SEISMIC HAZARD ZONE REPORT 074

SEISMIC HAZARD ZONE REPORT FOR THE PIRU 7.5-MINUTE QUADRANGLE, VENTURA COUNTY, CALIFORNIA

2002

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EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the Piru 7.5-minute Quadrangle, Ventura County, California. The map displays the boundaries of Zones of Required Investigation for liquefaction and earthquake-induced landslides over an area of approximately 51 square miles at a scale of 1 inch = 2,000 feet. About 83 percent of the quadrangle was evaluated for seismic hazards. The boundary of the Los Padres National Forest cuts across the northern third of the quadrangle. The Hooper Mountain National Wildlife Refuge and part of the Sespe Condor Sanctuary are also within the part of the quadrangle that was not evaluated for seismic hazards.

The Piru Quadrangle, in east-central Ventura County, consists mostly of rugged, mountainous terrain except for the lowlands along the Santa Clara River valley and in Piru Creek Canyon. A portion of Lake Piru, impounded behind the Santa Felicia Dam on Piru Creek, is in the northeastern corner. North of Piru the mountains rise to 4358 feet in the northwestern corner of the quadrangle. South of the Santa Clara River the north-facing slope of Oak Ridge reaches elevations above 2500 feet. In contrast to the major drainage channels of the Santa Clara River and Piru Creek, local drainage courses are confined to torturous canyons in the mountains. The entire quadrangle consists of unincorporated Ventura County land. The rural community of Piru, at the confluence of Piru Creek and the Santa Clara River Valley, is the only settlement. Land use includes agriculture, primarily citrus groves, and oil fields. Access to the region is via Telegraph Road (State Highway 126), which follows the Santa Clara River Valley. Piru Canyon road gives access to Lake Piru and the national forest to the north.

The map is prepared by employing geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information considered includes topography, surface and subsurface geology, borehole data, historical ground-water levels, existing landslide features, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. The shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10% probability of exceedance in 50 years.

In the Piru Quadrangle the liquefaction zone closely coincides with the beds and floodplains of Piru Creek and the Santa Clara River. The lower reaches of Hopper Canyon, Fairview Canyon, and several creeks that drain Oak Ridge are also in the zone. The combination of steep, deeply dissected topography, intensive structural deformation, and weak marine sedimentary rock units has produced widespread and abundant landslides. These conditions contribute to an earthquake-induced landslide zone that covers about 65 percent of the evaluated portion of the quadrangle.

How to view or obtain the map

Seismic Hazard Zone Maps, Seismic Hazard Zone Reports and additional information on seismic hazard zone mapping in California are available on the California Geological Survey's Internet page: http://www.conservation.ca.gov/CGS/index.htm

Paper copies of Official Seismic Hazard Zone Maps, released by CGS, which depict zones of required investigation for liquefaction and/or earthquake-induced landslides, are available for purchase from:

BPS Reprographic Services
945 Bryant Street
San Francisco, California 94105
(415) 512-6550

Seismic Hazard Zone Reports (SHZR) summarize the development of the hazard zone map for each area and contain background documentation for use by site investigators and local government reviewers. These reports are available for reference at CGS offices in Sacramento, San Francisco, and Los Angeles. **NOTE: The reports are not available through BPS Reprographic Services.**

INTRODUCTION

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 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 on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

The Act also 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 provide detailed standards for mapping regional liquefaction hazards. They also directed CGS 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.

This Seismic Hazard Zone Report summarizes the development of the hazard zone map. The process of zoning for liquefaction uses a combination of Quaternary geologic mapping, historical ground-water information, and subsurface geotechnical data. The process for zoning earthquake-induced landslides incorporates earthquake loading, existing landslide features, slope gradient, rock strength, and geologic structure. Probabilistic seismic hazard maps, which are the underpinning for delineating seismic hazard zones, have been prepared for peak ground acceleration, mode magnitude, and mode distance with a 10% probability of exceedance in 50 years (Petersen and others, 1996) in accordance with the mapping criteria.

This report summarizes seismic hazard zone mapping for potentially liquefiable soils and earthquake-induced landslides in the Piru 7.5-minute Quadrangle.

SECTION 1
LIQUEFACTION EVALUATION REPORT

Liquefaction Zones in the Piru 7.5-Minute Quadrangle, Ventura County, California

By
Ralph C. Loyd and Allan G. Barrows

California Department of Conservation
California Geological Survey

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 developed 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 seismic hazard zones. 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 on the Internet at http://gmw.consrv.ca.gov/shmp/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 liquefaction 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 under the auspices of the Southern California Earthquake Center (SCEC).

The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of liquefaction analysis, evaluation, and mitigation techniques (SCEC, 1999). This text is also on the Internet at: http://www.scec.org/

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Piru 7.5-minute Quadrangle. Section 2 (addressing earthquake-induced landslides) and Section 3 (addressing potential ground shaking), complete the report, which is one of a series that summarizes production of similar seismic hazard zone maps within the state (Smith, 1996). Additional information on seismic hazards zone mapping in California is on CGS's Internet web page: http://www.conservation.ca.gov/CGS/index.htm

BACKGROUND

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 region was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 40 feet of the ground surface. These geological and ground-water conditions exist in parts of southern, most notably in some densely populated valley regions and alluviated floodplains. In addition, the potential for strong earthquake ground shaking is high because of the many nearby active faults. The combination of these factors constitutes a significant seismic hazard in the southern California region, including areas in the Piru Quadrangle.

METHODS SUMMARY

Characterization of liquefaction hazard presented in this report requires preparation of maps that delineate areas underlain by potentially liquefiable sediment. The following were collected or generated for this evaluation:

- Existing geologic maps were used to provide an accurate representation of the spatial distribution of Quaternary deposits in the study area. Geologic units that generally are susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill

- Construction of shallow ground-water maps showing the historically highest known ground-water levels

- Quantitative analysis of geotechnical data to evaluate liquefaction potential of deposits

- Information on potential ground shaking intensity based on CGS probabilistic shaking maps

The data collected for this evaluation were processed into a series of geographic information system (GIS) layers using commercially available software. The liquefaction zone map was derived from a synthesis of these data and according to criteria adopted by the SMGB (DOC, 2000).

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 Piru Quadrangle consist mainly of alluviated valleys, floodplains, and 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. 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. They do not predict the amount or direction of liquefaction-related ground displacements, or the amount of damage to facilities that may result from liquefaction. Factors that control liquefaction-induced ground failure are the extent, depth, density, and thickness of liquefiable materials, depth to 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.

Information developed in the study is presented in two parts: physiographic, geologic, and hydrologic conditions in PART I, and liquefaction and zoning evaluations in PART II.

PART I

PHYSIOGRAPHY

Study Area Location and Physiography

The Piru Quadrangle covers about 62 square miles in east-central Ventura County. Much of the area consists of rugged, mountainous terrain except for the lowlands along mile-wide Santa Clara River valley and in Piru Creek Canyon. A portion of Lake Piru, impounded behind the Santa Felicia Dam on Piru Creek, is in the northeastern corner.

North of the Santa Clara River the mountains rise to Modelo Peak (3298 feet elevation) about two and one half miles north of Piru. The highest elevation is 4358 feet in the northwestern corner. South of the Santa Clara River the north-facing slope of Oak Ridge reaches elevations above 2500 feet. In contrast to the major drainage channels of the Santa Clara River and Piru Creek, local drainage courses are confined to torturous canyons in the mountains.

The entire quadrangle consists of unincorporated Ventura County land. The rural community of Piru, at the confluence of Piru Creek and the Santa Clara River Valley, is the only settlement in the quadrangle. Land use in the quadrangle includes agriculture, primarily citrus groves, and oil fields. Access to the region is via Telegraph Road (State Highway 126), which follows the Santa Clara River Valley. Piru Canyon road gives access to Lake Piru and the national forest to the north. The boundary of the Los Padres National Forest cuts across the northern third of the quadrangle. Also within the quadrangle are the Hooper Mountain National Wildlife Refuge and part of the Sespe Condor Sanctuary. These wilderness areas are within the part of the quadrangle that was not evaluated for zoning. About 83 percent (51 square miles) of the quadrangle was evaluated for zoning.

GEOLOGY

Bedrock and Surficial Geology

Geologic units generally susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. William Lettis and Associates (WLA) (2000) provided a digital Quaternary geologic map of the Piru Quadrangle (Plate 1.1). This map was merged with a digitized bedrock geologic map by Dibblee (1991) to provide a common geologic map for zoning liquefaction and earthquake-induced landslides. Nomenclature for labeling Quaternary geologic units followed that applied by the Southern California Areal Mapping Project (SCAMP) (Morton and Kennedy, 1989). The distribution of Quaternary deposits on this map was used in combination with other data, discussed below, to evaluate liquefaction potential and develop the seismic hazard zone map.

About 20 percent of the Piru Quadrangle is covered by young Quaternary deposits, mainly in the valleys of the Santa Clara River and Piru Creek (Plate 1.1). WLA (2000) mapped the various units primarily on the basis of depositional environment, geomorphic expression, and relative ages, as determined largely by topographic position, degree of soil profile development, and degree of surface erosion. Nearly all of the alluvial units are Holocene or, locally, late Pleistocene. A large patch of older alluvium (Qoa) of probable Pleistocene age occurs on the eastern slope of Modelo Mountain (Plate 1.1).

The most extensively exposed units mapped in the river valleys of the Piru Quadrangle are the series of older, younger, and latest Holocene (relative ages) alluvial fan deposits (Qyf1, Qyf2, and Qf, respectively) along the both sides of the Santa Clara River valley and within Piru Creek Canyon. Also abundant are older, younger, and latest Holocene (relative ages) river channel and stream wash sediments (Qw1, Qw2, and Qw, respectively) deposited within the bed of the Santa Clara River and Piru Creek (Plate 1.1). Surficially, the alluvial fan units are composed of materials that range from boulders to clay, with sand and silty sand being the major constituents.

The most widespread bedrock unit exposed in the Piru Quadrangle consists of marine sandstone and shale of the middle to late Miocene Monterey Formation (Dibblee, 1991). In addition, small areas within the quadrangle contain Sespe Formation sandstone, Rincon Shale, Topanga Sandstone, clay shale and sandstone of the Sisquoc Formation, sandstone, claystone, and siltstone of the Towsley Formation, sandstone and claystone of the Pliocene Pico Formation, sandy beds of the early Pleistocene Las Posas Formation, weakly consolidated pebble/cobble conglomerate and sandstone of the Pleistocene Saugus Formation (Dibblee, 1991). It is important to note that, except for deposition associated with the Santa Clara River and Piru Creek, the general lithologic characteristics of the Quaternary deposits in the lowland areas of the Piru Quadrangle are governed largely by the distribution of bedrock units in the adjacent upland regions. For example, where an alluvial fan has developed at the mouth of a canyon whose drainage area erodes bedrock units largely composed of claystone, then that alluvial fan typically will contain abundant clay. Conversely, if sandstone is exposed over much of the drainage area, the alluvial fan will contain abundant sand. Lastly, if a variety of rock types is exposed in the drainage area alluvial fan sedimentary deposits tend to alternate between fine- and coarser-grained materials. This, naturally, depends upon fluctuations in stream energy, changes in active stream channels and variations of erosion rates within the drainage basin due to localized landsliding, fires, and other natural processes. Conditions governing deposition of alluvial fans in the Piru Quadrangle, which contain sediment layers ranging from clay to boulders, appear to relate closely with variations in erosion rates. Refer to the earthquake-induced landslide portion (Section 2) of this report for further details on the bedrock units exposed in the Piru Quadrangle.

Structural Geology

The Piru Quadrangle is within the East Ventura Basin where folding and faulting has intensively deformed a thick section of Tertiary marine sedimentary rocks. Two major, active reverse faults dip in opposite directions on either side of the Santa Clara River. North of the river the north-dipping eastern or “Modelo” lobe of the San Cayetano Fault splits into two strands, the Piru and Main strands, in the vicinity of Piru (Yeats, 2001; Dolan and Rockwell, 2001)). The Piru strand, which is inferred to underlie the community of Piru (Dibblee, 1991), is the southern one. A trench cut across this strand in 1999 by Dolan and Rockwell (2001) revealed evidence of at least 4.3 m of surface slip after A.D.1660. Dolan and Rockwell (2001) speculate that the displacement could have occurred during an earthquake larger than Mw 7, possibly even the 21 December 1812 earthquake.

South of the Santa Clara River, at the base of Oak Ridge, is the south-dipping Oak Ridge Fault (Dibblee, 1991). Evidence for Holocene surface fault rupture along this fault within the Piru Quadrangle has not been reported. However, about five miles to the west-southwest a short segment within the Moorpark Quadrangle, where a strand of the Oak

Ridge Fault is expressed at the surface by a youthful-appearing scarp in alluvium near Bardsdale, is included in the Official Earthquake Zone prepared by CGS (DOC, 1999).

Recent geodetic studies of the Ventura Basin based upon the Global Positioning System (GPS) show that north-south shortening on the order of 6 to 7 mm/year is taking place (Donnellan and others, 1993a, 1993 b; Argus and others 1999). Within the Piru Quadrangle the entire shortening is accommodated between the Oak Ridge and San Cayetano faults (Dolan and Rockwell, 2001, p.1418). Near Piru these faults are only about two miles apart.

ENGINEERING GEOLOGY

Information on subsurface geology and engineering characteristics of sedimentary deposits was obtained from borehole logs collected from reports on geotechnical and environmental projects. For this investigation, six borehole logs were collected from the files of the Ventura County Water Resources and Engineering Department, Ventura County Hazardous Substances Control Program, and the California Department of Transportation (CalTrans). Locations of the exploratory boreholes considered in this investigation are shown on Plate 1.2. Staff entered the data from the geotechnical logs into CGS's GIS in order to create a database that would allow effective examination of subsurface geology through construction of computer-generated cross sections and evaluation of liquefaction potential of sedimentary deposits through the performance of computer-based quantitative analysis.

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. This in-field test consists of counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil at the bottom of a borehole at chosen intervals while drilling. 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, 1999). Recorded blow counts for non-SPT geotechnical sampling where the sampler diameter, hammer weight or drop distance differ from those specified for an SPT (ASTM D1586), are converted to SPT-equivalent blow counts. The actual and converted SPT blow counts are normalized to a common-reference, effective-overburden pressure of one atmosphere (approximately one ton per square foot) and a hammer efficiency of 60% using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$.

Six geotechnical borehole logs reviewed in this study include blow-count data from SPTs or from penetration tests that allow reasonable blow count translations to SPT-equivalent values. Non-SPT values, such as those resulting from the use of 2-inch or 2½-inch inside-diameter ring samplers, were translated to SPT-equivalent values if reasonable factors could be used in conversion calculations. The reliability of the SPT-equivalent values varies. Therefore, they are weighted and used in a more qualitative manner. Few borehole logs, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or using averaged test values of similar materials.

The Seed-Idriss Simplified Procedure for liquefaction evaluation was developed primarily for clean sand and silty sand. As described above, results depend greatly on accurate evaluation of in-situ soil density as measured by the number of soil penetration blow counts using an SPT sampler. However, many of the Holocene alluvial deposits in the study area contain a significant amount of gravel. In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and recent laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995). SPT-derived density measurements in gravelly soils are unreliable and generally too high. They are likely to lead to overestimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N values appear to have been affected by gravel content, correlations were made with boreholes in the same unit where the N values do not appear to have been affected by gravel content.

GROUND-WATER CONDITIONS

Depth to ground water is a key factor governing liquefaction hazard. Ground-water saturation reduces the effective normal stress acting on loose, sandy sediments, thus lowering the resistance of sediments to loss of strength when pore-water pressure increases during ground shaking. Liquefaction of subsurface sedimentary layers can result in structure damaging ground failure at the surface through differential settlement or lateral spreading, particularly if the phenomenon occurs at a depth from the surface of less than 40 feet.

Large fluctuations in ground-water levels over seasons, years and decades are caused by natural processes and human activities. These fluctuations generally make it impossible to predict what conditions might exist when future earthquakes could cause major ground shaking. To address this uncertainty, CGS develops ground-water maps that show depths to historically shallowest levels recorded from water wells and boreholes drilled over the past century. The evaluations are based on first-encountered water noted in the logs of geotechnical boreholes and water wells. Water depths from boreholes known to penetrate confined aquifers are not used. The resultant maps, which are based on measurements recorded over the past century or more, differ considerably from conventional ground-water maps that are based on measurements collected during a single season or year.

Historically shallowest depths to ground water in alluviated valley and canyon regions of the Piru Quadrangle are presented on Plate 1.2. Ground-water levels recorded at numerous monitoring water wells along and adjacent to the Santa Clara River show remarkable seasonal and long-term fluctuations since the measurements by the County of Ventura first began in the late 1920's. Variations ranging from depths of 10 to 180 feet are recorded at some wells north of the Santa Clara River and west of Piru Creek. Average depths to water in the bed of the Santa Clara River normally range between 10 and 40 feet, although much greater depths appear in some records. Ground-water levels drop sharply along the southern margin of the Santa Clara River where the river cuts into Oak Ridge.

LIQUEFACTION POTENTIAL

Liquefaction can occur in water-saturated sediment during moderate to great earthquakes. Liquefied sediment loses strength and might 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 the potential seismic ground shaking intensity.

The method applied in this study for evaluating liquefaction potential is similar to that of Tinsley and others (1985) who apply a combination of the techniques used by Seed and others (1983) and Youd and Perkins (1978) for their mapping of liquefaction hazards in the Los Angeles region. CGS's method combines geotechnical analyses, geologic and hydrologic mapping, and probabilistic earthquake shaking estimates following criteria adopted by the SMGB (DOC, 2000).

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 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 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 addressed in this investigation.

Saturation is required for liquefaction, and the liquefaction susceptibility of a soil varies with the depth to ground water. Very shallow ground water increases the susceptibility to liquefaction (soil is more likely to liquefy). 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.

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. CGS's qualitative assessment of liquefaction susceptibility relative to various geologic units and depth to ground water is summarized in Table 1.1.

Geologic Map Unit	Sediment Type	Environment of Deposition	Consistency	Susceptible to Liquefaction?*
Qw, Qw1, Qw2	Gravel, sand, silt	Stream channels	Very loose to loose	Yes
Qf	Sand, silt, clay	Active alluvial fans	Very loose to loose	Yes**
Qyf1-2 , Qya1-2, Qyat11-2	Sand, silt, clay	Young alluvial fan and valley deposits	Loose to moderately dense	Yes**
Qc	clay, silt, rock clasts	Colluvium, slope wash, rubble	loose to firm	Not Likely***
Qoa, Qof, Qop, Qoat1-2	Clay, silt, sand, and gravel deposits.	Older alluvial deposits	Dense to very dense	Not likely

* When saturated ** Not likely if all clay or sand and silt layers are clayey *** Usually thin surficial covering

Table 1. 1. General Geotechnical Characteristics and Liquefaction Susceptibility of Quaternary Sedimentary Units.

LIQUEFACTION OPPORTUNITY

Analysis of in-situ liquefaction potential requires assessment of liquefaction opportunity. Liquefaction opportunity is the estimation of the severity of expected future ground shaking over the region at a specific exceedance probability and exposure time (Real, 2002). The minimum level of seismic excitation to be used for such purposes is the level of peak ground acceleration (PGA) with a 10% probability of exceedance over a 50-year period (DOC, 2000). The earthquake magnitude used in CGS's analysis of liquefaction potential is the magnitude that contributes most to the calculated PGA for an area.

For the Piru Quadrangle, PGAs of 0.57g to 0.99g (for alluvium conditions), resulting from predominant earthquakes of magnitudes ranging from 6.6 to 6.9, were used for liquefaction analyses. The PGA and magnitude values were based on de-aggregation of the probabilistic hazard at the 10% in 50-year hazard level (Petersen and others, 1996; Cramer and Petersen, 1996). See the ground motion portion (section 3) of this report for additional discussion of ground motion characterization.

Quantitative Liquefaction Analysis

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using 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). The Seed-Idriss Simplified Procedure enables sediment resistance to liquefaction to be calculated and expressed in terms of cyclic resistance ratio (CRR), The procedure is based on SPT results, ground-water level, soil density, moisture content, soil type, and sample depth. CRR values are then compared to calculated earthquake-generated shear stresses expressed in terms of cyclic stress ratio (CSR). The Seed-Idriss Simplified Procedure requires normalizing earthquake loading to a M7.5 event. To accomplish this, CGS's analysis uses the Idriss magnitude-scaling factor (MSF) (Youd and Idriss, 1997). It is convenient to think in terms of a factor of safety (FS) relative to liquefaction, where: FS = (CRR / CSR) * MSF. FS, therefore, is a quantitative measure of liquefaction potential. CGS uses a factor of safety of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil. While an FS of 1.0 is considered the "trigger" for liquefaction, for a site specific analysis an FS of as much as 1.5 may be appropriate depending on the vulnerability of the site and related structures.

The CGS liquefaction analysis program calculates an FS for each geotechnical sample for which standardized blow counts were collected. Typically, multiple samples are collected from each borehole. The program then calculates an FS for each non-clay layer that includes at least one penetration test. If a layer contains more than one penetration test, the minimum $(N1)_{60}$ value is used. 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 values, as well as other considerations such as slope, presence of free faces, and thickness and depth of potentially liquefiable soil throughout a project area, are evaluated to delineate areas of relative high liquefaction potential. These areas then translate directly to zones of required investigation.

LIQUEFACTION ZONES

Criteria for Zoning

Areas underlain by materials susceptible to liquefaction during an earthquake were included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (DOC, 2000). 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 containing liquefaction-susceptible material 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 geotechnical data are insufficient

In areas of limited or no geotechnical data, susceptibility zones may be identified 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% probability of being exceeded in 50 years is greater than or equal to 0.10 g and the water table is less than 40 feet below the ground surface; 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% probability of being exceeded in 50 years is greater than or equal to 0.20 g and the historical high water table is less than or equal to 30 feet below the ground surface; 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% probability of being exceeded in 50 years is greater than or equal to 0.30 g and the historical high water table is less than or equal to 20 feet below the ground surface.

Application of SMGB criteria to liquefaction zoning in the Piru Quadrangle is summarized below.

Areas of Past Liquefaction

Although no accounts of liquefaction in the Piru Quadrangle were found in this study, liquefaction-like features have been reported in adjacent areas. For example, excerpts of 1858 topographic survey reports (California Division of Mines and Geology, 1976) describe ground lurch cracks and related features associated with liquefaction, triggered by the 1857 Fort Tejon earthquake, observed in the Santa Clara River near the City of San Buena Ventura, about 30 miles downstream from the City of Piru. Lateral-spreading fissures possibly associated with liquefaction were mapped less than a mile east of the Piru Quadrangle adjacent to the Santa Clara River and also within Potrero Canyon by Rymer and others (2001) following the 1994 Northridge earthquake. Areas showing evidence of paleoseismic liquefaction have not been reported.

Artificial Fills

Artificial fill areas in the Piru Quadrangle large enough to show at the scale of mapping consist of engineered fill for dams, river levees, and road construction. Since these fills are considered to be properly engineered, zoning for liquefaction in such areas depends on soil conditions in underlying strata. Non-engineered fills are commonly loose and uncompacted, and the material varies in size and type.

Areas with Sufficient Existing Geotechnical Data

Santa Clara River and Piru Creek. The logs of five geotechnical test boreholes, 20 water wells drilled in the beds of the Santa Clara River and Piru Creek, and geologic mapping indicate that deposits within 40 feet of the surface are composed mainly of loose to very loose sandy materials and that historically shallowest depths to ground water range from 10 to 40 feet. This suggests that the extremely high earthquake shaking intensities expected for this area (up to 0.99g; see Section 3) are likely to trigger liquefaction, which could cause ground failure in stream channel and floodplain environments. These areas, therefore, are designated zones of required investigation.

Areas with Insufficient Existing Geotechnical Data

Alluviated area west of Piru Creek. West of Piru Creek and north of the Santa Clara River is a 4.5 square-mile alluviated area that slopes very gently to the south and southwest from the base of the Ventura Hills toward the Santa Clara River. Although adequate geotechnical borehole data are lacking, geologic mapping by WLA (2001) and Dibblee (1991), logs of about 40 DWR water-well logs, ground-water level monitoring records collected by Ventura County Public Works, and opportunity for intense ground shaking (up to 0.99g; see section 3) indicate there is potential for liquefaction in this area. Geologic mapping shows that surface deposits covering this area consists of about two-thirds relatively young Holocene alluvial fan material (Qyf2) and about one-third relatively older Holocene alluvial fan material (Qyf1). A minor part of the surface is covered by river and creek floodplain alluvium (Qya1 and Qya2). The lithologic logs of almost all water wells penetrating the alluvial fan describe the upper 40 feet as being composed primarily of sand, gravel, cobbles, and boulders. Furthermore, first-encountered water and periodic water-well records extending from the mid-1920's to the present show that ground-water depths over most of the elevated alluvial fan surface are commonly less than 40 feet. Consequently, the lowland and slightly elevated alluvial fan surface north of the Santa Clara River and west of Piru Creek is designated a zone of required investigation.

Alluviated area east of Piru Creek. East of Piru Creek and north of the Santa Clara River is a one-square-mile alluviated lowland. Although adequate geotechnical borehole data are lacking, geologic mapping by WLA (2001) and Dibblee (1991), logs of about 10 DWR water- well logs, ground-water level monitoring records collected by Ventura County Public Works, and opportunity for intense ground shaking (up to 0.99g; see section 3) indicate there is potential for liquefaction in this area. Geologic mapping shows that surface deposits covering the lowest parts of this area consists of relatively young Holocene floodplain alluvium (Qya2), whereas slightly higher surfaces are composed of terrace surface (Qyat2) and alluvial fan deposits (Qyf1 and Qyf2). The lithologic logs of almost all water wells penetrating the alluvial fan describe the upper 40 feet as consisting primarily of sand, gravel, cobbles, and boulders. Furthermore, first-encountered water and periodic water-well records extending from the mid-1920's to present day show that ground-water depths over most of the area are less than 40 feet. Consequently, the slightly elevated alluvial fan surface north of the Santa Clara River and east of Piru Creek is designated a zone of required investigation.

Alluviated area south of the Santa Clara River. Wedged between the Santa Clara River and Oak Ridge are discontinuous strips of alluviated lowland and slightly elevated alluvial fans that have developed along the base of Oak Ridge. Although no geotechnical data exist for these areas, geologic mapping by WLA (2001) and Dibblee (1991), 8 DWR water-well logs, ground-water level monitoring records collected by Ventura County Public Works, and opportunity for intense ground shaking (up to 0.99g; see section 3) indicate there is potential for liquefaction in this area. Geologic mapping shows that surface deposits covering the lowland south of the river consist of relatively young Holocene floodplain alluvium (Qya2) and river channel deposits (Qw2) and relatively older Holocene river channel deposits (Qw1). Slightly higher surfaces are composed of active alluvial fans (Qf), relatively older Holocene alluviated terrace surface deposits (Qyat2), and relatively older Holocene alluvial fan deposits (Qyf1 and Qyf2). The lithologic logs of almost all water wells penetrating the alluvial fan describe the upper 40 feet as consisting primarily of sand, gravel, cobbles, and boulders. Furthermore, first-encountered water and periodic water-well records extending from the mid-1920's to the present show that ground-water depths over most of the area are less than 40 feet. Consequently, the alluviated area south of the Santa Clara River and north of Oak Ridge is designated a zone of required investigation.

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SECTION 2
EARTHQUAKE-INDUCED LANDSLIDE EVALUATION REPORT

Earthquake-Induced Landslide Zones in the Piru 7.5-Minute Quadrangle, Ventura County, California

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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://gmw.consrv.ca.gov/shmp/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 Piru 7.5-minute Quadrangle. Section 1 (addressing liquefaction) and Section 3 (addressing earthquake shaking), 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/index.htm

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, 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 hillside areas of the Piru Quadrangle.

METHODS SUMMARY

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 used to provide an up-to-date representation of slope gradient and slope aspect in the study area

- Geologic mapping was used to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether triggered by earthquakes or not, 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 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 of analysis (Newmark, 1965), resulting in a map of 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 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. See Section 1, Liquefaction Evaluation Report for the Piru Quadrangle, for more information on the delineation of liquefaction zones.

The remainder of this report describes in more detail the mapping data and processes used to prepare the earthquake-induced landslide zone map for the Piru Quadrangle. The information is presented in two parts. Part I covers physiographic, geologic and engineering geologic conditions in the study area. Part II covers the preparation of landslide hazard potential and landslide zone maps.

PART I

PHYSIOGRAPHY

Study Area Location and Physiography

The Piru Quadrangle covers about 62 square miles in east-central Ventura County. Much of the area consists of rugged, mountainous terrain except for the lowlands along mile-wide Santa Clara River valley and in Piru Creek Canyon. A portion of Lake Piru, impounded behind the Santa Felicia Dam on Piru Creek, is in the northeastern corner. North of the Santa Clara River the mountains rise to Modelo Peak (3298 feet elevation) about two and one half miles north of Piru. The highest elevation is 4358 feet in the northwestern corner. South of the Santa Clara River the north-facing slope of Oak Ridge reaches elevations above 2500 feet.

The structural framework for this quadrangle includes two west-trending major active faults. North of the Santa Clara River the mountains consist of tightly folded sedimentary strata that have been uplifted and thrust to the south along the north-dipping San Cayetano Fault, which lies along the mountain base just north of Piru. South of the Santa Clara River Oak Ridge contains sedimentary strata that have been uplifted along the south-dipping Oak Ridge reverse fault. In contrast to the major drainage channels of the Santa Clara River and Piru Creek, local drainage courses are confined to torturous canyons in the mountains.

The entire quadrangle consists of unincorporated Ventura County land. The rural community of Piru, at the confluence of Piru Creek and the Santa Clara River Valley, is the only settlement in the quadrangle. Land use in the quadrangle includes agriculture, primarily citrus groves, and oil fields. The boundary of the Los Padres National Forest cuts across the northern third of the quadrangle. Also within the quadrangle are the Hooper Mountain National Wildlife Refuge and part of the Sespe Condor Sanctuary. These wilderness areas are within the part of the quadrangle that was not evaluated for seismic hazards. About 83 percent (51 square miles) of the quadrangle was evaluated for seismic hazards.

Access to the region is via Telegraph Road (State Highway 126), which follows the Santa Clara River Valley. Piru Canyon road gives access to Lake Piru and the national forest to the north.

Digital Terrain Data

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 Piru 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 1947 aerial photography, has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy.

A slope map was made from the DEM using a third-order, finite difference, center-weighted algorithm (Horn, 1981). The DEM was also used to make a slope aspect map. The manner in which the slope and aspect maps were used to prepare the zone map will be described in subsequent sections of this report.

GEOLOGY

Bedrock and Surficial Geology

The bedrock geology for the Piru Quadrangle was mapped by Dibblee (1991) and digitized for this study by CGS. Landslide deposits were deleted from the map so that the distribution of bedrock formations and the landslide inventory would exist on separate layers for the hazard analysis. The surficial Quaternary geology was mapped and digitized by William Lettis and Associates (2000). CGS geologists merged the bedrock and surficial geologic maps and databases, and made adjustments to contacts between bedrock and surficial units to resolve differences. In the field, observations were made of exposures, aspects of weathering, and general surface expression of the geologic units.

Bedrock of the Piru Quadrangle consists of the following rock units that range from upper Eocene (?) to Pleistocene: Sespe, Rincon Shale, Topanga Sandstone, Monterey, Sisquoc, Towsley, Pico, Las Posas Sand, and Saugus formations (Dibblee, 1991). Stratigraphic nomenclature differs among the various geologists who have worked in the Piru and adjacent quadrangles. Alternative nomenclature is mentioned below under the description of each unit.

The oldest rock units in the quadrangle are found on Oak Ridge south of the Oak Ridge Fault near the southern boundary. Upper Eocene to lower Miocene (predominantly Oligocene according to Dibblee, 1991) Sespe Formation (Tsp) is comprised of nonmarine medium- to coarse-grained light gray to tan, bedded sandstone, with minor thin lenses of reddish to purplish-gray claystone. Stratigraphic dips are to the north. Also exposed on Oak Ridge are gray clay shale and interbedded silty sandstone of the marine Rincon Shale (Tr) of early Miocene age. Topanga Sandstone (Tts) was mapped by Dibblee (1991) immediately south of the Oak Ridge Fault. This late Oligocene (?) to early Miocene marine light-gray to tan arkosic sandstone was mapped as Vaqueros Formation by Kew (1924).

The early Miocene Rincon Shale (Tr) is the oldest unit exposed north of the Santa Clara River in the Piru Quadrangle. Poorly bedded, gray clay shale and siltstone occurs in the northwestern corner in the core of a regional anticlinal fold.

Middle to late Miocene marine sedimentary rocks of the Monterey Formation are exposed over more than half of the quadrangle. Earlier workers (Eldridge and Arnold, 1907; Kew, 1924; Weber and others, 1973) mapped Monterey Formation as Modelo Formation. Dibblee (1991) subdivided the Monterey Formation into several members based upon lithology. South of the Santa Clara River on Oak Ridge is the undivided shale unit (Tmu). North of the Santa Clara River and the San Cayetano Fault Monterey Formation includes a lower shale unit (Tml) comprised of white to tan soft, fissile, thin-bedded shale with interbedded harder siliceous layers that rests upon Rincon Shale in the northwestern quarter of the map area. The lower sandstone member (Tmss) with tan, thick-bedded sandstone is interbedded with and overlies the lower shale unit in the northwestern quarter of the map area and also interbedded with the upper shale member (Tm) west of Lake Piru. Typical platy "Monterey shale," which is widespread in the surrounding region, is represented by the white-weathering upper shale member (Tm). It consists of thin-bedded, hard, platy, siliceous and diatomaceous shale and is very abundant in the eastern half of the quadrangle, such as on Modelo Peak, and in the area just north of the San Cayetano Fault west of Piru. At the top of the Monterey Formation is the upper sandstone member (Tmsu) that is comprised of tan thick-bedded sandstone layers. This member is exposed in large folds across the central part of the quadrangle. Due to the complex folding, especially in the vicinity of the San Cayetano Fault, the orientation of beds within the Monterey Formation is locally highly variable.

Members of the marine, late Miocene Sisquoc Formation (Dibblee, 1991) rest upon Monterey Formation sandstone within synclinal folds in the area north of Piru. Earlier workers (Eldridge and Arnold, 1907; Kew, 1924; Weber and others, 1973) included these rocks within the Modelo Formation. Sisquoc Formation includes: light gray to tan, semi-friable sandstone (Tsqs); undivided shale (Tsq); light gray shale and siltstone with some semi-siliceous layers (Tsql); and an upper part with gray clay shale and siltstone (Tsqu).

Small exposures of Towsley Formation of latest Miocene to early Pliocene age occur in the eastern part of the quadrangle in the center of synclinal folds next to Lake Piru and Piru Canyon. South of the Santa Clara River a large area in the southeastern corner of the quadrangle is also underlain by Towsley Formation. Dibblee (1991) subdivided the marine Towsley Formation into three members: a gray basal conglomerate (Ttog) with rounded cobbles in a sandstone matrix; gray, poorly bedded claystone (Ttoc); and light gray to tan sandstone with thin interbeds of claystone or siltstone (Ttos).

Pico Formation rocks are exposed in the southeastern quarter of the quadrangle, both north and south of the Santa Clara River. The Pico Formation consists of marine rocks of Pliocene age. Dibblee (1991) subdivided the Pico Formation into three members: light gray to tan massive sandstone and pebble conglomerate (Tpsg); light gray to tan, semi-friable bedded sandstone (Tps); and gray micaceous claystone with local thin interbeds of sandstone (Tp). Due to its proximity to either the San Cayetano Fault or the Oak Ridge Fault, Pico Formation in the Piru Quadrangle exhibits steep to vertical dips and widespread overturned beds.

The late Pliocene to early Pleistocene Las Posas Formation (QTlp) consists of weakly indurated light gray to yellow-tan, fine- to coarse-grained, pebbly sand with scattered shell fragments confined to slivers along the Oak Ridge Fault south of the Santa Clara River. The Las Posas Sand is considered by some geologists to be a lower, marine member of the Saugus Formation (Irvine, 1995).

The Pleistocene nonmarine Saugus Formation (QTs) conformably overlies the Las Posas Formation and consists of weakly consolidated, light gray to light brown pebble-cobble gravel, sand and clay. The Saugus Formation is exposed on opposite sides of the Santa Clara River near Piru.

Pleistocene to Holocene surficial deposits, as mapped by William Lettis and Associates (2000) unconformably overlie the bedrock units. These units cover the beds and floodplains of the Santa Clara River, Piru Creek and several smaller creeks in the Piru Quadrangle. Surficial deposits consist of weakly indurated older alluvial gravel, sand and clay (Qoa), colluvium (Qc), older terrace deposits (Qoat1, Qoat2), stream channel deposits (Qw, Qw1, Qw2), alluvial fan deposits (Qf, Qyf1, Qyf2), younger terrace deposits (Qyat1, Qyat2), alluvium (Qya1, Qya2), and artificial fill (af) of the Santa Felicia Dam. Landslide deposits are not included in the bedrock/Quaternary geologic materials map used in this study, but are shown on a separate landslide inventory map (Plate 2.1). A more detailed discussion of Quaternary deposits in the Piru Quadrangle can be found in Section 1.

Structural Geology

The Piru Quadrangle is within the East Ventura Basin where folding and faulting has intensively deformed a thick section of Tertiary marine sedimentary rocks. Two major, active reverse faults dip in opposite directions on either side of the Santa Clara River. North of the river the north-dipping eastern or “Modelo” lobe of the San Cayetano Fault splits into two strands, the Piru and Main strands, in the vicinity of Piru (Yeats, 2001; Dolan and Rockwell, 2001)). The Piru strand, which is inferred to underlie the community of Piru (Dibblee, 1991), is the southern one. A trench cut across this strand in 1999 by Dolan and Rockwell (2001) revealed evidence of at least 4.3 m of surface slip after A.D.1660. Dolan and Rockwell (2001) speculate that the displacement could have occurred during an earthquake larger than Mw 7, possibly even the 21 December 1812 earthquake.

South of the Santa Clara River, at the base of Oak Ridge, is the south-dipping Oak Ridge Fault (Dibblee, 1991). Evidence for Holocene surface fault rupture along this fault within the Piru Quadrangle has not been reported. However, about five miles to the west-southwest a short segment within the Moorpark Quadrangle, where a strand of the Oak Ridge Fault is expressed at the surface by a youthful-appearing scarp in alluvium near Bardsdale, is included in the Official Earthquake Zone prepared by CGS (DOC, 1999).

Recent geodetic studies of the Ventura Basin based upon the Global Positioning System (GPS) show that north-south shortening on the order of 6 to 7 mm/year is taking place (Donnellan and others, 1993a, 1993 b; Argus and others 1999). Within the Piru Quadrangle the entire shortening is accommodated between the Oak Ridge and San

Cayetano faults (Dolan and Rockwell, 2001, p.1418). Near Piru these faults are only about two miles apart.

The multiplicity of anticlinal and synclinal folds within the Tertiary rocks to the north of the San Cayetano Fault not only has created structural traps for petroleum found in local oil fields but also has provided many areas where steeply dipping, relatively weak rocks are vulnerable to slope failure. This is manifested by the abundance of landslides in this quadrangle.

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the Piru 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 carried into the slope stability analysis. Landslides rated as questionable were not carried into the slope stability analysis due to the uncertainty of their existence. The completed landslide map was scanned, digitized, and the attributes were compiled in a database.

Rock slides and debris slides are the most common types of landslides in the area, and their locations are strongly influenced by the structural deformation of these relatively young sedimentary rocks. In Rodeo Flat, several rock slides are mapped on the nose of the plunging Santa Felicia Syncline. Debris slides and rock slides occur on both limbs of the series of anticlines and synclines south of Temescal Anticline. In the eastern part of the quadrangle, north of the San Cayetano Fault, numerous debris and rock slides occur on the southern limb of the Warring Syncline and on the nose of the plunging Buckhorn Anticline. Rock and debris slides with occasional debris flows are abundant in the southern part of the quadrangle where the folded and faulted sedimentary rocks exhibit moderate to steeply dipping beds or steeply dipping overturned beds.

The most susceptible formation to landsliding is the Monterey Formation followed by Sisqouc, Towsley, and Topanga formations. The distribution of landslides identified in the area is shown on Plate 2.1.

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 on the basis of their shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. Shear-strength data for the units identified on the Piru Quadrangle geologic map were obtained from Ventura County and Earth Systems Consultants (see Appendix A). The locations of rock and soil samples taken for shear testing within the Piru Quadrangle are shown on Plate 2.1. Shear test data for the Piru Quadrangle were difficult to obtain, mostly due to the lack of residential development. Rock strength groups for the Fillmore and Piru quadrangles were combined to augment shear test data. In addition, shear test data from the adjoining and nearby Val Verde, Moorpark, Simi Valley East, Santa Paula Peak, Simi Valley West, and Newhall quadrangles were used to augment data for several geologic formations for which little or no shear test information was available.

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped on the basis of average angle of internal friction (average phi) and lithologic character. Average (mean or median) phi values for each geologic map unit and corresponding strength group are summarized in Table 2.1. For most of the geologic strength groups in the map area, a single 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 Tables 2.1 and 2.2, and this map provides a spatial representation of material strength for use in the slope stability analysis.

The Sespe Formation (Tsp) was subdivided further, as described below.

Adverse Bedding Conditions

Adverse bedding conditions are an important consideration in slope stability analyses. Adverse bedding conditions occur where the dip direction of bedded sedimentary rocks is roughly the same as the slope aspect, and where the dip magnitude is less than the slope gradient. Under these conditions, landslides can slip along bedding surfaces due to a lack of lateral support.

To account for adverse bedding in our slope stability evaluation, we used geologic structural data in combination with digital terrain data to identify areas with potentially adverse bedding, using methods similar to those of Brabb (1983). The structural data, derived from the geologic map database, was used to categorize areas of common bedding dip direction and magnitude. The dip direction was then compared to the slope aspect and, if the same, the dip magnitude and slope gradient categories were compared. If the dip magnitude category was less than or equal to the slope gradient category, but greater than 25% (4:1 slope), the area was marked as a potential adverse bedding area.

The Sespe Formation, which contains interbedded sandstone and claystone, was subdivided based on shear strength differences between coarse-grained (higher strength) and fine-grained (lower strength) lithologies. Shear strength values for the fine- and coarse-grained lithologies were then applied to areas of favorable and adverse bedding orientation, which were determined from structural and terrain data as discussed above. It was assumed that coarse-grained material strength dominates where bedding dips into a slope (favorable bedding) while fine-grained material strength dominates where bedding dips out of a slope (adverse bedding). The geologic material strength map was modified by assigning the lower, fine-grained shear strength values to areas where potential adverse bedding conditions were identified. The favorable and adverse bedding shear strength parameters for the Sespe Formation are included in Table 2.1.

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 (Qls) must be based on tests of the materials along the landslide slip surface. Ideally, shear tests of slip surfaces formed in each mapped geologic unit would be used. However, this amount of information is rarely available, and for the preparation of the earthquake-induced landslide zone map it has been assumed that all landslides within the quadrangle have the same slip surface strength parameters. We collect and use 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 used. Within the Piru Quadrangle, only one direct shear test of landslide slip surface materials was obtained. To augment the strength parameters for existing landslides, six shear tests from the Val Verde Quadrangle and one shear test from the Moorpark Quadrangle were also used. The results are summarized in Table 2.1.

PIRU QUADRANGLE SHEAR STRENGTH GROUPS

	Formation Name	Number of Tests	Mean/Median Phi (degrees)	Mean/Median Group Phi (degrees)	Mean/Median Group C (psf)	No Data: Similar Lithology	Phi Values Used in Stability Analysis
GROUP 1	Tsp(fbc)	26	34	34	444/288	Tvq	34
GROUP 2	af	8	31/30	31	387/300	Qc, Qoat1	31
	Qa	58	29/30			Qoat2, Qof	
	Qf	1	30			Qof2, Qof	
	QTpm	8	32/34			Qw, Qw1	
	QTs	109	31/32			Qw2, Qya1	
	Tm	22	33/31			Qya2, Qyat1	
	Tp	40	30			Qyat2, Qyf1	
						Qyf2, QTlp	
						Tmss, Tmsu	
						Tmu, Tpsg	
						Tr, Tsq	
						Tsql, Tsqu	
						Ttoc, Ttog	
						Ttos, Tts	
GROUP 3	Qoa	4	26/25	26/25	751/725	Tml	25
	Tsp(abc)	10	24				
	Tps	7	26/25				
GROUP 4	Qls	8	13/12	13/12	428/295		12
	fbc = Favorable bedding conditions						
	abc = Adverse bedding conditions						
	Formations for strength groups from Dibblee (1991) and William Lettis and Associates (2000)						

Table 2.1. Summary of the Shear Strength Statistics for the Piru Quadrangle.

SHEAR STRENGTH GROUPS FOR THE PIRU 7.5-MINUTE QUADRANGLE			
GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**
Tsp(fbc)	af, Qa, Qc	Qoa	Qls
Tvq	Qf, Qoat1	Tps	
	Qoat2, Qof	Tsp(abc)	
	Qw, Qw1, Qw2		
	Qya1, Qya2		
	Qyat1, Qyat2		
	Qyf1, Qyf2		
	QTlp,		
	QTs, Tm		
	Tmss, Tmsu		
	Tmu, Tp, Tps		
	Tpsg, Tr		
	Tsq, Tsql		
	Tsqu, Ttoc		
	Ttog, Ttos, Tts		
fbc = favorable bedding conditions			
abc = adverse bedding conditions			

Table 2.2. Summary of Shear Strength Groups for the Piru Quadrangle.

PART II

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

Design Strong-Motion Record

To evaluate earthquake-induced landslide hazard potential in the study area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. The Newmark method 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 Piru 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:	6.7 to 6.8
Modal Distance:	2.5 to 5.2 km
PGA:	0.76 to 1.3 g

The strong-motion record selected for the slope stability analysis in the Piru Quadrangle is the Corralitos record from the 1989 magnitude 6.9 (M_w) 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.

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 yield accelerations of 0.234, 0.133 and 0.086g. 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 Piru Quadrangle.

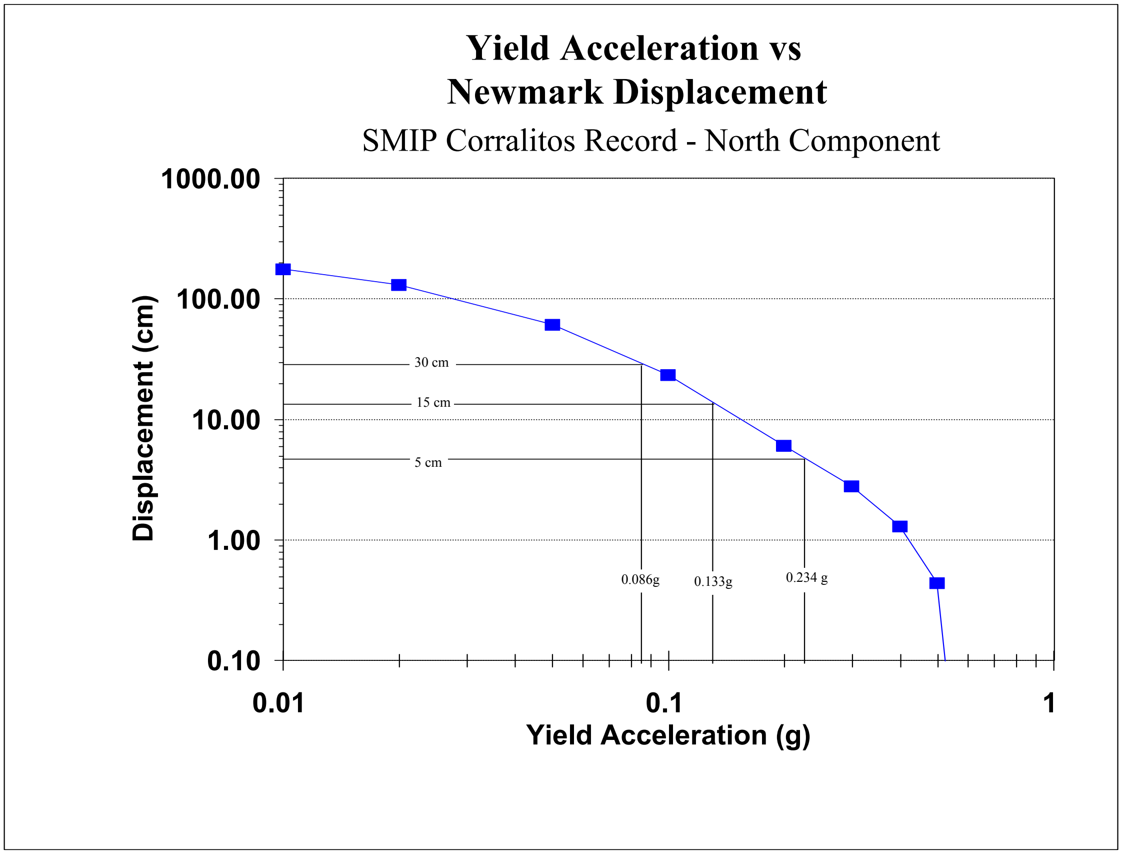

Figure 2.1. Yield Acceleration vs. Newmark Displacement for the 1989 Loma Prieta Earthquake Corralitos Record. Record from California Strong Motion Instrumentation Program (CSMIP) Station 57007.

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 (H on Table 2.3)

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 (M on Table 2.3)

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 (L on Table 2.3)

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 (VL on Table 2.3)

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.

PIRU QUADRANGLE HAZARD POTENTIAL MATRIX

Geologic Material Group	MEAN PHI	SLOPE CATEGORY (% SLOPE)									
		I	II	III	IV	V	VI	VII	VIII	IX	X
		0-10	10-14	14-23	23-34	34-38	38-42	42-46	46-51	51-58	>58
1	34	VL	VL	VL	VL	VL	VL	L	L	M	H
2	31	VL	VL	VL	VL	L	L	L	M	H	H
3	25	VL	VL	VL	L	M	H	H	H	H	H
4	12	L	M	H	H	H	H	H	H	H	H

Table 2.3. Hazard Potential Matrix for Earthquake-Induced Landslides in the Piru Quadrangle. Shaded area indicates hazard potential levels included within the hazard zone. H = High, M = Moderate, L = Low, VL = Very Low.

EARTHQUAKE-INDUCED LANDSLIDE HAZARD ZONE

Criteria for Zoning

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 in the following sections.

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.

No earthquake-triggered landslides had been identified in the Piru Quadrangle prior to the Northridge earthquake. The Northridge earthquake caused a number of relatively small, shallow slope failures and a number of very large landslides in the Piru Quadrangle (Harp and Jibson, 1995; Barrows and others, 1995). Soil falls, debris falls, and debris slides occurred in poorly indurated or highly fractured sedimentary rock on steep slopes and along roadcuts. Seismic shaking also enhanced previously existing headscarps of massive bedrock landslides and created additional cracks on steep slopes and ridge tops. Landslides attributed to the Northridge earthquake covered approximately 896 acres of land in the quadrangle, which is 2.1 percent of the total area covered by the map. All the verifiable landslides shown by Harp and Jibson (1995) as having been triggered by the Northridge earthquake were included in the seismic hazard zone.

Geologic and Geotechnical 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 the 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 4 is included for all slope gradient categories. (Note: Geologic Strength Group 5 includes all mappable landslides with a definite or probable confidence rating).

2. Geologic Strength Group 3 is included for all slopes steeper than 23 percent.

3. Geologic Strength Group 2 is included for all slopes steeper than 32 percent.

4. Geologic Strength Group 1 is included for all slopes steeper than 42 percent.

For the Piru Quadrangle, 83 percent of the entire quadrangle was evaluated for zoning. Of the evaluated area, 65 percent lies within the earthquake-induced landslide hazard zone.

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AIR PHOTOS

A-P Project, AXL Series; January 3, 1953, flight 3K, frames 46 to 48 and 180 to 185, scale 1:~19000; October 10, 1953, flight 9K, frames 27 to 30, approximate scale 1:21700; October 3, 1953, flight 10K, frames 87 to 91 and 93 to 97, scale 1:~26500; October 19/20, 1953, flight 11K, frames 9 to 12, 72 to 76 and 82 to 84, scale 1:~23300; black and white, vertical.

Pacific Western Aerial Surveys, November 22, 1988, flight PW VEN 6, frames 231 to 234, 264 to 268 and 298 to 303, color, vertical, approximate scale 1:25900

NASA (National Aeronautics and Space Administration) 04689, January 22, 1994, flight 23, frames 463 to 472, flight 24, frames 517 to 526, flight 25, frames 604 to 613, flight 26, frames 659 to 668, flight 27, frames 711 to 720, flight 28, frames 764 to 773, flight 29, frames 813 to 822, black and white, vertical, approximate scale 1:16250.

APPENDIX A
SOURCE OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
Ventura County	33
City of Fillmore	5
CGS EIR Review Files	3
Earth Systems Consultants	2
Val Verde Quadrangle	157
Moorpark Quadrangle	55
Simi Valley East Quadrangle	17
Santa Paula Peak Quadrangle	15
Simi Valley West Quadrangle	9
Newhall Quadrangle	5
TOTAL	301

SECTION 3
GROUND SHAKING EVALUATION REPORT

Potential Ground Shaking in the Piru 7.5-Minute Quadrangle, Ventura County, California

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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 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 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://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

This section of the evaluation report summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included are ground motion and related 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 (California Department of Conservation, 1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard.

This section and Sections 1 and 2 (addressing 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://www.conservation.ca.gov/CGS/index.htm

EARTHQUAKE HAZARD MODEL

The estimated ground shaking is derived from the statewide probabilistic seismic hazard evaluation released cooperatively by the California Department of Conservation, Division of Mines and Geology [California Geological Survey], and the U.S. Geological Survey (Petersen and others, 1996). That report documents an extensive 3-year effort to obtain consensus within the scientific community 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 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). The published hazard evaluation of Petersen and others (1996) only considers uniform firm-rock site conditions. In this report, however, we extend the hazard analysis to include the hazard of exceeding peak horizontal ground acceleration (PGA) at 10% probability of exceedance in 50 years on spatially uniform conditions of rock, soft rock, and alluvium. These soil and rock conditions approximately correspond to site categories defined in Chapter 16 of the Uniform Building Code (ICBO, 1997), which are commonly found in California. We use the attenuation relations of Boore and others (1997), Campbell (1997), Sadigh and others (1997), and Youngs and others (1997) to calculate the ground motions.

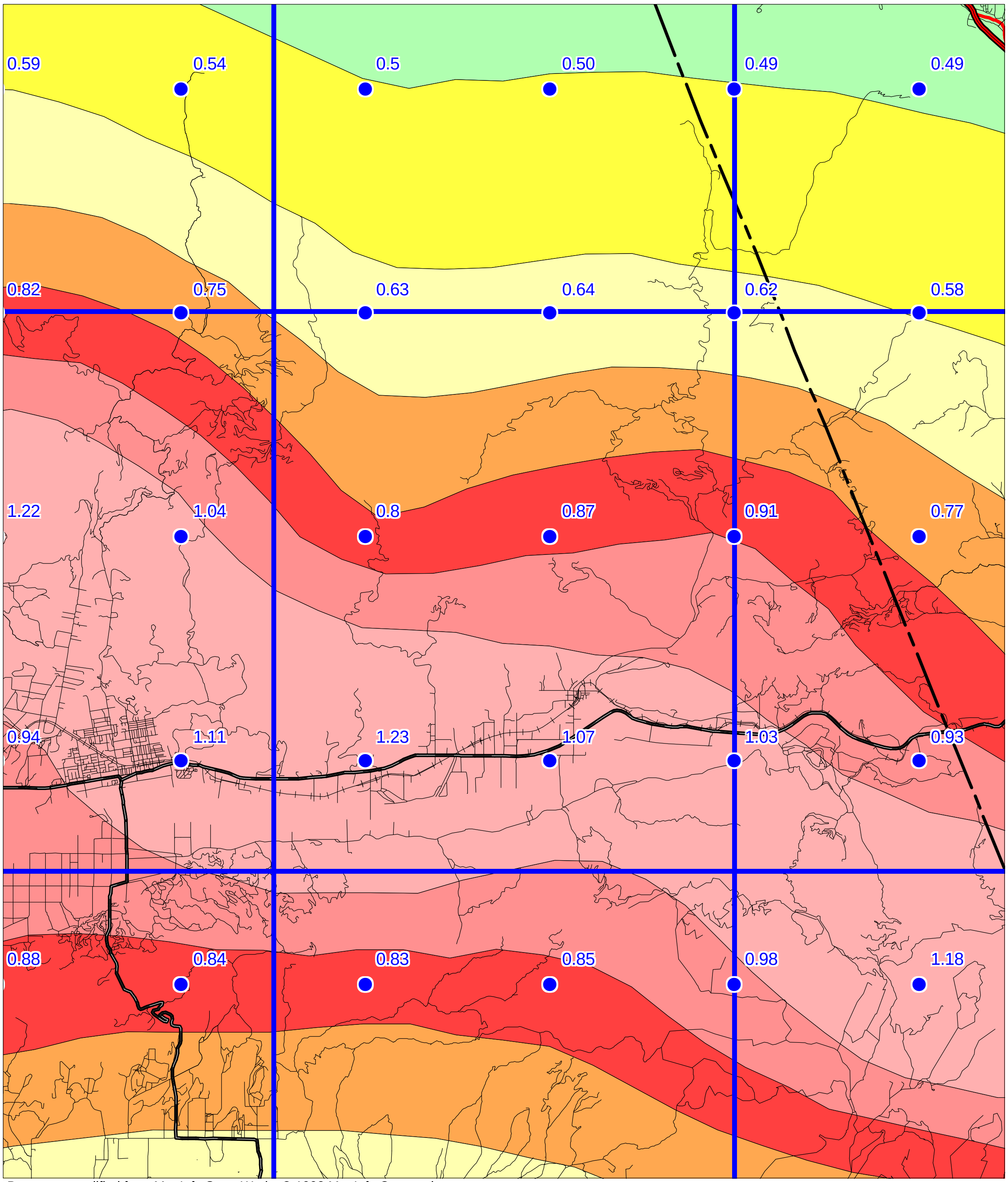
The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figures 3.1 through 3.3 show the hazard for PGA at 10% probability of exceedance in 50 years assuming the entire map area is firm rock, soft rock, or alluvial site conditions respectively. 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

PIRU 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

FIRM ROCK CONDITIONS



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 1.5 3

Miles

Department of Conservation
Division of Mines and Geology

Figure 3.1

PIRU 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

SOFT ROCK CONDITIONS

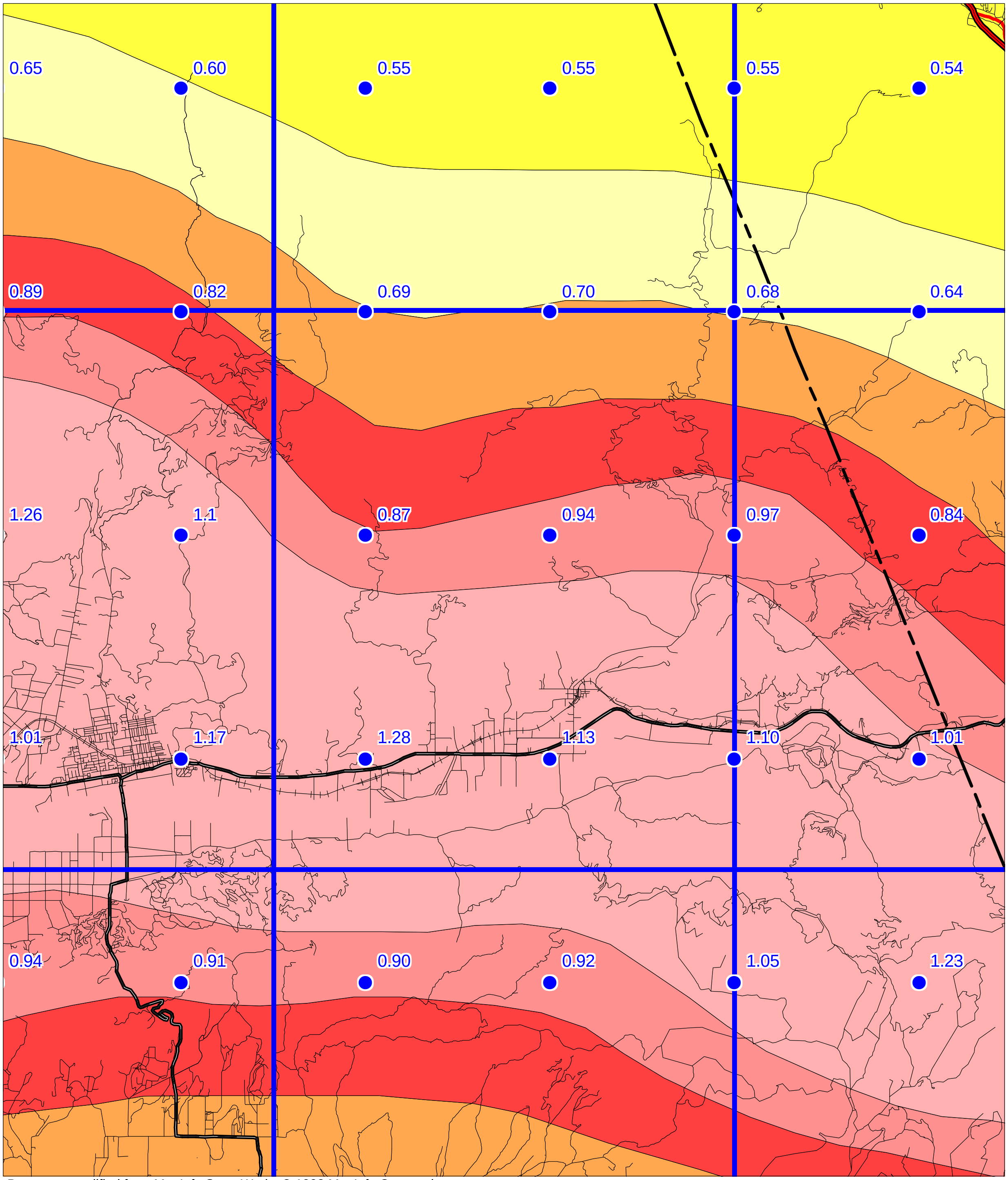


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Figure 3.2

PIRU 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

ALLUVIUM CONDITIONS

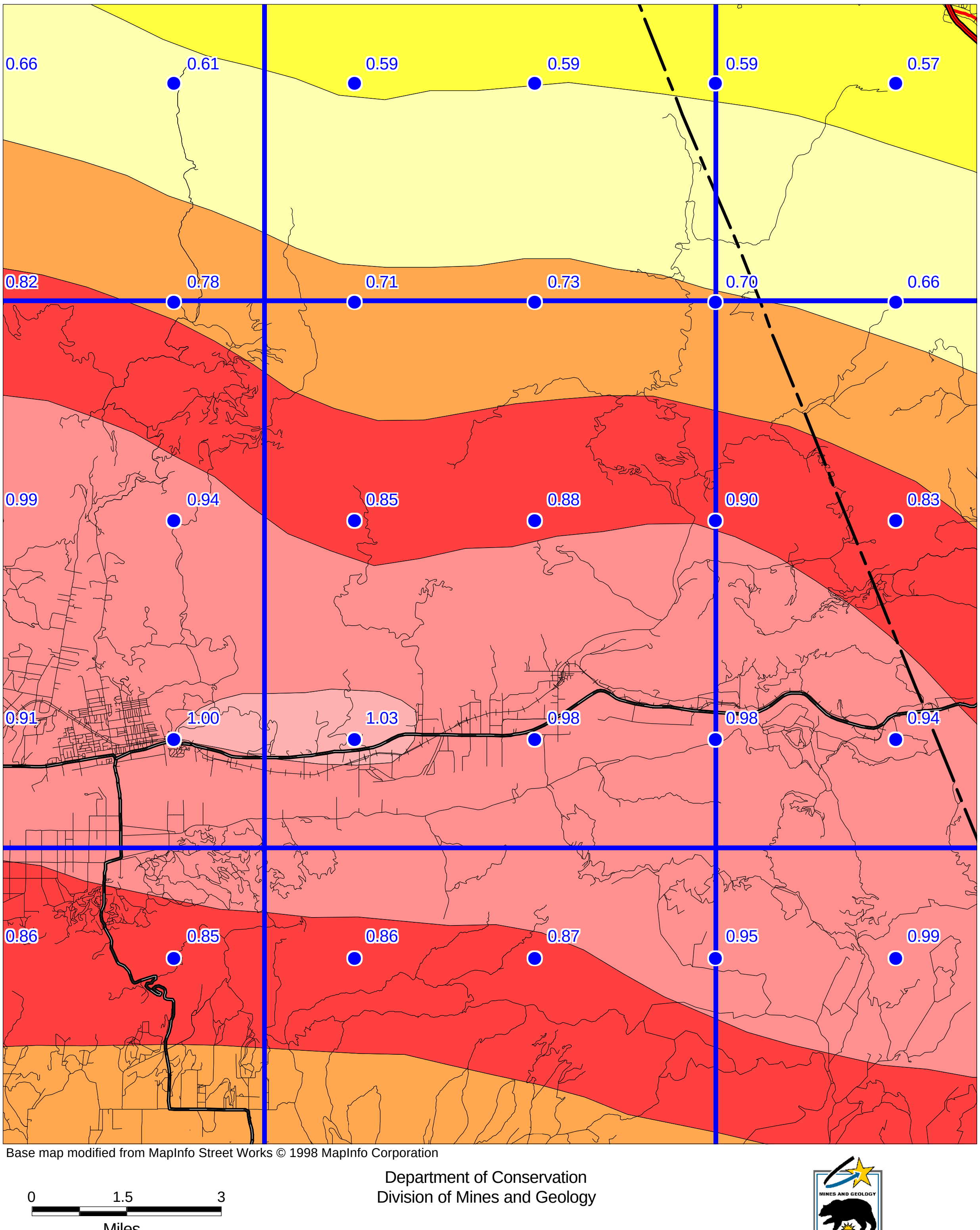

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Figure 3.3

quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating ground motion values by selecting the map that matches the actual site conditions, and interpolating from the calculated values of PGA rather than the contours, since the points are more accurate.

APPLICATIONS FOR LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENTS

Deaggregation of the seismic hazard identifies the contribution of each of the earthquakes (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (see Cramer and Petersen, 1996). The map in Figure 3.4 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10% probability of exceedance in 50 years on alluvial site conditions (*predominant earthquake*). This information gives a rationale for selecting a seismic record or ground motion level in evaluating ground failure. However, 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. For liquefaction hazard the predominant earthquake magnitude from Figure 3.4 and PGA from Figure 3.3 (alluvium conditions) can be used with the Youd and Idriss (1997) approach to estimate cyclic stress ratio demand. For landslide hazard the predominant earthquake magnitude and distance can be used to select a seismic record that is consistent with the hazard for calculating the Newmark displacement (Wilson and Keefer, 1983). When selecting the predominant earthquake magnitude and distance, 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.

A preferred method of using the probabilistic seismic hazard model and the “simplified Seed-Idriss method” of assessing liquefaction hazard is to apply magnitude scaling probabilistically while calculating peak ground acceleration for alluvium. The result is a “magnitude-weighted” ground motion (liquefaction opportunity) map that can be used directly in the calculation of the cyclic stress ratio threshold for liquefaction and for estimating the factor of safety against liquefaction (Youd and Idriss, 1997). This can provide a better estimate of liquefaction hazard than use of predominate magnitude described above, because all magnitudes contributing to the estimate are used to weight the probabilistic calculation of peak ground acceleration (Real and others, 2000). Thus, large distant earthquakes that occur less frequently but contribute *more* to the liquefaction hazard are appropriately accounted for.

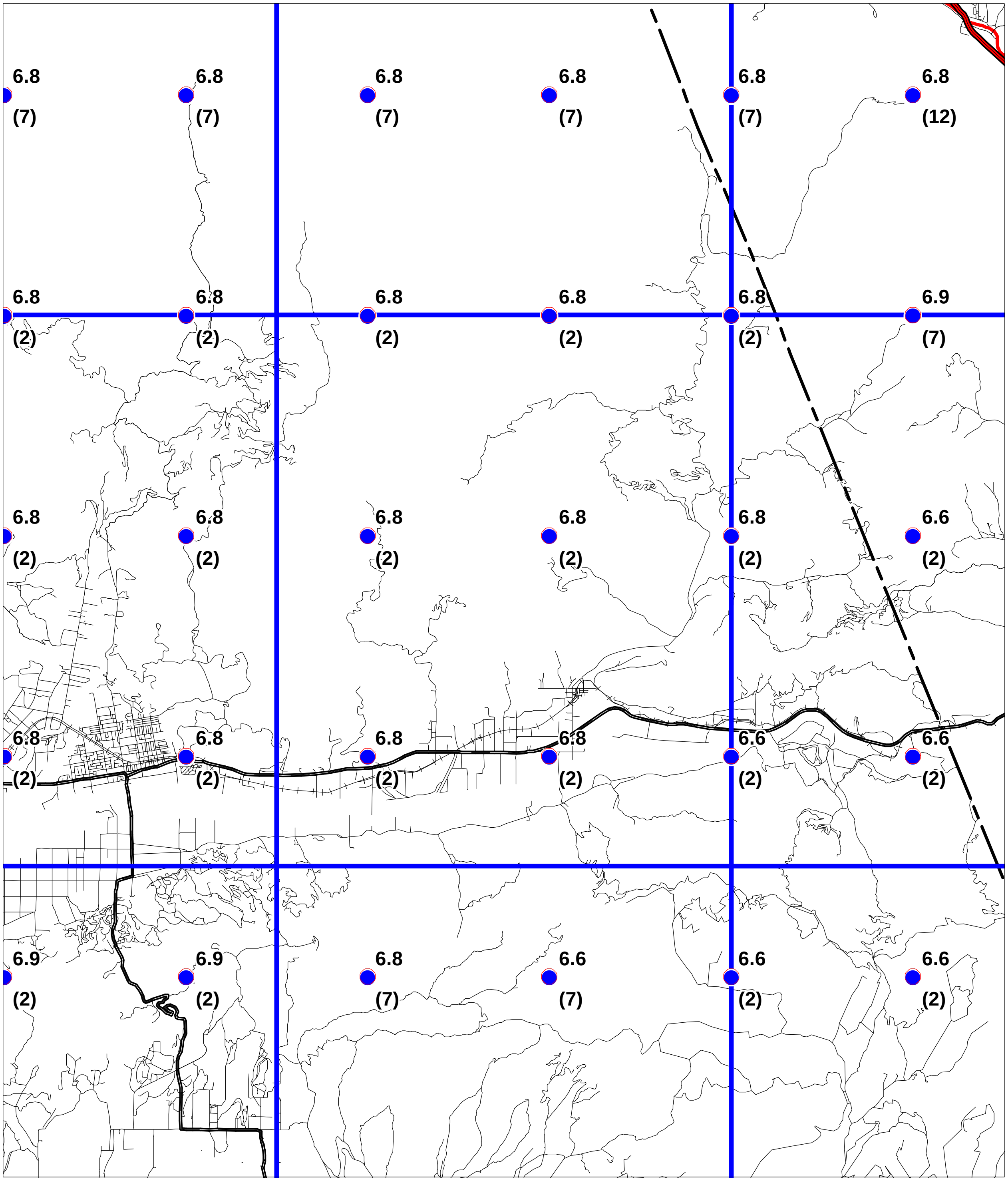
Figure 3.5 shows the magnitude-weighted alluvial PGA based on Idriss’ weighting function (Youd and Idriss, 1997). It is important to note that the values obtained from this map are pseudo-accelerations and should be used in the formula for factor of safety without any magnitude-scaling (a factor of 1) applied.

PIRU 7.5 MINUTE QUADRANGLE AND PORTIONS OF
ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION

1998

PREDOMINANT EARTHQUAKE
Magnitude (Mw)
(Distance (km))



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 1.5 3
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Division of Mines and Geology

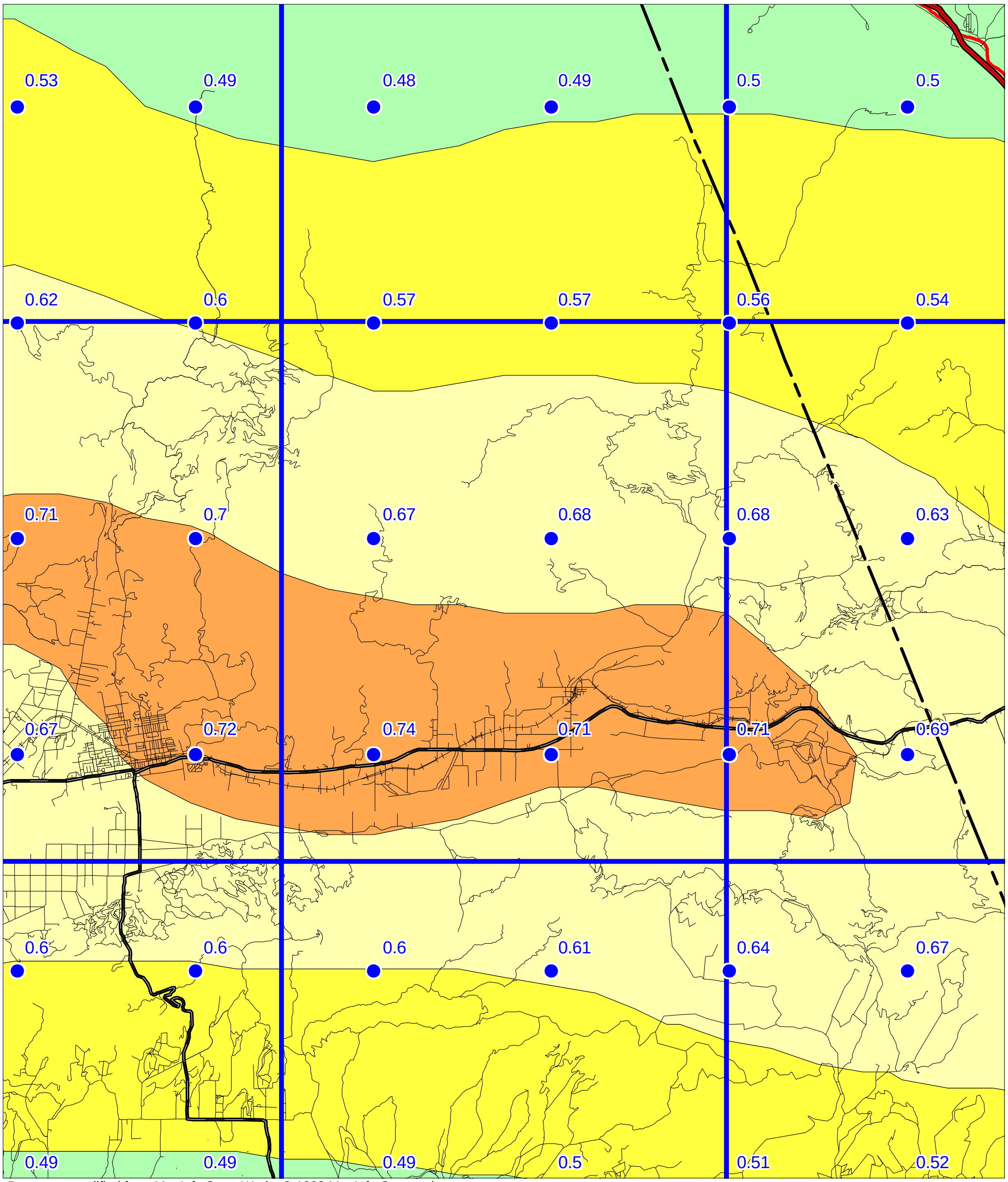
Figure 3.4

PIRU 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS MAGNITUDE-WEIGHTED PSEUDO-PEAK ACCELERATION (g) FOR ALLUVIUM

2001

LIQUEFACTION OPPORTUNITY



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

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Figure 3.5

USE AND LIMITATIONS

The statewide map of seismic hazard has been developed using regional information and is ***not appropriate for site specific 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 several 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 be about +/- 50% of the ground motion value at two standard deviations (Cramer and others, 1996).

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.

Because of its simplicity, it is likely that the SPPV method (DOC, 1997) will be widely used to estimate earthquake shaking loading conditions for the evaluation of ground failure hazards. 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 variance is represented to some degree by the recorded ground motions that form the basis of the hazard model used to produce Figures 3.1, 3.2, 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, 3.2, 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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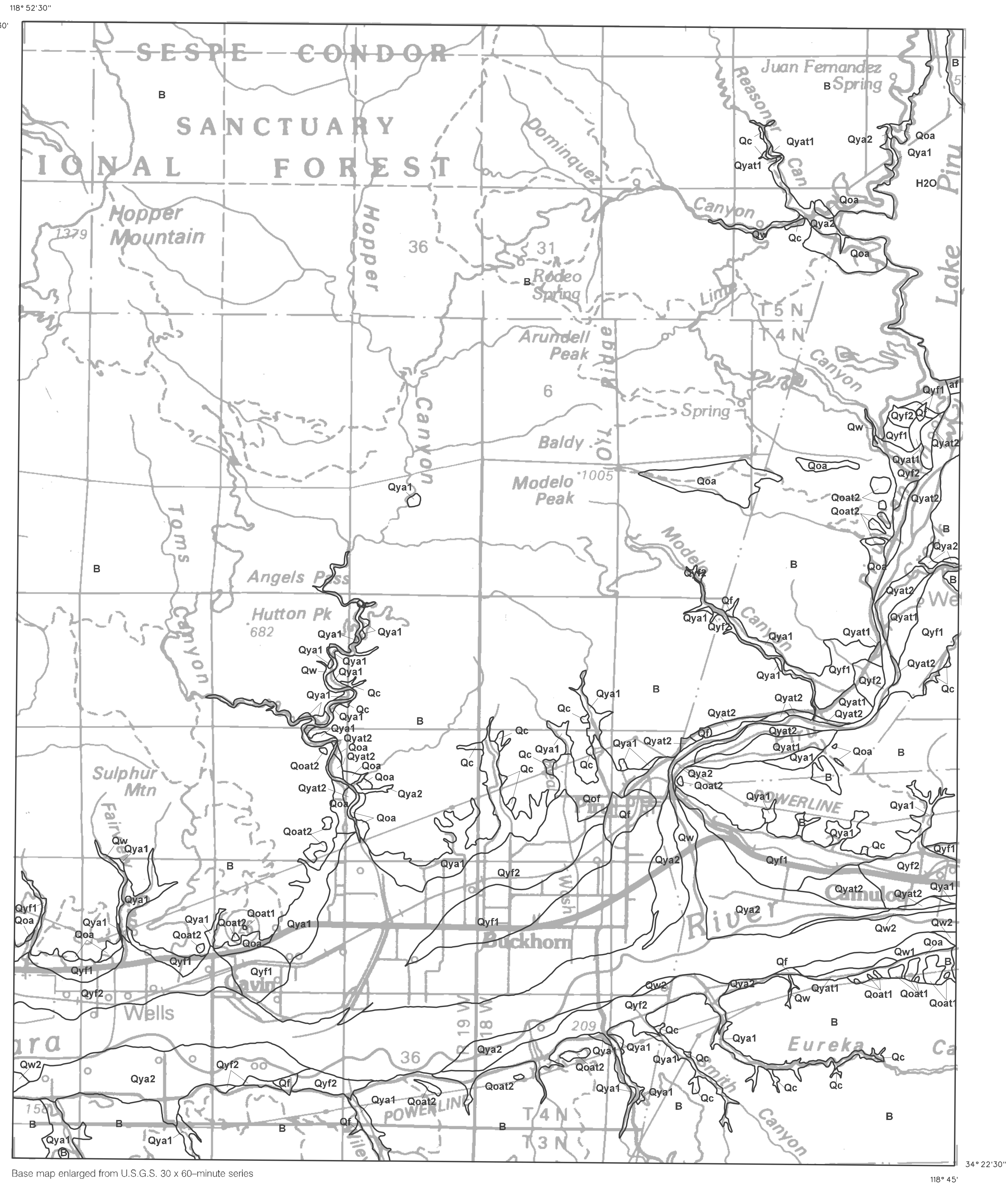
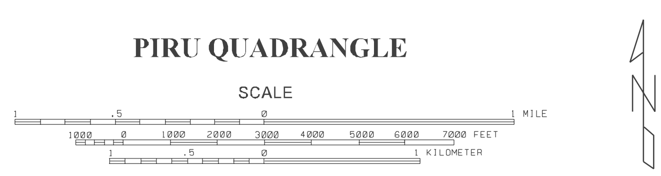


Base map enlarged from U.S.G.S. 30 x 60-minute series

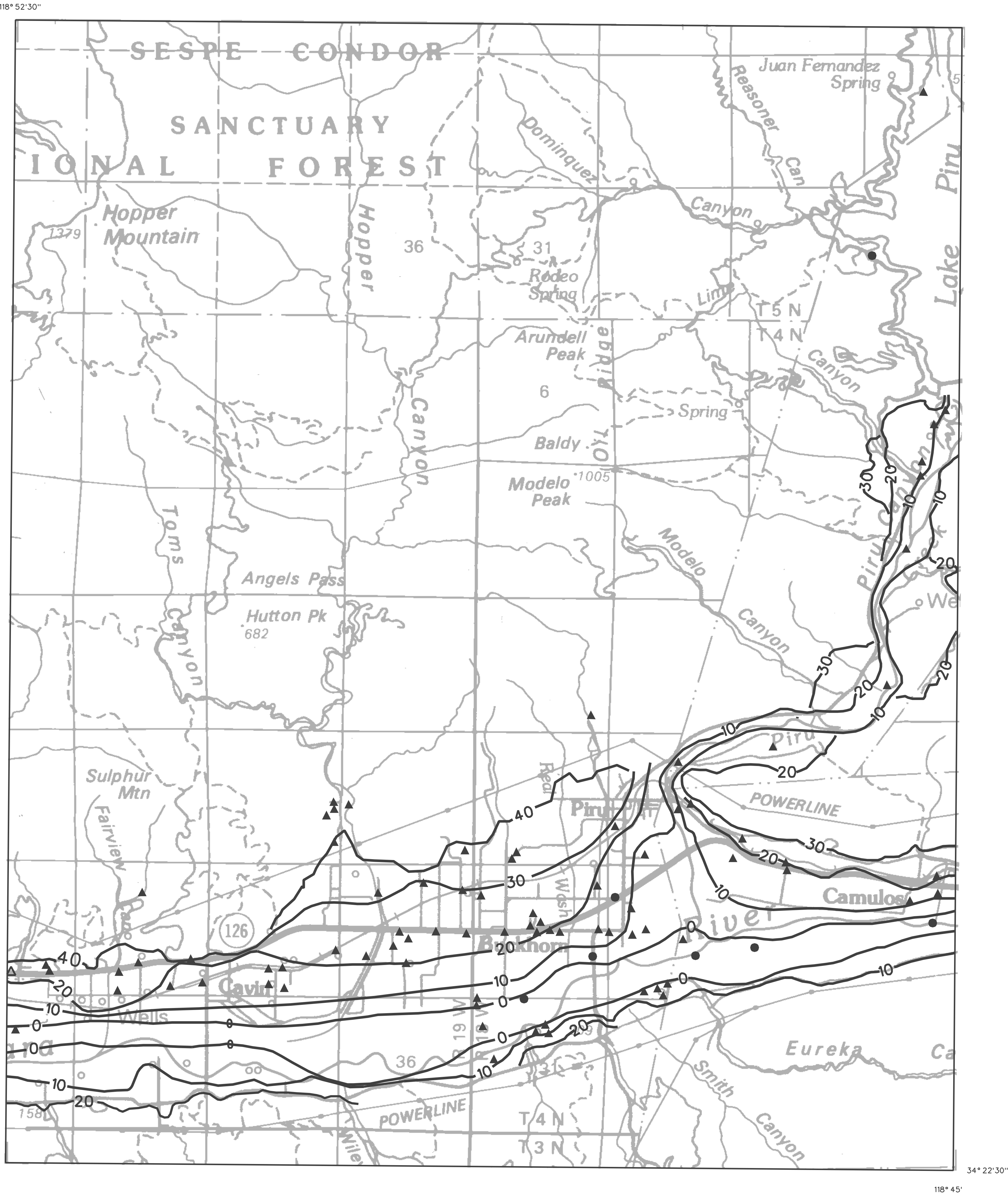
PIRU QUADRANGLE



B = Pre-Quaternary bedrock.

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

Plate 1.1 Quaternary Geologic Map of the Piru 7.5-minute quadrangle (William Lettis and Associates, 2000).



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

PIRU QUADRANGLE

SCALE

1 MILE — 1000 0 1000 2000 3000 4000 5000 6000 7000 FEET — 1 KILOMETER

N

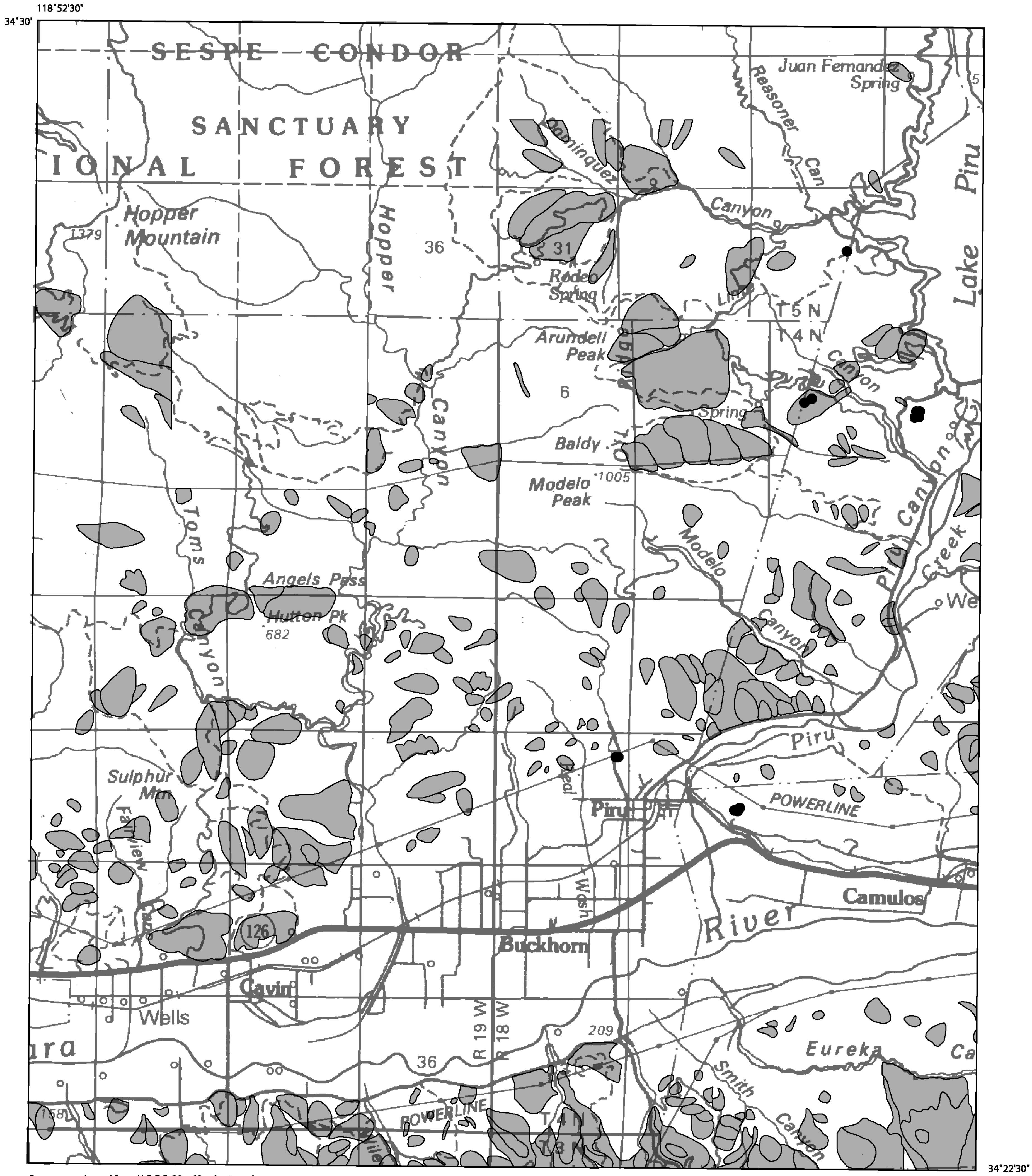
— 50 — Depth to ground water, in feet

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

● Geotechnical borings used in liquefaction evaluation

▲ Water Well

Plate 1.2 Depth to historically high ground water, and locations of boreholes used in this study, Piru 7.5-minute Quadrangle, California



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

PIRU QUADRANGLE

SCALE

1 .5 0 1 MILE
1000 0 2000 4000 6000 FEET
1 .5 0 1 KILOMETER

N

● Shear test sample location

Landslide

Plate 2.1 Landslide inventory and shear test sample locations, Ojai 7.5-minute quadrangle, Ventura County.