SEISMIC HAZARD ZONE REPORT 115

SEISMIC HAZARD ZONE REPORT FOR THE MURRIETA 7.5-MINUTE QUADRANGLE, RIVERSIDE COUNTY, CALIFORNIA

2007

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California Geological Survey

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Seismic Hazard Zone Report for the Murrieta 7.5-Minute Quadrangle
Riverside County, California

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December 5, 2007	Official Map Release

EXECUTIVE

SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the Murrieta 7.5-Minute Quadrangle, Riverside County, California. The map, which covers approximately 62 square miles at a scale of 1 inch = 2,000 feet, displays the boundaries of *Zones of Required Investigation* for liquefaction and earthquake-induced landslides in the southwestern part of Riverside County. About two-thirds of the map area lies within the City of Murrieta, which includes the community of Murrieta Hot Springs. A portion of the City of Temecula lies near the southeast corner of the map. The remaining area within the quadrangle consists of unincorporated areas, including the communities of Menifee, Winchester, and Wildomar. However, it must be noted that western Riverside County is presently experiencing extremely high population growth and a substantial part of what was recently rural, unincorporated land encompassed by the Murrieta and adjacent quadrangles is presently being rapidly developed.

Seismic hazard maps are prepared by the California Geological Survey (CGS) using geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information analyzed in these studies includes topography, surface and subsurface geology, borehole log data, recorded ground-water levels, existing landslide features, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. Ground shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years.

About 9 square miles of land in the Murrieta Quadrangle has been designated *Zones of Required Investigation* for liquefaction hazard, encompassing much of the Murrieta-Temecula Valley, most of the stream valleys and canyons leading into the valley, and several isolated canyon bottoms to the northeast and southwest of the valley. 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 to which this region could be subjected.

The amount of area designated as *Zones of Required Investigation* for earthquake-induced landsliding within the Murrieta Quadrangle is much smaller, less than a combined total of 2 square miles. These zones show up on the topographic map as small, discontinuous patches of land concentrated in narrow strips along some of the steeper slopes in the hilly to mountainous terrain encompassed by the quadrangle.

City, county, and state agencies are required by the California Seismic Hazards Mapping Act to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold 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 of real property within a *Zone of Required Investigation* to disclose that fact at the time such property is sold.

THE CALIFORNIA SEISMIC HAZARDS MAPPING PROGRAM

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the State Geologist to prepare maps identifying seismic hazard zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. City, county, and state agencies are directed to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold development permits for a site within a zone until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans. The Act also requires sellers (and their agents) of real property within a mapped hazard zone to disclose at the time of sale that the property lies within such a zone. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is online at http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf

The Act directs SMGB to appoint and consult with the Seismic Hazards Mapping Act Advisory Committee (SHMAAC) in developing criteria for the preparation of the seismic hazard zone maps. SHMAAC consists of geologists, seismologists, civil and structural engineers, representatives of city and county governments, the state insurance commissioner and the insurance industry. In 1991, SMGB adopted initial criteria for delineating seismic hazard zones to promote uniform and effective statewide implementation of the Act. These initial criteria, which were published in 1992 as California Geological Survey (CGS) Special Publication 118, were revised in 2004. They provide detailed standards for mapping regional liquefaction and landslide hazards. The Act also directed the State Geologist to develop a set of probabilistic seismic maps for California and to research methods that might be appropriate for mapping earthquake-induced landslide hazards.

In 1996, working groups established by SHMAAC reviewed the prototype maps and the techniques used to create them. The reviews resulted in recommendations that 1) the process for zoning liquefaction hazards remain unchanged and 2) earthquake-induced landslide zones be delineated using a modified Newmark analysis.

In April 2004, significant revisions of liquefaction zone mapping criteria relating to application of historically high ground water level data in desert regions of the state were adopted by the SMGB. These modifications are reflected in the revised CGS Special Publication 118, which is available on online at: http://gmw.consrv.ca.gov/shmp/webdocs/sp118_revised.pdf.

This Seismic Hazard Zone Report summarizes the development of the *Official Seismic Hazard Zone Map* for the Murrieta 7.5-Minute Quadrangle. The process of zonation for liquefaction hazard involves an evaluation of Quaternary geologic mapping, ground-water information, and subsurface geotechnical data. The process of zonation for earthquake-induced landslide hazard incorporates evaluations of earthquake loading, existing landslides, slope gradient, rock strength, and geologic structure. A statewide *Earthquake Shaking Potential Map*, based on probabilistic

seismic hazard analysis (PSHA), has been prepared so that uniformly generated ground motion parameters (peak ground acceleration, mode magnitude, mode distance) are applied to all CGS liquefaction and earthquake-induced landslide hazard assessments.

SECTION 1: EVALUATION REPORT FOR LIQUEFACTION HAZARD

in the

MURRIETA 7.5-MINUTE QUADRANGLE, RIVERSIDE COUNTY, CALIFORNIA

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INTRODUCTION

Background

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the State Geologist to delineate Seismic Hazard Zones. The Act requires that site-specific geotechnical investigations be performed for most urban development projects situated within seismic hazard zones before lead agencies can issue the building permit. Evaluation and mitigation of seismic hazards for liquefaction are conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is online at http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf

Following the release of CGS Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazard. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of liquefaction analysis, evaluation, and mitigation techniques (SCEC, 2002). This text is also online at: http://www.scec.org/

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

Liquefaction-induced ground failure historically has been a major cause of earthquake damage in southern California. During the 1971 San Fernando and 1994 Northridge earthquakes significant damage to roads, utility pipelines, buildings, and other structures in the Los Angeles area was caused by liquefaction. Localities most susceptible to liquefaction are underlain by loose, water-saturated, granular sediment present within 40 feet of the ground surface. These geological and ground-water conditions exist in many parts of southern California, commonly in densely populated valley and floodplains. Furthermore, the potential for strong earthquake ground shaking is high throughout much of region because many active faults are present. The combination of these factors constitutes a significant seismic hazard in the densely populated and developing areas of southern California region, including western Riverside County.

Methodology

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

- Compile digital geologic maps to delineate the spatial distribution of Quaternary sedimentary deposits
- Collect geotechnical borehole log data from public agencies and engineering geologic consultants
- Enter boring log data into the GIS
- Generate digital cross sections to evaluate the vertical and lateral extent of Quaternary deposits and their lithologic and engineering properties
- Evaluate and digitize historically highest ground-water levels in areas containing Quaternary deposits
- Characterize expected earthquake ground motion, also referred to as ground-shaking opportunity (see Section 3 of this report)

- Perform quantitative analyses of geotechnical and ground motion data to assess the liquefaction potential of Quaternary deposits

- Synthesize, analyze, and interpret above data to create maps delineating *Zones of Required Investigation* according to criteria adopted by the SMGB (DOC, 2004)

Scope and Limitations

Evaluation for potentially liquefiable soils generally is confined to areas covered by Quaternary (less than about 1.6 million years) sedimentary deposits. Such areas within the Murrieta Quadrangle consist of a main alluviated valley, several smaller stream valleys, and several isolated canyons. CGS's liquefaction hazard evaluations are based on information on earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and ground water depth, which is gathered from various sources. Although selection of data used in this evaluation was rigorous, the quality of the data used varies. Therefore, the State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data obtained from outside sources.

Liquefaction zone maps are intended to prompt more detailed, site-specific geotechnical investigations, as required by the Act. As such, liquefaction zone maps identify areas where the potential for liquefaction is relatively high. The maps do not predict the amount or direction of liquefaction-related ground displacements, or the amount of damage to facilities that may result from liquefaction. Factors that control liquefaction-induced ground failure are the extent, depth, density, and thickness of liquefiable materials, depth to ground water, rate of drainage, slope gradient, proximity to free faces, and intensity and duration of ground shaking. These factors must be evaluated on a site-specific basis to assess the potential for ground failure at any given project site.

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

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Murrieta 7.5-Minute Quadrangle map covers approximately 62 square miles in southwestern Riverside County, California. The City of Murrieta is approximately 38 miles south-southeast of Riverside Civic Center and about 83 miles southwest of the Los Angeles Civic Center. About two-thirds of the map area lies within the City of Murrieta, which includes the community of Murrieta Hot Springs. The Santa Rosa Ecological Reserve occupies approximately 5 square miles in the

southwest part of the map area. A portion of the City of Temecula lies within the southeast corner of the map. The remaining map area consists of unincorporated areas of Riverside County, including the communities of Menifee, Winchester, and Wildomar.

Major transportation routes through the Murrieta Quadrangle area include Interstate 15 and Interstate 215 freeways. Local access within the map area is provided by several paved roads and highways, including Highway 79 (Winchester Road), Murrieta Hot Springs Road, Rancho California Road, and smaller urban streets. The more rural areas of the quadrangle are accessed by unpaved ranch and fire roads.

Land Use

The cities and communities within the Murrieta Quadrangle have experienced rapid growth since the late 1980's, and residential and commercial development of the area continues to expand both within the cities of Murrieta and Temecula, as well as within unincorporated Riverside County land. Land-uses in the valley areas include commercial and light industrial development, residential tract housing, and minor agricultural activities. Hillside areas are primarily developed in residential properties, including private ranches. The Santa Rosa Plateau Ecological Reserve occupies a large portion of the southwest map area.

Topography

One of the most notable features in the Murrieta Quadrangle is the northwest-trending, broad linear valley that diagonally traverses the southwest half of the map, herein referred to as the Murrieta-Temecula Valley. This down-dropped structural valley is bounded by faults of the Elsinore Fault Zone and is geologically referred to as the Elsinore Trough. The valley is bordered on the southwest by steep to moderately steep slopes of the Santa Ana Mountains and by moderately to gently sloping hills along the east flank of the mountains. Several flat-topped mesas (Mesa de Burro, Mesa de la Punta) occur at the higher elevations in the southwest corner of the map. Terrain northeast of the valley consists of gently rolling, highly dissected hills. A narrow, steep-sided mesa named Hogbacks is present in the northeast quarter of the quadrangle. Elevations in the map area range from about 1000 feet within Murrieta Creek to 2279 feet in the northern highland area.

Major drainages in the Murrieta Quadrangle include Murrieta, Santa Gertrudis, Tucalota, and Warm Springs creeks. Murrieta Creek flows southeastward within the Elsinore Trough. Santa Gertrudis, Tucalota, and Warm Springs creeks flow south-southwest through wide, flat-bottomed canyons that drain into Murrieta Creek in the southeast map area. These and several other minor drainages are fed from the narrow canyons in the highland areas to the north and northeast. The southwest side of the valley is marked by steep narrow canyons of the Santa Ana Mountains with creeks that flow northeastward into Murrieta Creek. Drainage in the southwest corner of the map flows south via Sandia Canyon and Walker Basin.

GEOLOGY

Geologic units that are generally susceptible to liquefaction include latest Pleistocene and Holocene alluvial and fluvial sedimentary deposits and artificial fill. The primary source of geologic mapping used in the evaluation of these materials for the Murrieta Quadrangle was U.S.

Geological Survey Open-File Report, OF 03-189 (Kennedy and Morton, 2003). The Quaternary geologic nomenclature that is used parallels that used by the Southern California Areal Mapping Project (SCAMP), a provisional digital geologic-map database generated during compilation of the U.S. Geological Survey Santa Ana 30 x 60 minute quadrangle map (Morton, 2004). Quaternary units are described in detail in this section; bedrock units are described in Section 2, *Evaluation Report for Earthquake-Induced Landslide Hazard*.

Other geologic maps and reports were reviewed in this investigation, including Kennedy (1977). CGS staff conducted limited field reconnaissance to 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.

About 50 percent (31 mi^2) of the Murrieta Quadrangle is covered by Quaternary and Quaternary-Tertiary sediments, of which just under 10 mi^2 is composed of latest Pleistocene to Holocene in age (Plate 1.1). These sedimentary units are summarized in Table 1.1 and discussed below. The liquefaction susceptibility evaluation and development of the Seismic Hazard Zone Map for the quadrangle was based on the distribution of these deposits at a scale of 1:24,000 and analyses of associated geotechnical data as discussed under the Engineering Geology heading of this section. Structural features such as faults are not presented on the plate.

Bedrock

Exposed over the remaining area of the quadrangle are pre-Quaternary crystalline rocks that are divided into two distinct assemblages separated by the northwest-trending Elsinore Fault Zone. Bedrock exposed within the quadrangle northeast of the Elsinore Trough consists mainly of Cretaceous batholithic rocks dominated by gabbro, tonalite, granodiorite, pegmatite and ring dikes. Undiffentiated metasedimentary rock of Mesozoic age also occurs, but exposure is limited to the very northeast corner of the quadrangle. Miocene basalt also is present, but only as small, isolated exposures capping the Hogbacks, a linear ridge situated a few miles northeast of Murrieta. In contrast, the predominant rock cropping out in the quadrangle southwest of the Elsinore Fault Zone is Mesozoic undifferentiated metasedimentary rock composed of thick-layered quartzite and fissile phyllitic rock. A small exposure of Cretaceous tonalite is present in the southwest corner. Miocene basalt also crops out in the southwest, capping Mesa de Burro (excluded from project area). For more detail on bedrock exposed in the Murrieta Quadrangle, see Section 2 of this report, *Evaluation Report for Earthquake-Induced Landslide Hazard*.

Quaternary

Old Quaternary Units

There are two pre-late Pleistocene sedimentary units exposed in the Murrieta Quadrangle. The oldest is an unnamed late Pliocene/Pleistocene-age sandstone and conglomerate unit (QTw) exposed in the Wildomar area (Plate 1.1). The unit is highly dissected and crops out within and just northeast of the Elsinore Fault Zone. Overlying the unnamed unit is the Pleistocene-age Pauba Formation, which consists of a sandstone member (Qps) exposed on both sides of the valley and a coarser-grained fanglomerate member (Qpf) composed angular plutonic and metamorphic clasts in a well-indurated mudstone matrix that crops out on the southwest side of the valley.

Very old (early to middle Pleistocene age) alluvial deposits (Qvoa) overlie the Pauba Formation in the west-central part of the map and older bedrock units in the eastern part of the map. These older fluvial and valley deposits consist of sand and gravel with varying amounts of silt and clay. They are reddish brown in color, moderately- to well-indurated, moderately- to highly-dissected, with surfaces capped by well-developed pedogenic soils.

Older (middle to late Pleistocene age) alluvial channel deposits (Qoaa) occur in isolated outcrops near younger valley sediments. These older deposits consist of gravel, sand, silt, and clay-bearing stream sediments deposited on canyon floors. They are moderately indurated and slightly to moderately dissected. The upper surfaces of these older alluvial deposits may also be capped by moderately to well-developed pedogenic soils.

Map Unit	Environment of Deposition	Age
Qw	Fluvial	Late Holocene
Qyaa, Qyag	Fluvial	Holocene and latest Pleistocene
Qyva	Valley/Fluvial	Holocene and latest Pleistocene
Qyfa	Alluvial Fan	Holocene and latest Pleistocene
Qoaa	Fluvial	Middle to Late Pleistocene
Qvoa	Fluvial	Early to Middle Pleistocene
Qps, Qpf	Fluvial	Pleistocene
QTw	Fluvial	Late Pliocene and Pleistocene

Table 1.1. Quaternary units mapped in the Murrieta 7.5-Minute Quadrangle.

Young Quaternary Units

Young (latest Pleistocene and Holocene) alluvial valley deposits (Qyva) consist mainly of fluvial sediments deposited along the valley floor adjacent to Murrieta Creek. These deposits consist of unconsolidated sand, silt and clay-bearing alluvium. Young alluvial channel deposits (Qyaa, Qyag) consist of unconsolidated gravel, sand, silt, and clay-bearing alluvium. They represent fluvial deposition along tributary canyon floors. Young alluvial fan deposits (Qyfa) are unconsolidated deposits of gravel, sand and silt, with a high coarse-to-fine clast ratio. Late Holocene surficial deposits include channel and wash deposits (Qw) consisting of unconsolidated sand and gravel recently transported within active channel washes and streams. Young landslides are present in the area, but are not shown on Plate 1.1 (see Section 2 of this report for occurrences and descriptions).

Structure

The dominant structural feature of the Murrieta Quadrangle is the northwest-trending Elsinore Fault Zone. The down dropped structural valley associated with this zone is often referred to as the Elsinore Trough. The two main strands flanking the valley are the Willard Fault on the southwest and the Wildomar Fault on the northeast. The Willard Fault marks the eastern boundary of the steep northeast-facing slopes of the Santa Ana Mountains. The Wildomar Fault is not as well expressed topographically as is the Willard Fault, but its trace is fairly well defined by numerous lineaments along the east side of the valley. This fault forms a subsurface ground-water barrier and historically has had springs and artesian wells associated with it in the Pauba and Santa Gertrudis Valleys (Mann, 1955; Kennedy, 1977; Waring, 1919). The Murrieta Creek Fault, also a branch of the Elsinore Fault Zone, is mapped as a discontinuous linear fault between the Willard and Wildomar Faults along the southwestern side of the valley. The Wildomar Fault and the Murrieta Creek Fault are considered active faults (Hart and Bryant, 1997) and are designated as *Official Earthquake Fault Zones* in the Murrieta Quadrangle (DOC, 1990). Another fault, the Murrieta Hot Springs Fault strikes due east across the valley floor, extending through the intersection of Lemon Street and Adams Avenue (Kennedy and Morton, 2003).

ENGINEERING GEOLOGY

Ground Water

Saturated soil conditions are required for liquefaction to occur, and the susceptibility of a soil to liquefaction varies with the depth to ground water. Saturation reduces the effective normal stress of near-surface sediment, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). CGS compiles and interprets current and historical ground water data to identify areas characterized by, or anticipated to have in the future, near-surface saturated soils. For purposes of seismic hazard zonation, "near-surface" means at a depth less than 40 feet.

Part of the Murrieta-Temecula Valley Groundwater Basin underlies the project area, and is included in the DWR South Coast Hydrologic Region (DWR, 2003). Water-bearing materials in the basin include Holocene and Pleistocene alluvium and older sedimentary rocks. Several water districts operate within this region, namely the Eastern Municipal Water District, Murrieta County Water District, and Rancho California Water District. Ground water flows southeastward in the Murrieta-Temecula Valley. Natural recharge of the basin is from direct precipitation and from percolation in the channels of Warm Springs, Tucalota, Santa Gertrudis, and Murrieta Creeks.

Natural hydrologic processes and human activities can cause ground water levels to fluctuate over time. Therefore, it is impossible to predict depths to saturated soils when future earthquakes strike. One method of addressing time-variable depth to saturated soils is to establish an anticipated high ground-water level based on historical ground-water data. CGS thus develops contour maps to depict depths to ground water that is either currently near-surface or could return to near-surface levels within a land-use planning interval of 50 years.

It is important to note, that the initiation of large-scale, artificial recharge programs could significantly affect future ground water levels. When alerted of such programs, CGS will evaluate

their impact relative to liquefaction potential and revise official seismic hazard zone maps if necessary.

Plate 1.2 depicts alluviated areas in the Murrieta Quadrangle characterized by actual or anticipated shallow ground water. Depths to first-encountered, unconfined ground water were plotted onto a map of the project area and then the values contoured to constrain the estimate of historically shallowest ground water. Water depths from boreholes known to penetrate confined aquifers were not used.

Historic water well level records maintained by the California Department of Water Resources (Giessner, and others, 1971; DWR, 2007) were evaluated, plotted, and compared with water levels from geotechnical borehole logs collected for this study. DWR water data represents levels collected from the 1910's through the 1960's, with most records representing conditions of the mid 1950's to the 1960's. Modern ground water levels from borehole data range from late the 1970's to present. Early ground water studies for the Murrieta-Temecula Valley (Waring, 1919) indicate that in some alluviated areas, ground-water levels were within 20 feet of the surface during 1904 and 1915. Modern shallow ground water conditions were also noted in many of the geotechnical reports reviewed for this study. Hydrographs of wells in the area indicate that ground water levels have fluctuated greatly since 1980 (DWR, 2003).

Contour lines on Plate 1.2 do not generally represent present-day conditions as usually presented on typical ground-water contour maps. Areas where the historic ground-water levels are not well constrained often occur within the upper reaches of stream valleys and in canyons. These areas are assigned a value of less than 10 feet unless otherwise noted. In studies of the Elsinore Fault Zone, Mann (1955) and Kennedy (1977) both recognize the Wildomar Fault, extending along the northeast side of the valley, as a ground-water barrier. Water levels from deeper wells were noted to be higher on the northeast side of the northwest-trending fault. However, data collected for this evaluation indicate that faults buried beneath the main valley do not appear to block ground-water flow in the near-surface sediments.

Soil Testing

As stated above, soils that are generally susceptible to liquefaction are mainly late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. Deposits that contain saturated loose sandy and silty soils are most susceptible to liquefaction. Lithologic descriptions and soil test results reported in geotechnical borehole logs provide valuable information regarding subsurface geology, ground water levels, and the engineering characteristics of sedimentary deposits. For this investigation, borehole logs were collected from the files of the Riverside County Building and Safety Department, City of Murrieta, California Department of Transportation, and *Fault Investigation Reports* on file with CGS (Wong and others, 2003). Data from a total of 474 borehole logs were entered into the CGS geotechnical GIS database.

Of particular value in liquefaction evaluations are logs that report the results of downhole standard penetration tests in alluvial materials. Standard penetration tests (SPTs) provide a standardized measure of the penetration resistance of geologic deposits and are commonly used as an index of soil density. For this reason, SPT results are also a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and commonly by the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material (see Quantitative

Liquefaction Analysis in Part II of this section). SPT is an in-field test that is based on counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil. The driving force is provided by dropping a 140-pound hammer weight 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. Geotechnical characteristics of the Quaternary map units are generalized in Table 1.2.

Geologic Map Unit	Age	Sediment/material Type	Consistency	Liquefaction Susceptibility*
Qw	Late Holocene	Sand, gravel	Loose	Yes
Qyaa, Qyag	Holocene and latest Pleistocene	Sand, gravel, silt, clay	Loose	Yes
Qyva	Holocene and latest Pleistocene	Sand, silt, clay	Loose to medium dense	Yes
Qyfa	Holocene and latest Pleistocene	Sand, gravel, silt	Loose to medium dense	Yes
Qoaa	Middle to Late Pleistocene	Gravel, sand, silt, clay	Dense to very dense	Not likely
Qvoaa, Qvoag	Early to Middle Pleistocene	Gravel, sand, silt, clay	Dense to very dense	No
Qps, Qpf	Pleistocene	Sandstone, conglomerate, mudstone	Loose to dense	Not likely
QTw	Late Pliocene and Pleistocene	Sandstone and conglomerate	Dense to very dense	No

(*When saturated)

Table 1.2. Liquefaction susceptibility of Quaternary units in the Murrieta 7.5-Minute Quadrangle.

Borehole logs show that Holocene alluvial layers containing a significant amount of gravel are common in the subsurface of the Murrieta-Temecula Valley and adjacent stream valleys and canyons. 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 474 geotechnical borehole logs analyzed in this study (Plate 1.3), most included blow-count data from SPTs or from penetration tests that allow reasonable blow count conversions to SPT-equivalent values. Few of the borehole logs collected, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal analysis using the Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed either using recorded density, moisture, and sieve test values or using averaged test values of similar materials.

Ground Subsidence

In the late 1980's and early 1990's, subsidence and associated ground cracking within the Murrieta-Temecula Valley were linked to changes in ground-water levels. Ground cracks first appeared in the area around Temecula, Rancho California, and Wolf Valley in 1987. Subsequent studies indicate that the ground cracks coincide with pre-existing subsurface faults that locally offset Holocene sediments (Bergman and Rockwell, 1989; Wills, 1988). Evidence from these studies prompted the State to create an additional *Official Earthquake Fault Zone* encompassing the Murrieta Creek Fault (Wills, 1988). The fault zone included a part of the County of Riverside's newly created *Subsidence Report Zone*. Studies indicated that although the location of the cracks were in part controlled by subsurface discontinuities associated with faulting, significant ground water withdrawals within the valley contributed most to their development (Kupferman, 1992, 1998; Shlemon and Davis, 1992; Shlemon and Hakakian, 1992).

In 1991, another *Subsidence Report Zone* was created by Riverside County in the Murrieta area in response to additional ground cracking taking place a few miles north of the Temecula cracks. These cracks were determined to be the result of a rising ground water table that caused hydroconsolidation of alluvium (Shlemon and Hakakian, 1992). The limits of the county's *Subsidence Report Zone* for this area were based on natural, hydrologic and political boundaries (Kupferman, 1995; 1998).

PART II: LIQUEFACTION HAZARD ASSESSMENT

MAPPING TECHNIQUES

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. When this occurs, sediment loses strength and may fail, causing damage to buildings, bridges, and other structures. Many methods for mapping liquefaction hazard have been proposed. Youd (1991)

highlights the principal developments and notes some of the widely used criteria. Youd and Perkins (1978) demonstrate the use of geologic criteria as a qualitative characterization of liquefaction susceptibility and introduce the mapping technique of combining a liquefaction susceptibility map and a liquefaction opportunity map to produce a liquefaction potential map. Liquefaction susceptibility is a function of the capacity of sediment to resist liquefaction. 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 which 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 (DOC, 2004).

LIQUEFACTION SUSCEPTIBILITY

Liquefaction susceptibility reflects the relative resistance of a soil to loss of strength when subjected to ground shaking. Physical properties of soil such as sediment grain-size distribution, compaction, cementation, saturation, and depth from the surface govern the degree of resistance to liquefaction. Some of these properties can be correlated to a sediment's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment. Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not specifically addressed in this investigation. Soil characteristics that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. In summary, soils that lack resistance (susceptible soils) typically are saturated, loose and sandy. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross-sections, geotechnical test data, geomorphology, and ground-water hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to ground water are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on similar soil observations, liquefaction susceptibility maps typically are often similar to Quaternary geologic maps, depending on local ground-water levels. CGS's qualitative relations between susceptibility and geologic map unit are summarized in Table 1.2.

GROUND SHAKING OPPORTUNITY

Ground shaking opportunity is a calculated measure of the intensity and duration of strong ground motion normally expressed in terms of *peak horizontal ground acceleration* (PGA). Ground motion calculations used by CGS exclusively for regional liquefaction zonation

assessments are currently based on the *2002 California Probabilistic Seismic Hazard Assessment (PSHA) Model* developed jointly by the CGS and USGS (Frankel and others, 2002; Cao and others, 2003). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance level. CGS calculations of probabilistic peak ground acceleration deviate slightly from the model by incorporating additional programming that weights each earthquake's estimated ground shaking contribution by a scaling factor derived as a function of its magnitude. The function is simply the inverse of the liquefaction threshold scaling factor used in the Seed-Idriss Simplified Procedure, the quantitative analysis method used by CGS to generate seismic hazard zone maps for liquefaction (see Liquefaction Analysis). The result is a magnitude-weighted, pseudo-PGA that CGS refers to as *Liquefaction Opportunity* (LOP). LOP is then used to calculate cyclic stress ratio (CSR), the seismic load imposed on a soil column at a particular site. This approach provides an improved estimate of liquefaction hazard in a probabilistic sense, ensuring that both large, infrequent, distant earthquakes, as well as smaller, more frequent, nearby events are appropriately accounted for (Real et al., 2000).

Calculated LOP for alluviated valley areas in the Murrieta Quadrangle range from 0.44 to 0.63g (see Section 3, Figure 3.3). These values were obtained by applying the NEHRP corrections (FEMA, 1994; see Table 3.1) to the firm-rock LOP values derived from the CGS liquefaction application of the 2002 probabilistic ground motion model. The calculations are based on an earthquake of Moment Magnitude 6.75 with a Modal Distance of 0 to 12.5 miles.

LIQUEFACTION ANALYSIS

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using an in-house developed computer program based on the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997; Youd and others, 2001). The procedure first calculates the resistance to liquefaction of each soil layer penetrated at a test-drilling site, expressed in terms of cyclic resistance ratio (CRR). The calculations are based on standard penetration test (SPT) results, ground-water level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The procedure then estimates the factor of safety relative to liquefaction hazard for each of the soil layers logged at the site by dividing their calculated CRR by the pseudo PGA-derived CSR described in the previous section.

CGS uses a factor of safety (FS) of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil layers. The liquefaction analysis program calculates an FS for each geotechnical sample where blow counts were collected. Typically, multiple samples are collected for each borehole. The program then independently calculates an FS for each non-clay layer that includes at least one penetration test using the minimum $(N_1)_{60}$ value for that layer. The minimum FS value of the layers penetrated by the borehole is used to determine the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data. FS, as well as other considerations such as slope, presence of free faces, and thickness and depth of potentially liquefiable soil, are evaluated in order to construct liquefaction potential maps, which are then converted to *Seismic Hazard Zonation* maps.

ZONATION CRITERIA: LIQUEFACTION

Areas underlain by materials susceptible to liquefaction during an earthquake are included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (DOC, 2004). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following:

1. Areas known to have experienced liquefaction during historical earthquakes

2. All areas of uncompacted artificial fill that are saturated, nearly saturated, or may be expected to become saturated

3. Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable

4. Areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard. Within such areas, zones may be delineated by geologic criteria as follows:

    a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; or

    b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; or

    c) Areas containing soil deposits of latest Pleistocene age (11,000 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

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

DELINEATION OF SEISMIC HAZARD ZONES: LIQUEFACTION

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

Areas of Past Liquefaction

No areas of documented historical surface liquefaction are known to have occurred in the Murrieta Quadrangle. However, two trenches excavated across subsidence cracks in the Murrieta-Temecula Valley exposed sand-filled fractures in the subsurface, thus indicating liquefaction (Plate 1.2). It appears that sand from the layer exposed at the bottom of both trenches was injected up into fractures present in the overlying layers (Wills, 1988). These sites are designated *Zones of Required Investigation* based upon that information. However, they also fall within the bounds of a larger liquefaction zone where designation is based on analysis of borehole data (see below).

Artificial Fills

Non-engineered fill placements vary in size and type and because they are often composed of uncompacted, silty or sandy material, they are generally considered to have a high potential for liquefaction when saturated. No significant placements of non-engineered artificial fill were identified in the study area. Conversely, significant amounts of engineered artificial fill have been used in the construction of river levees and elevated freeways within the Murrieta Quadrangle. However, seismic hazard zonation for liquefaction in areas where engineered fill has been placed does not depend on the fill, but on soil conditions in underlying strata.

Areas with Sufficient Existing Geotechnical Data

Most of the 474 logs evaluated for this study are from boreholes located within the Murrieta-Temecula Valley. Collectively, the logs provide the level of subsurface information needed to conduct a regional assessment of liquefaction susceptibility with an acceptable level of certainty. Much of surface area of the valley floor is covered by Holocene alluvium with a thickness generally greater than 40 feet, which CGS considers the maximum depth at which liquefaction can cause damaging ground failure at the surface. Examination of geotechnical boring logs show that the valley alluvium is composed mainly of discontinuous layers of sand, silts, and gravel, with lesser amounts of clay. Analysis of blow count values and other soil property measurements reported in the logs indicate that most of the boreholes penetrated one or more layers of liquefiable material where seismic stress ratio (CSR) is greater than the soils' seismic resistance ratio (CRR). Accordingly, all areas covered by Holocene alluvium that is saturated within 40 feet of the surface are designated *Zones of Required Investigation*.

Areas with Insufficient Existing Geotechnical Data

Adequate geotechnical borehole information is lacking for most parts of secondary canyons in the hilly to mountainous terrain to the northeast and southwest of the Murrieta-Temecula Valley. Holocene to late Holocene sediments deposited in upland creeks and canyons include modern channel and wash deposits (Qw), channel deposits (Qyaa, Qyag), and fan deposits (Qyfa). All of these deposits are likely to contain loose, granular materials that are saturated because of their proximity to active stream channels and the presence of near-surface ground water. Those conditions, along with the strong ground motions expected to occur in the region, combine to form a sufficient basis for designating these areas *Zones of Required Investigation* for liquefaction.

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SECTION 2: EVALUATION REPORT FOR EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

MURRIETA 7.5-MINUTE QUADRANGLE, RIVERSIDE COUNTY, CALIFORNIA

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INTRODUCTION

Purpose

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use seismic hazard zone maps prepared by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997). The text of this report is on the Internet at http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing landslide hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee in 1998 under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of landslide analysis, evaluation, and mitigation techniques (SCEC, 2002). This text is also on the Internet at: http://www.scec.org/

This section of the evaluation report summarizes seismic hazard zone mapping for earthquake-induced landslides in the Murrieta 7.5-minute Quadrangle. Section 1 (addressing liquefaction hazard) and Section 3 (addressing earthquake shaking hazard) complete the report, which is one of a series that summarizes the preparation of seismic hazard zone maps within the state (Smith,

1996). Additional information on seismic hazard zone mapping in California can be accessed on the California Geological Survey's Internet page: http://www.conservation.ca.gov/cgs/shzp/.

Background

Landslides triggered by earthquakes historically have been a significant cause of earthquake damage. In California, large earthquakes such as the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes triggered landslides that were responsible for destroying or damaging numerous structures, blocking major transportation corridors, and damaging life-line infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, sloped areas underlain by loose, weak soils, and areas on or adjacent to existing landslide deposits. These geologic and terrain conditions exist in many parts of California, including numerous hillside areas that have already been developed or are likely to be developed in the future. The opportunity for strong earthquake ground shaking is high in many parts of California because of the presence of numerous active faults. The combination of these factors constitutes a significant seismic hazard throughout much of California, including the mountainous and hilly areas within the Murrieta Quadrangle.

Methodology

The mapping of earthquake-induced landslide hazard zones presented in this report is based on the best available terrain, geologic, geotechnical, and seismological data. If unavailable or significantly outdated, new forms of these data were compiled or generated specifically for this project. The following were collected or generated for this evaluation:

- Digital terrain data were collected or generated to provide an up-to-date representation of slope gradient and slope aspect in the study area.

- Geologic mapping was compiled to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether or not triggered by earthquakes, was prepared.

- Geotechnical laboratory test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area.

- Seismological data in the form of CGS probabilistic shaking maps and catalogs of strong-motion records were compiled and used to characterize future earthquake shaking within the mapped area.

The data collected for this evaluation were processed into a series of GIS layers using commercially available software. A slope stability analysis was performed using the Newmark method (Newmark, 1965), in order to generate a map showing landslide hazard potential. The earthquake-induced landslide hazard zone was derived from the landslide hazard potential map according to criteria developed in a CGS pilot study (McCrink and Real, 1996; McCrink, 2001) and subsequently adopted by the State Mining and Geology Board (DOC, 2000).

Scope and Limitations

The methodology used to make this map is based on earthquake ground-shaking estimates, geologic material-strength characteristics and slope gradient. These data are gathered from a variety of outside sources. Although the selection of data used in this evaluation was rigorous, the quality of the data is variable. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data gathered from outside sources.

Earthquake-induced landslide zone maps are intended to prompt more detailed, site-specific geotechnical investigations as required by the Act. As such, these zone maps identify areas where the potential for earthquake-induced landslides is relatively high. Due to limitations in methodology, it should be noted that these zone maps do not necessarily capture all potential earthquake-induced landslide hazards. Earthquake-induced ground failures that are not addressed by this map include those associated with ridge-top spreading and shattered ridges. It should also be noted that no attempt has been made to map potential run-out areas of triggered landslides. It is possible that such run-out areas may extend beyond the zone boundaries. The potential for ground failure resulting from liquefaction-induced lateral spreading of alluvial materials, considered by some to be a form of landsliding, is not specifically addressed by the earthquake-induced landslide zone or this report.

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

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Murrieta 7.5-Minute Quadrangle map covers approximately 62 square miles in southwestern Riverside County, California. The City of Murrieta is approximately 38 miles south-southeast of Riverside Civic Center and about 83 miles southwest of Los Angeles Civic Center. About two-thirds of the central map area lies within the City of Murrieta, which includes the community of Murrieta Hot Springs. The Santa Rosa Ecological Reserve occupies approximately 5 square miles of the southwest map area. A portion of the City of Temecula lies within the southeast corner of the map. The remaining map area is within unincorporated areas of Riverside County, including the communities of Menifee, Winchester, and Wildomar.

Major transportation routes to and within the Murrieta Quadrangle area include the Interstate 15 and Interstate 215 freeways. Local access within the map area is provided by several paved roads and highways, including Highway 79 (Winchester Road), Murrieta Hot Springs Road, Rancho California Road, and smaller city streets. Access to the more rural areas of the quadrangle is by unpaved ranch and fire roads.

Land Use

The cities and communities within the Murrieta Quadrangle have experienced rapid growth since the late 1980's and residential and commercial development of the area continues to expand both within the cities of Murrieta and Temecula as well as unincorporated Riverside County land. Land use in the valley areas includes commercial and light industrial development, residential tract housing, and minor agricultural activities. Hillside areas are primarily developed with residential properties, including private ranches. The Santa Rosa Plateau Ecological Reserve occupies a large portion of the southwest map area.

Topography

One of the most notable features in the Murrieta Quadrangle is the northwest-trending, broad linear valley that diagonally traverses the southwest half of the map, herein referred to as the Murrieta-Temecula Valley. This down-dropped structural valley is bounded by faults of the Elsinore Fault Zone and is informally referred to as the Elsinore Trough. The valley is bordered on the southwest by steep to moderately steep slopes of the Santa Ana Mountains and by moderately to gently sloping hills along the east flank of the mountains. Several flat-topped mesas (Mesa de Burro, Mesa de la Punta) occur at the higher elevations in the southwest corner of the map. Terrain northeast of the valley consists of gently sloping dissected hills. The northern part of the quadrangle contains areas of moderately steep mountainous terrain with intervening arcuate bands of gently sloping dissected hills. A narrow, steep-sided mesa named Hogbacks is present in the northeast quarter of the quadrangle. Elevations in the map area range from about 1000 feet within Murrieta Creek to 2279 feet in the northern highland area.

Major drainages in the Murrieta Quadrangle include Murrieta, Santa Gertrudis, Tucalota, and Warm Springs creeks. Murrieta Creek flows southeastward within the Elsinore Trough. Santa Gertrudis, Tucalota, and Warm Springs creeks flow south-southwest through wide, flat-bottomed canyons that drain into Murrieta Creek in the southeast map area. These and several other minor drainages are fed from the narrow canyons in the highland areas to the north and northeast. The southwest side of the valley is marked by steep narrow canyons of the Santa Ana Mountains whose creeks flow northeastward into Murrieta Creek. Drainage in the southwest corner of the map flows south via Sandia Canyon and Walker Basin.

Digital Topography

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. An accurate slope gradient calculation begins with an up-to-date map representation of the earth's surface in the form of a digital topographic map. Within the Murrieta Quadrangle, a Level 2 digital elevation model (DEM) was obtained from the USGS (U.S. Geological Survey, 1993). This DEM, prepared from the 7.5-minute quadrangle topographic contours based on 1951 aerial photography, has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy.

Areas that have undergone large-scale grading since 1951 were updated to reflect the new topography. A DEM reflecting this recent grading was obtained from an airborne interferometric synthetic aperture radar (IfSAR) sensor flown in 2002 and 2003, with a vertical accuracy of approximately 1.08 meters and horizontal accuracy of 2.5 meters (NOAA, 2004). An interferometric radar DEM is prone to creating false topography where tall buildings, metal

structures, or trees are present. Due to the low-lying chaparral vegetation and relatively small-structure/residential construction types present, this type of DEM is appropriate for use in the Murrieta Quadrangle. Nevertheless, the final hazard zone map was checked for potential errors. Graded areas where the radar DEM was applied are shown on Plate 2.1. Slope maps were made from both DEMs using a third-order, finite difference, center-weighted algorithm (Horn, 1981).

GEOLOGY

The primary source of 1:24,000-scale bedrock geologic materials map generated for this slope stability evaluation was U.S. Geological Survey Open-File Report 03-189 (Kennedy and Morton, 2003), which was obtained from the USGS in digital format. Additionally, the USGS digital Preliminary Geologic Map of the Santa Ana 30’ x 60’ Quadrangle (Morton, 2004) was used as a source for geologic unit nomenclature, as this version of the map was the most recent available at the time of our report preparation. Bedrock units are described in detail in this section. Surficial geologic units are briefly described here and are discussed in more detail in Section 1 of this report.

CGS geologists modified the digital geologic map in the following ways. Landslide deposits were deleted from the map so that the distribution of bedrock formations and the newly created landslide inventory would exist on separate layers for the hazard analysis. Contacts between bedrock and surficial units were revised to better conform to the topographic contours of the U.S. Geological Survey 7.5-minute quadrangle. Air-photo interpretation, digital ortho-photo quarter quadrangle review, satellite imagery review, and field reconnaissance were performed to assist in adjusting contacts between bedrock and surficial geologic units and to review geologic unit lithology and geologic structure. Surficial geology and fault traces were modified in some areas to reflect more detailed mapping (Kennedy, 1977 and Wills, 1988). In addition, the relationship of the various geologic units to the development and distribution of landslides was recorded.

The northwest-trending Elsinore Fault, which diagonally traverses the southwest part of the Murrieta Quadrangle, is a significant tectonic boundary that separates bedrock into two distinct structural blocks within the Peninsular Ranges Province: the Santa Ana Mountains block to the southwest and the Perris block to the northeast. The predominant rock type cropping out in the Santa Ana Mountains block within the quadrangle is metasedimentary rock along with minor plutonic rocks and basalt. In contrast, bedrock exposed in the Perris block within the quadrangle consists mainly of batholithic rocks along with limited exposures of metasedimentary rock and basalt. Late Pliocene and Quaternary sediments fill the Murrieta-Temecula Valley and occur locally as surficial deposits overlying bedrock exposed in both the Santa Ana Mountains and Perris blocks.

The following descriptions of geologic units exposed in the Murrieta Quadrangle are taken primarily from Kennedy and Morton (2003). Map unit names are from Morton (2004), except where indicated. Please refer to the Liquefaction Evaluation section of this report (Section 1) for more detailed descriptions of Quaternary units than is presented below.

Perris Block

The oldest rock unit exposed in the map area within the Perris block consists of Mesozoic undifferentiated metasedimentary rock (Mzu), which crops out in the northeast corner of the map. This unit is predominantly composed of medium metamorphic grade schist, which commonly weathers into small, platy, elongate pieces along biotite-rich foliation. Soils developed on weathered bedrock within this unit are fairly thin where present.

Cretaceous-age Peninsular Ranges Batholith rocks are exposed in the northern third of the map area and consist of both a generic group of crystalline bedrock and a distinctive group belonging to the Paloma Valley Ring Complex. The generic crystalline bedrock group includes gabbro, tonalite, and granodiorite. The gabbro unit (Kgb) consists primarily of hornblende gabbro. It commonly contains large poikilitic hornblende crystals and is locally pegmatitic. Weathering takes place in the upper few feet and generally consists of fine- to medium-grained grus. The gabbro also occurs as stoped blocks within the Paloma Valley Ring Complex discussed below. The undifferentiated tonalite (Kt) is gray, foliated, medium-grained hornblende tonalite. The undifferentiated granodiorite (Kgd) is exposed along the eastern map boundary and consists of a medium-grained biotite and hornblende-biotite granodiorite.

The Paloma Valley Ring Complex consists of a younger set of thin ring dikes and an older ring-dike set. The older dikes include a foliated biotite-hornblende tonalite (Kpvt), and monzogranite to granodiorite (Kpvg), which is typically pale gray, massive, and contains small to large blocks of stoped gabbro. This unit weathers to fine- to coarse-grained grus. The younger ring dike set is intruded primarily into the older ring dikes and consists of numerous granitic pegmatites (Kpvp), which are leucocratic and both texturally and compositionally zoned. Associated with the younger ring dike set is a granophyre (Kpvgr) that is pale gray and contains plagioclase phenocrysts and some pegmatitic stringers.

Two Miocene-age basalt units exposed within the Perris block crop out northeast of, and within, the Elsinore Fault Zone. The Basalt of the Hogbacks (Tvh) is exposed several miles northeast of the City of Murrieta. It is a remnant channel-filling basalt flow that is slightly vesicular and breaks into slabby fragments. The Basalt of Temecula (Tvt) is exposed as a small outcrop of vesicular basalt within the Elsinore Fault Zone north of Murrieta. East of Temecula, this unit also includes exposures of a possible dissected cinder cone with scattered volcanic bombs.

The oldest sedimentary deposits mapped in the Perris block are unnamed Pleistocene and late Pliocene sandstone and conglomerate units of the Wildomar area (QTw). The sandstone (QTws) is friable, pale yellowish-green, medium grained and caliche rich. This unit is highly dissected and crops out within and just north of the Elsinore Fault Zone. The conglomerate (QTwc) is a cobble and boulder conglomerate containing locally derived clasts. These sedimentary units only occur within and on the northeast side of the Elsinore Fault Zone and have been offset locally by subparallel faults within the fault zone.

The Pleistocene-age Pauba Formation unconformably overlies the unnamed sandstone and conglomerate unit. The formation includes two informal members, only one of which, the sandstone member, occurs in the Perris block. The member is exposed along the northeast side

of the Elsinore Fault Zone (Qps). This sandstone unit is brown, slightly micaceous, moderately well indurated, locally cross-bedded, and contains sparse cobble to boulder conglomerate beds.

Very old alluvial channel deposits of middle to early Pleistocene age (Qvoa of Kennedy and Morton, 2003) conformably overlie the Pauba Formation. This unit includes a very coarse to very fine sand, silt, and clay-bearing alluvial deposit (Qvoaa) and a gravelly alluvial deposit (Qvoag).

Latest Pleistocene to Holocene alluvial and fluvial deposits composed of unconsolidated sand, gravel, silt, and clay unconformably overlie the older Pleistocene deposits in the Perris block. Latest Holocene surficial deposits consist of modern channel and wash deposits (Qw). Also mapped within the Perris block are a few young landslide deposits consisting of highly fragmented to locally coherent masses of rock fragments and soil material (Qyls).

Santa Ana Mountains Block

The oldest rock unit exposed in the map area within the Santa Ana Mountains block consists of Mesozoic undifferentiated metasedimentary rocks (Mzu). These rocks crop out across the southwest portion of the map and include an undifferentiated, thick-layered quartzite and a fissile, phyllitic rock of low metamorphic grade. The upper part of this unit weathers to saprolite.

Small outcrops of Cretaceous-age Peninsular Ranges Batholith rocks are exposed in the southwestern area of the map. A heterogeneous granitic rock unit (Khg) is mapped south of the Elsinore Fault Zone at the west central map boundary. This unit includes tonalite, monzogranite, granodiorite, and gabbro. The other Cretaceous granitic rock unit, undifferentiated tonalite (Kt), is a gray, foliated, medium-grained hornblende tonalite, which crops out in the southwest map corner.

The Miocene-age Santa Rosa Basalt (Tvsr) caps the Mesa de Burro southeast of Murrieta. The unit consists of brown, vesicular, moderately weathered basalt flows that unconformably overlie Mesozoic metasedimentary bedrock.

Both the sandstone and fanglomerate members of the Pleistocene Pauba Formation are exposed within the Santa Ana block where they unconformably overlie bedrock along the east flank of the range in the southwest part of the quadrangle. The fluvial sandstone member (Qps) is brown, slightly micaceous, moderately well indurated, locally cross-bedded, and contains sparse cobble to boulder conglomerate beds. The fanglomerate member (Qpf) is grayish brown and consists of poorly sorted, angular, plutonic and metamorphic clasts in a well-indurated mudstone matrix. The fanglomerate crops out up slope from the sandstone member and may represent sheetwash or mudflow deposits derived from the moderately steep slopes of the range front.

Locally within the Santa Ana block, the Pauba Formation is conformably overlain by very old (early to middle Pleistocene age) fluvial and valley deposits (Qvoag), while middle to late Pleistocene fluvial sediments (Qoaa) and young alluvial channel deposits (Qyaa; Qyag) typically cover the canyon floors. Active channels within the canyons and washes contain recently

transported loose sand and gravel deposits (Qw). A more detailed discussion of Quaternary map units is included in the Liquefaction Evaluation section (Section 1).

Structure

The dominant structural feature in the quadrangle is the northwest-trending Elsinore Fault Zone, which is the controlling structure dividing the central and western portions of the Peninsular Ranges Province into the Perris block on the northeast and the Santa Ana Mountains block on the southwest. Both of these blocks are relatively stable internally and are characterized by extensive erosional surfaces of relatively low relief within the quadrangle (Kennedy and Morton, 2003). The Elsinore Fault Zone consists of a series of high-angle, right-lateral strike-slip and normal faults with a dominant vertical component, expressed topographically as linear features and pull-apart depressions such as the Murrieta graben block (Mann, 1955).

The two main strands flanking the valley are the Willard Fault to the southwest and the Wildomar Fault to the northeast. The Willard Fault forms the western boundary of the valley along the steep northeast-facing slopes of the Santa Ana Mountain front. The latest movement along this fault is reported as late Pleistocene (Kennedy, 1977). The Wildomar Fault is not as well expressed topographically as is the Willard Fault, but its trace is fairly well defined by numerous lineaments along the east side of the valley. This fault forms a subsurface ground-water barrier and historically has had springs and artesian wells associated with it in the Pauba and Santa Gertrudis Valleys (Mann, 1955; Kennedy, 1977; Waring, 1919). The Murrieta Creek Fault, also a part of the Elsinore Fault Zone, is mapped as a discontinuous linear fault zone between the Willard and Wildomar Faults along the southwestern side of the valley. Another fault, the Murrieta Hot Springs Fault, strikes due east across the valley floor, extending through the intersection of Lemon Street and Adams Avenue (Kennedy and Morton, 2003).

The Wildomar Fault and the Murrieta Creek Fault are considered active faults (Hart and Bryant, 1997) and are designated as Official Earthquake Fault Zones in the Murrieta Quadrangle (California Department of Conservation, 1990). Recent studies in the area have reported ground cracking related to change in ground water levels due to development within the broad alluvial valley areas. These ground cracks resulted from subsidence along pre-existing Holocene subsurface faults, which are also included in the revised Official Earthquake Fault Zone Map (Wills, 1988 and California Department of Conservation, 1990).

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the Murrieta Quadrangle was prepared by field reconnaissance, analysis of stereo-paired aerial photographs and a review of previously published landslide mapping. Landslides were mapped at a scale of 1:24,000. For each landslide included on the map a number of characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable and questionable) and other properties, such as activity, thickness, and associated geologic unit(s). Landslides rated as definite and probable were incorporated into the landslide zoning as described later in this report. Landslides rated as questionable were not carried into the landslide zoning due to the uncertainty of their existence. The completed landslide map was digitized, and the attributes were compiled in a database.

Landslides are not common in the Murrieta Quadrangle. The few mapped landslides are small- to medium-size rotational rockslides that occur within the Pauba Formation and the unnamed sandstone of the Wildomar area. Local agricultural activities involving plowing and grading have obscured the original morphology of the landslides making it difficult to identify them in the field and on recent aerial photographs. In addition to the rotational rock slides described above, minor debris slides were observed along steep canyon walls, especially in crystalline bedrock; however, these deposits are too small to be shown at the scale of the map. The distribution of landslides mapped for this study is roughly similar to that mapped by Kennedy and Morton (2003) and Kennedy (1977), with some minor modifications. Landslides identified in the map area are shown on Plate 2.1.

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

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above were 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 Murrieta Quadrangle geologic map were obtained from the City of Murrieta and Riverside County (see Appendix A). The locations of rock and soil samples taken for shear testing within the Murrieta Quadrangle are shown on Plate 2.1. Shear tests from the adjoining quadrangles (Bachelor Mountain, Pechanga, Wildomar, Temecula, and Romoland) were used to augment data for several geologic formations for which little or no shear test information was available within the Murrieta Quadrangle.

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. Average (mean or median) phi values for each geologic map unit and corresponding strength groups are summarized in Table 2.1. For each geologic strength group (Table 2.2) in the map area, the average shear strength value was assigned and used in our slope stability analysis. A geologic material strength map was made based on the groupings presented in Table 2.1 and Table 2.2, and this map provides a spatial representation of material strength for use in the slope stability analysis.

Existing Landslides

As discussed later in this report, the criteria for landslide zone mapping state that all existing landslides that are mapped as definite or probable are automatically included in the landslide zone of required investigation. Therefore, an evaluation of shear strength parameters for existing landslides is not necessary for the preparation of the zone map. However, in the interest of completeness for the material strength map, to provide relevant material strength information to project plan reviewers, and to allow for future revisions of our zone mapping procedures, we

have collected and compiled shear strength data considered representative of existing landslides within the quadrangle.

The strength characteristics of existing landslides (Qyls) 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. Back-calculated strength parameters, if the calculations appear to have been performed appropriately, have also been included in our compilation. For the Murrieta Quadrangle, strength parameters applicable to existing landslide planes were not available, so the strength parameter for existing landslides (Qyls) is not included in this analysis.

MURRIETA QUADRANGLE							
SHEAR STRENGTH GROUPS							
	Formation Name	**Number Tests**	**Mean/Median Phi (deg)**	**Mean/Median Group Phi (deg)**	**Mean/Median Group C (psf)**	**No Data: Similar Lithology**	**Phi Values Used in Stability Analyses**
GROUP 1	**Kgb**	**11**	**35/36**	**36/37**	**379/282**	**Kpvgr, Kpvt, Kt**	**36**
	Kgd	**2**	**38/38**				
	Khg	**3**	**37/38**				
	Kpvg	**34**	**36/36**				
GROUP 2	**Qoaa**	**7**	**32/33**	**31/32**	**425/300**	**Qvoaa, Qvoag, Qw, Qyag, Qyfa, Qyva, Tvh, Tvsr, Tvt**	**31**
	Qpf	**4**	**33**				
	Qps	**48**	**32/33**				
	Qyaa	**13**	**30**				
	QTwc	**1**	**29**				
	QTws	**16**	**32**				
	Mzu	**10**	**30/29**				
Formation name (abbreviations from Morton (2004))							

Table 2.1. Summary of the shear-strength statistics for the Murrieta Quadrangle.

SHEAR STRENGTH GROUPS FOR THE MURRIETA 7.5-MINUTE QUADRANGLE	
GROUP 1	**GROUP 2**
Kgb	Mzu
Kgd	Qoaa
Khg	Qpf, Qps
Kpvg	Qw, Qyaa
Kpvgr	Qyag, Qyfa, Qyva
Kpvt	Qvoaa, Qvoag
Kp	QTwc, QTws
	Tvh
	Tvsr
	Tvt

Table 2.2. Summary of shear-strength groups for the Murrieta Quadrangle

PART II: EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT

GROUND SHAKING OPPORTUNITY

To evaluate earthquake-induced landslide hazard potential in the study area, CGS uses a method of dynamic slope stability analysis developed by Newmark (1965). The Newmark method analyzes dynamic slope stability by calculating the cumulative down-slope displacement for a given earthquake strong-motion time history. As implemented for the preparation of earthquake-induced landslide zones, the Newmark method necessitates the selection of a design earthquake strong-motion record to provide the "ground shaking opportunity." For the Murrieta Quadrangle, selection of a strong motion record was based on an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA). The parameters were estimated from maps prepared by CGS for a 10% probability of being exceeded in 50 years (Petersen and others, 1996).

The parameters used in the record selection are:

Modal Magnitude:	6.8
Modal Distance:	2.6 to 15.3 km
PGA:	0.4 to 0.65 g

The strong-motion record selected for the slope stability analysis in the Murrieta Quadrangle is the Corralitos record from the 1989 magnitude 6.9 Loma Prieta earthquake (Shakal and others, 1989). This record had a source to recording site distance of 5.1 km and a peak ground acceleration (PGA) of 0.64. The selected strong-motion record was not scaled or otherwise modified prior to its use in the analysis.

LANDSLIDE DISPLACEMENT CALCULATION

The design strong-motion record was used to develop a relationship between landslide displacement and yield acceleration (a_y), defined as the earthquake horizontal ground acceleration above which landslide displacements take place. This relationship was prepared by integrating the design strong-motion record twice for a given acceleration value to find the corresponding displacement, and the process was repeated for a range of acceleration values (Jibson, 1993). The resulting curve in Figure 2.1 represents the full spectrum of displacements that can be expected for the design strong-motion record. This curve provides the required link between anticipated earthquake shaking and estimates of displacement for different combinations of geologic materials and slope gradient, as described in the Slope Stability Analysis section below.

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). Applied to the curve in Figure 2.1, these displacements correspond to threshold yield accelerations of 0.086, 0.133 and 0.234g. Because these yield acceleration values are derived from the design strong-motion record, they represent the ground shaking opportunity thresholds that are significant in the Murrieta Quadrangle.

SLOPE STABILITY ANALYSIS

A slope stability analysis was performed for each geologic material strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration 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 angle. The yield accelerations resulting from Newmark's equations represent the susceptibility to earthquake-induced failure of each geologic material strength group for a range of slope gradients. Based on the relationship between yield acceleration and Newmark displacement shown in Figure 2.1, hazard potentials were assigned as follows:

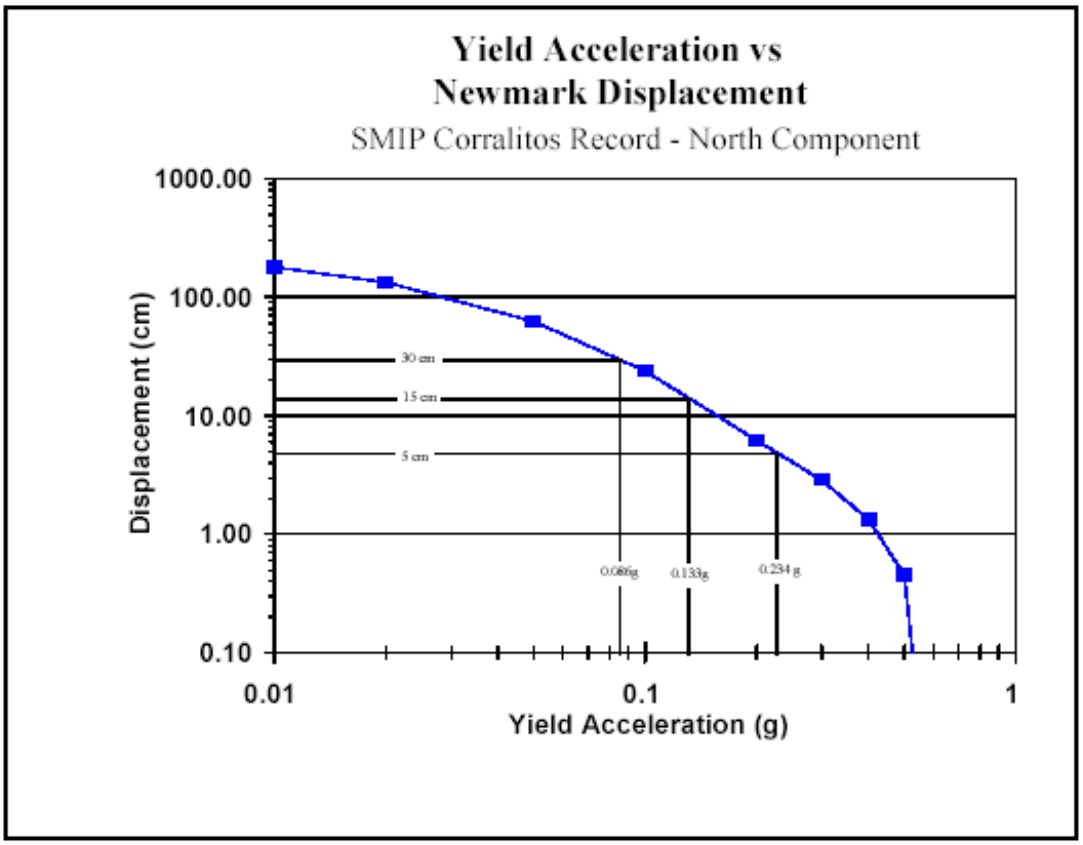
1. If the calculated yield acceleration was less than 0.086g, Newmark displacement greater than 30 cm is indicated, and a HIGH hazard potential was assigned.

2. If the calculated yield acceleration fell between 0.086g and 0.133g, Newmark displacement between 15 cm and 30 cm is indicated, and a MODERATE hazard potential was assigned.

3. If the calculated yield acceleration fell between 0.133g and 0.234g, Newmark displacement between 5 cm and 15 cm is indicated, and a LOW hazard potential was assigned.

4. If the calculated yield acceleration was greater than 0.234g, Newmark displacement of less than 5 cm is indicated, and a VERY LOW potential was assigned.

Table 2.3 summarizes the results of the stability analyses. The earthquake-induced landslide hazard potential map was prepared by combining the geologic material-strength map and the slope map according to this table. Values in the table show the range of slope gradient (expressed as percent slope) corresponding to calculated Newmark displacement ranges from the design earthquake for each material strength group.



Record from California Strong Motion Instrumentation Program (CSMIP) Station 57007.

Figure 2.1. Yield Acceleration vs. Newmark Displacement for the Corralitos Record of the 1989 Loma Prieta Earthquake.

MURRIETA QUADRANGLE HAZARD POTENTIAL MATRIX				
Geologic Material Strength Group (Average Phi)	**HAZARD POTENTIAL (Percent Slope)**			
	Very Low	**Low**	**Moderate**	**High**
1 (36)	0 to 48%	48 to 57%	57 to 64%	>64%
2 (31)	0 to 36%	36 to 46%	46 to 50%	>50%

Table 2.3. Hazard Potential Matrix for earthquake-induced landslides in the Murrieta Quadrangle.

ZONATION CRITERIA: EARTHQUAKE-INDUCED LANDSLIDES

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (DOC, 2000). Under these criteria, earthquake-induced landslide hazard zones are defined as areas that meet one or both of the following conditions:

1. Areas that have been identified as having experienced landslide movement in the past, including all mappable landslide deposits and source areas as well as any landslide that is known to have been triggered by historic earthquake activity.

2. Areas where the geologic and geotechnical data and analyses indicate that the earth materials may be susceptible to earthquake-induced slope failure.

These conditions are discussed in further detail below.

DELINEATION OF SEISMIC HAZARD ZONES: EARTHQUAKE-INDUCED LANDSLIDES

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

Existing Landslides

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

Hazard Potential Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), it has been concluded that earthquake-induced landslide hazard zones should encompass all areas that have a High, Moderate or Low level of hazard potential (see Table 2.3). This would include all areas where computer analyses indicate earthquake displacements of 5 centimeters or greater. Areas with a Very Low hazard potential, indicating less than 5 centimeters displacement, are excluded from the zone.

As summarized in Table 2.3, all areas characterized by the following geologic strength group and slope gradient conditions are included in the earthquake-induced landslide hazard zone:

1. Geologic Strength Group 2 is included in the zone for all slopes greater than 36 percent.

2. Geologic Strength Group 1 is included for all slopes greater than 48 percent.

This results in 3.4 percent of the portion of the quadrangle zoned and 3.1 percent of the entire quadrangle lying within the earthquake-induced landslide hazard zone for the Murrieta Quadrangle.

ACKNOWLEDGMENTS

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 Riverside County General Plan - Geologic Hazard Zone information was collected with the assistance of David Jones (Riverside County). Additionally, Jim Mackenzie and Robin Bateson (City of Murrieta) arranged access and provided assistance in retrieving geotechnical data from files maintained at their facility. At CGS, Janis Hernandez, and Cynthia Pridmore collected shear strength data for the Murrieta Quadrangle as well as surrounding quadrangles. Pamela Irvine and Siang Tan provided assistance with landslide inventory reconnaissance and review. Diane Vaughan, Terilee McGuire, Lee Wallinder, and Bob Moscovitz provided GIS support. Barbara Wanish prepared the final landslide hazard zone maps and the graphic displays for this report.

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AIR PHOTOS

Riverside County Flood Control District, 1984 Flight, B/W, 1:19,200 Scale

dated 11-23-83, frames: 177 through 182.

dated 11-27-83, frames: 194 through 201.

dated 12-8-83, frames: 358 through 366, and 392 through 400.

dated 12-15-83, frames: 551 through 559, and 584 through 591.

1967 WRD-USGS B/W dated 6-27-67, 1:6,000 Scale, frames: 6155 through 6160

1967 WRD-USGS B/W dated 6-28-67, 1:6,000 Scale, frames: 6353 through 6360, 6456 through 6462, and 6646 through 6651.

1953 AXM Flight, B/W, dated 8-28-53, 1:20,000 Scale, frames: 2K-40 through 42, 55 through 60, 131 through 134, and 148 through 154.

1953 AXM Flight, B/W, dated 9-22-53, 1:20,000 Scale, frames: 5K-31 through 38.

Digital Orthophoto Quarter Quadrangle Photos, B/W, 9/30/1996, entire quadrangle area, Murrieta Quadrangle. (DOQQ and information concerning them can be obtained at http://www-wmc.wr.usgs.gov/doq/).

APPENDIX A: SOURCES OF ROCK-STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City of Murrieta	104
Riverside County, Dept of Building and Safety	19
CGS Hospital Site Review	1
Bachelor Mountain Quadrangle	20
Wildomar Quadrangle	6
Pechanga Quadrangle	6
Temecula Quadrangle	3
Romoland Quadrangle	1
Total Number of Shear Tests	**160**

SECTION 3: GROUND SHAKING ASSESSMENT

for the

MURRIETA 7.5-MINUTE QUADRANGLE, RIVERSIDE COUNTY, CALIFORNIA

using the

2002 Probabilistic Seismic Hazard Assessment Model

By
Charles R. Real and Marvin Woods
Department of Conservation
California Geological Survey

INTRODUCTION

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation, California Geological Survey (CGS) to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the Seismic Hazard Zone Maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects located within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (CGS, 1997). The guidelines are available on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

This section of the evaluation report summarizes the calculations of ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included are ground motion maps, a brief overview on how these maps were prepared, precautionary notes concerning their use, and related references. The maps provided herein are presented at a scale of approximately 1:150,000 (scale bar provided on maps), and show the full 7.5-minute quadrangle and portions of the adjacent eight quadrangles. They can be used to assist in the specification of earthquake loading conditions for the analysis of ground failure according to the "Simple Prescribed Parameter Value" method (SPPV) described in the site investigation guidelines (CGS, 1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard. Site ground motion

levels from the 2002 seismic hazard model are also available interactively online: http://eqint.cr.usgs.gov/deaggint/2002 or http://www.consrv.ca.gov/cgs/rghm/pshamap/pshamain.html.

This section and Sections 1 and 2, which address liquefaction and earthquake-induced landslide hazards, constitute a report series that summarizes development of seismic hazard zone maps in the state. Additional information on seismic hazard zone mapping in California can be accessed on the California Geological Survey's Internet page: http://conservation.ca.gov/CGS/shzp.

2002 PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL

The estimated ground shaking is derived from the revised statewide Probabilistic Seismic Hazard Analysis (PSHA) model released cooperatively by the California Geological Survey and the U.S. Geological Survey (Cao et al., 2003; Frankel et al., 2002). This model replaces the previous ground-motion model of Peterson and others (1996) used in previous Official Seismic Hazard Zone Maps. Like the previous model, the 2002 model is the product of an extensive effort to obtain consensus within the scientific and engineering communities regarding fault parameters that characterize the seismic hazard in California. Fault sources included in the model were evaluated for long-term slip rate, maximum earthquake magnitude, and rupture geometry. These fault parameters, along with historical seismicity, were used to estimate return times of moderate to large earthquakes that contribute to the hazard. The 2002 model improves the way energy is partitioned among fault types and source areas and significantly narrows the gap that has existed between the earlier model and historical recurrence rates of earthquakes in the M6.5 to M7.0 range.

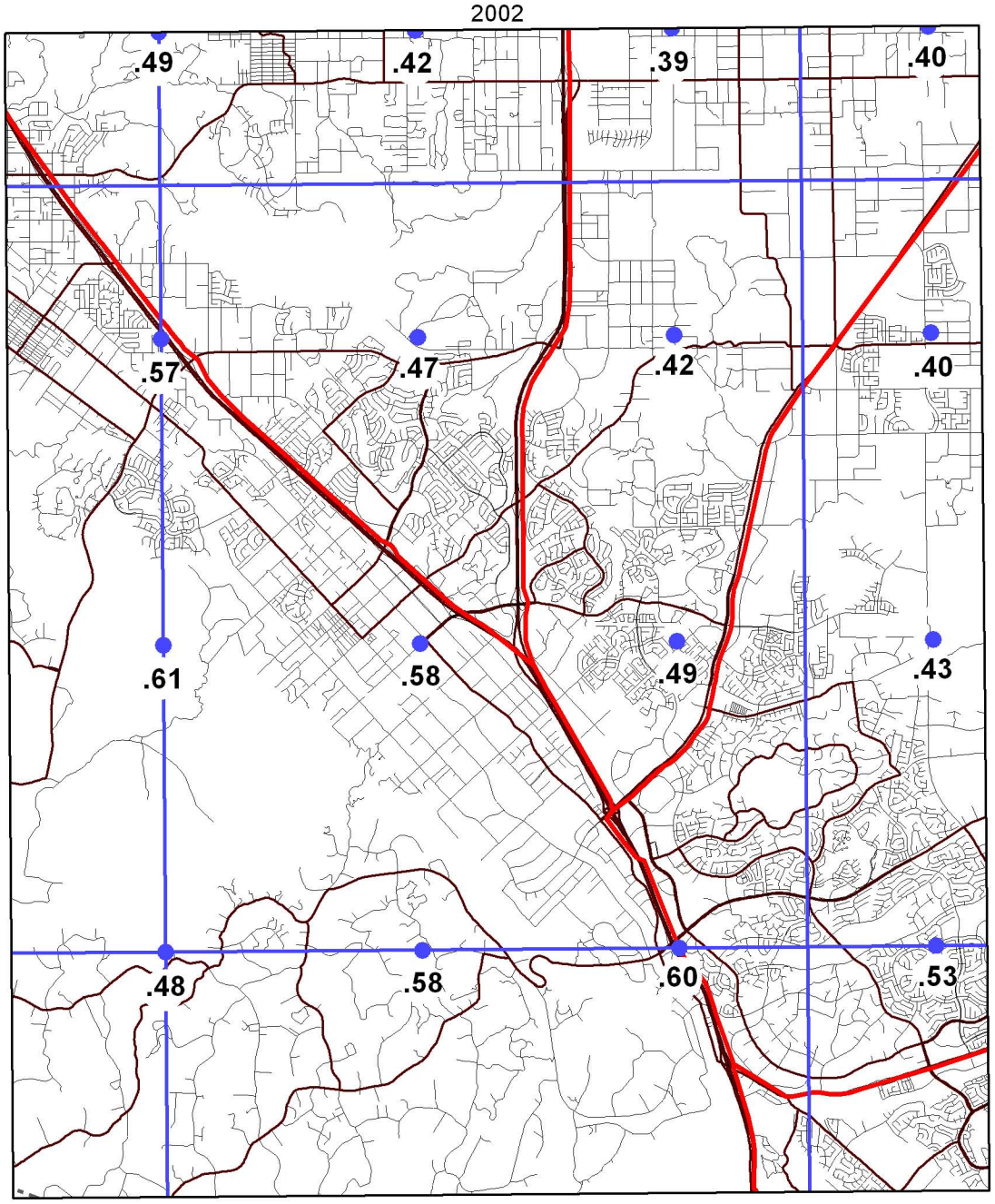
The ground shaking levels are estimated for each of the sources included in the seismic source model using attenuation relations that relate earthquake shaking with magnitude, distance from the earthquake, and type of fault rupture (strike-slip, reverse, normal, or subduction). Unlike the previous model, which used attenuation relations for various soil types, the current model considers only uniform firm-rock site conditions. In a separate post-PSHA step, we apply the NEHRP soil profile type D factor for PGA (FEMA, 1994) to adjust for alluvial soil conditions. For more details on changes in the new PSHA model see Cao and others (2003) and Frankel and others (2002).

The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figure 3.1 shows the hazard for PGA at 10 percent probability of exceedance in 50 years assuming the entire map area is firm rock (NEHRP B/C boundary soil condition). The sites where the hazard is calculated are represented as dots and ground motion contours as shaded regions. The quadrangle of interest is outlined by bold lines and centered on the map. Portions of the eight adjacent quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating PGA by interpolating ground motion from the calculated values of PGA rather than the contours, since the points are more accurate, and adjusting the value to site conditions using the NEHRP soil factors (Table 3.1).

MURRIETA 7.4-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

PEAK GROUND ACCELERATION FOR FIRM ROCK NEHRP B/C CONDITIONS
(Vs30 = 760 m/sec) AT 10 PERCENT EXCEEDENCE IN 50 YEARS

2002



Basemap from GDT

Department of Conservation
California Geological Survey

0 1 2 3 Miles
0 2 4 Kilometers

Figure 3.1

Soil Profile Type	**NEHRP (1994) Correction Factors for Different PGA Values (g)**				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
B	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
C	**1.2**	**1.2**	**1.1**	**1.0**	**1.0**
D	**1.6**	**1.4**	**1.2**	**1.1**	**1.0**
E	**2.5**	**1.7**	**1.2**	**0.9**	**-**

Table 3.1. 1994 NEHEP soil factors for peak ground acceleration

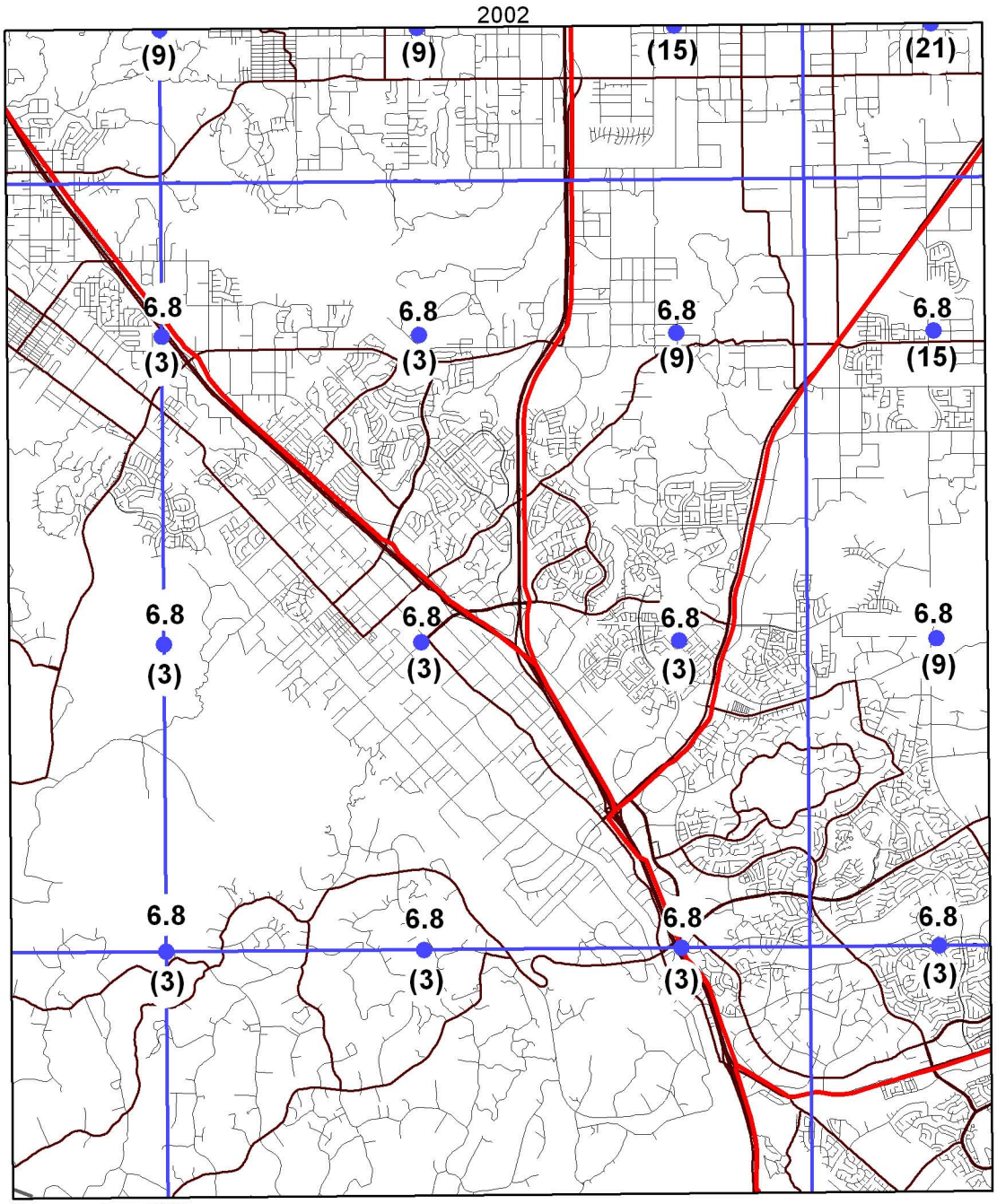
APPLICATION TO LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENT

Deaggregation of the seismic hazard identifies the contribution of each earthquake source (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (Cramer and Petersen, 1996). The map presented in Figure 3.2 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10 percent probability of exceedance in 50 years (*predominant earthquake*). This information provides a rationale for selecting seismic records or ground motion level for evaluating ground failure potential. For zoning earthquake-induced landslide hazard, the predominant earthquake distance and magnitude is used to select ground motion recordings that are consistent with the hazard for calculating landslide displacement using the simple rigid sliding-block approach (Wilson and Keefer, 1983) described more fully in Section 2 of this report.

Predominant earthquake information shown in Figure 3.2 can also be used with more complex fully coupled-compliant models for site-specifiec estimates of landslide displacement (Rathje and Bray, 2000). It can also be used with the Seed-Idriss simplified procedure (Youd et al., 2001) to

MURRIETA 7.4-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

MAGNITUDE OF AND DISTANCE TO (VALUE IN PARENTHESES) THE PREDOMINATE EARTHQUAKE AT10 PERCENT EXCEEDENCE IN 50 YEARS



Basemap from GDT

Department of Conservation
California Geological Survey

0 1 2 3 Miles

0 2 4 Kilometers

Figure 3.2

estimate seismic demand (cyclic stress ratio) for site-specific assessment of liquefaction hazard. The predominant earthquake is used to identify the causative fault, then an appropriate attenuation relation and predominant magnitude are used to estimate PGA at the site. The predominant magnitude is then used to adjust the liquefaction cyclic stress ratio threshold curves by a scaling factor in the final calculation of factor of safety according to the simplified procedure.

When selecting the predominant earthquake magnitude and distance it is important to keep in mind that more than one earthquake may contribute significantly to the hazard at a site, and those events can have markedly different magnitudes and distances. It is advisable to consider the range of values in the vicinity of the site and perform the ground failure analysis accordingly. This would yield a range in ground failure hazard from which recommendations appropriate to the specific project can be made. Grid values for predominant earthquake magnitude and distance should **not** be interpolated at the site location, because these parameters are not continuous functions.

When calculating probabilistic peak ground acceleration for purposes of zoning liquefaction hazard, we weight each earthquake's contribution to the hazard estimate by a factor that is a function of its magnitude. The function is simply the inverse of the liquefaction threshold scaling factor mentioned previously. The result is a "magnitude-weighted" ground motion that we then adjust for NEHRP alluvial conditions and use directly in the calculation of the induced cyclic stress ratio demand and thus the estimate of the factor of safety against liquefaction. Unlike the predominant–earthquake approach described previously, this approach provides an improved estimate of liquefaction hazard in a probabilistic sense. All magnitudes contributing to the hazard estimate are used to weight the probabilistic calculation of peak ground acceleration, effectively causing the cyclic stress ratio liquefaction threshold curves to be scaled probabilistically when computing factor of safety. This procedure ensures 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 et al., 2000).

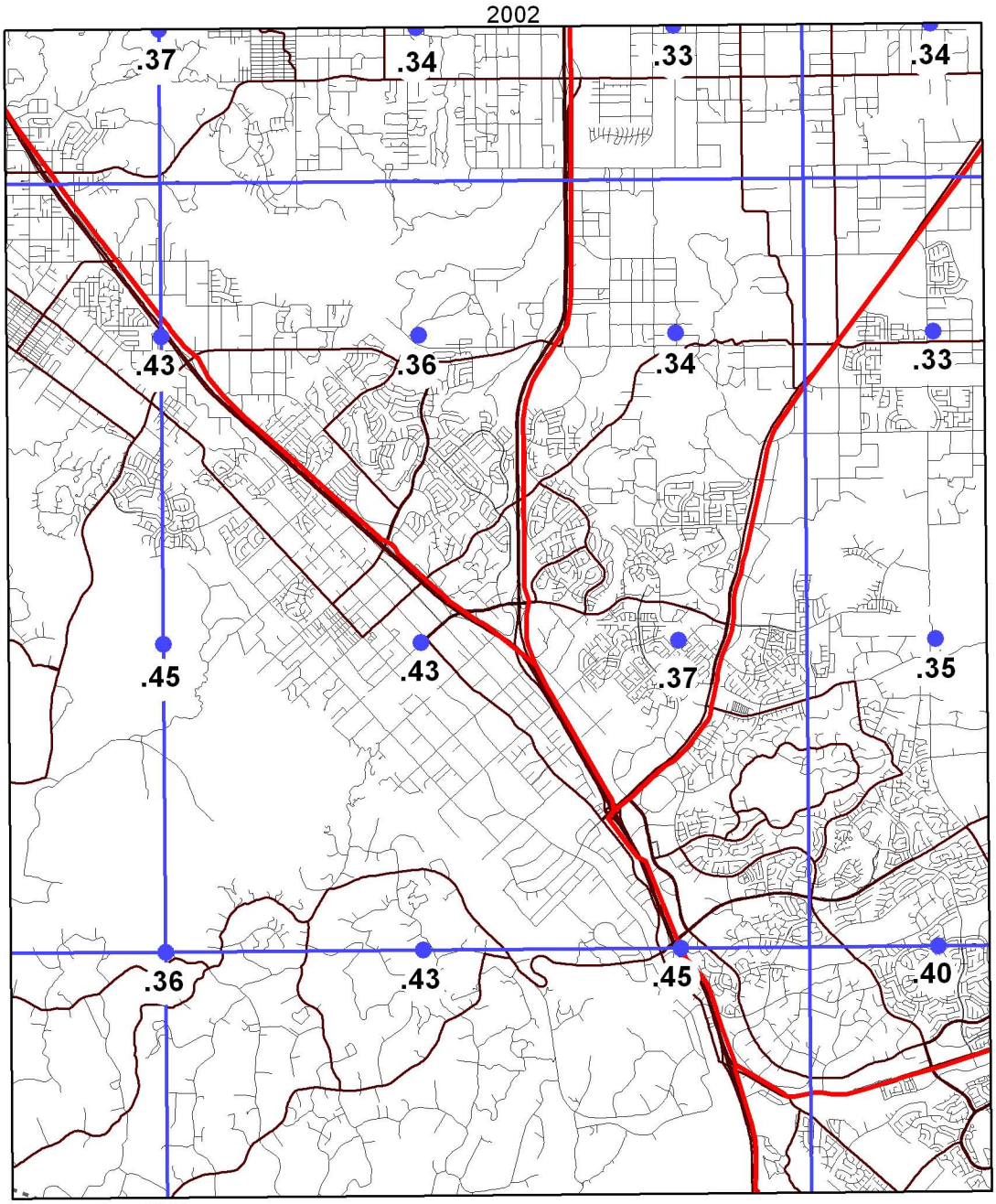
Figure 3.3 shows the magnitude-weighted alluvial PGA based on the Idriss scaling function (Youd et al., 2001). It is important to note that the values obtained from this map are pseudo-accelerations and should be used only in the simplified formulas for computing liquefaction factor of safety without applying any additional magnitude-scaling factor. We refer to this parameter as "liquefaction opportunity."

MURRIETA 7.4-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

LIQUEFACTION OPPORTUNITY MAP

VALUES ARE MAGNITUDE-WEIGHTED PSEUDO-PEAK GROUND ACCELERATION FOR ALLUVIAL CONDITIONS AT 10 PERCENT EXCEEDENCE IN 50 YEARS

2002



Basemap from GDT

Department of Conservation
California Geological Survey

0 1 2 3 Miles

0 2 4 Kilometers

Figure 3.3

USE AND LIMITATIONS

The statewide map of seismic hazard has been developed using regional information and is ***not appropriate for site-specifiec structural design applications***. Use of the ground motion maps prepared at larger scale is limited to estimating earthquake loading conditions for preliminary assessment of ground failure at a specific location. We recommend consideration of site-specific analyses before deciding on the sole use of these maps for the following reasons.

1. The seismogenic sources used to generate the peak ground accelerations were digitized from the 1:750,000-scale fault activity map of Jennings (1994). Uncertainties in fault location are estimated to be about 1 to 2 kilometers (Petersen and others, 1996). Therefore, differences in the location of calculated hazard values may also differ by a similar amount. At a specific location, however, the log-linear attenuation of ground motion with distance renders hazard estimates less sensitive to uncertainties in source location.

2. The hazard was calculated on a grid at sites separated by about 5 km (0.05 degrees). Therefore, the calculated hazard may be located a couple kilometers away from the site. We have provided shaded contours on the maps to indicate regional trends of the hazard model. However, the contours only show regional trends that may not be apparent from points on a single map. Differences of up to 2 km have been observed between contours and individual ground acceleration values. *We recommend that the user interpolate PGA between the grid point values rather than simply using the shaded contours*.

3. Uncertainties in the hazard values have been estimated to range from about +/- 10 to 30 percent of the ground motion value at two standard deviations for most of California (Cao et al., 2005). It may be as high as 50 percent in some locations where the earthquake source parameters have higher uncertainty.

4. Not all active faults in California are included in this model. For example, faults that do not have documented slip rates are not included in the source model. Scientific research may identify active faults that have not been previously recognized. Therefore, future versions of the hazard model may include other faults and omit faults that are currently considered.

5. A map of the predominant earthquake magnitude and distance is provided from the deaggregation of the probabilistic seismic hazard model. However, it is important to recognize that a site may have more than one earthquake that contributes significantly to the hazard. Therefore, in some cases earthquakes other than the predominant earthquake should also be considered.

6. Because of its simplicity, it is likely that the SPPV method (CGS, 1997) will be widely used to estimate earthquake shaking for the evaluation of ground failure hazards. Because ground motion models evolve with time it is best to refer to the aforementioned

web sites in order to obtain the most current ground shaking information when using this method: http://eqint.cr.usgs.gov/deaggint/2002 or http://www.consrv.ca.gov/cgs/rghm/pshamap/pshamain.html.

As a final caution, it should be kept in mind that ground motions at a given distance from an earthquake will vary depending on site-specific characteristics such as geology, soil properties, and topography, which may not have been adequately accounted for in the regional hazard analysis. Although this variability is represented to some degree by the recorded ground motions that form the basis of the hazard model used to produce Figures 3.1 and 3.3, extreme deviations can occur. More sophisticated methods that take into account other factors that may be present at the site (site amplification, basin effects, near source effects, etc.) should be employed as warranted. The decision to use the SPPV method with ground motions derived from Figures 3.1 or 3.3 should be based on careful consideration of the above limitations, the geotechnical and seismological aspects of the project setting, and the "importance" or sensitivity of the proposed building with regard to occupant safety.

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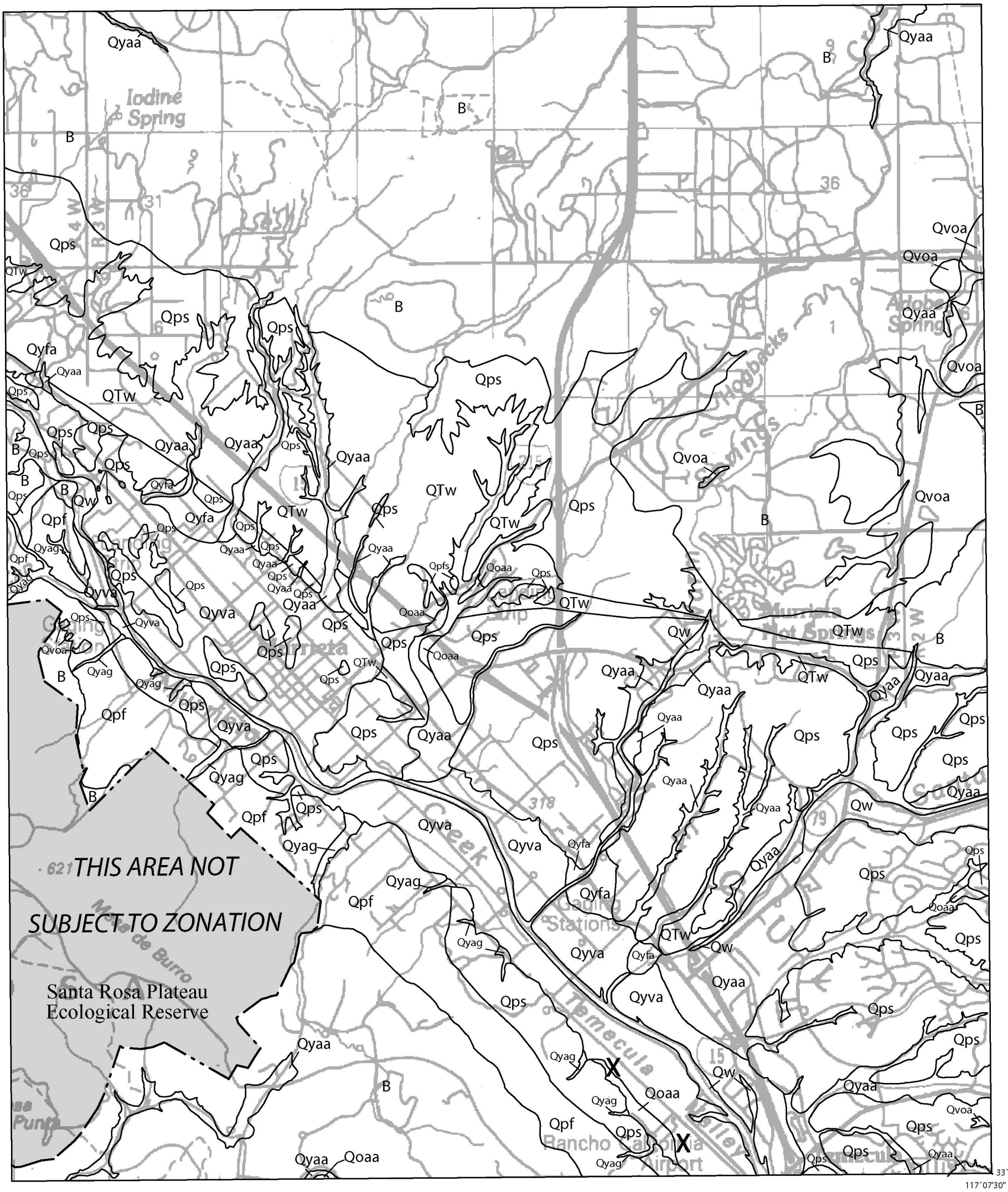


Base map enlarged from U.S.G.S. 30 x 60-minute series

MURRIETA QUADRANGLE

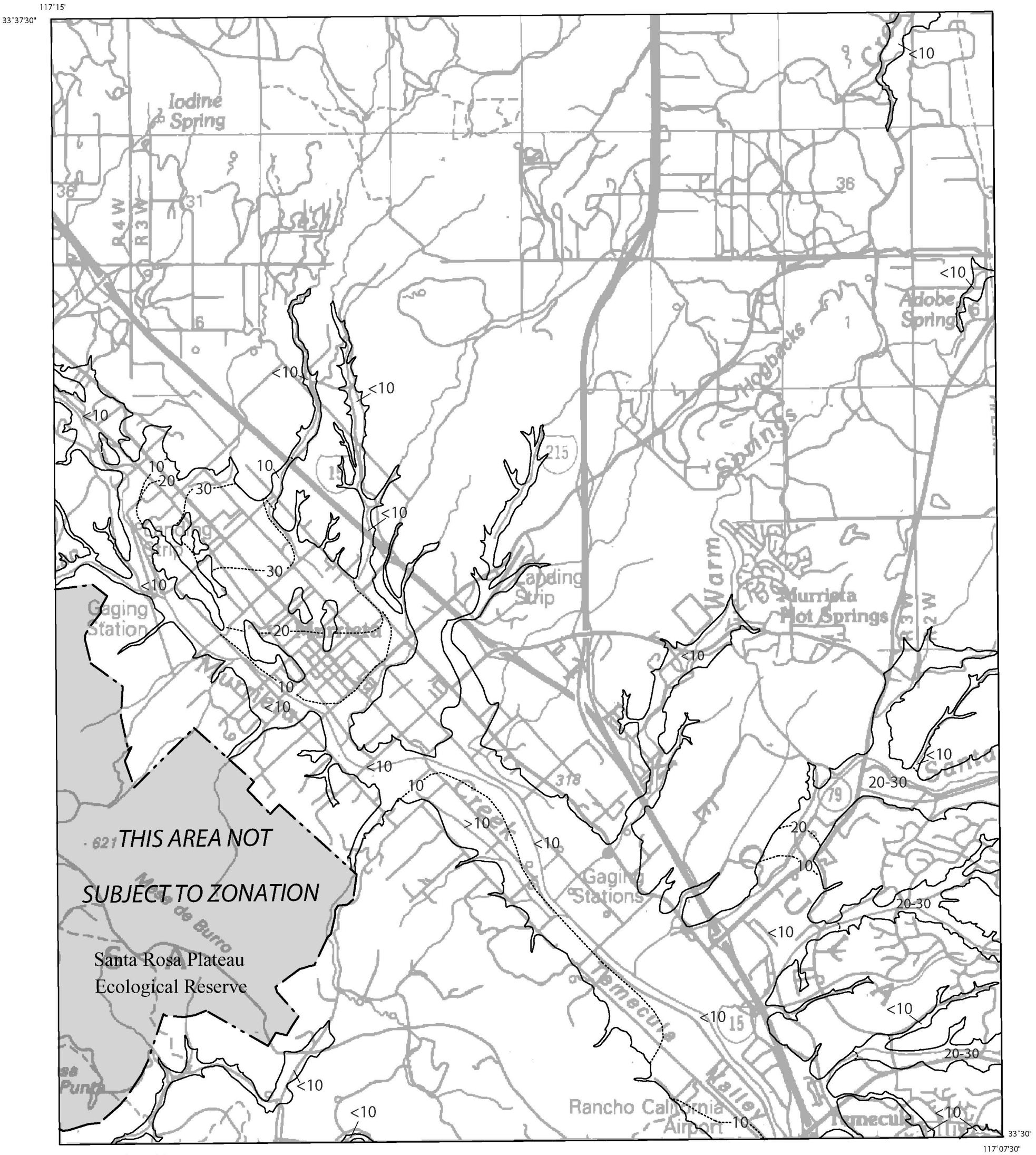
SCALE

N

See " Geology" in Section 1 of report for descriptions of units.
B = Pre-Quaternary bedrock.

X Location of trench sites that show evidence of liquefaction

Plate 1.1 Quaternary Geologic Materials Map of the Murrieta 7.5-Minute Quadrangle.



Base map enlarged from U.S.G.S. 30 x 60-minute series

MURRIETA QUADRANGLE

SCALE

1 MILE

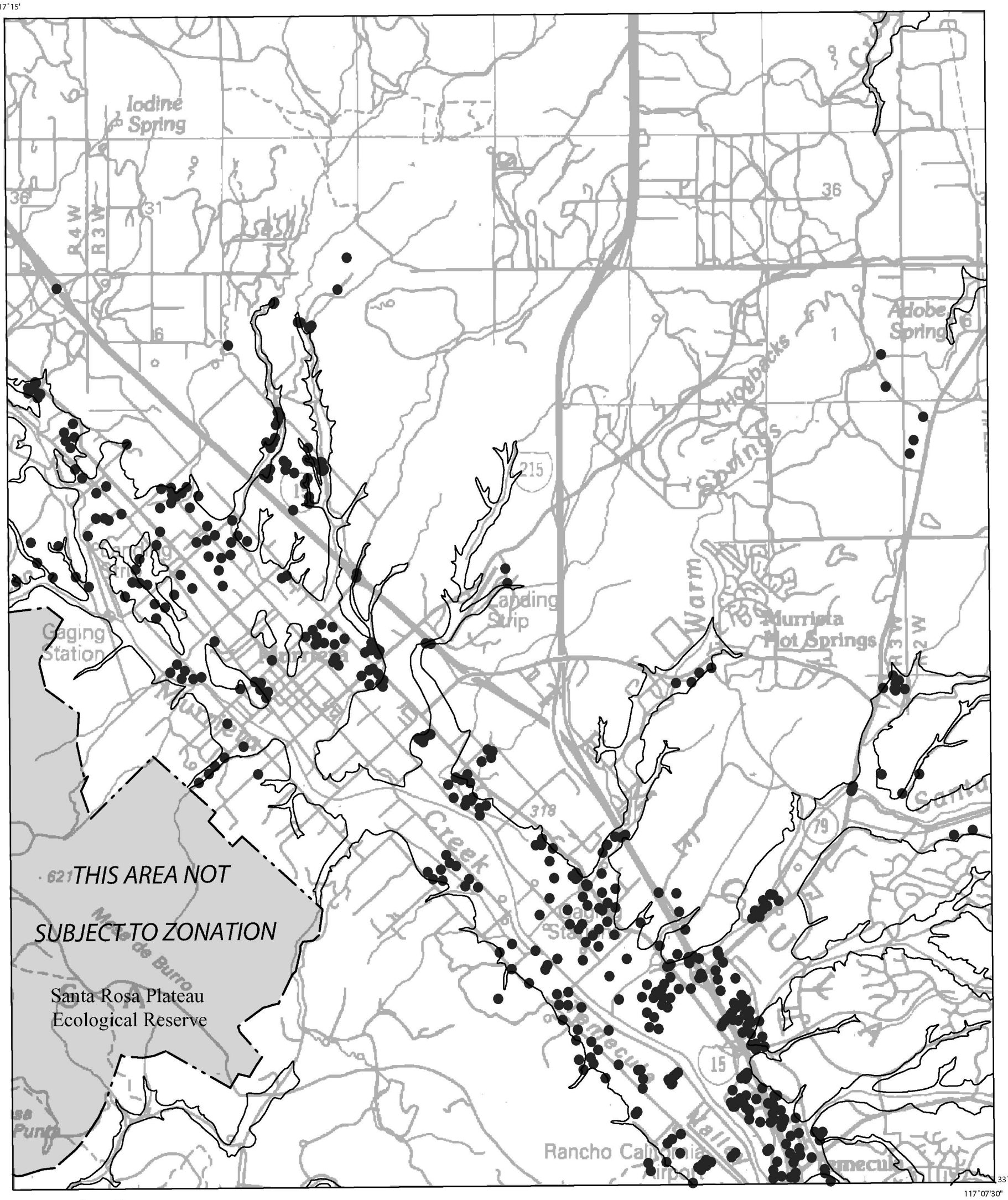
7000 FEET

1 KILOMETER

N

<10 10 Ground-water depth contours (in feet)

Plate 1.2 Depth to Historically High Ground-Water Levels in Quaternary Alluvial Deposites, Murrieta 7.5-Minute Quadrangle, California.



Base map enlarged from U.S.G.S. 30 x 60-minute series

MURRIETA QUADRANGLE

N

SCALE

1 .5 0 1 MILE

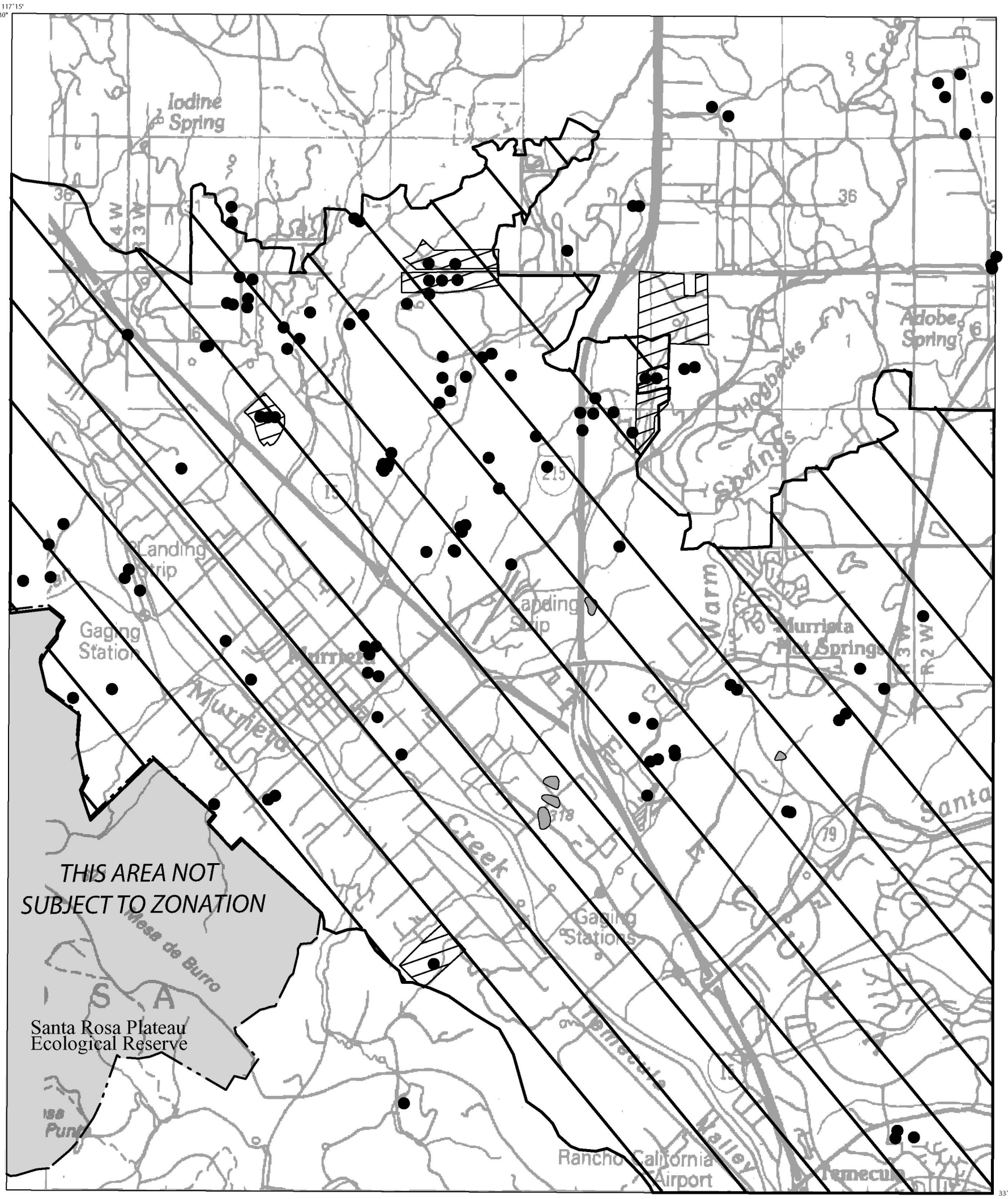
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

● Geotechnical borings used in liquefaction evaluation

— Quaternary boundary

Plate 1.3 Locations of Boreholes Used in Evaluating Liquefaction Hazard, Murrieta 7.5-Minute Quadrangle, California.



Base map enlarged from U.S.G.S. 30 x 60-minute series

MURRIETA QUADRANGLE

SCALE

0 .5 0 1 MILE

1000 0 2000 4000 6000 FEET

1 .5 0 1 KILOMETER

N

● Shear test sample location

Landslide

Area of significant grading

Tract report with multiple shear tests

Plate 2.1 Landslide inventory, and shear test sample locations, Murrieta 7.5-Minute Quadrangle, California.