SEISMIC HAZARD ZONE REPORT 133

SEISMIC HAZARD ZONE REPORT FOR THE SAN FRANCISO SOUTH 7.5-MINUTE QUADRANGLE, SAN MATEO COUNTY, CALIFORNIA

2021

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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 San Francisco South 7.5-Minute Quadrangle, San Mateo County, California. The topographic quadrangle map, which covers approximately 103 square kilometers (~40 square miles) at a scale of 1:24,000 (41.7 mm = 1,000 meters; 1 inch = 2,000 feet) of San Mateo County, displays the boundaries of the EZRI for liquefaction and earthquake-induced landslides. The San Mateo County potion of the mapped area includes the cities of Brisbane, South San Francisco, Colma, Daly City, parts of San Bruno and Pacifica, and some small areas of unincorporated San Mateo County. The mapped area also includes San Bruno Mountain State and County Park and a small northeastern section of the San Francisco International Airport.

This Seismic Hazard Zone Report describes the development of the Seismic Hazard Zone for the San Francisco South 7.5-Minute Quadrangle, San Mateo County. 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 2014 *Update of the United States National Seismic Hazard Maps*.

About 23 square kilometers (9 square miles) of land within the San Francisco South Quadrangle, San Mateo County has been designated as EZRI for liquefaction, encompassing beaches and most of the alluvial plain along the shores of San Francisco Bay and the Pacific coastline. The zones extend inland along the alluvial valley associated with Colma Creek and the creeks that feed northward into Lake Merced. The zone extends into upland alluvial valleys dissecting the San Bruno Mountains and hills between Pacifica and the Colma valley, most of which feed into Colma Creek. Borehole logs of test holes drilled in these areas indicate the widespread presence of near-surface soil layers composed of saturated, loose sandy sediments. Geotechnical tests indicate that these soils generally have a moderate to high likelihood of liquefying, given that the region is subject to strong ground motion.

The area designated as EZRI for earthquake-induced landslides within the San Francisco South Quadrangle, San Mateo County is approximately 18 square kilometers (7 square miles). These zones are prominent around San Bruno Mountain and the hills between the City of Pacifica and cities of San Bruno, South San Francisco and Daly City.

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 San Francisco South Quadrangle, San Mateo County 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 San Francisco South Quadrangle, San Mateo County. Sections 3 and 4 summarize the analyses and criteria used to delineate liquefaction and earthquake-induced landslide hazard zones, respectively, in the San Francisco South Quadrangle, San Mateo County.

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 San Francisco South Quadrangle, San Mateo County 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 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 with links to the Seismic Hazards Mapping Act and the Alquist-Priolo Earthquake Fault Zoning Act is available on the CGS website: http://www.conservation.ca.gov/cgs/shp/.

SECTION 1: GEOGRAPHY, GEOLOGY AND ENGINEERING GEOLOGY

of the

SAN FRANCISCO SOUTH 7.5-MINUTE QUADRANGLE, SAN MATEO 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 San Francisco South Quadrangle, San Mateo County and then discuss the collection, processing, and analyses of primary geologic and engineering geologic data that were used to delineate EZRI.

GEOGRAPHY

Location

The San Francisco South Quadrangle, San Mateo County covers an area of approximately 103 square kilometers (40 square miles) in northern San Mateo County. The map area is within the northern part of the Coast Ranges Geomorphic Province of California. The center of the quadrangle is about 12 kilometers (7 miles) south of the City of San Francisco Civic Center and about 19 kilometers (12 miles) north-northeast of the City of San Mateo Civic Center. The San Mateo County potion of the mapped area includes the cities of Brisbane, South San Francisco, Colma, Daly City, parts of the cities of San Bruno and Pacifica, and some small areas of unincorporated San Mateo County. The mapped area also includes San Bruno Mountain State and County Park and a small northeastern portion of the San Francisco International Airport.

The northeastern and southwestern corners of the study area is dominated by San Bruno Mountain and the northern Santa Cruz Mountains, whereas the relatively flat-lying intervening Colma Valley dominates the area between these hilly parts. This flat-lying swath of land extends from the northwest corner to the southeast corner of the map. A watershed exists between Colma Creek and its tributaries, which drain both hilly areas before heading southeastwards toward the San Francisco Bay in the City of South San Francisco, and creeks or streams that drain northwards into Lake Merced, which is located towards the northwest corner of the map. Major seasonal streams within the quadrangle include Colma Creek (and its unnamed tributary creeks) and San Bruno Creek, both of which drain into San Francisco Bay. Elevations in the map area range from sea level along the Pacific Ocean coastline on the west and San Francisco Bay on the east, to 400 meters (1,314 feet) at the summit of San Bruno Mountain in the northeastern portion of the map.

Land Use

The Cities of South San Francisco, Brisbane, Colma, Daly City, and parts of the cities of Pacifica and San Bruno comprise about 76 square kilometers (29 square miles) of land along the two coastlines and through the Colma Valley that extends from Daly City through the center of the map southeastward towards the San Francisco International Airport. There are about 16.5 square kilometers (6.4 square miles) of unincorporated land in the San Francisco South Quadrangle, San Mateo County. Most of land in the quadrangle has been developed except for San Bruno Mountain State and County Park, which occupies 9.5 square kilometers (3.7 square miles), two small pieces of Golden Gate National Recreation Area, and some hills within the City of Pacifica. Other unincorporated areas include Lake Merced and the California Country Club, the Olympic Golf Club, Thornton Beach State Park along the northern Pacific coastline, and part of San Francisco International Airport on the edge of San Francisco Bay.

The primary transportation routes in the study area is are I280 and US 101, which traverse the quadrangle from the north. US 1 splits off I280 in Daly City and heads southwest to the coast, which it follows down through Pacifica. I280 traverses southeastward along the edge of the hills and I380 joins this freeway to US101 to the north of San Francisco International Airport. US 101 traverses along the edge of the Bay from the northern boundary with San Francisco County, curving inland slightly past Oyster Point, as it heads southward.

Digital Terrain Data

A digital representation of the earth’s surface is a key component in delineating liquefaction and landslide hazards. For the San Francisco South Quadrangle, San Mateo County, digital topography in the form a lidar-derived digital elevation model (DEM) with a cell size of 1.5 meters was obtained from the USGS (USGS, 2005).

For liquefaction hazard analyses, surface elevations derived from the 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. 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 sources used to evaluate the areal distribution of bedrock units and Quaternary deposits in the San Francisco South Quadrangle, San Mateo County are regional geologic maps compiled by Witter and others (2006), Brabb and others (1998), Bonilla (1998), and Brabb (1983). These maps 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 descriptions of geologic units exposed in the San Francisco South Quadrangle, San Mateo County are taken primarily from Brabb and others (1998), Bonilla and others (1998) and Witter and others (2006).

Bedrock Units

Bedrock units in the map area lie within a series of fault-bounded structural blocks and form stratigraphic assemblages that differ in depositional and deformational history.

Mesozoic rocks

The San Francisco South Quadrangle in San Mateo County is underlain by deformed Mesozoic age rocks of the Franciscan complex. Southwest of the San Andreas Fault, the Franciscan complex is composed of Jurassic oceanic crustal and pelagic deposits overlain by Late Jurassic to Late Cretaceous turbidites. It includes metamorphics (**fm**), greenstone (**KJg**), and sandstone (**KJs**). To the north of the San Andreas Fault and comprising the majority of San Bruno Mountain, the Franciscan complex includes metamorphics (**fm** and **KJm**), serpentinite (**sp**), isolated blocks of chert (**KJc**) and greenstone (**KJg**), and sandstone (**KJs** and **KJsk**).

Cenozoic rocks

The Tertiary strata in the San Francisco South Quadrangle, San Mateo County consists of units resting unconformably on Mesozoic rock complexes. Merced sandstone (**QTm**, early Pleistocene to Late Pliocene) was deposited over the Franciscan rocks and is mapped adjacent to the San Andreas Fault on its northeast side. Sandstones from the Colma Formation (**Qc**, Pleistocene) are mapped adjacent to the Merced sandstone and appear to be faulted against it by the Serra Fault (Hengesh and others, 2004; Kennedy, 2004). Colma Formation sandstones fill the valley that lies between the San Andreas Fault to the southwest and San Bruno Mountain to the northeast.

A small sliver of fault gouge (**fr**) is mapped by Bonilla (1998) along the San Andreas Fault, and includes breccia, fractured, and sheared rock. The fault gouge has a gradational contact with surrounding rocks and its limits are poorly known. Its age extends into the Holocene.

Quaternary Sedimentary Deposits

Quaternary sedimentary units mapped in the San Francisco South Quadrangle, San Mateo County (Plate 1.1) are divided into groups based on age, origin, and composition (Table 1.1).

Pleistocene to Holocene alluvial sediments

Alluvial sediments occur along stream channels and adjoining flood prone areas in and at the mouth of valleys cutting through the northern Santa Cruz mountains. These deposits include undifferentiated alluvium (**Qpa**, late Pleistocene; **Qa**, late Pleistocene to Holocene; **Qha**, Holocene; **Qhay**, Holocene), alluvial fans (**Qof**, Pleistocene; **Qpf**, late Pleistocene; **Qf**, Late Pleistocene to Holocene; **Qhf**, Holocene), and stream channel deposits (**Qhc**, 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.

Pleistocene to Holocene marine sediments

Marine Terraces (**Qmt**, Pleistocene) are present on uplifted abrasion platforms between the hills east of Pacifica and the Pacific Ocean and consist of moderately to well sorted, moderately to well bedded sand and gravel. Beach Sand (**Qhbs**, Latest Holocene) is mapped along the Pacific coastline and consists of well sorted, fine to coarse sand with some fine gravel.

Pleistocene to Holocene detrital sediments

Colluvium deposits (**Qco**, Pleistocene to early Holocene; **Qcy**, Holocene) occur on lower slopes in the Santa Cruz mountains and San Bruno Mountain and consist of friable unsorted sand, silt, clay, gravel, rock debris, and organic materials in varying proportions.

Holocene estuarine sediments

Estuarine deposits such as the San Francisco Bay Mud (**Qhbm**, Holocene) are deposited at the mouths of tidally influenced coastal streams where fresh water mixes with seawater and between the modern shoreline and the historical limits of tidal marshes and mudflats. These sediments primarily consist of silt and clay with interbedded organic-rich layers and occasionally well sorted sand and/or gravel.

Holocene basin deposits

A few small basin deposits (**Qhb**) are mapped overlying the Merced formation, east of the San Andreas Fault.

Holocene eolian sediments

Dune Sands (**Qds**, Latest Pleistocene to Holocene) occur just inland of the Pacific coastline and consist of very well sorted, fine to medium grained eolian sand that is semi-consolidated and weakly cemented.

Historical artificial fills

Artificial undifferentiated fill (**af**) is material deposited by human activity. It is found throughout the San Francisco South Quadrangle, San Mateo County, and fills many of the valley areas within the hilly parts of the quadrangle where there has been extensive development. Fill may be engineered or non-engineered material, both of which may occur within the same area on the map. Large earthen dams are mapped as artificial dam fill (**adf**). Artificial stream channels (**ac**) are modified stream channels including flood control channels and concrete canals. Artificial channel fill (**acf**) is material emplaced in historically active stream channels to re-route water flow. Artificial fill over estuarine mud (**afem**) is material deposited over estuarine sediments to develop marsh lands and mudflats.

Table 1.1 Quaternary units mapped in the San Francisco South Quadrangle, San Mateo County.

Map Unit	Environment of Deposition	Age
af	Artificial	Historical
ac	Artificial	Historical
acf	Artificial	Historical
adf	Artificial	Historical
afem	Artificial	Historical
Qcy	Colluvial/Detrital	Latest Holocene
Qha	Alluvial	Holocene
Qhb	Basin	Holocene
Qhbm	Estuarine	Holocene
Qhbs	Marine	Holocene
Qhc	Fluvial	Holocene
Qht	Fluvial	Holocene

Qhds	Marine	Holocene
Qhf	Alluvial	Holocene
Qhfy	Alluvial	Latest Holocene
Qhay	Fluvial	Latest Holocene
Qco	Colluvial/Detrital	Latest Pleistocene to Holocene
Qds	Aeolian	Latest Pleistocene to Holocene
Qa	Fluvial	Latest Pleistocene to Holocene
Qf	Alluvial	Latest Pleistocene to Holocene
Qpt	Fluvial	Latest Pleistocene
Qmt	Marine	Pleistocene
Qpf	Alluvial	Latest Pleistocene
Qpa	Alluvial	Latest Pleistocene
Qof	Alluvial	Early to late Pleistocene

Geologic Structure

The San Francisco South Quadrangle, San Mateo County, is located within the Coast Ranges geomorphic province. The Coast Ranges are northwest-trending mountain ranges and valleys subparallel to the San Andreas Fault system, which is the transform boundary between the Pacific and North American plates. Shearing is distributed across a complex system of primarily northwest-trending, right-lateral, Tertiary and Quaternary age strike-slip faults truncating and juxtaposing stratigraphic assemblages.

The Peninsula section of the right-lateral strike-slip San Andreas Fault extends 7.4 kilometers (4.6 miles) across the southwest portion of the San Francisco South Quadrangle, San Mateo County. It occupies the aligned northwest-trending linear rift valley that contain San Andreas Lake and Lower Crystal Springs Reservoir to the south in the Montara Mountain Quadrangle. This portion of the San Andreas Fault ruptured during the 1906 San Francisco earthquake (Lawson and others, 1908) and is designated by CGS as an Earthquake Zone of Required Investigation (EZRI) under the Alquist-Priolo Earthquake Fault Zoning Act.

The Serra Fault also crosses the San Francisco South Quadrangle, San Mateo County, just east of and subparallel to the San Andreas Fault. The Serra Fault extends from near the center of the southern edge of the quadrangle northwestward along the southwestern side of the Colma Valley towards the Pacific Coast, where it appears to be buried at the core of a fault-propagation fold near Fort Funston (Kennedy, 2004). Hengesh and others (2004) describe the Serra Fault as “part of a system of high-angle reverse faults that trend along the east side of the San Andreas Fault on the San Francisco Peninsula.” They refer to the system as the Peninsula Fold and Thrust Belt, which includes other similar faults such as the Sargent, Berrocal, and Shannon Faults. The Serra Fault is a southwest-dipping fault that extends for at least 20 km from Hillsborough to near Daly City. Hengesh and others (2004) propose that the Serra Fault may intersect the San Andreas Fault at shallow depths and so may not be an independent seismic source, and so may co-rupture with the San Andreas Fault. Kennedy (2004) and Hengesh and others (2004) suggest, based on dating fold growth at Fort Funston and fault trenching studies, that the last surface rupture along the Serra Fault is of late Pleistocene to Holocene age. This fault is not currently included in a

CGS designated Earthquake Fault Zone of Required Investigation (EZRI) under the Alquist-Priolo Earthquake Fault Zoning Act.

Existing Landslides

As a part of the geologic data compilation, an inventory of existing landslides in the San Francisco South Quadrangle, San Mateo County was prepared by analysis of shaded relief maps (various illumination directions) and contour data, limited field reconnaissance, and a review of previously published (Harding-Lawson, 1983; Bonilla, 1988; Jacobs Associates, 1999; Brabb and others, 2000; Wentworth and others, 1998) and unpublished geologic-landslide mapping. Landslides were reviewed using the lidar shaded-relief map (USGS, 2005), Google Earth Pro DigitalGlobe and Historical Imagery, and stereo-paired aerial photos. For each landslide included on the map several characteristics (attributes) were collected and compiled in a geodatabase. These characteristics include recency of activity, type, thickness, associated geologic unit(s), and the confidence of interpretation (definite, probable, or questionable). 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 the landslide inventory map is shown on Plate 1.2.

A total of 257 landslides were mapped in the San Francisco South Quadrangle, San Mateo County covering about 2 percent of the geologic units. There are 177 rock slides, 47 debris slides, and the rest (33) are historic and dormant earth and soil slides or debris flows. These landslides developed on moderate to steep slopes and along the coastline on over-steepened cliffs. Adverse bedding conditions do not appear to be a significant factor in any of the slope failures. However, Brabb (1983) categorizes the dips of the bedrock geologic units within the San Francisco South Quadrangle, San Mateo County as too variable to generalize in his investigation of direction and amount of bedding dip of sedimentary rocks in San Mateo County.

The largest amount of land covered by landslides occurs in areas mapped as Merced formation (**QTm**), followed by the Franciscan assemblage rocks (**KJsk**) and Franciscan greenstone (**KJg**). In terms of area percentage affected by landslides, the bedrock geologic units that appear most susceptible to landsliding are the Merced formation (**QTm**, 23%), Franciscan mélange (**fm** 11%), other Franciscan metamorphic rocks (**KJsk**, 5%; **KJs** 4% and **KJg** 4%), and fault gouge rock (**fr**, 4%). The coastline from Pacifica in the south to Thornton Beach in the north is particularly prone to slope failure due to the wave action that has accelerated erosion at the base of the coastal bluffs.

A notable historic landslide known as the Mussel Rock landslide is located along the coastline where the northwest-striking San Andreas Fault heads offshore close to Mussel Rock. The slide is located within the friable and poorly cemented sandstone of the Merced formation (Q**Tm**). The Mussel Rock Landslide and associated landslides were mapped by various authors (Smelser, 1987; Wentworth and others, 1998; Bonilla, 1998) and are thought to have been activated during all known large historical earthquakes in the area, including the 1957 San Francisco earthquake (Smelser, 1987) and the well-documented 1906 earthquake (Lawson, 1908), whose epicenter is thought to have been just offshore of here (Lomax, 2005). Some sub-slides within the Mussel Rock Landslide and other landslides in the San Francisco South Quadrangle, San Mateo County, have been graded and their geomorphology is no longer visible. Because it is not within the scope of this study to review and monitor grading practices to confirm if past slope failures have been properly mitigated, all documented slope failures, whether or not the 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 depth to groundwater surface. Plate 1.3 depicts contours reflecting the present or historic-high depth to groundwater surface within the San Francisco South Quadrangle, San Mateo County.

Groundwater Basins

The study area lies within the San Francisco Bay hydrologic region, and covers most of the California Department of Water Resources (CDWR, 2003) designated Westside Groundwater Basin (Number 2-35) and Visitacion Valley Groundwater Basin (Number 2-32). Water bearing formations are also found in smaller undesignated groundwater basins in the Milagra Valley, Laguna Salada, and along the San Andreas rift valley. Water-bearing formations are divided in two groups: unconsolidated Plio-Pleistocene materials overlying bedrock (Merced and Colma formations) and Quaternary alluvial and marine deposits. 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 rainfall percolation. Mean annual precipitation in the study area is in the range of 20 to 32 inches, with a 20-year historical average of about 23 inches (SFPUC, 2018). Additionally, artificial recharge includes infiltration of irrigation water and leakage from water and sewer pipes.

Groundwater Data

For this study, groundwater conditions were investigated for alluvial basins and plains within the San Mateo County portion of the South San Francisco Quadrangle. The evaluation was based on first-encountered, unconfined water noted in geotechnical borehole logs acquired from San Mateo County and the cities of Daly City, Colma, Brisbane, South San Francisco, Pacifica, and San Bruno, as well as depth to water levels recorded by the State Water Resources Control Board on GeoTracker (CWRCB, 2019a) and GeoTracker Groundwater Ambient Monitoring & Assessment (CWRCB, 2019b). These datasets reflect water levels from 1970 to present. As they represent a measurement at a point in time, this information is only valuable when compared to measurements in neighboring boreholes with an understanding of local seasonal variability. Additional groundwater measurements were collected from the California Department of Water Resources Statewide Groundwater Elevation Monitoring (CDWR, 2018) and the San Francisco Water District (SFPUC, 2018). The data collected from these sources are generally of higher quality as they consist of monitoring wells with strict measurement protocols. Water levels are recorded on hydrographs and account for variability throughout the last decade.

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 historic-high groundwater map was modified, where warranted, with input from current ground surface water, such as active creeks, recharge ponds, detention basins, other water impoundments, and reservoirs. The depth to groundwater contours depicted on Plate 1.3 do not represent conditions at a point in time, as usually presented on typical groundwater contour maps, but rather the historic high groundwater levels anticipated for the San Francisco South Quadrangle, San Mateo County.

Groundwater Levels

Historic-high groundwater levels are shallow (0-10 feet below the surface) along the San Francisco Bay and Pacific Ocean shorelines and adjoining flatlands, reflecting the neighboring open water. The water table generally is a subdued replica of the surface topography. Water contours to the depth of 10, 20 and 30 feet have been mapped in the unconsolidated materials covering the gentle slopes of the Colma Valley, Guadalupe Valley and the Visitacion Valley. Shallow water levels ranging from 0 to 10 feet below ground surface were also observed in marine terrace deposits and alluvium mapped along the Pacific coast, in alluvium mapped in the San Andreas Rift valley, the tributaries to Colma Creek, in alluvium mapped in and alongside river channels dissecting the Santa Cruz Mountains, and alluvium in streams that drain northwards into Lake Merced, just to the north of the San Mateo County boundary. These materials are seasonally saturated with increased precipitation, heavy runoff, and stream flow. Water contours were not extended into pre-Quaternary formations mapped at the surface as these areas were not evaluated for liquefaction hazard potential.

Geologic Material Testing

Liquefaction Hazard Zoning: In-Situ Penetration Resistance

Borehole logs that report the results of downhole standard penetration tests in alluvial materials are of value in liquefaction evaluations. 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 unconsolidated 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 San Francisco South Quadrangle, San Mateo County, borehole logs were collected from the files of the San Mateo County Building and cities of Brisbane, Colma, Daly City, Pacifica, San Bruno, and South San Francisco. Data from a total of 515 borehole logs were entered into the CGS geotechnical database. Borehole logs show that Holocene and latest Pleistocene alluvial layers containing gravel may occur in the stream valleys and canyons in the study area. 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.

Of the 515 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 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 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 San Francisco South Quadrangle, San Mateo County geologic map were obtained from the cities of Brisbane, Colma, Daly City, Pacifica, San Bruno and South San Francisco, and as well as from San Mateo County. The locations of rock and soil samples taken for shear testing within the San Francisco South Quadrangle, San Mateo County are shown on Plate 1.2. Shear tests from the adjoining quadrangles (San Francisco, San Mateo, and Montara Mountain) were used to augment data for several geologic formations for which little or no shear test information was available within the San Francisco South Quadrangle, San Mateo County (see Appendix A at the end of this Section).

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 in Section 4, the criteria for landslide zone mapping places all existing landslides that are mapped as definite or probable 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 San Francisco South Quadrangle, San Mateo County, strength parameters applicable to existing landslide planes were not available, so the strength parameter for existing landslides (**Qls**) is not included in this analysis.

Table 1.2. Summary of shear strength statistics for the San Francisco South Quadrangle, San Mateo County.

	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	KJg KJsk Qco Qcy Qhay Qha	9 5 36 4 7 3	31 / 30 32 / 31 29 / 30 30 / 30 31 / 32 27 / 28	31 / 30	777 / 665	KJc Qhc Qht Qhf Qhfy	31
GROUP 2	Af Qmt Qpf QTm(fine)	27 7 2 9	28 / 28 26 / 32 27 / 27 30 / 33	28 / 28	776 / 748	Qpf Qpa Qpt Qf QTm*§ Qc* KJs*	28
GROUP 3	Qobm fm	5 2	21 / 21 22 / 22	21 / 21	844 / 900	fr? sp? fm§ Qhb Qhed Qa	21
GROUP 4	Qls Qhbm	3 2	15 / 14 15 / 8	15 / 14	625 / 446	afem	15

*Units QTm and Qc and KJs were added to this group as the fine-grained units had lower Phi than the coarse-grained units. §The majority of landslides in the San Francisco South Quadrangle, San Mateo County are in QTm and fm

Table 1.3. Summary of shear strength groups for the San Francisco South Quadrangle, San Mateo County.

GROUP 1	GROUP 2	GROUP 3	GROUP 4
KJsk	KJs	fr?	Qls
KJc	QTm	sp?	Qhbm
Qco	Qmt	fm	afem
Qcy	Qof	Qobm	
Qhay	Qpf	Qa	
Qha	Qpa	Qhb	
Qhc	Qpt	Qhed	
Qht	Qf		
Qhf	Qc		
Qhfy	af		

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APPENDIX A: Sources of Rock Strength Data

SOURCE	NUMBER OF TESTS SELECTED
San Mateo County, Dept. of Building and Safety	21
City of Brisbane	5
City of Colma	3
City of Daly City	48
City of Pacifica	38
City of San Bruno	5
City of South San Francisco	55
Total Number of Shear Tests	175

SECTION 2: GROUND MOTION ASSESSMENT

for the

SAN FRANCISCO SOUTH 7.5-MINUTE QUADRANGLE, SAN MATEO COUNTY, CALIFORNIA

using the

2014 NATIONAL SEISMIC HAZARD MODEL

by

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

In PSHA, ground motion hazards from potential earthquakes of all magnitudes and distances on all potential seismic sources are integrated. GMPEs are used to calculate 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 m beneath a site (V_{S30}). In previous applications that were based on the 2008 update of the NSHM (Petersen and others, 2008), a uniform firm-rock site condition was assumed in PSHA calculation and, in a separate post-PSHA step, National Earthquake Hazard Reduction Program (NEHRP) amplification factors were applied to adjust all sites to a uniform alluvial soil condition to approximately account for the effect of site condition on ground motion amplitude. In the current application, site effect is directly incorporated in PSHA via GMPE scaling. Specifically, V_{S30} is built into GMPEs as one of the repressors or 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 San Francisco South Quadrangle, San Mateo County 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 the USGS hazard codebase, nshmp-haz (version 1.1.6), 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 2014 NSHM is adopted in its entirety. The 2014 source model is also hosted in GitHub and is publicly available at: https://github.com/usgs/nshmp-model-cous-2014/.

APPLICATION TO LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENT

The current CGS liquefaction hazard analysis approach requires 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, a 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 hazards in the quadrangle are controlled predominantly by the San Andreas Fault zone. Other sources that contribute to ground motion hazards include the Hayward Fault, San Gregorio Fault, Calaveras Fault, Pilarcitos Fault and background (gridded) seismicity. Modal magnitude reflects the magnitudes of earthquakes that the San Andreas Fault can produce (Plate 2.4). Ground motion distribution is controlled by proximity to these faults and is affected by subsurface geology. In general, expected PGA is higher where there are softer Quaternary sediments (lower V_{S30} values) and lower where there are harder 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)
0.44 to 0.74	0.39 to 0.71	7.52 and 7.86	176 to 733

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SECTION 3: EVALUATION OF LIQUEFACTION HAZARD

in the

SAN FRANCISCO SOUTH 7.5-MINUTE QUADRANGLE, SAN MATEO 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 San Francisco South Quadrangle, San Mateo County.

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 SMGB (CGS, 2004).

Liquefaction Susceptibility

Liquefaction susceptibility reflects the relative resistance of a soil to loss of strength when subjected to ground shaking. Physical properties of soil such as sediment grain-size distribution, 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 San Francisco South Quadrangle, San Mateo County.

Geologic Map Unit	Age	Sediment/material Type	Consistency	Liquefaction Susceptibility*
af, ac, acf, adf, afem, alf	Historical	Sand, silt, gravel, clay, cobbles, concrete	Loose to dense	Yes
Qa	Late Pleistocene to Holocene	Sand, gravel, silt, clay	Loose to dense	Yes
Qcy	Late Pleistocene to Holocene	Sand, gravel, silt, clay	Loose to dense	Yes
Qhbm	Holocene	Silt, clay, peat, sand	Loose	Yes
Qhc	Holocene	Sand, gravel, cobbles, silt, clay	Loose	Yes
Qhf, Qha	Holocene	Gravel, sand, silt, clay	Loose to dense	Yes
Qpf	Late Pleistocene	Gravel, sand, silt, clay	Loose to dense	Yes
Qt	Late Pleistocene to Holocene	Sand, gravel, silt, clay	Loose to dense	Yes
Qc	Pleistocene	Sand with some silt, clay, gravel	Loose to dense	Not likely
QTm	Late Pliocene and Early Pleistocene	Sandstone	Dense to very dense	No

*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, 2014; 2015) for the 2014 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 a project quadrangle, CGS applied the above criteria to its findings to delineate Seismic Hazard Zones for liquefaction. Based on the evaluation, about 22.8 square kilometers (8.8 square miles) of the quadrangle are included in the Seismic Hazard Zone for liquefaction. The zones encompass most of the surface streams in the quadrangle, including Colma Creek and its tributaries, the creeks that drain into Lake Merced, Guadalupe Valley, (Tucolota Creek), parts of Visitacion Valley, as well as low lying areas along the San Francisco Bay margin (including San Francisco Airport) and the Pacific coast (beaches of Daly City and around Pacifica). Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the San Francisco South Quadrangle, San Mateo County.

Areas of Past Liquefaction

There are at least 18 documented observations of historical liquefaction (five lateral spread locations and ten involving settlement, and one involving both) recorded for the area encompassed by the San Francisco South Quadrangle, San Mateo County, based on the compilation by Youd and Hoose (1978). This publication describes historical liquefaction observed during the **M** 7.8 1906 San Francisco earthquake or the **M** 5.7 1957 San Francisco earthquake, both of which affected the project area. Most of these historical observations occurred during the 1906 earthquake and were observed along the margins of Colma Creek and its tributaries, most of which occurred in artificial fill overlying Holocene deposits. One description of a lateral spread from an electric tramway south of Baden is described thus:

> *"One crack varied from 2 inches to a foot in width and extended about 1,000 feet along the filled-in roadbed. For this distance, the double tracks were twisted back and forth in a zig-zag fashion, and up and down to some extent"* (Youd and Hoose, 1978, Location No. 137).

Artificial Fills

Artificial fill areas in the San Francisco South Quadrangle, San Mateo County large enough to show at the scale of project mapping (1:24,000) consist of engineered and non-engineered fill. Examples of these fill areas are the San Francisco airport; along some of the freeways; the San Francisco Bay margins where it overlies young estuarine mud deposits (Holocene Bay Mud or **Qhbm**); infilling of valleys and creeks, mostly tributaries to Colma Creek; small areas in

Guadelupe Valley; and the landfill areas northeast and east of Visitacion Point. Non-engineered fills are commonly loose and uncompacted, and the material varies in size and type. Artificial fill in creek and valley bottoms, where overlying the young Bay Mud, and where groundwater is shallow were included in the liquefaction zone of required investigation.

Areas with Sufficient Existing Geotechnical Data

CGS collected over 500 borehole logs that included standard penetration tests and associated geotechnical test data required to quantitatively analyze liquefaction potential. These boreholes indicate a high potential for liquefaction of young Quaternary sedimentary deposits that are saturated and indicate a low potential for liquefaction of older Quaternary deposits, which is characteristic of Pleistocene and older sediments such as the Colma formation (Qc).

Areas with Insufficient Existing Geotechnical Data

Where borehole logs and associated geologic classification and material testing data are not sufficient to quantitatively analyze the potential for liquefaction in the study area, more generalized criteria are used. In general, the magnitude-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.44 g for the study area. Based on the consistent levels of high ground shaking across the study area, the age of the Quaternary sedimentary deposits and historic-high depth to groundwater are used to delineate liquefaction zones with insufficient existing geotechnical data.

Areas mapped as Late Pleistocene to modern soils, with anticipated depth to saturated soil of less than 40 feet, are included in the liquefaction zone.

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SECTION 4: EVALUATION OF EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

SAN FRANCISCO SOUTH 7.5-MINUTE QUADRANGLE, SAN MATEO 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 San Francisco South Quadrangle, San Mateo County.

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 2014 Update of the National Seismic Hazard Maps (Petersen and others, 2014; 2015). 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 San Francisco South Quadrangle, San Mateo County 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 an earthquake-induced landslide hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings to delineate Earthquake Zones of Required Investigation for earthquake-induced landslides. Based on the evaluation, approximately 18 square kilometers (7 square miles) of the quadrangle are included in the Seismic Hazard Zone for earthquake-induced landslides. These zones are prominent near the Pacific Coast, San Bruno Mountain, and the northern end of the Santa Cruz Mountains. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the San Francisco South Quadrangle, San Mateo County.

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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The authors would like to thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project. Geologic material strength data and San Mateo County General Plan - Geologic Hazard Zone information was collected with the assistance of personnel at San Mateo County. Additionally, personnel from the cities of Colma, South San Francisco and Pacifica and BART arranged access and aided in retrieving geotechnical data from files maintained at their facilities. At CGS, Florante Perez provided peer review of the landslide inventory, and Carla Rosa compiled GIS files and geology references for this quadrangle. Thanks go to students Dave Olsen, Nathan Barrett, Francisco Saldaña, and Ed Southwick, who input the geotechnical borehole data into the QGIS database and performed QA on the dataset. Terilee McGuire, Bob Moskovitz, Janine Bird, and Kate Thomas of CGS provided GIS operations and database support. Kate Thomas prepared the final Seismic Hazard Zone Map and Janine Bird prepared the graphic displays for this report. Tim McCrink and Erik Frost provided technical review for this report.

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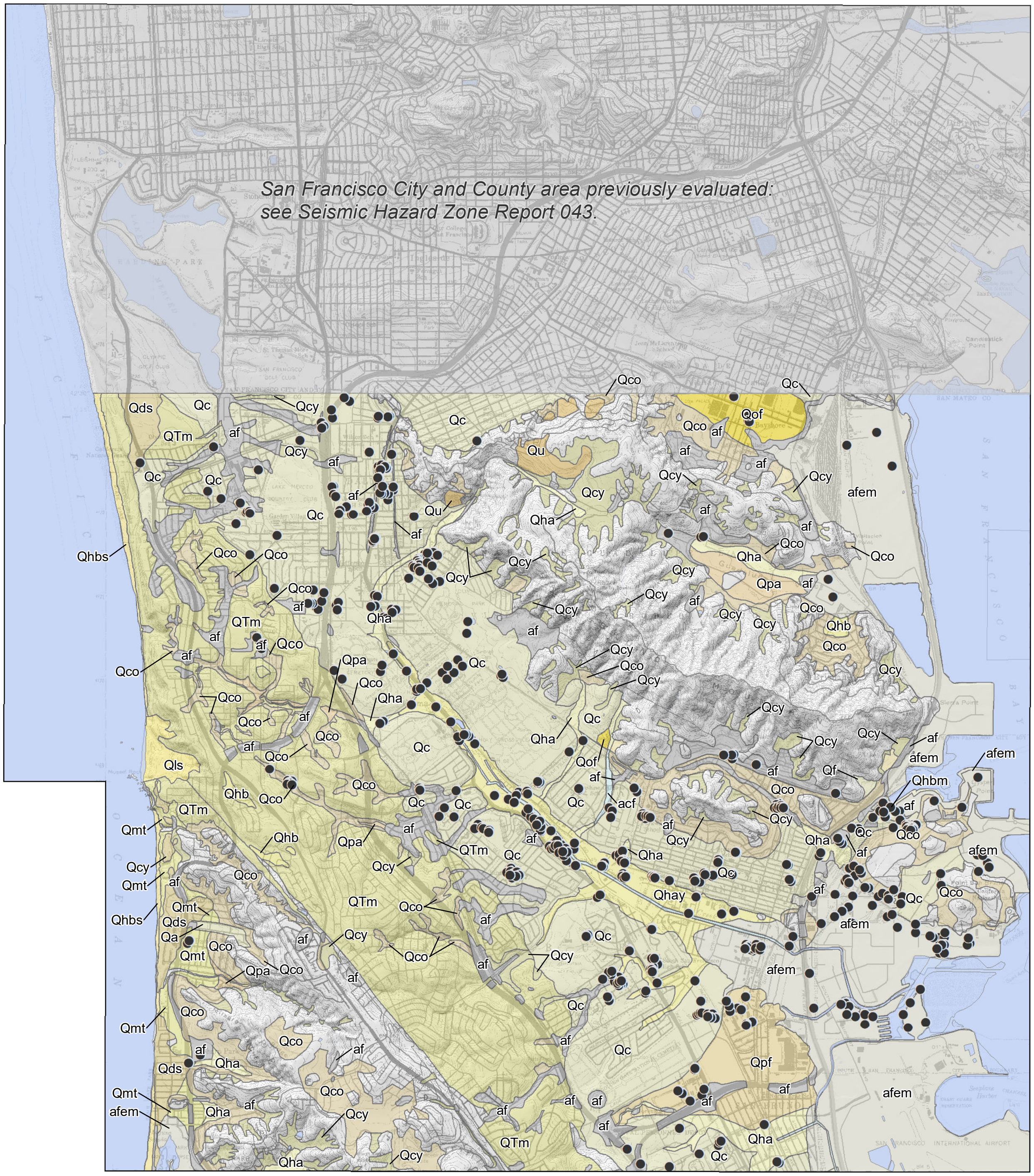
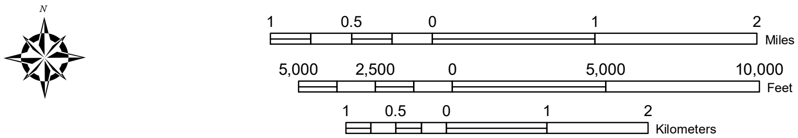


Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Janine Bird, CGS.

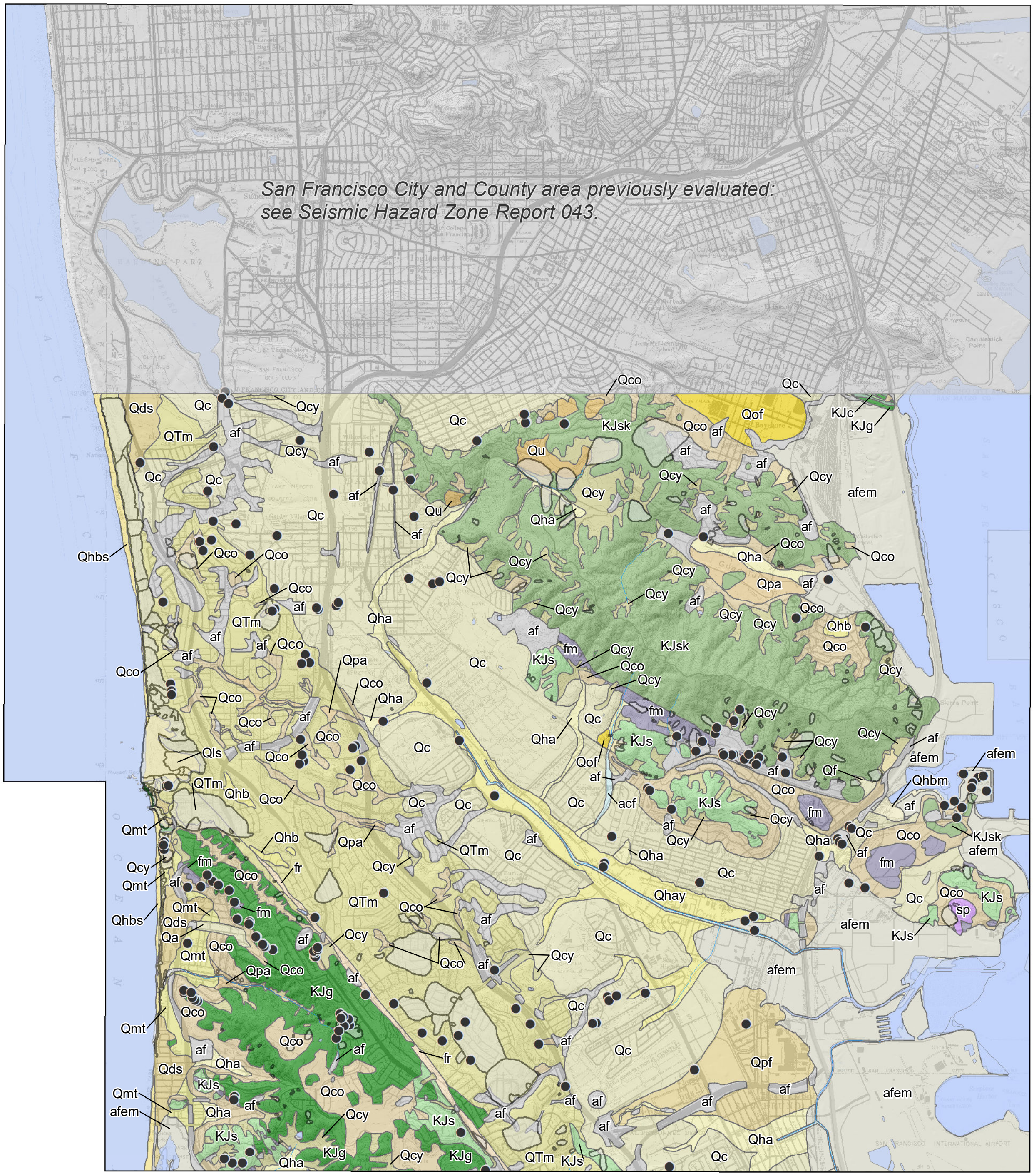
SAN FRANCISCO SOUTH QUADRANGLE



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

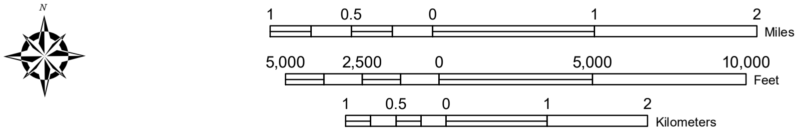
● Geotechnical boring used in liquefaction evaluation

Plate 1.1 Quaternary geologic materials map and locations of boreholes used in evaluating liquefaction hazard, San Francisco South Quadrangle, San Mateo County, California.



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

SAN FRANCISCO SOUTH QUADRANGLE

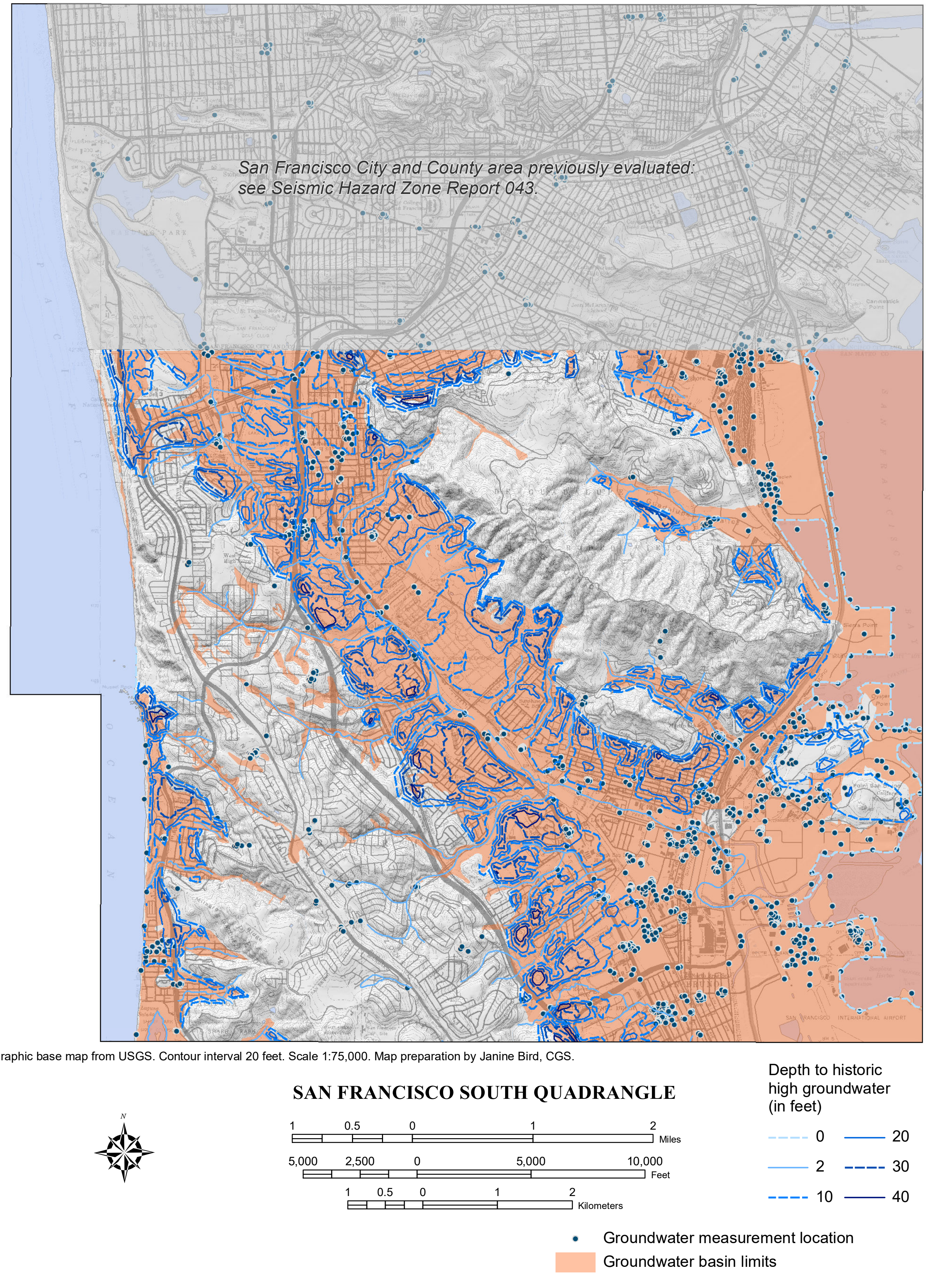


See "Geology" in Section 1 of report for descriptions of units.

● Shear test sample location

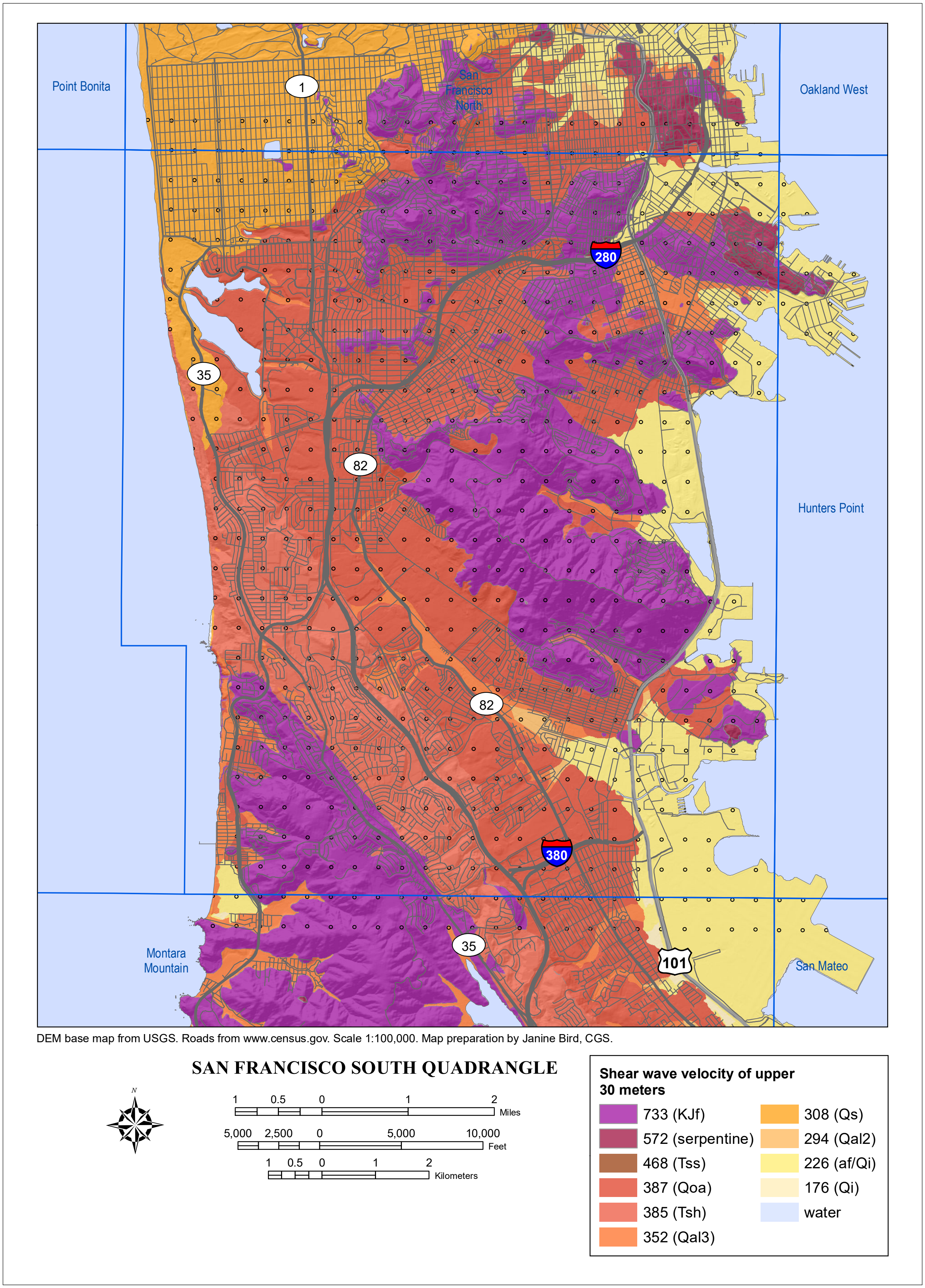
Landslide

Plate 1.2 Geologic materials and landslide inventory map with locations of shear test samples used in evaluating earthquake-induced landslide hazard, San Francisco South Quadrangle, San Mateo County, California.



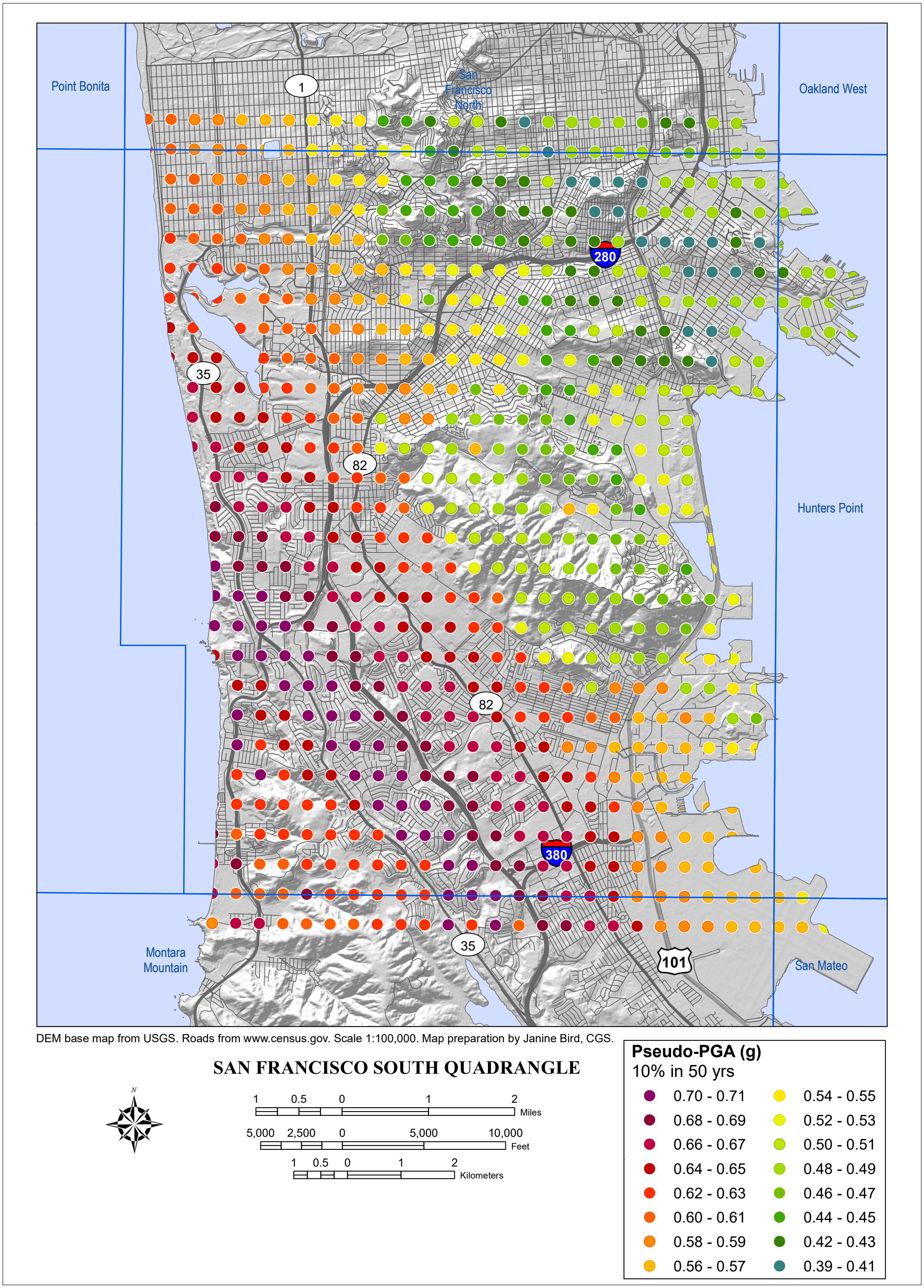
Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Janine Bird, CGS.

Plate 1.3 Groundwater basins, depth to historic-high groundwater levels, and groundwater data points, San Francisco South Quadrangle, San Mateo County, California.



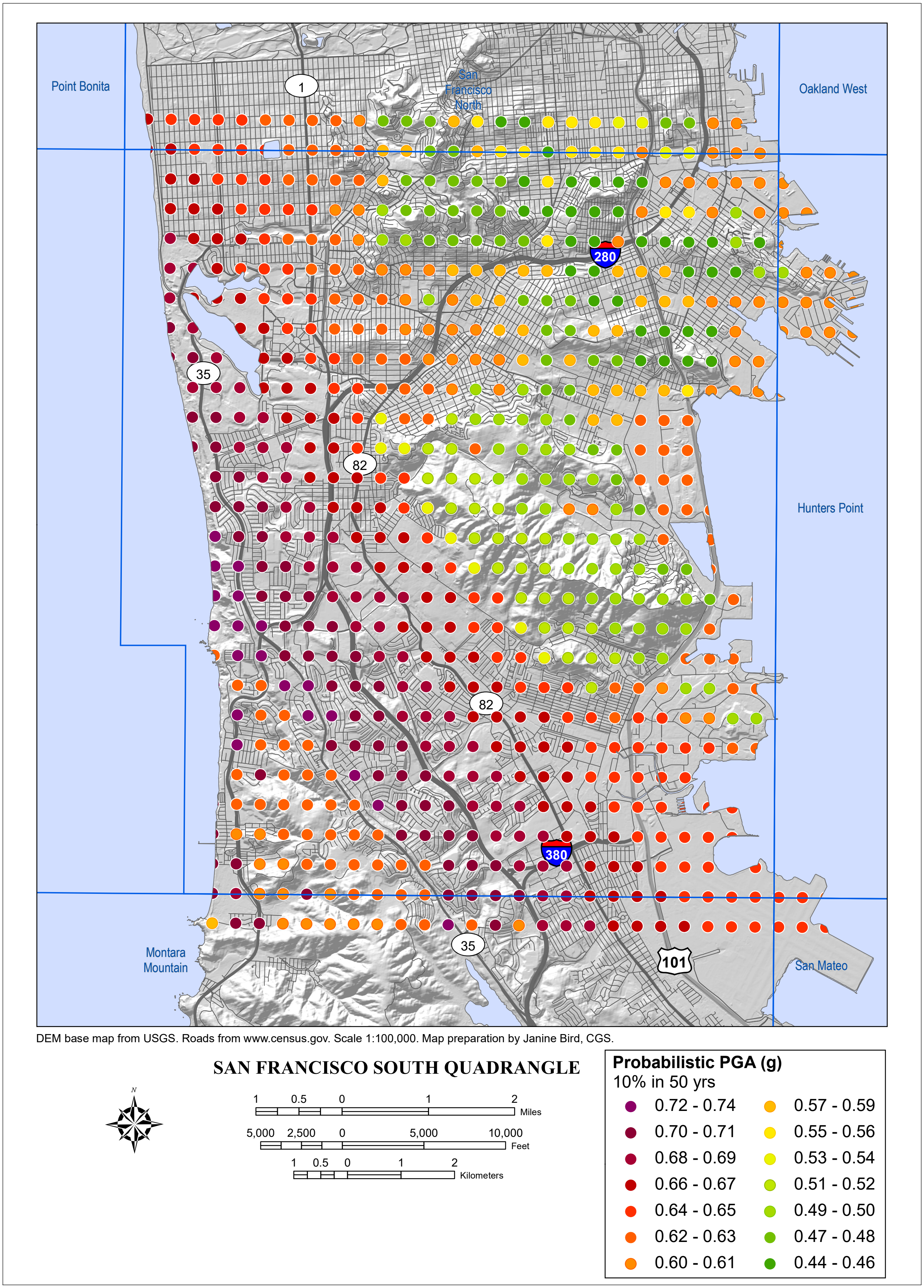
DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

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), San Francisco South Quadrangle and surrounding area, California.



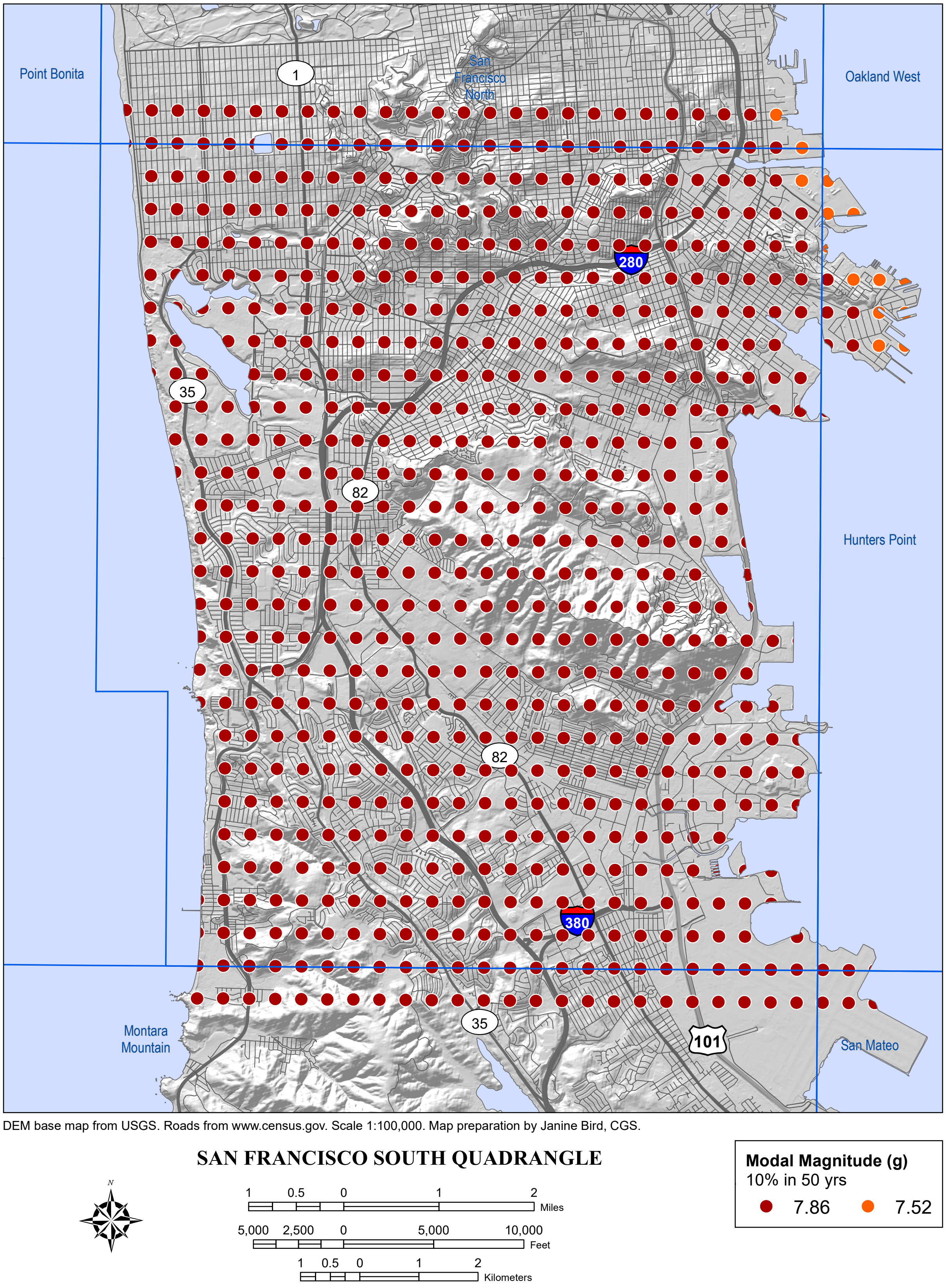
DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

Plate 2.2 Pseudo-PGA for liquefaction hazard mapping analysis, San Francisco South 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.

Plate 2.3 Probabilistic peak ground acceleration for landslide hazard mapping analysis, San Francisco South 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.

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Modal Magnitude (g)
10% in 50 yrs
● 7.86 ● 7.52

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