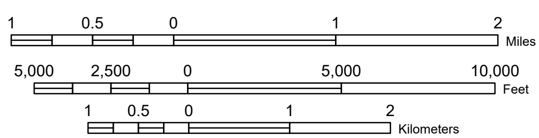
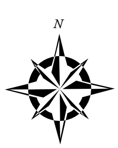


Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. See "Geology" in Section 1 of report for descriptions of units.
Pre-Quaternary bedrock units shown without color. Map preparation by Michael Falsetto, CGS.

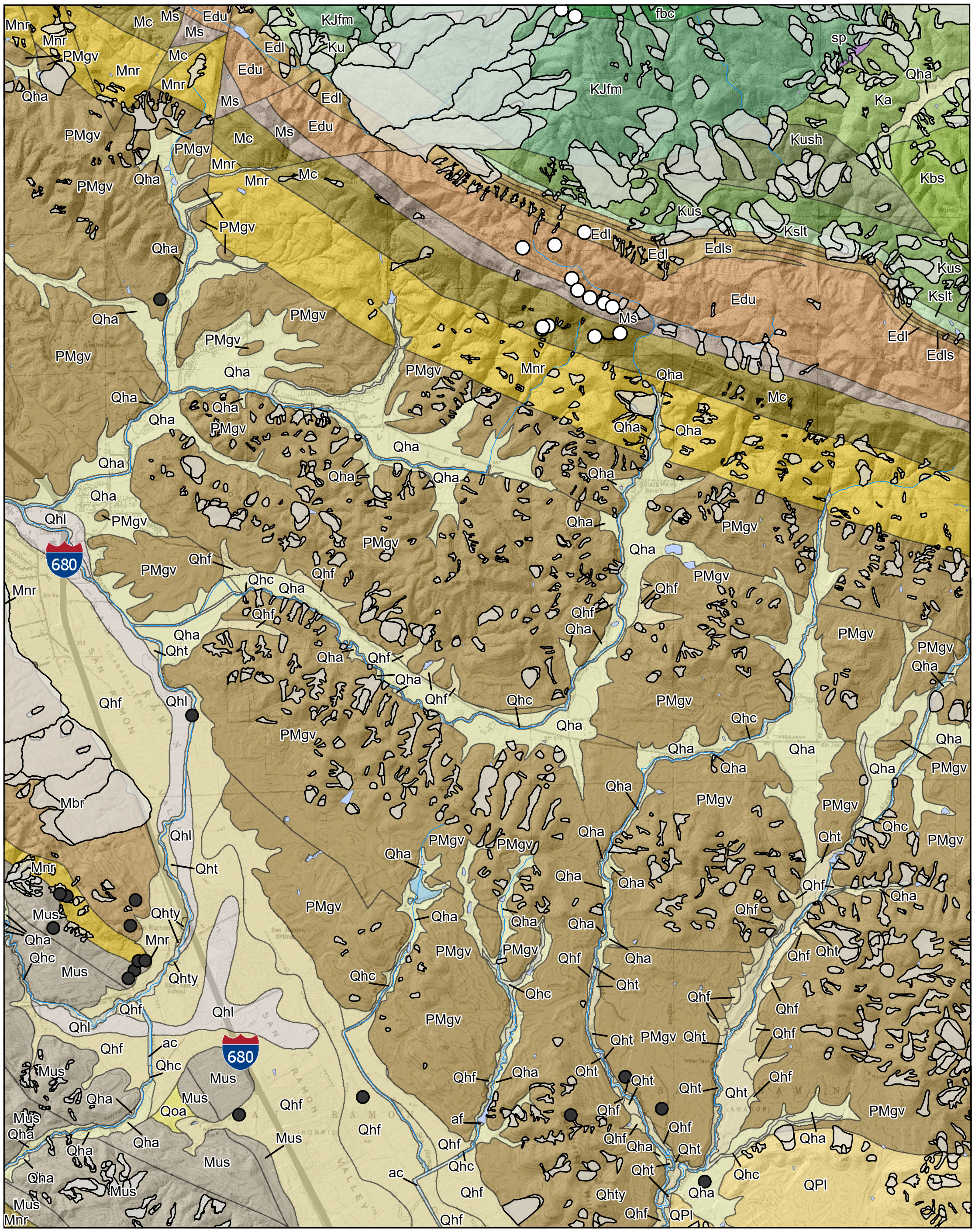
DIABLO QUADRANGLE





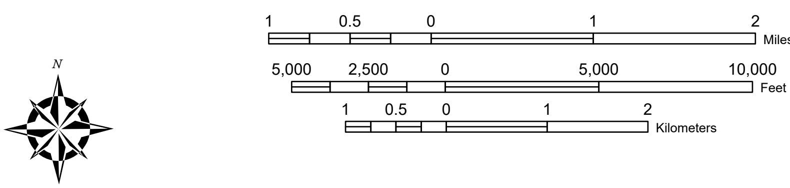
● Geotechnical boring used in liquefaction evaluation

Plate 1.1 Quaternary geologic materials map and locations of boreholes used in evaluating liquefaction hazard, Diablo Quadrangle, Contra Costa County, California.



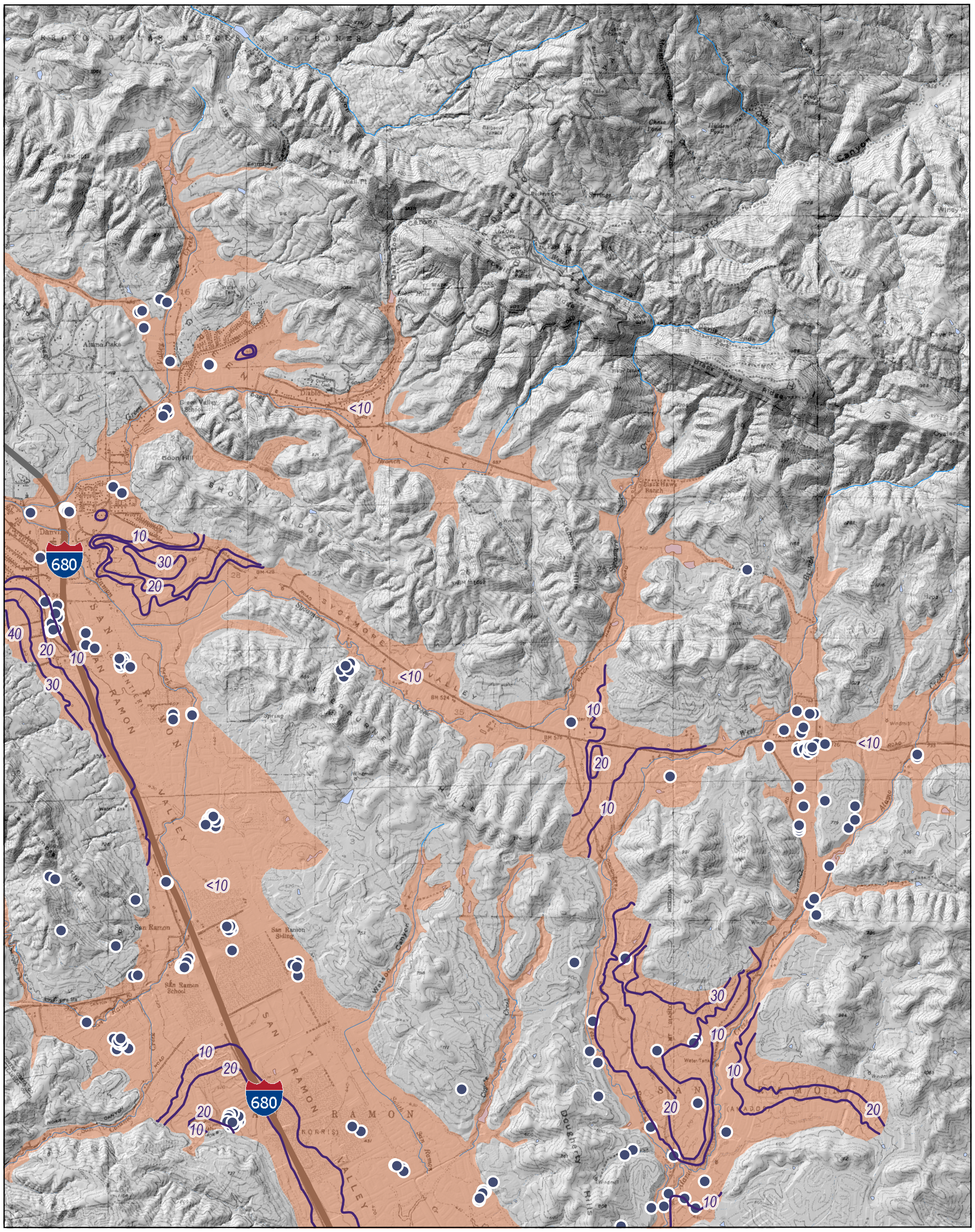
Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. See "Geology" in Section 1 of report for descriptions of units.
Map preparation by Michael Falsetto, CGS.

DIABLO QUADRANGLE



- ● 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, Diablo Quadrangle, Contra Costa County, California.



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

DIABLO QUADRANGLE

1 0.5 0 1 2 Miles

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

1 0.5 0 1 2 Kilometers

N

Groundwater measurement location

Depth to historic-high groundwater (feet)

Groundwater basin limits

Plate 1.3 Groundwater basins, depth to historic-high groundwater levels, and groundwater data points, Diablo Quadrangle, Contra Costa County, California.

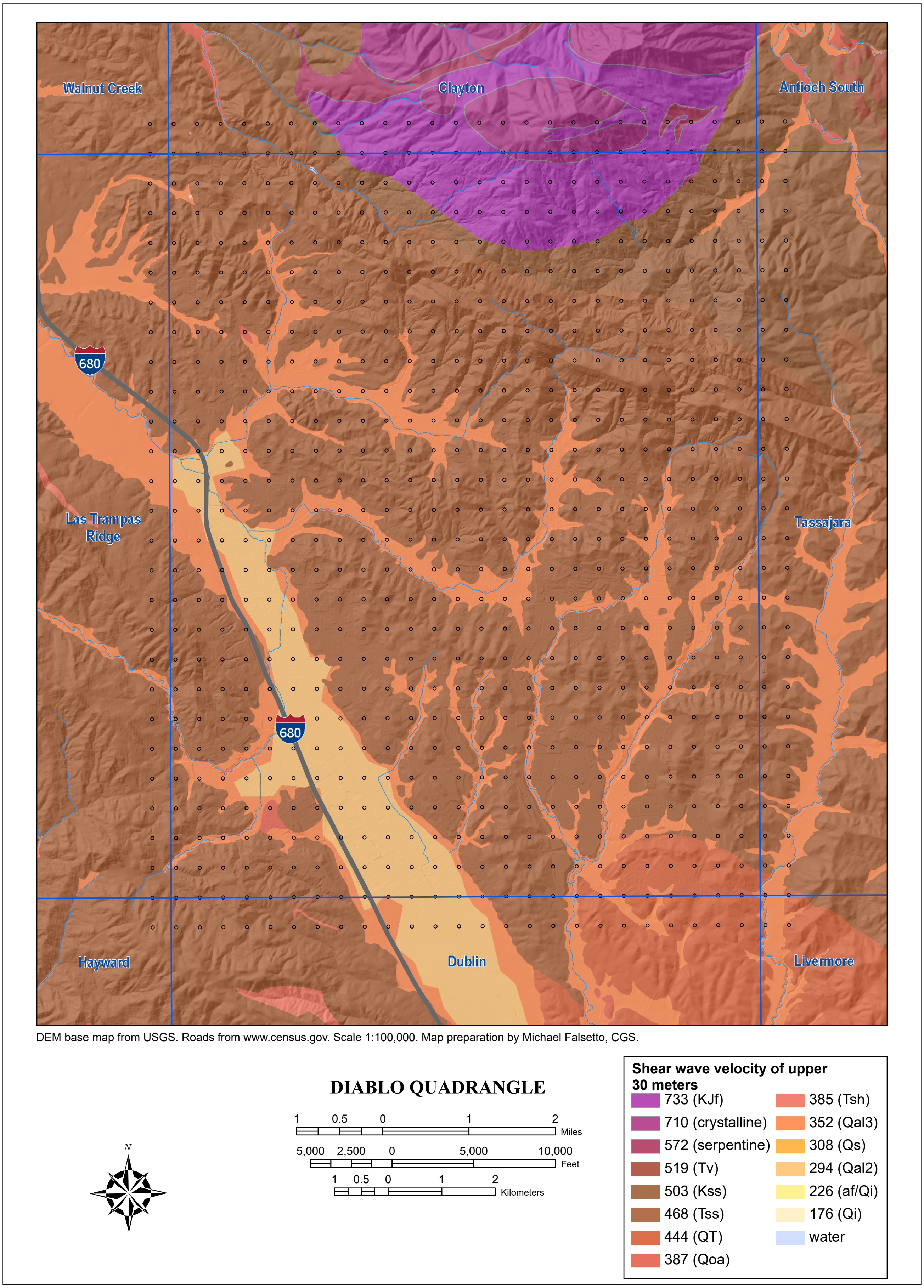
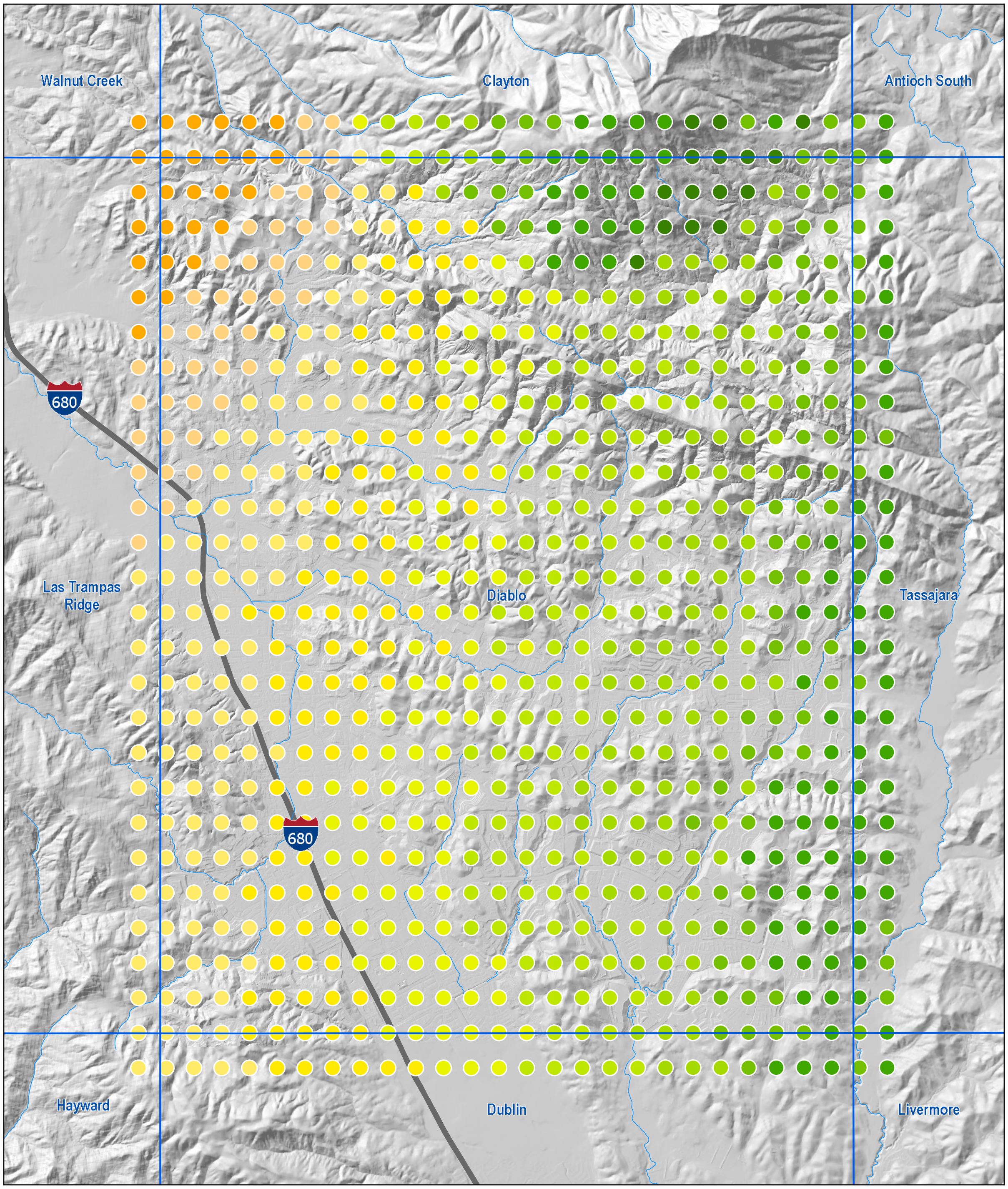
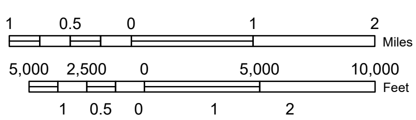


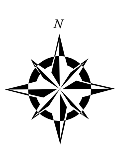
Plate 2.1 Map of V_{S30} groups and corresponding geologic units extracted from the state-wide V_{S30} map developed by Wills and others (2015), Diablo Quadrangle and surrounding area, California.



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

DIABLO QUADRANGLE





Pseudo-PGA (g)
10% in 50 yrs

0.57 - 0.60	0.49 - 0.50
0.56 - 0.56	0.48 - 0.48
0.54 - 0.55	0.47 - 0.47
0.52- 0.53	0.45 - 0.46
0.51 - 0.51	0.42 - 0.44

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

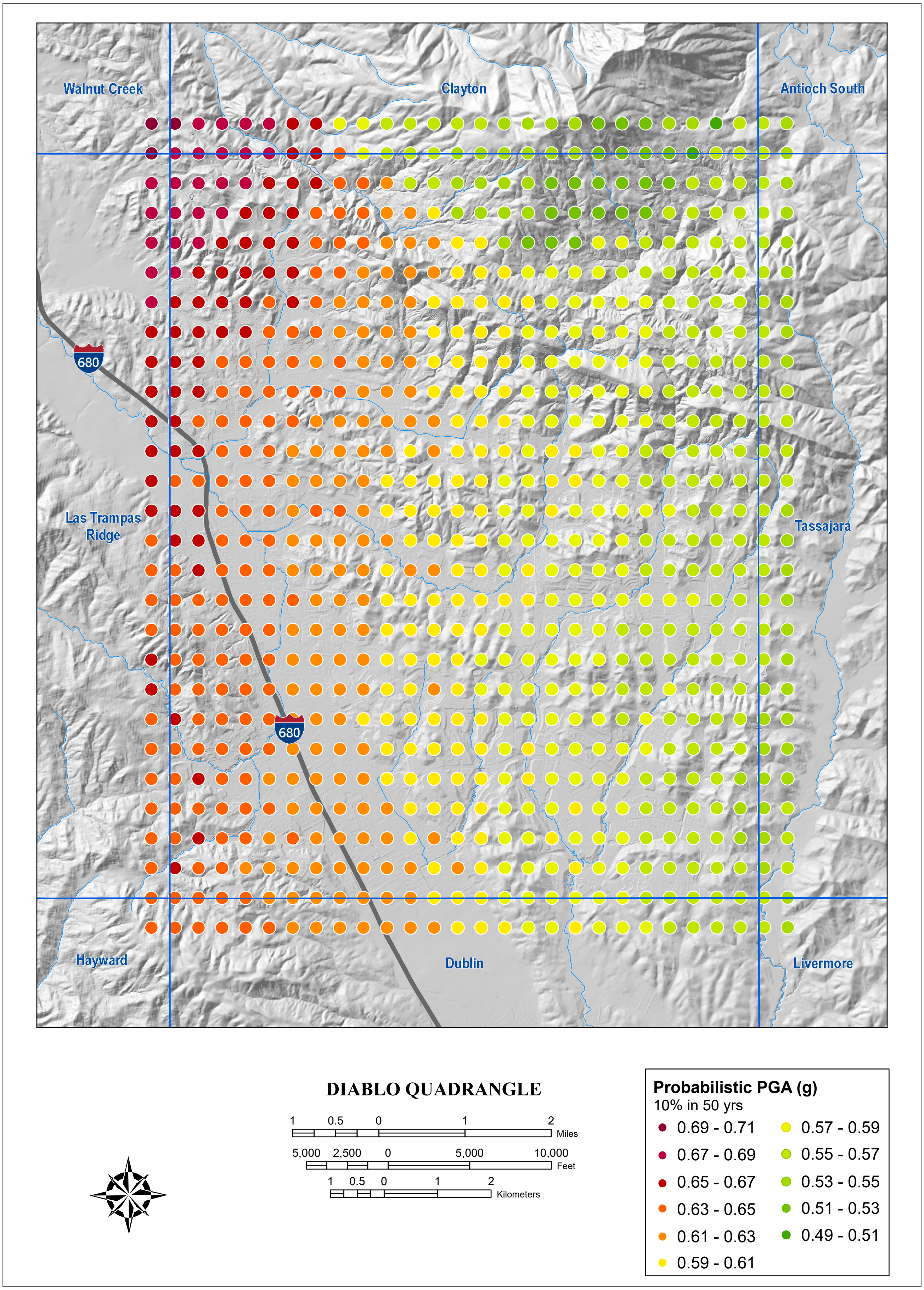


Plate 2.3 Probabilistic peak ground acceleration for landslide hazard mapping analysis, Diablo Quadrangle and surrounding area, California.

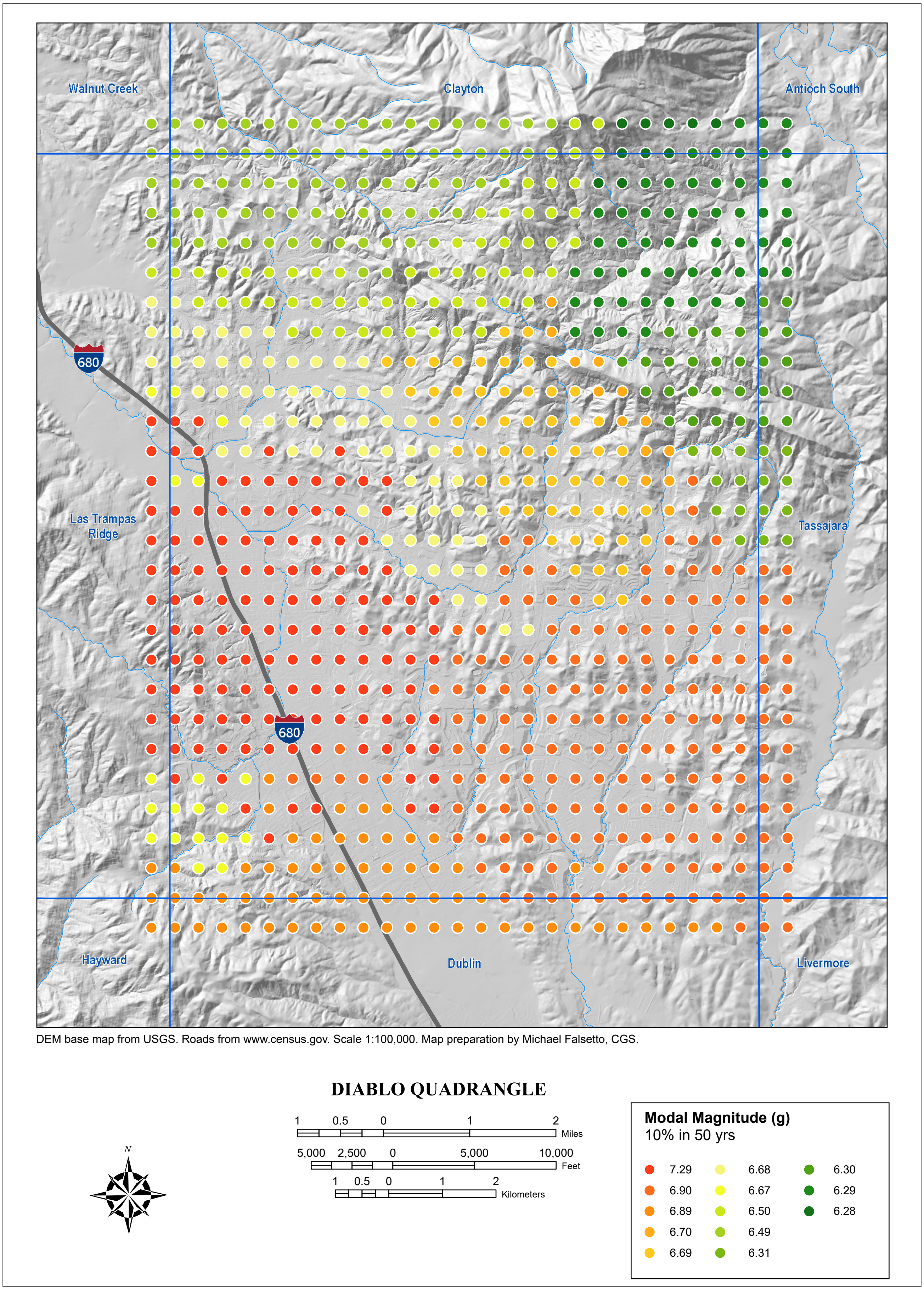


Plate 2.4 Modal magnitude for landslide hazard mapping analysis, Diablo Quadrangle and surrounding area, California.

AUTHORSHIP CREDITS

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