CHAPTER 1
GEOLOGICAL RESOURCES

LANDSLIDING AND HUMMOCKY TERRAIN IN A NAPA VALLEY GRASSLAND

UPDATE CHRONOLOGY

NOVEMBER 30, 2005—VERSION 1

PURPOSE

The purpose of this chapter is to provide a current summary of baseline geologic features and related hazards in Napa County and to provide a current map inventory of these features. This document and the data assembled provide broad tools for site and regional planning as well as the basis for future planning documents relating to the protection and management of geological resources.

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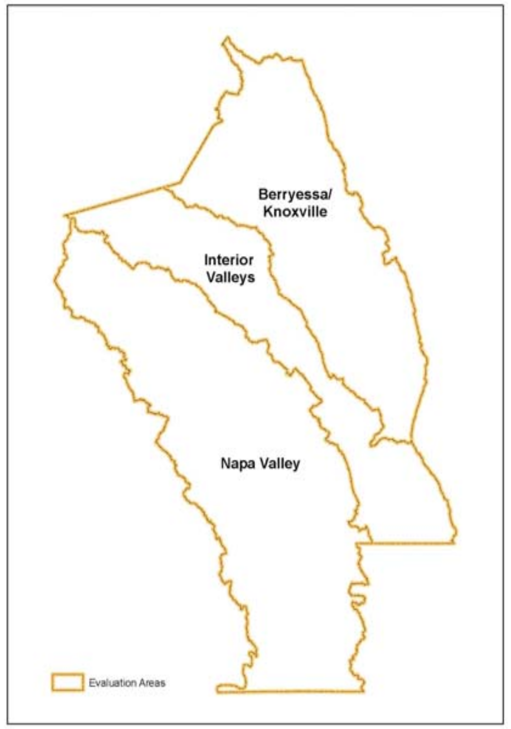
LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
Bay Area	San Francisco Bay Area
BDR	Baseline Data Report
BMPs	Best management practices
Caltrans	California Department of Transportation
CBC	California Building Code
CDF	California Department of Forestry
County	Napa County
CWA	Federal Clean Water Act
DSA	California Division of State Architect
DSOD	California Division of Safety of Dams
EFZs	Earthquake Fault Zones
EIR	Environmental impact report
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FERs	Fault Evaluation Reports
g	The force an earthquake applies to a structure is expressed in terms of a percentage of gravity
General Permit	General Permit for Storm Water Discharges Associated with Construction Activity
GIS	Geographic information systems
Ka	Thousand years ago
m	Meters
Ma	Million years ago
NPDES	National Pollutant Discharge Elimination System
NRCA	National Resources Conservation Agency
NRCS	Natural Resources Conservation Service
NTMPs	Non-Industrial Timberland Management Plans
PGADBE	Design-Basis Earthquake Ground-Motion
PGAs	Peak ground accelerations
PGAUBE	Upper-Bound Earthquake Ground Motion
Program	Seismic Hazard Mapping Program
SMARA	Surface Mining and Reclamation Act
SSURGO	Soil Survey Geographic
SWPPP	Stormwater pollution prevention plan
THP	Timber Harvesting Plan
UBC	Uniform Building Code
USGS	U.S. Geological Survey
Valley	Napa Valley

INTRODUCTION

This chapter provides a discussion of the geologic features and hazards known in the three subregions into which Napa County (County) has been divided for geologic evaluation (Map 1-1; all maps appear at the end of the chapter). The chapter provides a baseline discussion of federal, state, and local policies and regulations that involve geologic hazards and Earth resources in the County. This chapter includes a description of the methodology used to identify and quantify the geologic hazards and Earth resources present in the evaluation areas. This chapter provides a countywide overview of several geologic topics, including regional geologic history, physiography, principal bedrock units, unconsolidated deposits, soils, and geologic structure. In addition, the chapter provides a discussion of geologic processes that influence the existing geology, geologic hazards and physiography of the County.



Napa County subregions for geologic analysis

PURPOSE

The purpose of this chapter is to provide a comprehensive and current review of baseline geologic features and related hazards within the County and to provide a current map inventory of these features. In addition to the geographic information systems (GIS) maps included within this chapter, other geologic information, including non-digital maps, are listed in the references.

This information has been assembled to assist the land use planning, permitting, and environmental compliance process. Much of the information included or referenced in this geologic section should be suitable for General Plan update and for preparation of a Programmatic environmental impact report (EIR). For technically correct inclusion of this information in either of these documents, the assistance of a qualified geologist and/or engineering geologist is necessary.

LIMITATIONS AND USE

The *Napa County Baseline Data Report* (BDR) can be used to indicate the level of detail required for on-site geologic evaluations. The referenced GIS-based and hard copy maps are suitable for use in planning, preliminary environmental assessments, and assessing the need for more detailed investigation. Additional application of this information includes using the maps early in the planning process to (1) learn of the bedrock/surficial geologic conditions and (2) develop an initial indication of the degree of hazard and impact of a particular project. Maps are useful indicators; however, they are not a substitute for detailed site-specific investigations that are required for earthquake fault identification, landslide investigations, and the development of design-level geotechnical recommendations.

Although not generally anticipated, these maps may also in some instances incorrectly predict hazards. For instance, a particular landform interpreted to be a hazard (such as a landslide) and indicated as such on a landslide map may, in fact, not be of landslide origin. This possibility exists because many of the maps, especially the landslide maps, are partially or largely prepared using aerial photographs. While aerial photo geology is powerful, effective and time efficient, it is also interpretive, and its accuracy largely depends on the experience and skill of the geologist. This fact underscores the need to perform site-specific geologic work to confirm the existence of features shown in the maps and to better characterize them once their presence has been confirmed.

Some maps were prepared at a scale of 1:24,000 and others at 1:62,500 or smaller. Electronically enlarging a map beyond its original scale of preparation does not provide additional detail or better information and can be misleading. Each geologic hazard section contains a table that indicates the sources that were used in preparation of this chapter—each geologic hazard discussion is dependent on the scale of detail referenced in its preparation.

POLICY CONSIDERATIONS

This section provides a general discussion of the federal, state, and local policies that apply to geologic hazards and Earth resources in the County and are known to require significant geological and geotechnical input.

FEDERAL POLICIES

SECTION 402 OF THE CLEAN WATER ACT/NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM

The federal Clean Water Act (CWA) is discussed in detail in Chapters 15, 16, and 17. Because CWA Section 402 is directly relevant to earthwork, additional information is provided here.

Amendments to the CWA in 1987 added Section 402[p], which establishes a framework for regulating municipal and industrial storm water discharges under the National Pollutant Discharge Elimination System (NPDES) program. The U.S. Environmental Protection Agency (EPA) has delegated to the State Water Resources Control Board the authority for the NPDES program in California, where it is implemented by the state's nine Regional Water Quality Control Boards. Under the NPDES Phase II Rule, any construction activity disturbing 1 acre or more must obtain coverage under the state's General Permit for Storm Water Discharges Associated with Construction Activity (General Permit). General Permit applicants are required to prepare a Notice of Intent stating that stormwater will be discharged from a construction site, and a stormwater pollution prevention plan (SWPPP) that describes the best management practices (BMPs) that will be implemented to avoid adverse effects on receiving water quality as a result of construction activities, including earthwork.

STATE POLICIES

ALQUIST-PRIOLO EARTHQUAKE FAULT ZONING ACT

The Alquist-Priolo Earthquake Fault Zoning Act was signed into law on December 22, 1972, and went into effect March 7, 1973. The act, codified in the Public Resources Code as Division 2, Chapter 7.5, has been amended eleven times. The law was initially designated the Alquist-Priolo Geologic Hazard Zones Act. The act was renamed the Alquist-Priolo Special Studies Zones Act effective May 4, 1975, and the Alquist-Priolo Earthquake Fault Zoning Act effective January 1, 1994. The original designation *Special Studies Zones* was changed to *Earthquake Fault Zones* when the act was last renamed. The purpose of the act is to prohibit the location of most structures for human occupancy across the traces of active faults and thereby to mitigate the hazard of fault rupture (Section 2621.5).

Under the act, the State Geologist (Chief of the Division of Mines and Geology, now the California Geological Survey) is required to delineate Earthquake Fault Zones (EFZs) along known active faults in California. Cities and counties affected by the zones must regulate certain development projects within the zones. They must withhold development permits for sites within the zones until geologic investigations demonstrate that the sites are not threatened by surface displacement from future faulting. The State Mining and Geology Board provides additional regulations (their “Policies and Criteria”) to guide cities and counties in their implementation of the law (California Code of Regulations, Title 14, Div. 2).

Requirements of the act, including procedures for zoning and updating geologic and seismic data for the Fault Evaluation Reports (FERs), are described in Special Publication 42, *Fault-Rupture Hazard Zones in California, Alquist-Priolo Earthquake Fault Zoning Act with index to Earthquake Fault Zones Maps* (Hart and Bryant 1997). FERs and Alquist-Priolo Maps are produced by the California Department of Conservation, California Geological Survey. Digital images of the maps and FERs are available on CD-ROM (CD 2000-004, 2000 for map images; CD 2002-01, 2002 for FERs) (California Department of Conservation, California Geological Survey 2000, 2002). The Alquist-Priolo Earthquake Fault Zoning Act establishes regulatory zones that average 0.25 mile on either side of the active fault; the Alquist-Priolo Maps for earthquake fault zones are updated as zones are revised based on earthquake-trenching investigations that reveal new evidence of earthquakes.

The law’s intent is to protect the public from the hazard of surface fault rupture. The application approval process for building permits requires that Alquist-Priolo Maps be consulted and responded to as necessary before permits are issued. However, the act has several exceptions; building within an Alquist-Priolo zone is allowable for certain types of structures/dwellings, and setbacks (distances from an active, Alquist-Priolo zoned earthquake trace) may be used in order to allow building within an established Alquist-Priolo zone.

1997 UNIFORM BUILDING CODE AND 2001 CALIFORNIA BUILDING CODE

The Uniform Building Code (UBC) was first enacted in 1927 and has been revised approximately every three years since then. The function of the UBC is to promote and ensure the development of improved building construction and greater safety to the public by uniformity in building laws.

The UBC is founded on broad-based principles that make possible the use of new materials and new construction systems. It is designed to be compatible with related publications to provide a complete set of documents for regulatory use.

The UBC recognizes that nearly all of western California is seismically active, and that within this broad region there are areas underlain by deeper unconsolidated deposits that are subject to higher amplitude, longer duration shaking motions. Thus, while these shaking impacts are potentially more damaging, implementation of UBC criteria tend to reduce their effects.

From the standpoint of earthworks construction and seismic criteria, the UBC and the California Building Code (CBC) are nearly identical.

SEISMIC HAZARDS MAPPING ACT

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Section 2690-2699.6) directs the Department of Conservation, California Geological Survey to identify and map areas prone to earthquake hazards of liquefaction, earthquake-induced landslides, and amplified ground shaking. The purpose of the act is to reduce the threat to public safety and to minimize the loss of life and property by identifying and mitigating these seismic hazards. The act was passed by the state Legislature following the 1989 Loma Prieta earthquake. This pertains to seismic hazards other than the fault surface rupture hazard regulated by the Alquist-Priolo Earthquake Fault Zoning Act of 1972.

The maps produced per the Seismic Hazards Mapping Act are the *Seismic Hazard Zone Maps*, prepared by California Geological Survey geologists in the Seismic Hazard Mapping Program (Program). The program will ultimately map all of California’s principal urban and major growth areas. Each map covers an area of approximately 60 square miles and uses a scale of 1 inch = 2,000 feet (1:24,000 scale).

The Seismic Hazard Zone maps include designated “Zones of Required Investigation” for areas prone to liquefaction and earthquake-induced landslides. Once a map becomes available for a certain area, cities and counties within that area are required to withhold development permits for projects proposed within a Zone of Required Investigation until geologic and soil conditions are investigated and appropriate mitigations, if any, are incorporated into development plans.

A Certified Engineering Geologist, Geotechnical Engineer, or Registered Civil Engineer with competence in the field of seismic hazard evaluation is required to prepare, review, and approve the

The State of California has enacted measures to protect the public from earthquake-related hazards. The Alquist-Priolo Act prohibits the location of most structures for human occupancy across the traces of active faults. The Seismic Hazards Mapping Act identifies seismic hazards to improve public safety and minimize the potential loss of life and property.

The unique combination of topography, soils, and climate in Napa County create the physical setting to produce the premium wine grapes for which the County is famous.

geotechnical report. A copy of each approved geotechnical report, including the mitigation measures, is required to be submitted to the Program within 30 days of approval of the report. The act requires peer review; the reviewer may be either local agency staff or a retained consultant. The Department of Conservation does not have authority to approve or disapprove these geotechnical reports; rather, the data is used to monitor the effectiveness of the Program and is used for future updates. Further, cities and counties must incorporate the Seismic Hazard Zone Maps into their Safety Elements. Both the act and the Natural Hazard Disclosure Statement also require sellers of real property to disclose to buyers if property is in a Seismic Hazard Zone of Required Investigation.

Maps under development are distributed as *Preliminary* and *Official* versions. The Preliminary version is released for a 90-day public comment period for technical review and comment. Once the public review period has ended, the Department of Conservation has 90 days to revise the maps and to issue the Official versions to affected cities, counties and state agencies.

As of early 2005, Seismic Hazard Zone Maps have been prepared for portions of Southern California and the San Francisco Bay Area (Bay Area). The intent is to first prepare the maps for areas that are undergoing the most rapid urbanization and which have recognized hazards. However, the maps have yet to be prepared for any part of the County. When the maps are prepared and acquired by the County and other lead agencies, e.g., cities, it will then be necessary for those agencies to respond to the provisions of the act. Further information on the act can be obtained from Special Publication 117, *Guidelines for Evaluating and Mitigating Seismic Hazards in California* (California Geological Survey 1997).

CALIFORNIA WATER CODE-DIVISION 3, DAMS AND RESERVOIRS

Since 1929, the State of California has supervised dams to prevent failure in order to safeguard life and protect property. The legislation resulted from the failure of St Francis Dam in March of 1928. Legislation enacted in 1965, as a result of the failure of Baldwin Reservoir in 1963, revised the statutes to include off stream storage. This legislation is regulated by the California Department of Water Resources, Division of Safety of Dams. Two classifications of dam types are covered: (1) dam structures that are or will be in the future 25 feet or more in height from the natural bed of the stream or water course at the downstream toe of the barrier and (2) dams that have an impounding capacity of 50 acre feet or more (California Department of Water Resources 2004).

Implementing the legislation involves use of geology and geotechnical engineering over the entirety of the dam's useful life for site selection, dam design and construction, and on-going inspection of the impounding structures.

SURFACE MINING AND RECLAMATION ACT

The Surface Mining and Reclamation Act (SMARA) was signed into law in 1975, went into effect in 1976, and has been amended 24 times since its effective date. The intent of the act is to (1) assure reclamation of mined lands, (2) encourage production and conservation of minerals, and (3) create and maintain surface mining and reclamation policy (regulations).

SMARA applies to anyone, including government agencies. There are a number of exceptions to the act, among them those related to agriculture, flood control, small mines (less than 1000 cubic yards or no more than 1 acre), and emergency work. SMARA is administered by lead agencies (most often counties or cities) and the California Department of Conservation.

TIMBER HARVESTING PLAN PROJECTS

The Timber Harvesting Plan (THP) Projects provide engineering geologic review of proposed THPs, Non-Industrial Timberland Management Plans (NTMPs), and other regional-scale land management projects, submitted to the California Department of Forestry (CDF) under the 1973 Z'Berg-Nejedley Forest Practice Act and Rules. It is the intent of the state legislature to create and maintain an effective and comprehensive system of regulation and use of all timberlands in order to assure that (1) where feasible, the productivity of timberlands is restored, enhanced, and maintained; and (2) the goal of maximum sustained production of high-quality timber products is achieved while at the same time values relating to recreation, watershed, wildlife, range and forage, fisheries, regional economic vitality, employment, and aesthetic enjoyment are upheld. Since 1975, the California Geological Survey has provided advisory comments to CDF and the Board of Forestry regarding geologic and slope stability concerns as they pertain to THPs.

The California Geological Survey also provides review and comment to applicants who have had the THPs prepared. This is done because of the potential for accelerated soil erosion and landsliding associated with timber harvesting.

LOCAL POLICIES

GENERAL PLAN POLICIES

Seismic hazards and safety concerns within the County are addressed within the Seismic Safety and Safety Elements of the County's existing General Plan (Napa County 1992). This information directly relates to the geology and seismic section of the BDR because it discusses the existing conditions of seismic hazards in the County, including background information about the following issues.

- Structural geology of the County.
- Fault displacement in the County.
- Ground shaking.
- Ground failure.

- Flood zones from dam failures.
- Tsunamis.

The Seismic Safety Element includes three primary goals (Goal A, Goal B, and Goal C below) and associated policies related to seismic safety.

Goal A: Use existing authority of local governments to reduce hazards to life and property. This goal is supported by 11 policies.

- Evaluation of geologic/seismic hazards for environmental impact reports.
- Requirements for geologic/seismic reports.
- Discouragement of development within 0.125 mile of an active fault, unless a geologic or seismic reports indicate the development is consistent with public safety guidelines.
- Installation of strong-motion accelerographs, where appropriate.
- An inventory of existing structures to improve public safety.
- Restriction of development in areas adjacent to active faults.
- Geologic/seismic report requirements for issuance of building permits.
- Development of a program for on-site inspection of grading work.
- Encouragement of planting of native vegetation on unstable slopes.
- Review of safety standards for risk of earthquake induced dam failure and resulting downstream inundation.
- Rezoning of open space lands subject to extreme geologic hazards and geologically sensitive areas.

Goal B: Promote intergovernmental cooperation directed towards lessening known hazards and defining uncertain hazards. This goal is supported by 13 policies.

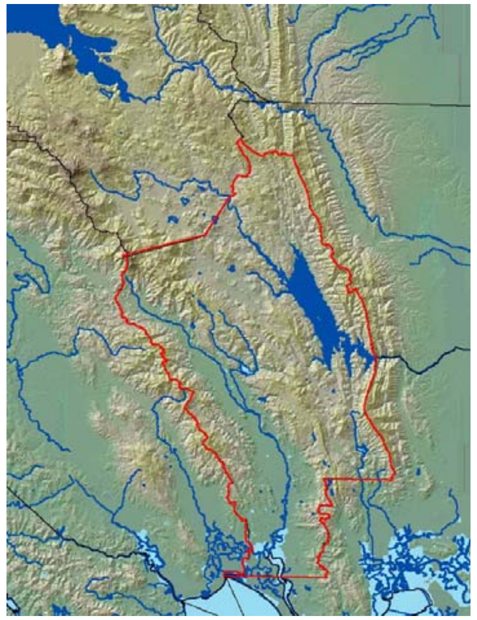
- Support for mandatory requirement of earthquake insurance as a condition to loan granting for residential structures.
- Encouragement for the purchase of National Flood Insurance.
- Promotion of inter-government collaboration for technical assistance regarding seismic hazards.
- Assessment of potential hazards from failure of above-ground tanks containing water, wine, or petroleum products.
- Discouragement of development in wetlands and drained wetlands in southern Napa County.
- Application of the 1974 California Urban Geology Master Plan program to the County.
- Development of a geologic mapping program with federal and state agencies.
- Support for development of dam safety programs.
- Encouragement for development of emergency preparedness programs by local governments.
- Implementation of recommendations of the Joint California Legislative Committee on Seismic Safety, 1972.
- Revision of the County Zoning Ordinance to identify a combined geologic hazard zone.
- Potential requirement for dynamic analysis of designs for proposed buildings.
- Support for research and development of seismic protection standards for inclusion in the County Building Code.

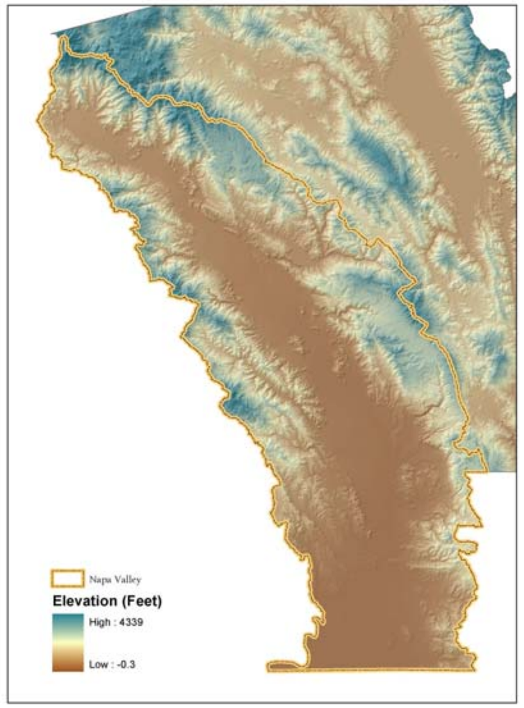
Goal C: Participate in public education programs. This goal is supported by two policies.

- Preparation of materials to inform the public of potential seismic hazards in the county.
- Support for first-aid training for emergency/hazard situations in schools.

In addition to the policies stated above, the Safety Element includes the following seven policies to address geologic hazards.

- Consider safety hazards prior to county land use decisions, such as General Plan amendments, rezoning, or project approvals.
- Restrict extensive grading on slopes over 15% where landslides or other geologic hazards are present.
- Assure that future residential lots on hillsides are large enough to provide a stable buildable site and driveway.
- Restrict construction of roads on or adjacent to landslides, hills, or areas subject to liquefaction, subsidence, or settlement.


Napa County's relative location within the Coast Ranges north of San Francisco Bay.



Physiography of the Napa Valley subregion.

- Encourage the Building Inspection Division to analyze slope failure records and improve the county grading ordinance.
- Discourage urban development in reclaimed wetlands.
- Where necessary, rezone lands subject to extreme geologic hazards and geologically sensitive areas into a combined geologic hazard zone.

It is anticipated that the County will update and revise the Seismic Safety and Safety Elements of the General Plan in 2005. The baseline information contained in this BDR should be useful for the following purposes.

- Bringing geologic/seismic data up to date with current data.
- Providing a comprehensive geologic overview of the County.
- Providing more detail on the existing baseline information relating to seismic hazards.

In addition to General Plan policies, the County has incorporated a number of ordinances into the Napa County Municipal Code that relate to geologic resources and seismic safety. It is not anticipated that the BDR would directly affect the existing code or ordinances within the code. However, revisions to the General Plan may in turn require revisions to the Napa County Municipal Code. The following specific sections of the code relate to geologic resources and seismic safety: 13.16.390, 13.28, 15.08.050, 16.12, 17.08, 17.14, 17.42, 18.04, 18.88, 18.180.027(F), 18.108.060, 18.108.080, 18.108.140, 18.117.040.

METHODOLOGY

DEFINITION OF STUDY AREA

The study area is all of Napa County. For the purposes of this chapter on geological resources, the study area was divided into three subregions: the Napa Valley (including the Napa River Watershed), the interior valleys, and the Berryessa/Knoxville area. Following each countywide overview, details unique to each of the three subregions are described.

TECHNICAL APPROACH

The preparation of this chapter included the review of numerous GIS-based and hard-copy geologic maps and documents collected from numerous sources (see *References* section below). The purpose of this data collection was to identify the most current, comprehensive geologic information for inclusion in the BDR.

PHYSIOGRAPHY

PHYSIOGRAPHY OF NAPA COUNTY

Eleven distinct and diverse geomorphic provinces are recognized in California. Each of these provinces displays unique, defining features based on geology, faults, topographic relief, and climate. The County is located in the Coast Ranges Geomorphic Province. This province is bounded on the west by the Pacific Ocean and on the east by the Great Valley geomorphic province. The Coast Ranges Province extends several hundred miles northward from southern California to near the Oregon border.

A conspicuous characteristic of this province, including Napa County, is the general northwest-southeast orientation of physiographic features such as valleys and ridgelines. In the County, located in the eastern, central section of the province, this trend consists of a series of long, linear, major and lesser valleys, separated by steep, rugged ridge and hill systems of moderate relief that have been deeply incised by their drainage systems (Map 1-2).

The County's highest topographic feature is Mount St. Helena, which is located in the northwest corner of the County and whose peak elevation is 4,343 feet. Principal ridgelines have maximum elevations that roughly vary between 1,800 and 2,500 feet. These elevations decrease in the southern part of the County. This physiography has influenced the local climate (creating several microclimates), the development of soils, and the existence and location of geologic hazards such as landsliding. The combination of physiography, soils, and climate has helped give rise to the production of premium wine grapes and other agricultural products for which the County is famous.

The physiography of the County is strongly influenced by its bedrock geology, geologic structure, and the mountain building and erosion processes operative during the Quaternary (the last two million years). These topics are described in subsequent sections. Maps for Napa County's physiography and slope conditions are shown in Maps 1-2 and 1-3.

Napa Valley is the main valley in the County. It extends southeast along the west side of the County to near the edge of San Pablo Bay. Valley floor elevations are up to approximately 400 feet near the north end of the valley and approach sea level on the south. Along the east central part of the County is a similar but smaller valley occupied by Lake Berryessa Reservoir (formerly Berryessa Valley). Between these two principal valleys are a series of lesser valleys including Pope Valley in the north, a somewhat smaller Chiles Valley slightly further south, and much smaller valleys, such as Capell and Wooden Valleys in the southern parts of the County. Elevations of these interior valleys vary between approximately 700 and 900 feet. In the west and east, the County line coincides with the crest of major northwest-trending ridge systems that border on Sonoma and Yolo Counties, respectively. The County is also bounded by Lake County to the north and Solano County to the south.

PHYSIOGRAPHY OF COUNTY SUBREGIONS

NAPA VALLEY SUBREGION

The Napa Valley subregion comprises the Napa Valley and flanking continuous ridge systems. The Napa Valley (Valley) is the principal valley in the County. The Valley is relatively narrow and northwest-southeast trending. The northwest-southeast trend is typical of most of the intermontane valleys and ridge systems of the Coast Range Geomorphic Province.

The Valley is about 31 miles long, commencing about 2.5 miles north of Calistoga and extending southeastward to its mouth about 3 miles south of the City of Napa, where it meets the extensive marshlands that surround the north half of San Pablo Bay. The Valley is up to 3.5 miles wide in its southern half, and narrows to between 0.8 and 1.2 miles along the north half. The valley floor elevations are up to approximately 400 feet near the north end of the valley and approach sea level on the south.

The Napa Valley contains the Napa River, which is the principal drainage course in the County. It has numerous tributary streams that drain its flanking ridge systems. Some of these contain reservoirs, such as Rector Reservoir and Lake Hennessey. The Napa River empties into San Pablo beyond a few miles south of this subregion.

The flanking ridge systems comprise the rest of this subregion. They have higher elevations on the northwest, which decrease to the southeast toward the mouth of the Valley and adjacent marshlands. The physiography of the ridge systems has been influenced by the geology of recent (Miocene-Pliocene) tectonism and volcanism (with associated ash and flow rocks from the Sonoma Volcanics). Along the west ridge system, the principal peaks are Mt. Veeder (2,677 feet) and Mt. St. John (2,375 feet); and along the east, the principal peaks are Table Rock (2,462 feet), the Palisades (up to 2,574 feet), and Atlas Peak (2,663 feet).

The Napa Valley is one of several fault-formed basins of the northern California Coast Ranges. The bordering ridge systems are the result of recent, ongoing tectonism (mountain building) as described elsewhere in this chapter. The combination of mountain building and regionally high erosion rates has resulted in ongoing shedding from the ridge side slopes of sediment that has accumulated in the Napa Valley, forming thick deposits of sand gravel and volcanic debris. In the vicinity of the City of Napa, these deposits may be several thousand feet thick (U.S. Geological Survey 2003). Although previously it was thought that these unconsolidated valley deposits generally thinned toward the north in the valley, it is now believed that there are local pockets of very deep deposits. For example, in the Calistoga area (based on geothermal exploratory drilling) valley-filling deposits are at least 1800 feet deep near downtown Calistoga (Taylor 1981, Enderlin 1993). This deep asymmetric accumulation of valley-filling material is attributed to subsidence along an inferred growth fault system, which bounds the western margin of the upper Napa Valley. Similar downwarping along growth fault(s)is observed in the Clear Lake structural basin. Such local deeper areas of unconsolidated deposits may have important consequences in terms of seismic design criteria in the upper valley.

There are also a few, much smaller valleys within this subregion. These include the northwest-trending Carneros Valley (elevation about 150 feet) on the west and on the east, the upland valley that contains Angwin (elevation about 200 feet), and Foss Valley (elevation about 1,400 feet).

To the south, beyond the mouth of the Napa Valley and the north edge of San Pablo Bay, is the large, flat area of marsh and inter-tidal deposits through which the Napa River meanders to its mouth at San Pablo Bay.

INTERIOR VALLEYS SUBREGION

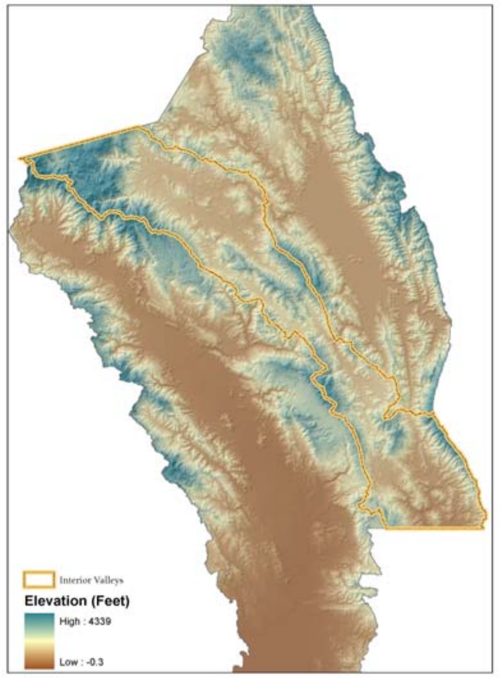
The physiography of the interior valleys subregion is distinctly different from that of the Napa Valley subregion. Unlike the Napa Valley subregion, which has a single, long, well-developed valley with extensive marshlands at its mouth, the interior valleys subregion consists of a series of much shorter valleys that vary considerably in their general outline. From north to south, the principal named valleys of the interior are Pope, Chiles, Capell, Foss, Gordon, and Wooden Valleys.

The largest and most irregular in outline is the northwest-trending Pope Valley, which is approximately 10 miles long and up to about 2.5 miles wide. It is roughly bisected by a linear, discontinuous series of hills with a maximum elevation of 1,200 feet. With the exception of occasional peaks, peripheral ridgelines to the east and west are up to 1,600 and 1,900 feet in elevation, respectively. The valley floor elevation is about 700 feet. The principal stream of the valley is Pope Creek, which drains southeast through a narrow canyon into Lake Berryessa.

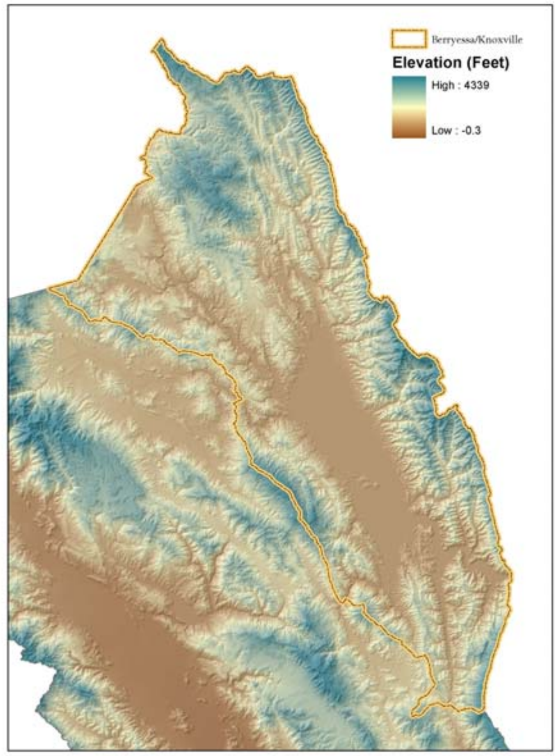
The next valley to the south is Chiles Valley. The form of this valley is distinctly different from Pope Valley. It is long and narrow, with a consistent northwest trend. The valley length is about 8 miles and has a width between 1,000 and 3,000 feet. Peripheral ridgelines have elevations between 1,600 and 2,000 feet and 1,500 and 1,700 feet, respectively. The valley floor elevation is about 800 feet.

The remaining above-named valleys are to the south of Pope and Chiles Valleys. They are much smaller, generally northwest trending, about 2 to 3 miles long, and between about 0.5 and 1 mile in width. Valley floor elevations are between 400 and 600 feet. Peripheral ridge elevations to either side of these smaller valleys range from as high as 2,500 feet opposite Foss Valley to as low as 800 feet (Wooden Valley). Generally, ridge top and valley floor elevations decrease toward the southern part of the County.

Details on the geomorphic evolution of this subregion are not known. However, the strong northwest trend of the ridges and major valleys of this subregion has developed in response to geologically recent transpressive tectonic forces generated by the San Andreas fault system. These forces are responsible for the development of folds and numerous faults of the same orientation, as well as the regional, tectonic uplift (mountain building) that is occurring. The direction of major streams of this subregion has preferentially controlled this structural grain, which is common to the all of the California Coast Ranges. As a result, the principal streams and valleys have this same general northwest trend. The tectonic uplift and rainfall have combined to produce deeply incised side drainages, and high erosion rates, which generate the sediment that has partially filled the valleys of this subregion.



Physiography of the interior valley subregion.



Physiography of the Berryessa/Knoxville subregion.

Berryessa/Knoxville Area Subregion

The principal physiographic feature of the Berryessa/Knoxville area subregion is the former Berryessa Valley now occupied by Lake Berryessa. This valley is about 12 miles long and about 3 miles wide. The principal drainage is Putah Creek, which enters the reservoir from the northwest. The elevation of the valley floor is not known, but the spillway elevation of the reservoir is about 440 feet. No other valleys of any significance are known within this subregion.

The northwest and southeast areas of this subregion are occupied by generally northwest-trending ridge systems with intervening, deeply incised stream canyons. Maximum ridgeline elevations are mostly less than 2,000 feet. Along the upper reaches of Putah Creek, an area, covering approximately 3 miles in width by 5 miles in length, projects southeast into this subregion from Lake County. This area has lower elevations (maximum ridge tops of about 1,100 feet), less deeply incised streams, and broader appearing ridge tops. This area is part of a more extensive area of this type that extends well into Lake County. The presence of pervasively sheared, erodible serpentinite bedrock capped by younger volcanic flows and possibly faulting appears to have controlled the development of this noticeably more subdued terrain.

The easternmost part of this subregion is occupied by the Vaca Mountains, whose ridgeline is the County line. The ridgeline of these mountains is uniformly higher in elevation than ridges west of the reservoir and the range has a pronounced and uniform northwest trend. This is due to the presence of structurally less deformed and uniformly eastward dipping sedimentary rock of the Great Valley Sequence. Maximum ridgeline elevations are typically about 2,500 feet to 3,000 feet.

The geomorphic evolution of this subregion includes the effects of San Andreas transpression and climate as described above for the interior Valleys. It is also is due to the presence of bedrock types and geologic structures. Large masses of fracture/sheared, erodible serpentinite are present in the north part of this subregion and structurally more uniform, often less erodible sedimentary rocks of the Great Valley Sequence occupy much of the region including the topographically prominent Vaca Mountains.

BEDROCK FORMATIONS AND GEOLOGIC STRUCTURE

Much of the information in the following sections on bedrock geology and structure is technical and has been excerpted with some modification from the recent geologic work in the County by Graymer et al. 2002 and 2005 (in press). Additional published sources on County geology are referenced.

Evolution of the Northern California Coast Ranges

As discussed above in the *Physiography* section, the County is located in the northern part of the Coast Range Geomorphic Province. A conspicuous characteristic of this province is the northwest orientation of the landscape, which consists of a series of long, northwest-trending ranges separated by river valleys of the same trend. Like many of California's landscape features, the orientation of these ranges and river valleys is controlled by regional tectonics—the deformation and motion of the Earth's crust, e.g., faulting, mountain building. Landscape controlled by such processes is often referred to as *structurally controlled topography* (Hardin 2004). Even a brief glance at the regional terrain of the County reveals the pronounced northwest orientation of the main valleys and intervening ranges.

The forces resulting in the eventual evolution and orientation of this present physiography started about 140 million years ago (Mesozoic Era). They involve the geometry and long-term relative motions between the regionally very large Farallon, Pacific, and North American Plates. At this early time, the eastward migrating Farallon Plate and the opposing North American Plate were colliding. The result was the accretion and subduction of oceanic crust along the north-south boundary of these plates.

At about 28 million years ago (mid-late Cenozoic Era) the Pacific Plate, which was trailing the Farallon Plate in its eastward path, made contact with the North American Plate. When this occurred, the earliest stage of a major transform fault resulted at the contact between the plates, which grew in length as the contact migrated both north and south along what is now the California coastline. As this migration continued, subduction and accretion associated with the Farallon Plate progressively ended. This major transform fault is the San Andreas. Over the last 28 million years, subsequent motions (the west side of the fault moving northward relative to the southward-moving east side of the fault) along the San Andreas and related faults to the east have left their regional physiographic imprint on the terrain in the form of the northwest-trending ranges and valleys mentioned above.

Faults and Geologic Structures of Napa County

Structural geology refers to the study of the architecture of the Earth's crustal rocks. As such, it pertains to the general disposition, attitude, arrangement or relative positions of bedrock folds, faults and igneous intrusions, and their analysis, including the forces that created them. In the greater San Francisco Bay Area, including Napa County, mapped structures fall into two general age categories: younger and older. The younger structures are north-northwest-trending faults and associated folds generated by the transpressional forces (a combination of compressional and shearing forces) acting along Pacific-North American plate margin. The faults have a predominantly right-lateral strike-slip offset, but also accommodate a component of compression at a ninety-degree angle to the faults, as shown by the uplift of fault-parallel ridges and formation of fault-parallel folds (Jones et al. 1994). These younger structures probably initiated with the establishment of the transpressional plate margin in the region in the wake of the northward migration of the Mendocino Triple Junction, which passed through the San Francisco Bay region between about 12 and 4 million years ago (Ma). These younger structures therefore cut and deform late Miocene and somewhat younger rocks.

Important among these younger structures in the North Bay Area are the Quaternary-active, including Holocene-active (within the last 11,000 years), faults of the San Andreas fault system, including the Maacama, Healdsburg, and Rodgers Creek faults. In the County, the Holocene-active faults include the West Napa fault, the northernmost few miles of the Green Valley (historically active) and Cordelia faults and the Hunting Creek fault. On the Graymer map faults are shown in magenta (Holocene-active, as defined by Hart and Bryant 1999) and orange (Quaternary-active). A Holocene-active fault (fault movement has occurred in the last 11,000 years) must be investigated if structures for human habitation are to be built in its close proximity. A Quaternary-active fault has not experienced such geologically recent movement and for this reason does not require investigation but should be considered during development. The details regarding Holocene-active investigation are discussed in the *Policy and Regulatory Considerations* section of this chapter.

The mountainous topography west of Napa Valley has resulted from the latest Pliocene and Quaternary uplift associated with the geologic younger structures. This topography was absent in earlier Pliocene, but since latest Pliocene at least 650 meters (m) of uplift has apparently occurred. This rate of uplift exemplifies that tectonics and associated mountain building are active in the County.

The structures in the mountains east of Napa Valley are more complex. Mesozoic rocks in this area have undergone much compressional deformation, resulting in imbricate faulting and overturned folds. Some of these structures have evidence of Pliocene or younger activity, whereas others are mapped as overlapped by young (<4 Ma) parts of the Sonoma and Clear Lake Volcanics. Swinchett and Howell (2004) have hypothesized that uplift of the mountains east of Napa Valley was caused by Neogene thrusting on these structures that has continued into the Quaternary, and has generated massive landslides. This hypothesis, however, is not universally accepted and is under scientific debate. However, normal faults also cut the Sonoma Volcanics and Clear Lake in the area, and the regional gravity expression (Langenhein et al. 2003) suggests that there may be volcanic rock filled basins that could be *grabens* (an elongated bedrock block that has downdropped between two parallel faults relative to rock of the surrounding area).

In the area northeast of Napa Valley, Great Valley Sequence, Coast Range Range ophiolite,and Franciscan Complex rocks are *imbricated* (a series of closely spaced thrust fault sheets dipping in the same direction) along northwest to west-northwest-trending reverse faults. These faults, and associated folds, also involve Franciscan Complex rocks (Phipps 1984). The map area also includes a broad, regional deformation that is manifested as a somewhat disrupted east-dipping homocline (a series of beds of rock that all have a similar orientation, i.e., similar strike and dip) northeast of Lake Berryessa and reverse fault repetition of Great Valley Sequence strata in the eastern part of the map area. These older structures are largely pre-Miocene, as shown by the large angular unconformity at the base of the Putnam Peak Basalt east of the map area (Graymer et al. 2002). However, the more modest deformation of the Pliocene Tehama Formation, also east of the map area (Graymer et al. 2002), as well as the uplift of early to late Pleistocene alluvial deposits in the map area (QTc, Qoa), suggests that deformation on the older structures may have continued into the Quaternary. The young deformation is probably the result of the same compression that is postulated above for the mountains east of Napa Valley. This compression has resulted in ongoing eastward-directed wedging of Franciscan Complex rocks beneath the upturned western margin of the Great Valley.

The structural geology of the County, like all of the Coast Ranges, is complex and continues to evolve due to broadly regional forces acting along the above-described plate boundary. However, the overall picture (generally shown in Map 1-4) is consistent with Pliocene and Quaternary compressional deformation superimposed on earlier extensional deformation. Resolution of further details of the structural history of this region is beyond the scope of this study.

MAJOR BEDROCK GROUPS IN NAPA COUNTY

The rock units associated with the above-described tectonics in the San Francisco Bay region, including those of the County, are made up of two principal components: (1) an older set of rocks composed of amalgamated, highly deformed tectonostratigraphic terrenes that have been displaced (at least in part) via plate tectonics, from hundreds to thousands of kilometers from their position of origin; and (b) a younger, less deformed set of rocks that overlie the accreted terrenes and which are roughly in their original position (except for San Andreas fault system offsets and smaller dislocations described below). Throughout Graymer's maps, the older set of rocks are Mesozoic in age and the younger are Cenozoic (see Geologic Time Scale).

MESOZOIC UNITS

The Mesozoic-aged rocks can be grouped into three related tectono-stratigraphic units, two of which crop out in the mapped area. The three Mesozoic that are generally recognized in the geologic literature are: (1) Franciscan Complex, (2) Coast Range ophiolite, and (3) the Great Valley Sequence (or Group) (see Map 1-4).

The Jurassic-aged Coast Range ophiolite in the map area consists mostly of serpentinite, serpentinite-matrix mélange, gabbro, diabase, basalt, and metasediments. The serpentinite and serpentinite-matrix mélange are generally known for their poor engineering properties and relatively high incidence of landsliding.

The Great Valley Sequence is composed of sandstone, conglomerate, and shale of Jurassic and Cretaceous age. Although the sedimentary rocks and ophiolite have been tectonically separated almost everywhere in the map area, the Great Valley Sequence was originally deposited on top of the ophiolite. This depositional relationship is preserved locally in the Chiles Valley and St. Helena quadrangles. This complex represents the accreted and deformed remnants of arc-related Jurassic oceanic crust with a thick sequence of overlying turbidites, at least in part related to the North American forearc. See the Graymer report and geologic map with accompanying legend for more information on the details and locations of these various units within the County.

Phanerozoic Eon (343 mya to present)	Cenozoic Era (65 mya to today)	Quaternary (1.8 mya to today) Holocene (10,000 years to today) Pleistocene (1.8 mya to 10,000 yrs) Tertiary (65 to 1.8 mya) Pliocene (5.3 to 1.8 mya) Miocene (23.8 to 5.3 mya) Oligocene (33.7 to 23.8 mya) Eocene (54.8 to 33.7 mya) Paleocene (65 to 54.8 mya)
	Mesozoic Era (248 to 65 mya)	Cretaceous (144 to 65 mya) Jurassic (206 to 144 mya) Triassic (248 to 206 mya)
	Paleozoic Era (543 to 248 mya)	Permian (290 to 248 mya) Carboniferous (354 to 290 mya) Pennsylvanian (323 to 290 mya) Mississipian (354 to 323 mya) Devonian (417 to 354 mya) Silurian (443 to 417 mya) Ordovician (490 to 443 mya) Cambrian (543 to 490 mya) Tommotian (530 to 527 mya)
Precambrian Time (4,500 to 543 mya)	Proterozoic Era (2,500 to 543 mya)	Neoproterozoic (900 to 543 mya) Vendian (650 to 543 mya) Mesoproterozoic (1,600 to 900 mya) Paleoproterozoic (2,500 to 1,600 mya)
	Archaean (3,800 to 2,500 mya)	
	Hadean (4,500 to 3,800 mya)	

Geologic Time Scale

The dominant exposures within this subregion are the rocks of the Sonoma Volcanics.

The second set of accreted terrenes makes up the Franciscan Complex, which is composed of weakly to strongly metamorphosed greywacke, argillite, basalt, serpentinite, chert, limestone, and other rocks. The rocks of the Franciscan Complex in the map area are mostly derived from Jurassic to Cretaceous oceanic crust and pelagic (open ocean organic oozes and clays) deposits overlain by Late Jurassic to Late Cretaceous turbidites (a sediment deposited in water by turbidity currents). Although most Franciscan Complex rocks are little metamorphosed, high-pressure, low-temperature metamorphic minerals are common in rocks that crop out as mélange blocks (Bailey et al. 1964) and in several fault-bounded lenses within the map area. High-grade metamorphic blocks, enclosed in relatively unmetamorphosed argillite, (a sedimentary rock formed from shale or mudstone by pressure and cementation) (Blake and Jones 1974) reflects the complicated history of the Franciscan Complex.

The parts of the Franciscan Complex that crop out in the map area were subducted beneath the Coast Range ophiolite, a process that continued through Late Cretaceous time, after the deposition of the Franciscan Complex sandstone containing Campanian (Late Cretaceous) fossils that crops out just south of the map area (Blake et al. 2000). The youngest parts of the Franciscan Complex do not crop out in the map area, but are well exposed to the northwest in Sonoma and Mendocino Counties. These include Eocene and younger sedimentary rocks of the Coastal Belt that must have accreted deposition. However, their original relationship to the older Franciscan Complex rocks and Great Valley Sequence rocks seen in the map area is not well understood. Because much of the Franciscan Complex was accreted under the Great Valley Sequence and structurally linked Coast Range ophiolite, the contact between the two structural blocks is everywhere faulted (Bailey et al. 1964), and the Franciscan Complex presumably underlies the entire San Francisco Bay area east of the San Andreas fault. Rocks of the Franciscan Complex are highly variable in their engineering properties. The more highly sheared varieties, especially mélanges, can have very poor engineering properties and are often subject to landsliding.

A third rock complex is exposed west of the San Andreas fault zone and well west of the map area. This complex consists of the granitic rocks of the Salinian Block.

Both the Franciscan Complex and Coast Range ophiolite have been further divided into a number of fault-bounded tectonostratigraphic terranes (Blake et al. 1982, 1984). Terrane distribution in the map area is shown in the index map of terranes on the map sheet. Faults and shears associated with these fault-bounded terranes are likely subject to landsliding and also probably have poor engineering properties. The various Mesozoic terrains are described in detail elsewhere. See Blake et al. (2002) for a recent discussion of the origin of the Coast Range ophiolite and the Franciscan mélange, as well as a description of the terrains listed above.

TERTIARY (CENOZOIC) UNITS

In the San Francisco Bay area, Franciscan Complex *detritus* (erosional debris) in the Paleocene strata overlying Great Valley Sequence rocks in Rice Valley and the eastern Diablo Range (Bartow 1985), as well as unmetamorphosed early Eocene quartzofeldspathic strata overlying Franciscan Complex metamorphic rocks (Pampeyan 1993), indicate that much of the tectonic activity that brought the two Mesozoic complexes together was complete by early Tertiary time.

In the map area, most Paleogene strata was probably eroded prior to the eruption of the Sonoma Volcanic field in Miocene and Pliocene time, as indicated by the little early Tertiary strata that is exposed at the base of the volcanic deposits.

The Sonoma Volcanics are continuously exposed along the rugged range of hills that borders the east side of the Napa Valley (Map 1-4). To the northwest these hills become the Palisades, a particularly prominent volcanic mountain range that terminates at Mt. St. Helena, the highest peak in the County. North of the City of St Helena the Sonoma Volcanics also occupy the hills to the west of the valley. The Sonoma Volcanics are Late Pliocene to Late Miocene in age. They consist predominantly of basalt, andesite, and silicic flows, breccias and tuffs. The fine grained, dark gray andesites and basalts are quite hard, and when their flows are sufficiently thick and free of other less desirable rock types, they have the potential to produce high grade quarry rock. In the recent past, these rock types were extensively mined in the hills just south and east of Napa. Most mining has since ceased and the mined areas have been reclaimed. The tuff (ash) of the volcanics is variable in its engineering properties. Where deeply weathered, tuff is often subject to landsliding.

A large fault-bounded block of Eocene and Paleocene strata (Td) is preserved in the area of the west Napa Valley in the Napa Quadrangle, which is in the same structural block as a thick section of Eocene strata that unconformably overlie Late Cretaceous strata in the Cordelia quadrangle (Graymer et al. 2002). A very small outcrop of Paleogene strata (Ts) is present at the border of Chiles Valley and Walter Springs quadrangles in angular unconformity on lower Great Valley Sequence strata (KJgvl), which has been tentatively correlated (Wagner 1975) with Paleogene strata that conformably overlie the Late Cretaceous rocks northwest of Vacaville, east of the map area. Small outcrops of Paleogene strata are also found in the vicinity of Knoxville (Dean Enderlin, personal communication) and north of the map area near Lower Lake (Brice 1953). In the western part of the map area, the Franciscan Complex, Coast Range ophiolite, and Great Valley Sequence rocks are unconformably overlain by Miocene sedimentary and volcanic rocks.

The Tertiary stratigraphic relationships in the area also reveal significant late Tertiary and Quaternary fault offset. For example, in the southwest part of the Napa Quadrangle Sonoma Volcanic are underlain by Oligocene to late Miocene marine strata (Tkt, Tms, Tci, Tn) more than 850 m (2,800 feet) thick that are completely missing just to the east where Sonoma Volcanics overlie Eocene strata (Td). This juxtaposition suggests that many kilometers of offset on the intervening Carneros fault have brought deposits from different depositional basins or widely separated parts of the same basin.

GEOLOGY OF COUNTY SUBREGIONS

NAPA VALLEY

BEDROCK FORMATIONS AND THEIR CHARACTERISTICS

The principal bedrock formations within the Napa Valley subregion are the Sonoma Volcanics of Miocene-Pliocene age and the underlying, geologically much older rocks of the Franciscan Complex of Jurassic to Cretaceous age, and the Great Valley Sequence (Late Jurassic to Late Cretaceous). These various bedrock formations are exposed along the prominent, northwest-trending ridges that flank the east and west sides of the Napa Valley (and seen in the low hills in the valley near Yountville). For the distribution of these various bedrock formations see Graymer et al. 2004.

The dominant exposures within this subregion are the various rock types of the Sonoma Volcanics. In this subregion they consist primarily of andesite-basalt flows (Tsa) and rhyolitic flows (Tsr), with subordinate amounts of other rock types including tuff (Tsft), tuff breccia (Tslt), pumicitic ash-flow tuff (Tst), welded tuff (Tswt), agglomerate (Tsag), and volcanic sand and gravel (Tss). The exposures of tuff and sand and gravel are probably the most susceptible to erosion and landsliding. The andesite-basalt flows are probably relatively more susceptible to rock falls and topples. Their outcrops occupy nearly the entire length of the ridge system that flanks the east side of the Napa Valley (a distance of nearly 40 miles). Franciscan Complex and Great Valley Sequence rocks (KJfm, KJgv) are exposed across the mid to upper part of this ridge system for a total of about 7 miles to either side of Lake Hennessey Reservoir. These rocks consist of metagraywacke sandstone with greenstone, chert and associated serpentinite. Of these Franciscan rock types, the associated serpentinite is likely the most susceptible to landsliding and erosion. Soils derived from highly sheared and weathered serpentinite are also expected to have expansive properties.

On the west flanking ridge system, Sonoma Volcanics dominate on the north. The predominant rock type shown is pumiceous ash-flow tuff (Tst), with minor included exposures of andesite to basalt flows (Tsa). In the vicinity of St Helena these rocks are replaced along a depositional contact by underlying exposures of Franciscan rocks of early Cretaceous and late Cretaceous age that are predominantly mélange (KJfs), and associated serpentinite. These rocks continue southward along the ridge for about 7 miles, where, approximately opposite Oakville, they terminate against the St. Johns Mountain fault. Mélange and serpentinite are known to be susceptible to landsliding and erosion.

From this fault contact southward, the dominant rocks of the ridge are early Cretaceous and late Jurassic sandstone and shale of the Great Valley Sequence (KJgvl). These rocks are dominant until the ridge terminates at the mouth of the Napa Valley (Map 1-4). These rocks are subject to landsliding and, when well weathered, are susceptible to erosion. The weathered shales may have expansive properties. Commencing just north of Oakville and continuing southward for about 6 miles, the mid-lower flanks of the west-flanking ridge contain exposures of Sonoma Volcanics that are predominantly andesite-basalt flows with minor rhyolitic flows. These Sonoma Volcanic rocks that bound the west valley are separated from the core rocks comprising the ridge (Great Valley Sequence) by the West Napa Fault. Discontinuous slivers of the same volcanic rock are exposed further south commencing opposite the City of Napa and continuing to the end of the ridgeline at the mouth of the Napa River. The Yountville Hills are also composed of andesite-basalt flows and rhyolitic intrusives of the Sonoma Volcanics.

GEOLOGIC STRUCTURE

The younger, mapped (Graymer et al. 2004) geologic structures within the Napa Valley subregion are north-northwest-trending faults and associated folds generated by the transpressional Pacific-North American plate margin (San Andreas fault system). The faults have a predominant right-lateral strike-slip offset, but also have a component of fault-normal compression (at a ninety-degree angle to the fault). This component is shown in the uplift of fault-parallel ridges and the development of fault-parallel folds.

The only known active fault in this subregion is the West Napa fault, which flanks the west side of the Napa Valley. This fault is known to be active south of the City of Napa (Hart and Bryant 1997 [revised]) and is suspected to be active as far north as St Helena (Graymer pers. comm.).

INTERIOR VALLEYS

BEDROCK FORMATIONS AND THEIR CHARACTERISTICS

The number of geologic units and their outcrop pattern are more numerous and complex in the interior valleys subregion. These relationships can be seen in Graymer et al. 2004 and in Graymer et al. 2005 (in press).

The most widespread bedrock types within the interior valleys subregion are the early Cretaceous and Late Jurassic sandstones and shales of the Great Valley Sequence (KJgvl) and late Cretaceous to late Jurassic sandstone, shale and conglomerate (KJgv), also part of the Great Valley Sequence (Graymer et al. 2004). These rocks occupy most of the area from just north of Pope Valley to the south terminus of this subregion at the south border of the County. The early Cretaceous-late Jurassic rocks are mostly rhythmically thin bedded, fine-grained quartz-lithic wacke (sandstone that contains lithic fragments of primarily quartz but may also contain other rock fragments) and greenish gray to black mudstone and shale. Locally this unit contains beds of massively bedded sandstone or conglomerate that can be mapped for several miles before pinching out. The late Cretaceous-Late Jurassic rocks, not described here in detail, are expected to be similar to those of the KJgvl unit. Weathered mudstones and shales of these units may have expansive properties, and weathered sandstones and conglomerates may be susceptible to erosion. Zones of massive, deep landsliding have occurred in this unit, as described in the *Soil Deposits of County Subregions* section of this chapter.

Bordering the above unit on the west and east for over one-half of its length, and in fault contact with it, are continuous northwest-trending zones of serpentinite. These rocks are generally pervasively sheared. They are subject to landsliding and to the development of large zones of massive sliding and are erodible. The more sheared and correspondingly weathered varieties probably have expansive properties.

Franciscan Complex rocks are also exposed in this subregion, but not extensively. The Franciscan unit (KJfm) is exposed east of Lake Hennessey Reservoir and extends both north and south along the ridge at this location. These rocks consist of metagreywacke (poorly sorted lithic sandstone) with greenstone and chert. In general these rocks are subject to a nominal amount of landsliding and probably localized erosion hazards. The cherts located in the east central part of this unit are suspected to be quite hard.

Other subordinate rock units present in this subregion are a variety of units assigned to the Sonoma Volcanics. These are located along the west edge of this subregion in both the north and south. The outcrop pattern (Graymer et al. 2004) is complex. The rock types shown to be present are undifferentiated Sonoma Volcanics (Tsv), welded ash- flow tuff (Tswt), agglomerate (Tsag), tuff (Tsft),

Slump and earthflow type landslides are observed in several locations throughout the County.

Except for very minor exposure within the Interior Valley subregion, olivine basalts are unique to the Knoxville/Knoxville subregion.

pumicitic ash-flow tuff (Tst), rhyolite flows (Tsr) and andesite to basalt flows (Tsa). These rocks exhibit a wide range of physical characteristics. In general, the tuff and pumiceous ash-flow tuff are suspected to be subject to landsliding and erosion, and possibly have expansive properties. The welded ash-flow tuff, agglomerate, and andesite-basalt flows are expected to be generally more competent and less subject to landsliding, erosion and expansive properties.

Exposed basalt

Geologic Structure

The geologic structures in the mountains of the interior valleys subregion are relatively more complex than those to the west. Mesozoic rocks (pre-Sonoma Volcanics) in this area have undergone much compressional deformation, resulting in imbricate faulting and overturned folds. Some of these structures have evidence of Pliocene or younger activity, whereas others are overlapped by young (less than 4 Ma) parts of the Sonoma Volcanics (Graymer et al. 2004). It has been hypothesized (Swinchett and Howell 2004) that Neogene thrusting on these structures—that has continued into the Quaternary and has generated some of the massive landslide zones described earlier in this geology chapter—caused uplift of the mountains east of the Napa Valley. However, normal faults also cut the Sonoma Volcanics in the area, and the regional gravity expression (Langenheim et al. 2003) suggests that volcanic filled basins could be grabens. However, the overall structural picture of the area is consistent with Pliocene and Quaternary compressional deformation superimposed on earlier extensional deformation.

As the above description indicates, there are many faults cutting this subregion. The principal faults are northwest trending. There is only one known active fault in this subregion, the Green Valley fault, which extends northwestward into this subregion from Solano County. This fault has undergone movement in historic times. The nearby, possibly Holocene-active Cordelia fault extends a few miles into the County from Solano County as a series of short disconnected segments until it dies out near Lake Curry.

Berryessa/Knoxville Area

Bedrock Formations and Their Characteristics

The number and type rock of bedrock units present in Berryessa/Knoxville area subregion is similar to those of the interior valleys subregion. The bedrock relationships can be seen in Graymer et al. 2004 and Graymer et al. 2005 (in press).[1]

The predominant bedrock units present are those of the Great Valley Sequence (either KJgv or KJgvl). Both of these units have been described immediately above in the subsection on the interior valleys subregion. The north part of the unit contains extensive exposures of serpentinite. The serpentinite is associated with the Coast Range fault, a regional northwest-trending fault of probable late Mesozoic to Pleistocene age. The general characteristics of serpentinite have also been described above.

A discontinuous band of volcanic rocks projects into the northwestern part of this subregion from Lake County. The band narrows and terminates along the northwest shore of Lake Berryessa. Except for very minor exposure at the County line within the interior valleys subregion, these rocks are unique to the Berryessa/Knoxville subregion. They are predominantly olivine augite basaltic andesite and basalt of Pleistocene and Pliocene age. They are dark gray and black olivine-porphyry and basalt, and grayish to brownish gray basaltic andesite and andesite. The unit also includes some interlayered rhyolite, rhyolite tuff, and conglomerate. [Note that most historically described rhyolites in this district are actually hydrothermally altered basaltic andesitepyroclastics. Rarerhyolitic airfall tuff deposits (possibly correlating with the Putah tuff) are known in the vicinity of Knoxville. These predate the basaltic andesite eruptions in the vicinity]. These rocks generally correlate with and are the southernmost extent of the Clear Lake Volcanics. The basalts are expected to be generally competent, but may be occasionally subject to rock toppling due to their often rim rock form with associated abrupt, steep breaks in slope.

Geologic Structure

The geologic structure of this subregion is similar to that of the eastern part of the interior valleys subregion and is not further discussed.

The Hunting Creek-Knoxville fault is present in the north part of this subregion. This fault is active (Holocene) and is associated with the regional San Andreas fault system. The Hunting Creek-Knoxville fault is up to a few miles wide and extends from the vicinity of Wilson Valley southward to Cedars Rough west of Lake Knoxville. The fault is divided from north to south into the Wilson, Hunting Creek, and Lake Knoxville sections. The section boundaries of this fault are based on changes in their geomorphic expression.

SOIL DEPOSITS

GEOLOGIC SURFICIAL DEPOSITS IN NAPA COUNTY

Unconsolidated surficial deposits generally consist of unstratified, geologically very young materials (clay, silt, sand, rock fragments and gravel, and organic material) lying on bedrock (or older deposits or other sedimentary materials) at or near the Earth's surface. They are of Quaternary age (the last 2 million years). Relative to the underlying rock, they are most often weak, soft, loose, and generally susceptible to erosion. They are the product of weathering, erosion, and deposition. These deposits are of variable thickness and comprise valley alluvium, alluvial fans, levee deposits, estuarine deposits, colluvium, stream channel and terrace deposits, and various types of landslide deposits, and the soil horizons that have developed upon them. Within the County the larger and thicker of these deposits are principally found within the major valleys—Napa, Chiles and Pope. Symbols on the geologic maps that start with an "a" or a "Q" should generally be considered unconsolidated surficial deposits. Soils and landslides, which are surficial deposits, are described in more detail in following subsections. Unconsolidated surficial deposits are shown in Map 1-5.

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[1] There are discrepancies in map symbols between these published and in-press maps. The principal ones are between sedimentary rock units of the Great Valley sequence. For example, the 2004 publication contains KJgvl, while the in press map shows KJgv for the same unit. The lithologies are similar. The principal difference seems to be in the age difference between the units. Once the U. S. Geological Survey completes technical review, these differences will be rectified.

MAJOR SOIL GROUPS IN NAPA COUNTY

A discussion of soil must indicate how the term *soil* is being used. The term has many definitions, depending on who is using it (Birkeland 1999).[2] To soil scientists, *soil* is mainly the medium for plant growth (agricultural soils) and as such is a resource that should be conserved. From this perspective, its study at a given location relies heavily on the nature and depth of soil horizons. This section primarily deals with soils from the soil science/agricultural perspective. This also includes information on the general engineering properties that can be deduced from characterization of the soils. Soil texture and engineering properties for Napa County are shown in Maps 1-6 and 1-7 respectively.

A soil is generally defined as a natural body consisting of *horizons* (layers) of mineral and/or organic constituents of variable thickness, which differ from the parent materials in their morphological, physical, chemical, and mineralogical properties and their biological characteristics (Birkeland 1999). In an agricultural context, *soil* refers to the unconsolidated and/or organic material at the ground surface that serves as the natural medium for growth of plants.

The interaction of five forming factors is usually used to define the state of a soil system. These are climate, organisms, topography, parent material, and time. More information on the importance of these factors and on soils in general can be found in the Soil Survey of Napa County, described below.

The Soil Survey of Napa County (Lambert and Kashiwagi 1978), prepared by the U.S. Soil Conservation Service (now known as the Natural Resources Conservation Service [NRCS]), contains photo-based maps (1:24,000 scale) delineating the approximate boundaries of identified soils units and provides detailed written descriptions that characterize these soils. This information can be used for a variety of purposes, including assistance in the management of agricultural properties and woodlands, and initial evaluations that are useful in selecting potential sites for roads, ponds, and structures. The survey information is also useful for assisting in land appraisals and for general land use planning purposes. Engineering tables present information on the engineering properties of the soil units and name soil features that affect engineering practices and structures.

Other uses of the information in the soil survey include environmental impact identification and the relation between soil types and landforms, which have both applied and research value. The more detailed characterization of the physical and chemical properties of a soil at a particular location through further site-specific study can also be used to estimate the age of the soil. For example, this information can be particularly important to investigative geologists in determining if a fault through a site is active or inactive.

As useful as the soils maps and the soils descriptions are, it is important to appreciate that the information is general rather than specific, due to the scale (1:24,000) of the mapping, and cannot be used with great reliability for site-specific characterizations. Site-specific investigation is necessary to develop this information.

The Soil Survey of Napa County is available in both electronic and hard copy forms as described below. The Soil Survey Geographic (SSURGO) Database contains a series of reports (e.g., soil properties) and describes soil groups according to properties such as engineering classification and chemical properties.

Presently, the SSURGO website of the NRCS is the primary source of the online soil data, including Napa County. In an effort to improve the distribution of this regional soil mapping data, the NRCS has recently developed the Soil Data Mart. Soon, the Data Mart will supersede the National SSURGO website as the repository for this information. During this period of transition, data for a particular a survey, such as that for the County, may reside at either site, but never at both sites simultaneously.

As of the preparation of Napa County BDR, the SSURGO database is still being used to compile soil maps for the County. The Napa County soil units have been defined on the GIS Metadata Sheets (layers of a data set) and the units are outlined on these individual soil sheets.

The SSURGO user is allowed to make queries and download data through using the Internet. The website contains all of the details for this database (data at http://datagateway.nrcs.usda.gov). In addition, the State Soil Scientist can be reached for questions and directions on how the database was made and its many applications.

The following chapters accompany the SSURGO database:

- 618.20: AASHTO Engineering Characteristics and classification.
- 618.21: Erosion-Accelerated, and Kind.
- 618.22: Erosion Class.
- 618.23: Excavation Difficulty Classes.

The soils that have a high shrink-swell potential, rapid run-off, and excavation difficulties are described in the SSURGO database, listed in the above database chapters. In addition, this database contains information on the American Association of State Highway and Transportation Officials (AASHTO) Engineering Characteristics and classifications. The database is available in GIS.

The following are additional sources of soil information.

- National Soil Handbook (http://soils.usda.gov/technical/handbook/detailedtoc.html).

Soil Profile in Napa County

Soils information can be used for a variety of purposes, including management of agricultural properties and woodlands; initial site evaluations for roads, ponds, and structures; land appraisals; general land use planning purposes; and identification of potential environmental impacts.

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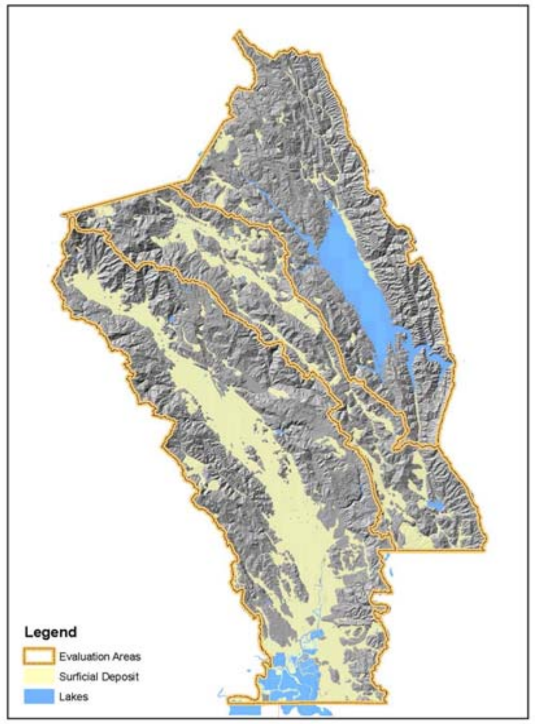
[2] For example, to many engineers, soil is unconsolidated surficial material. Whether it has or has not undergone weathering and the consequent development of soil horizons may or may not be of significance to the engineer; rather, it is the physical properties that are of interest. To the geologist, soils and other weathering products are the loose, unconsolidated products of weathering and erosion that can present clues that greatly assist in the unraveling of their relative ages and add detail to the geologic history of the area within which such materials have been deposited.



Map of Napa County showing surficial deposits and significant water bodies.

- USDA Geospatial Gateway (http://datagateqay.nrcs.usda.gov/).
- Other available GIS layers for California (http://www.pacificsites.com/~cbrooks/gisl.shtml).

Surficial Geologic Deposits and Soil Types of County Subregions

Characteristics and properties of geologic surficial deposits and soil types in the County are described below by subregion. Additional information that may be needed on the characteristics and properties of geologic surficial deposits in the County can be found in the various referenced geologic maps and reports in this chapter. The level of detail of this information is uniform throughout the County.

Needed information on soil behavior properties for the County can presently be found electronically on the SSURGO website of the Natural Resources Conservation Service. This information includes engineering classification, erosion potential, erosion class, and excavation difficulty. The Data Mart will supersede the National SSURGO website in the near future as the repository for soil information. During this period of transition, data for a particular soil survey, such as that for the County, may be found at either site, but never at both sites simultaneously.

Napa Valley

Geologic Surficial Deposits

The surficial geologic deposits of the Napa Valley subregion consist of widespread, locally deep alluvium in the Napa Valley and generally discontinuous deposits on the flanking ridge systems of colluvium, soil creep, and landslides (Maps 1-5 and 1-8). Between the mouth of the Napa Valley and the edge of San Pablo Bay is the large area of soft, largely saturated marsh and inter-tidal deposits that are mapped as predominantly Bay Mud deposits. Thin, discontinuous deposits of predominantly sand and gravel are present along the lesser stream channels that drain into the Valley.

The valley alluvium consists predominantly of alluvial fan, stream channel, flood plain, and terrace deposits that range in age from Earliest Pleistocene (slightly less than 2 Ma) to Holocene (10 thousand years ago [Ka] or less). Typically they are stratified to discontinuously or poorly stratified sands, gravels, silts and clays in various combinations. Generally, the Holocene deposits are relatively thin, found at or near the surface, and are loose, unconsolidated, and highly permeable. In contrast, Pleistocene deposits are generally thicker and more deeply buried (though some may be found at the surface locally), remain permeable, and are more prone to be semi-consolidated, but not yet rock in their mechanical properties. The alluvium of Napa Valley is the largest, continuous source of groundwater in the County.

The colluvial and landslide deposits are typically more heterogeneous in composition and consist of various combinations of mostly unconsolidated soil and rock fragments. They are mostly Holocene in age, but larger landslides and thicker, more continuous colluvial deposits are likely Late Pleistocene or slightly older in age.

The density of known landslide occurrence in the ridge systems of the Napa Valley subregion is variable and ranges form mostly low or moderate to locally high. Most commonly they are combined slump-earthflows and less commonly very rapid failures such as debris flows, mudflows, rock falls, and toppling.

One of the areas of higher landslide density is on the ridge slopes separating Carneros Valley from the Napa Valley. In this area, several large and many smaller landslides have been mapped (Wills and Majmundar 1999; Dwyer et al. 1976).

In some locations, extremely large, deep, presumably dormant slides have been mapped (Dwyer et al. 1978). These large features can be up to 3 or 4 miles wide and over a mile in length. For example, the south canyon of Sage Creek, immediately east of Lake Hennessy Reservoir, is the location of such a mapped slide. A group of these slides have also been mapped about 3 miles west of the Yountville Hills along the Napa-Sonoma County boundary.

While obvious to an experienced aerial photo geologist, such features are so large, as well as partially subdued by erosion, that they can easily go unnoticed by the layperson at the ground surface. Because they provide relatively large, flat areas on otherwise steeper hillside terrain, they are attractive for residences, vineyards, and other improvements. For this reason, flatter areas on steeper hillsides should be carefully evaluated prior to approving significant development on their surfaces. This comment applies to such slide features regardless of the subregion in which they are found.

Other geologic hazards locally associated with surficial deposits of this subregion include accelerated erosion, weak/expansive properties, and the potential for earthquake shaking effects, particularly in deeper valley alluvium and marsh and inter-tidal deposits. The potential for subsidence is significant within the weak, saturated Bay Mud deposits associated with the marsh and tidal deposits.

Soils and Their Characteristics

Soil types (agricultural) and their characteristics in the Napa Valley subregion are controlled in part by location, i.e., valley or hillside. The principal soil series in the Napa Valley is Bale-Cole-Yolo. Soils of this series have formed on the nearly level to gently sloping, deep alluvium of the Valley. The soils are well drained to somewhat poorly drained loams, silt loams, and clay loams on flood plains, alluvial fans and terraces (Map 1-6). These soils are among the most agriculturally productive in the County.

The principal soil series on the ridge system to the west of the Valley are Maymen-Lodo-Felton, Forward-Boomer-Felton, Bressa-Dibble- Sobrante, and Forward-Aken. On the ridge system to the east, the principal soil series are Rock Outcrop-Kidd-Hambright, and Bressa-Dibble-Sobrante, and Forward-Aiken.

Soils present on the ridge systems to either side of the Valley have formed from a wide range of parent materials under varying conditions of slope steepness and stability, slope aspect, time, and annual rainfall. Therefore, it is not surprising that the properties of these soils, including their hazards, are more variable than those formed on the more uniformly flat Valley floor (stable geomorphic surface), with its more homogeneous parent materials (alluvium).

Geologic hazards are essentially the same as those discussed above for surficial geologic deposits.

INTERIOR VALLEYS

GEOLOGIC SURFICIAL DEPOSITS

The surficial geologic deposits of the interior valleys subregion consist of alluvium and associated fan, terrace, and flood plain deposits that occupy the several valleys of this subregion (Map 1-5). Since these valleys are small, their deposits are not as thick or continuously distributed as those of the Napa Valley subregion. Thin, discontinuous channel and peripheral terrace deposits of predominantly sand and gravel are present along the stream channels that drain into the valleys of this subregion. The geologic age of these various deposits is latest Pleistocene to latest Holocene. The surficial deposits of the hill and ridge systems consist of colluvium, soil creep and landslides. The deposits are mostly Holocene. Some of the very large landslide deposits are quite possibly of late Pleistocene age.

The density of mapped landslide occurrence in the hills and ridge systems of the interior valleys subregion (Map 1-8) is variable and ranges form mostly low or moderate to locally high and very high (Dwyer et al. 1976). Most commonly the slides are interpreted to be combined slump-earthflows and less commonly very rapid failures such as debris flows, mud flows, rock falls, and toppling. Mapped slides typically range in length from less than 100 feet to several hundred feet. Activity levels are from recently active to dormant.

Within this subregion are several areas where extremely large and deep slides and slide zones have been mapped (Dwyer et al. 1978; Sims and Frizzell 1976). Most of these slides are classified as dormant through aerial photo interpretation, but in most cases without onsite investigations to confirm geologic mapping and related issues. In the northernmost part of the subregion, these features are up to 2 miles wide and 1.5 miles long. Slightly further south, there is a nearly continuous, northwest-trending zone of such sliding 7 to 8 miles long. This linear zone has developed on the west facing slopes above Hardin and Soda Creeks, just below the ridge crest of the Cedars Rough.

A similar or even larger zone of sliding is present in the south part of the subregion. This area is south and west of Wooden Valley and extends discontinuously northwestward for several miles along high, east-facing slopes. Similar but somewhat smaller zones large landsliding is also present on east facing slopes of Soda Creek, west of Gordon Valley. It is roughly estimated that 30% of this southernmost part of the subregion is composed of landslide deposits of various dimensions.

While obvious to an experienced aerial photo geologist, such features are so large as well as partially subdued by erosion, that they can easily go unnoticed by the layperson at the ground surface. Because they provide relatively large, flat areas on otherwise steeper hillside terrain, they are attractive for residences, vineyards and other improvements. For this reason, flatter areas on steeper hillsides should be carefully evaluated prior to approving significant development on their surfaces.

Other geologic hazards locally to extensively associated with surficial deposits of this subregion include accelerated erosion, extensive areas of weak/expansive soils associated with serpentinite bedrock, and the potential for amplified earthquake shaking and related effects in the deeper alluvium of valleys. The potential for earthquake shaking to reactivate portions of large landslide zones is potentially high.

SOILS AND THEIR CHARACTERISTICS

Soil types (agricultural) and their characteristics in the interior valleys subregion are controlled in part by valley versus hillside location. The principal soil series in the named valley areas are Bressa-Dibble-Sobrante (Pope Valley), Tehama (Chiles Valley), Bale-Cole-Yolo (Wooden, Gordon and Foss Valleys), and Henneke-Montara (Capell Valley).

The principal soil series on the hills and ridge system on the west side of the subregion are Forward-Aiken, Rock Outcrop-Kidd-Hambright, and Bressa-Dibble-Sobrante. On the east side the soil series are Henneke-Montara, Bressa-Dibble-Sobrante, Forward-Aiken, and Tehama.

The above-listed soil series are numerous and variable in their agricultural resources, physical properties, and hazard potential. This is due to the variation throughout the subregion in soil forming properties, including slope steepness and parent material, both of which are highly variable.

As discussed at the beginning of this subsection, details on the properties of these various soils can be obtained electronically from the National Resources Conservation Agency (NRCA).

Interior Valleys have significant areas of alluvium and associated fan, terrace, and flood plain deposits, and landslides.

BERRYESSA/KNOXVILLE AREA

GEOLOGIC SURFICIAL DEPOSITS

Surficial geologic deposits of the Berryessa/Knoxville subregion consist primarily landslide, colluvial and soil creep deposits on sloping terrain, and minor, widely spaced gravel/sand/silt deposits associated with very narrow stream valleys and the confluences of streams. The principal valley of the subregion is occupied by Lake Berryessa Reservoir. There are no other sizable valleys in the subregion. Snell Valley is a minor alluviated valley on the northwest border of the County.

The narrow stream valley and confluence deposits consist of alluvium, alluvial fans, terraces, and overbank deposits. These deposits range in age from latest Holocene to late Pleistocene. They are primarily found along the upper reaches of Putah and Eticuera Creeks and Long Canyon in the north part of the subregion, and in the south, the very narrow Cherry Valley (Wragg Canyon) and Steel Canyon immediately south and tributary to Lake Berryessa.

Landslides occur throughout the subregion. The intensity of mapped landslide development varies from mostly low to moderate to occasionally high (Dwyer et al. 1976; Sims and Frizzell 1976). Most commonly the slides are interpreted to be combined slump-earthflows and less commonly very rapid failures such as debris flows, mud flows, rock falls, and toppling. Mapped slides typically range in length from less than 100 feet to several hundred feet. Activity levels are from recently active to dormant. The geologic age of the landslide and colluvial deposits is predominantly Holocene, with some of the massive landslide zones probably latest Pleistocene.

The chance for a magnitude 6.7 or larger earthquake to occur in the Bay Area by the year 2032 is 62%.

There are occasional large zones of landsliding, but the level is substantially lower than in the interior valleys subregion. In the north, zones of such landsliding are located between Turner Mountain on the west and Eticuera Creek on the east. The west facing slopes above Lake Berryessa on the east contain a moderate numbers of landslides with maximum lengths up to several hundred feet. However, massive landslide zones have not been mapped on these slopes. This absence appears due to uniformly eastward dipping, less structurally disturbed and broken sedimentary rocks of the Great Valley Sequence.

Landslide conditions in the south part of the subregion are similar to those on the north. Just below the ridge crest of the Vaca Mountains (County line) and slightly north of Vaca Mountain, there is one area of large massive landsliding on west-facing slopes.

Soils and Their Characteristics

The principal soil series of the Berryessa/Knoxville subregion are few in number; in the north-northwest part of the subregion they consist of the Henneke-Montara Series, and in the north-northeast of the Bressa-Dibble-Sobrante Series. The Maymen-Lodo-Felton Series is found long the top of Blue Ridge (County Line). The Tehama series occupies part of the eastern shore of Lake Berryessa. In the south part of the subregion, the predominating soil series are Bressa-Dibble-Sobrante and Maymen-Lodo-Felton.

As discussed at the beginning if this subsection, details on the properties of these various soils can be obtained electronically from the NRCA.

SEISMICITY

The County is located within a seismically active area and will therefore experience the effects of future earthquakes. Earthquakes are the product of the buildup and sudden release of stress along a *fault zone*, or zone of weakness in the Earth's crust. Stored energy may be released as soon as it is generated or it may be accumulated and stored for long periods of time. Individual releases may be so small that only sensitive instruments detect them, or they may be violent enough to cause destruction over vast areas.

When an earthquake occurs, energy waves are radiated outward from the fault. The amplitude and frequency of earthquake ground motions partially depends on the material through which it is moving and distance from the source.

When an earthquake occurs, energy waves are radiated outward from the fault. The amplitude and frequency of earthquake ground motions partially depends on the material through which it is moving and distance from the source. The earthquake force is transmitted through hard rock in short, rapid vibrations, while this energy movement becomes a long, high-amplitude motion when moving through soft ground materials, such as valley alluvium or bay mud. The force an earthquake applies to a structure is expressed in terms of a percentage of gravity (g). For example, an earthquake that produces 0.30g horizontal ground acceleration will impose a lateral force on a structure equal to 30% of its total vertical weight.

The intensity of an earthquake is expressed in terms of its effects, as measured by the Modified Mercalli Intensity Scale, and in terms of the quantity of energy released, or magnitude, as measured by the Richter, or Moment Magnitude, Scale.

The Modified Mercalli Intensity Scale (Table 1-1) describes the physical effects of an earthquake with the lowest ratings based on human reactions, such as "felt indoors by few" and the highest intensities measured by geologic effects such as "broad fissures in wet ground, numerous and extensive landslides, and major surface faulting." Moderate intensities are determined by the degree of observed structural damage to buildings. Therefore, a single earthquake can have different intensity ratings based on geologic conditions, structural design, or distance from the earthquake's epicenter.

The Richter Scale provides a method to deduce the magnitude of an earthquake from seismologic instruments. The measurement of magnitude provides a rating that is independent of the place of observation and thus allows a comparison of seismic events. Magnitude is measured on a logarithmic scale; every one-unit increase indicates an increment of roughly 30 times the energy. For example, an 8.0 magnitude earthquake would have an energy level 30 times that of a 7.0 magnitude and 900 times that of a 6.0 magnitude earthquake. Earthquakes are ranked as "Large" between magnitudes 6.0 and 6.9, "Major" between magnitudes 7.0 and 7.9, and "Great" when over 8.0. On a worldwide basis there is usually only one Great earthquake per year. However, many small earthquakes occur in the same time frame. For example about 100,000 small (less than magnitude 3.5) earthquakes occur each day on a worldwide basis (Keller et al. 2006 in press)

Table 1-1. Modified Mercalli Intensity Scale

Average peak velocity (cm/s)	Intensity value and description	Average peak acceleration (g = 9.80 m/s)
Less than 1	I. Not felt except by a very few under especially favorable circumstances.	Less than 0.015g
	II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	
	III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration estimated.	
1–2	IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.	0.015g–0.02g
2–5	V. Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.	0.03g–0.04g
5–8	VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight.	0.06g–0.07g
8–12	VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.	0.10g–0.15g
20–30	VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stack, columns, monuments, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed.	0.25g–0.30g
45–55	IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	0.50g–0.55g
More than 60	X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks.	More than 0.60g
	XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.	
	XII. Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into the air.	

Notes:

cm/s = centimeters per second.

g = the force an earthquake applies to a structure is expressed in terms of a percentage of gravity.

m/s = meters per second.

Source: Bolt 1993.

HISTORIC FAULT ACTIVITY

Numerous earthquakes have occurred in the Napa County region within historic times. The computer database search (NCEDC Northern California Earthquake Catalog Search, joint effort by UCB and USGS) indicated that 97 earthquakes of magnitude 5.0 or larger have occurred within 200 kilometers of the center of the County between 1735 and 2005. The significant historic earthquakes that have affected the County are summarized in Table 1-2.

The County is located within a seismically active area. Earthquakes are the product of the buildup and sudden release of stress along a *fault zone*, or zone of weakness in the Earth's crust. Stored energy may be released as soon as it is generated or it may be accumulated and stored for long periods of time. Individual releases may be so small that only sensitive instruments detect them, or they may be violent enough to cause destruction over vast areas.

Table 1-2. Significant Historic Earthquake Activity—Napa County

Epicenter latitude – longitude	Magnitude	Year	Distance from County Center (km)	Median Peak Bedrock Acceleration
37.70–122.50	8.3	1906	89	0.10g
37.80–122.20	6.8	1836	76	0.05g
37.60–122.40	7.0	1838	98	0.04g
38.40–122.00	6.4	1892	27	0.10g
37.70–122.10	6.8	1868	88	0.04g
38.20–122.40	6.2	1898	33	0.07g
38.38–122.41	5.2	2000	15	0.08g

Notes:

g = The force an earthquake applies to a structure is expressed in terms of a percentage of gravity.

km = Kilometers.

Sources: U.S. Geological Survey 2001; Idriss 1995.

The calculated bedrock accelerations are reasonable estimates at the center of the County. Many factors (soil conditions, distance, orientation to the fault, etc.) can influence the actual ground surface accelerations. Significant deviation from the values presented is possible due to geologic variations from the typical conditions used in the empirical correlations.

PROBABILITY OF FUTURE EARTHQUAKES

The historical records do not directly indicate either the maximum credible earthquake or the probability of such a future event. To evaluate earthquake probability in this region, the U.S. Geological Survey (USGS) has convened a group of researchers into the Working Group on California Earthquake Probabilities to estimate the probabilities of earthquakes on active faults. Potential sources were analyzed considering fault geometry, geologic slip rates, geodetic strain rates, historic activity, and micro-seismicity, to arrive at estimates of probabilities of earthquakes.

The probability studies focus on seven fault systems within the Bay Area. Fault systems are composed of different, interacting fault segments capable of producing earthquakes within the individual segment or in combination with other segments of the same fault system. The probabilities for the individual fault segments in the San Francisco Bay Area are shown in Table 1-3.

Faults are seldom single breaks or fissures in the Earth's crust, but typically are braids of breaks that comprise shatter zones which link to form networks of major and minor faults. Within the Bay Area, active faults are components of the San Andreas fault zone, a broad north-northwest trending system that extends across the Bay Area and includes many active faults, including the main trace of the San Andreas fault.

In addition to the seven fault systems, the studies included probabilities of *background earthquakes*. These earthquakes are not associated with the identified fault systems and may occur on lesser faults (i.e., West Napa) or previously unknown faults (i.e., the 1989 Loma Prieta and 1994 Northridge earthquakes). Based on a combined probability of all seven fault systems and background earthquakes, there is a 62% chance for a magnitude 6.7 or larger earthquake to occur in the Bay Area by the year 2032. Smaller earthquakes (between magnitudes 6.0 and 6.7), capable of considerable damage depending on proximity to urban areas, have about an 80% chance of occurring in the Bay Area by 2030 (U.S. Geological Survey 2003).

Additional studies by the USGS regarding the probability of large earthquakes in the Bay Area are ongoing. These current evaluations include data from additional active faults and updated geological data.

GENERAL PROBABILISTIC SEISMIC DESIGN

For detailed planning studies of important or critical structures (schools, hospitals, police, fire, etc.), the California Division of State Architect (DSA) requires two probabilistic seismic hazard ground motions to be utilized for project design. The first ground motion is the Upper-Bound Earthquake Ground Motion (PGAUBE) and is caused by an earthquake with a 10% chance of exceedance in 100 years. The second ground motion defined by DSA is the Design-Basis Earthquake Ground-Motion (PGADBE) and is caused by an earthquake with a 10% chance of exceedance in 50 years. Because the PGAUBE has a longer return period, larger earthquakes and subsequently larger ground motions are associated with it. DSA requires the more conservative PGAUBE to be utilized when determining the sites susceptibility to liquefaction and the PGADBE to be utilized for structure design.

A common approach for site-specific analysis is to use the PGAUBE and PGADBE listed below in Table 1-3 from the USGS Earthquake Hazards Program (Seed et al. 1997). Note, however, that these numbers are generalized for large physiographic regions across the County; for planning purposes, individual latitudes and longitudes must be used to obtain correct peak ground accelerations (PGAs).

The interpolated probabilistic ground-motion values, in percent g, at the three sub regions are listed below in Table 1-3.

Table 1-3. Probabilistic Seismic Hazard Analysis—Three Physiographic Regions of Napa County, California

Physiographic Regions	Peak Ground Accelerations	Statistical Return Period	Statistical Return Period	Statistical Return Period
City of Napa		10% PE in 50 year PGA=0.422g	2% PE in 50 year PGA=0.751	10% in 100 yr = 0.501g
	0.2 sec SA	1.016g	1.795g	
	1.0 sec SA	0.371g	0.640g	
Interior Valleys: Pope Valley		10% PE in 50 year PGA=0.354g	2% PE in 50 year PGA=0.621g	10% in 100 yr = 0.417g
	0.2 sec SA	0.840g	1.506g	
	1.0 sec SA	0.324g	0.563g	
Berryessa/ Knoxville Area		10% PE in 50 year PGA=0.455g	2% PE in 50 year PGA=0.901g	10% in 100 yr = 0.561g
	0.2 sec SA	1.056g	2.174g	
	1.0 sec SA	0.390g	0.827g	

Source: U.S. Geological Survey 2004.

MAJOR EARTHQUAKE FAULTS IN NAPA COUNTY

Faults are seldom single breaks or fissures in the Earth's crust, but typically are braids of breaks that comprise shatter zones which link to form networks of major and minor faults. Within the Bay Area, active faults are components of the San Andreas fault zone, a broad north-northwest trending system that extends across the Bay Area and includes many active faults, including the main trace of the San Andreas fault.

The movement between rock formations along either side of a fault may be horizontal, vertical, or a combination. An *active* fault is one that shows displacement within the last 11,000 years and is therefore considered more likely to generate a future earthquake than a fault that shows no sign of recent rupture. The active faults are classified into two types. *Type A* faults are capable of large magnitude earthquakes and have a high rate of seismic activity. *Type* B faults are capable of large magnitude earthquakes with a low rate of seismic activity or are smaller faults with a high rate of seismic activity.

A large number of faults have been mapped within the County (Graymer et al. 2000; Graymer et al. 2005 in press). Only a very small number of these faults have been designated as active by the California Geological Survey (formerly the California Division of Mines and Geology). To be so designated a fault must be judged as "sufficiently active and well defined." That is, it must have undergone movement during the Holocene (the last 11,000 years), and the trace of the fault must be clearly detectable by a trained geologist as a physical feature at or just below the ground surface. When a fault meets this criterion it is zoned as active according to the mandates of the Alquist-Priolo Earthquake Fault Zoning Act of 1972. Such zones are known as *earthquake fault zones*. These zones are graphically shown for the entire state on a series of quadrangle maps available to the public. Within the County, three faults are designated as active based on the above-described criteria. These are the West Napa fault, the Green Valley fault, and the Hunting Creek fault (Map 1-4). (The Cordelia fault is a potential fourth active fault in the County.) Their characteristics are summarized in Table 1-4.

The locations of the major faults are indicated on the Geologic Maps of Graymer (2002 and 2004) and shown in Map 1-4. Additional geologic maps that were used for this study include recent maps by the California Geological Survey, the Unified Building Code Map of known active faults, and the California Department of Transportation's (Caltrans') 1996 map of maximum credible earthquake events.

Five 7.5-minute quadrangles contain faults that are Alquist-Priolo zones: Cordelia, Cuttings Wharf, Jericho Valley, Knoxville, and Mt. George maps. A map indicating the County's 7.5-minute quadrangles can be found at http://www.conservation.gov/CGS/rghm/ap/Map_index/county.htm.

Additional investigations are underway on the West Napa fault, particularly the northern part. Portions are believed to be active, and additional earthquake trenching studies may be required to definitively zone segments as "Sufficiently Active." Bill Bryant of the California Geological Survey in Sacramento is the head of the Special Studies Zones mapping program for the State of California (Alquist-Priolo Zone mapping). For development in any areas of suspected faulting, cities and counties should be contacted and previous geological and geotechnical reports should be reviewed.

Table 1-4. Known Active Faults in Napa County

Fault Name	General Information	Activity; AP Zoned	Mapped/Investigated by
Hunting Creek-Berryessa, Hunting Creek section (medial Section)	This fault has 3 segments in Napa County. Section boundaries are based on a change in geomorphic expression of the fault.	Active: AP Zoned	Bryant (1982) Investigation by Steffen, Robertson, and Kirsten and Woodward-Clyde Consultants (1983) demonstrated latest Pleistocene and probable Holocene displacement along some traces.
Hunting Creek-Berryessa, Lake Berryessa section	Extends from the vicinity of Wilson Valley south-southeast to the Cedar Roughs area west of Lake Berryessa.	Active	Compiled by William A. Bryant, California Geological Survey, 2000.
Hunting Creek-Berryessa, Wilson section (northern section)	Probably transfers dextral slip to the Bartlett Springs fault system. The whole system is expressed as a zone of discontinuous fault traces as much as 3.5km wide.	Active	Compiled by William A. Bryant, California Geological Survey, 2000Working Group on Northern California Earthquake Potential (1996).
West Napa fault Napa County Airport section (southern section)	Delineated by northwester-striking dextral slip faults that exhibit geomorphic evidence of Holocene displacement.	Yes: Exhibits geomorphic evidence of Holocene displacement	Helley and Herd (1977), and Bryant (1982).
West Napa fault, Browns Valley section (northern section)	Delineated by a zone of north-northwestern-striking late Pleistocene faults that generally lack geomorphic evidence of Holocene displacement.	No	Mapped by Weaver (1949), Fox et al. (1973), Helley and Herd (1977) Pampeyan (1979) and Bryant (1982).
Green Valley fault: This dextral fault borders the eastern side of the Sulphur Springs Mountains	Holocene Active. Slip rate category: between 1.0 and 5.0 mm/yr.	Portions are AP Zoned.	Borchardt trenched at Hwy 12 and 80, not found evidence of active. Evidence of Holocene movement may be found in stream.
Possibly a section of the Cordelia fault	A road on the north end, but the fault only goes a short distance into Napa County. Not listed as part of Napa County, but should be evaluated on a case-by-case basis.	Possibly Active	Working Group on Northern California Earthquake Potential, 1996, Database of potential sources for earthquake larger than magnitude 6 in northern California: U.S. Geological Survey Open-File Report 96-705, 40p.

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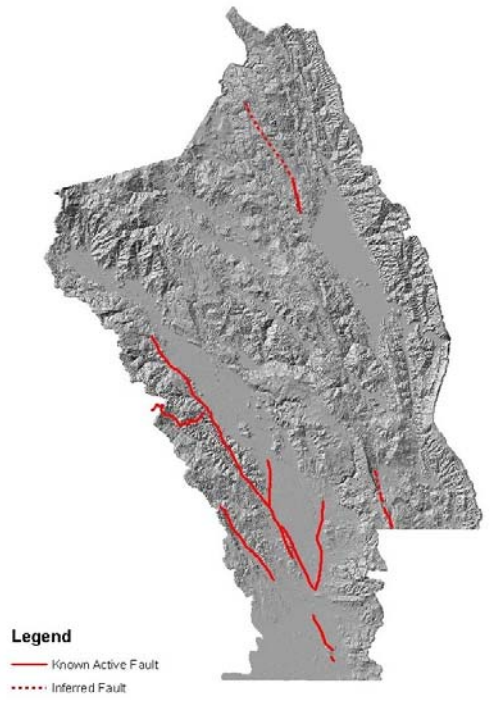
mm/yr = millimeters per year.



Active Faults in Napa County

Major Active Faults in Napa County

Three faults are designated as active in the County: the West Napa fault, Green Valley fault and Hunting Creek fault, discussed below. The Cordelia fault can possibly also be considered active within Napa County.

West Napa Fault

The West Napa fault has been mapped as Holocene-active (California Division of Mines and Geology 2000) in the southern part of the map area (south from the Napa Airport to very near the Napa-Solano County boundary). It is not presently designated as active along its northern segment that is shown to terminate in the vicinity of Yountville (Helley and Herd 1977). However, recent work (Langenhein et al. 2003) has shown that the damaging M5.2 2000 Yountville earthquake may have occurred on the northern segment West Napa fault. In this northern area (Rutherford Quadrangle), right-deflected streams along the western margin of Napa Valley could have resulted from right-lateral offset associated with Holocene activity on the West Napa fault. However, the detailed paleoseismic work (detailed trenching and logging of the fault) required to prove Holocene activity on the West Napa fault in this northern segment has not yet been done. Therefore, while the mapping of Graymer is suggestive regarding activity, it is not conclusive.

The West Napa fault is a dextral (right lateral) strike-slip fault that forms a part of the larger San Andreas fault system. This fault is generally located along the western side of Napa Valley and extends from Yountville southeast to the vicinity of Napa Junction. Fox (1983) suggested that the West Napa fault may continue further to the northwest in the bedrock hills to near St. Helena, rather than striking more northerly into the alluvium of Napa Valley. However, fault recency has not been documented along this northwestern part of the trace other than the fact that it offsets Pliocene Sonoma Volcanics against rocks of the Cretaceous Great Valley Sequence (Fox 1983). Cumulative lateral displacement on the fault is unknown. Helley and Herd (1977) reported that at least 24 m (about 75 feet) of down-to-east vertical (normal dip slip) has occurred along a strand just north of Browns Valley. Fox (1983) reported that this down-to-the east vertical component might be greater than 79 m (about 240 feet), based on the thickness of alluvium logged in a water well just east of the fault in western Napa Valley.

According to other research geologists, such as Langenheim (2003), the north-northwest striking West Napa fault is mapped along the western margin of Napa Valley, California. The epicenter of the M5.2 earthquake in 2000 was located west of Yountville and may have occurred on a strand of the West Napa fault. A linear aeromagnetic anomaly along strike with the Holocene West Napa fault extends northwest 30 km (about 21 miles) from just north of the Napa County Airport to the latitude of the town of Rutherford. North of Rutherford, another linear aeromagnetic anomaly can be traced 20 km north to Calistoga. The source of the anomalies resides within the pre-Cenozoic basement rocks, most likely unexposed ophiolitic basement rocks of the Great Valley Sequence. Both of the aeromagnetic anomalies occur near the base of a linear east-facing gravity gradient. The gravity gradient is caused by the juxtaposition of Great Valley and Franciscan rocks to the southwest with less dense Cenozoic Sonoma Volcanics all along the west side of the valley.

The correlation of the potential-field anomalies suggests that a steeply west-dipping reverse fault bounds the western margin of the Napa Valley basin. The alignment of the reverse fault with the Holocene mapped West Napa fault suggests that they are related. The focal mechanism of the Yountville Earthquake, which occurred at a depth of about 10 km, indicates slip occurred on a steeply southwest-dipping, northwest-striking fault plane. Projection of this fault plane to the surface coincides closely with the location of the geophysically defined fault bounding the western margin of the Napa Valley basin and the surface trace of the West Napa fault as mapped by Fox (1983) and Graymer et al. 2005 (in press). Although the focal mechanism indicates nearly pure right-lateral slip, aftershocks of the event include both right-lateral and reverse mechanisms. Despite the relatively small magnitude of the Yountville earthquake, it probably occurred on a fault capable of much larger earthquakes. Given the length of the geophysically defined West Napa fault, it may be capable of producing an M6.8-7.1 earthquake (large to major earthquake). An unusual characteristic of the Yountville earthquake was more extensive damage in the city of Napa than in communities more proximal to the epicenter. A preliminary inversion of the gravity data indicates that the Cenozoic basin fill is as much as 2 km thick beneath the town of Napa and substantially thinner beneath Yountville. The variation in thickness of the basin fill, combined with variable groundwater saturation, may be a factor that contributed to the unusually strong ground accelerations recorded in parts of Napa and the lack of damage to older buildings at Yountville during the 2000 earthquake.

Green Valley Fault

The Green Valley fault extends northward 4 to 5 miles into the southeast part of the County and terminates along the west edge of Wooden Valley. It is a Holocene active, right lateral strike-slip fault, which is the easternmost significant strike-slip fault of the larger San Andreas system within the San Francisco Bay area. It is characterized by seismic creep (slow, gradual movement on a fault not associated with felt earthquakes), and has been monitored by Galehouse (1992) since 1984. In addition to Graymer (2002), other geologic publications providing information on this fault and other faults in the region include Weaver 1949, Sims et al. 1973, Dooley 1973, Frizzell and Brown 1976, Bryant 1982 and 1992, Sowers et al. 1995, and Bezore et al. 2004.

Several site-specific studies have been completed in compliance with Alquist-Priolo Earthquake Fault Zoning Act (Hart and Bryant 1997), which have documented the location and approximate time of the most recent faulting. Information from the Lopes Ranch paleoseismic site indicates that the Green Valley fault has produced multiple surface-rupturing events in the past 2.7-thousand (ka) and has minimum late Holocene dextral slip rate of 3.8 mm/yr to 4.8 mm/yr (Baldwin and Lienkemper 1999)

Hunting Creek Fault

The Hunting Creek-Berryessa fault is an active (Holocene) dextral strike-slip fault system associated with the larger San Andreas fault system. The Hunting Creek-Berryessa fault system extends from the vicinity of Wilson Valley south-southeast to the Cedar Roughs area west of Lake Berryessa. In the USGS Fault and Fold Database, the fault zone is divided from north to south into the Wilson, Hunting Creek, and Lake Berryessa sections. The section boundaries are based on changes in geomorphic expression of the faults. The Wilson section probably transfers dextral slip to the Bartlett Springs fault system, north of the County.

The Hunting Creek-Berryessa fault system is expressed as a zone of discontinuous fault traces as much as 3.5 km wide. This fault system is locally delineated by geomorphic evidence of Holocene dextral strike-slip displacement, predominantly along the Hunting Creek section (Bryant 1982). An investigation by Steffen, Robertson, and Kirsten and Woodward-Clyde Consultants (1983) demonstrated latest Pleistocene and probable Holocene displacement along traces of the Hunting Creek-Berryessa fault system. The investigation by Steffen et al. (1983) inferred a late Pleistocene dextral slip rate of 0.09 mm/yr to 0.4 mm/yr, based on apparent vertical separation of a late Pleistocene to Holocene colluvium. Bryant (1983) argued that the geomorphic expression of the Hunting Creek fault indicated a dextral slip rate of at least 1 mm/yr. It is generally necessary to establish a slip rate of at least 1 mm/yr on a given fault before it is designated as sufficiently active by the California Geological Survey and therefore zoned according to the provisions of the Alquist-Priolo Fault Zoning Act. The Hunting Creek fault has been zoned as active.

CORDELIA FAULT

The Cordelia fault is roughly parallel to and located a few miles east of the Green Valley fault. According to Helley and Herd 1977 and Wagner and Bortugno 1982, the fault extends into the County from Solano County and terminates a few miles north of the County boundary near Lake Curry. The Cordelia fault is Holocene-active based on a slip rate of 1mm/yr as determined from fault trenching investigations conducted near the north end of the fault (Borchardt, verbal communication, 2005).

The USGS Earthquake Hazards Program's Fault and Fold Database provides detailed information on faults and on the consultants who have investigated the faults. This information can be accessed at http://eqint.cr.usgs/neic/eq-bin/epic, or at the USGS Earthquake Hazards Program, which provides a broad link of earthquake data, both recent and historical.

SEISMICITY OF COUNTY SUBREGIONS

The data presented below comes form the USGS Earthquake Hazards Program, USGS National Earthquake Information Center. The data is collected using a "Circular Search" (i.e., a 100-km radius from a given latitude and longitude). Two sets of data were accessed for this presentation: (1) *USGS/NEIC (PDE) 1973–Present* and (2) *California, 1735–1974*. This information is generalized; for planning purposes, detailed fault investigations are recommended.

NAPA VALLEY

Historical and preliminary data indicate that there have been eight earthquakes within a 100-km radius of the City of Napa between 1950 and 2005. Magnitudes have ranged from 5.0M to 5.9M.

Between 1900 and 1950, there were three recorded earthquakes ranging from 5.5M to 8.25M (the 1906 earthquake). Between 1836 and 1900, there were nineteen recorded earthquakes, with estimated magnitudes (pre Richter scale development) ranging from 5.1M to 7.0M.

INTERIOR VALLEYS

Historical and preliminary data indicate that there have been seven earthquakes within a 100-km radius of the interior Pope Valley between 1950 and 2005. Magnitudes have ranged from 5.0M to 5.9M.

Between 1900 and 1950, there was one recorded earthquake event of magnitude 5.5M. Between 1836 and 1900, there were twelve recorded earthquake events with estimated magnitude ranging from 5.10M to 6.8M.

Further information on faults and earthquakes can be found on the USGS Earthquake Hazards Program website at: http://eqint.cr.usgs/neic/eq-bin/epic.

BERRYESSA/KNOXVILLE AREA

Historical and preliminary data indicate that there have been three recorded earthquakes within a 100-km radius of the Berryessa/Knoxville area between 1950 and 2005. Magnitudes have ranged from 5.0M to 5.9M.

Between 1900 and 1950, there was one recorded earthquake event and that was a 5.5M in the year 1902. Between 1836 and 1900, there were twelve earthquakes recorded, with estimated magnitude ranging from 5.1M to 6.8M.

GEOLOGIC AND SEISMIC HAZARDS

Napa County is subject to several seismic and geologic hazards. In accordance with the State Government Code §65302 (g), the geologic hazards to be evaluated include slope instability leading to mudslides and landslides, expansive soils, seismically induced surface rupture, ground shaking, ground failure, dam failure, seiches and tsunamis, and subsidence. Bedrock geology has recently been completed (1:24,000 scale) of the southern parts of the County by the California Geological Survey. These maps also show geologic hazards such as landslides and fault traces. A map of Napa County's landslides is shown in Map 1-8.

Landsliding is generally considered the most potentially damaging cumulative geologic hazard in the County because of the widespread and frequent occurrence of damaging events.

HAZARD SUMMARY

Landsliding is generally considered the most potentially damaging cumulative geologic hazard in the County because of the widespread and frequent occurrence of damaging events. [Note that it is important to distinguish between a single event and the cumulative effect when comparing hazards. The most damaging single event would likely be a large (M~7) earthquake on the West Napa fault. However, the probability of such an event is much less than that of damaging slides, so the cumulative potential damage from slides as a class of hazard is greater.] All the major ridge and hills systems within the County have experienced landsliding to varying degrees. Because of similar geology, terrain and climate, this condition is common to the entire Bay Area. Numerous GIS-based and hard copy landslide maps of the County have been developed. Most landslides present the risk of property damage. However, rapid slides such as debris flows and debris avalanches also present the risk of

Earthquake damage in Napa County winery

injury and death. These latter slides are often referred to in the media as mud slides. They are much less prevalent in the County than slower moving types of sliding.

Expansive soils are present within numerous areas throughout the County. While landslides are restricted to hilly areas, the base of hill slopes, and steep banks, expansive soils, along with accelerated erosion (minor rutting and rilling to extensive gullying) can occur on both hills and gently sloping valley areas. While not perceived to present as high a risk as landsliding, these latter two hazards can be damaging to various kinds of improvements. The locations of expansive soils and soils with high erosion potential are shown in the GIS-based soil maps of the County.

Seismic hazard effects are classified as those of seismic shaking and those caused by surface fault rupture. Structural damage from seismic shaking should be anticipated in the County sometime within the next few decades. This risk is high because shaking damage can be caused by one of several of the Bay Areas major faults, which are located outside of the County. In addition, shaking damage can be caused by one of the lesser, active faults within the County. When an earthquake will occur within this decades-long time frame is uncertain.

Depending on the severity of the shaking and the nature of the deposits at the location being shaken, structural damage of various types could occur, including that caused by liquefaction and other ground failures. Older, unreinforced masonry buildings and other city buildings constructed before 1930 that have not been seismically retrofitted are most subject to shaking-induced structural failure/collapse.

The largest area where greater shaking damage is anticipated is within the various valleys of the County. Deeper, unconsolidated alluvial deposits occupy these areas, especially the lower part of the Napa Valley, which is underlain by saturated, estuarine deposits, including the very weak compressible bay muds. Deep, unconsolidated deposits associated with valleys are subject to higher amplitude, longer duration shaking motions (ground shaking amplification), which can cause more damage to improvements than those sited on firmer, shallower deposits. Other areas where ground failure potential exists have been mapped within the County. The locations of areas are shown in the regional, generalized GIS-based maps that are part of the County's database. Generalized maps by Caltrans (1996) showing estimated ground accelerations from a maximum credible earthquake in the Bay Area are also part of the database.

While deep unconsolidated deposits have greater potential for stronger earthquake shaking, this greater potential is recognized in the 1997 UCB or the 2001 CBC. These codes provide for more stringent earthquake resistant design parameters for such areas. Thus, while these shaking impacts are potentially more damaging, they also will tend to be reduced in their structural effects due to UBC or CBC criteria that recognize this potential.

The highest potential for surface fault rupture is along the three known, active faults within the County—the West Napa, Green Valley and Hunting Creek faults. These faults are zoned (at least in part) for special investigation according to the provisions of the Alquist-Priolo Earthquake Fault Zoning Act of 1972. Unlike ground shaking, which has the potential to damage broad areas, surface fault rupture is confined to the relatively narrow zone that brackets the trace of the breaking fault. Extensive damage from fault rupture within the County is judged to have a lower probability of occurring than shaking damage. Fault creep, which is a very slow form of surface faulting, is documented to be occurring along the Green Valley fault, but it is not known if it occurs along the northernmost part of this fault that extends into the County. The potential for seismically induced failures of dams, levees, and large tanks is presumably low, but requires site-by-site evaluation. The more likely candidates for failure damage of this type are older, smaller dams not under the jurisdiction of the Division of Dam Safety of the California Department of Water Resources.

The potential for damage caused by seiches and tsunamis is judged to be low due to lack of bay front exposure within the County. There may be some potential for seiche within large bodies of water within the County, such as reservoirs. While presumably low, the risk has not been evaluated and is beyond the scope of this chapter. To evaluate seiche risk to large tanks requires a site-specific investigation. The Federal Emergency Management Agency (FEMA)-mapped flood zones for Napa County are shown in Map 1-9.

The potential for geologic and seismic hazards to occur at a given location or within a broad area can first be indicated by review of the numerous maps that are listed in this chapter. The actual potential and the characterization of the hazard severity, as well as development of adequate mitigation measures is then determined by geologic and geotechnical investigation done in sufficient detail.

It is beyond the scope of this chapter to predict on a detailed, countywide basis the risk of damage and injuries from future geologic and seismic events. Over the years, a number of reports have been prepared that assess the possibilities of such damaging events on a regional basis throughout California (Hart et al. editors 1982, Ziony editor 1985, Borchardt editor, 19.X, Rowshandel et al. 2005). The only County-specific information acquired that shows specific damage locations was for reported landslide damage as a result of the 1997–1998 El Niño rainstorms (Godt et al. 1999). As a result of these storms, 16 damaging slides were reported. This is a nominal amount of sliding and the County was relatively unaffected. No homes were condemned or in need of significant repair. The Napa County Road Department estimated a total of $1.1 million was required for repair of road surfaces and for debris removal (Godt et al. 1999). Had a large earthquake occurred during these wet winter months, the landslide incidence and damage could have been many times greater.

Rowshandel et al. (2005) have developed estimates of future earthquake shaking damage in the ten Bay Area Counties. This has been done for a number of earthquake scenarios throughout the region. Depending on the scenario, the estimated building damage for the County ranged from a few tens of millions of dollars to 200 to 300 million dollars. Most of this damage would be in the southern, more populated part of the County. Smaller earthquakes, even when on more local faults would result in much less damage. A good example is the Napa Earthquake of 2000, which caused a nominal amount of property damage in the City of Napa, but little damage elsewhere.

The following discusses in more detail the hazards that have been summarized above.

SURFACE FAULT RUPTURE

Surface fault rupture occurs when a fault breaks through to the ground surface as a result of an earthquake. The movement is essentially instantaneous (several kilometers per second) and one side of the fault is displaced relative to the other. The sense of movement can be horizontal, vertical, or a combination of these. The amount of the displacement can vary from a few inches or less to several feet, depending on the characteristics of the fault and the specific event. The length of the rupture varies widely, again depending on fault characteristics. For example, the Great San Francisco Earthquake of 1906 had a magnitude of about 8.0 and broke for a length along the fault of about 430 kilometers (287 miles). Typically, shorter faults correspondingly experience lower maximum magnitude earthquakes and undergo less rupture length. The width of the ground breakage associated with fault rupture depends on a number of factors, including the movement and type and thickness of material the fault breaks through as it nears the ground surface. The surface pattern of mapped faults in the Coast Ranges is typified by those encountered in the County and consists of a series of parallel to sub-parallel traces of varying length comprising a zone that may be up to several hundred or, in some cases, thousands of feet wide. The traces partially overlap their neighboring trace or traces and this pattern is referred to as *en echelon*.

Structures built astride a fault that experience the effects surface fault rupture can be severely damaged or undergo collapse from the nearly instantaneous stress imposed by the fault displacement. Such damage presents high risk for injury and death. Although there is a body of developing research and application for minimizing the surface rupture effects on structures built across active faults, it is still evolving, is relatively expensive compared to standard foundation design, and does not necessarily mitigate all risk of damage (Bray 2001). In the majority of cases at this time, the simplest, least expensive, and safest approach is to avoid the active fault trace. This is done by exposing the fault trace(s) at the project location through trenching and detailed logging. As necessary, this is followed by the development of setback recommendations of human-habitation structures to avoid the trace(s).

The California Geological Survey has designated three faults within the County as active and capable of undergoing surface fault rupture. They are the West Napa, Green Valley and Hunting Creek faults. The characteristics of these faults have been described in detail in the *Seismicity* section of this chapter, above. Since designated as active, these faults are zoned according the provisions of the State mandated Alquist-Priolo Earthquake Zoning Act. With very few exceptions, this act requires detailed investigation of projects intended for human habitation. The intent of the act is to mitigate the risk of damaging surface rupture by avoidance. This includes identifying the fault traces(s) at the project site through detailed subsurface investigation and "setting back" the proposed structure(s) from the trace(s) a specified distance. Provisions for identifying and mitigating the hazard of surface fault rupture for dams above certain dimensions and storage capacities is supervised by the California Department of Water Resources, Division of Safety of Dams (California Department of Water Resources 2004). The California Division of State Architects (DSA) requires the California Geological Survey to review for accuracy and completeness geologic/geotechnical reports prepared for proposed schools and hospitals.

In addition to sudden fault rupture, as described above, a much slower form of rupture exists, known as fault creep. In addition to its slow rate of movement (as slow as a few millimeters per year), creep movements are not associated with the sudden generation of ground shaking that results from rapid rupture events. Although lacking great rupture speed and associated ground shaking, creep movements can nonetheless cause substantial damage to improvements over time. Several faults in the Bay Area are known to be associated with creep movements of various types (Yeats et al.1997). The Green Valley fault that extends into the southeast part of the County is known to have undergone creep movements (Galehouse 1992). It is zoned according to the provisions of the Alquist-Priolo Earthquake Zoning Act.

SEISMICALLY INDUCED GROUND SHAKING

Damage to structures and infrastructure from *seismic ground shaking* caused by the Bay Region's active faults is likely in the County sometime within the next few decades. Based on a combined probability of all seven fault systems and background earthquakes, there is a 62% chance for a magnitude 6.7 or larger earthquake to occur in the Bay Area by the year 2032. Smaller magnitude earthquakes (between magnitudes 6.0 and 6.7), capable of considerable damage depending on proximity to urban areas, have about an 80% chance of occurring in the Bay Area by 2032 (U.S. Geological Survey 2002). A map of Napa County's liquefaction susceptibility conditions is shown in Map 1-10.

Landsliding is one of the most common types of failure resulting from earthquake shaking, which can reactivate dormant landslides, cause new landslides, and accelerate or aggravate movement on active slides.

The severity of the shaking damage at a particular location within the County depends not only on the magnitude of the earthquake and the distance to its epicenter, but also on other factors including the nature and thickness of the deposits at the location. For example, the Napa Earthquake of 2000 resulted in unusually strong ground accelerations (relative to its magnitude) in the City of Napa with attendant damage to structures, while nearer the epicenter at Yountville damage was minimal, even to older buildings. These stronger accelerations and related damage appear to have been contributed to by the apparently much deeper alluvial fill beneath the valley at Napa than at Yountville, which intensified or amplified shaking damage.

The severity of ground shaking damage at a particular location depends not only on the magnitude of the earthquake and the distance, but also on other factors including the nature and thickness of the deposits at the location.

Caltrans' (1996) map of Maximum Credible Earthquake shaking indicates (with contour lines), the maximum credible earthquake event (deterministic approach) for the entire state of California. A summary table of faults and their Maximum Credible Earthquake can be accessed online at http://www.dot.ca.gov/hq/esc/earthquake_engineering/Seismology/MapReport.PDF.

DSA requires two probabilistic seismic hazard ground motions to be utilized for design of projects. The first ground motion is the PGAUBE and is caused by an earthquake with a 10% chance of exceedance in 100 years. The second ground motion defined by DSA is the PGADBE and is caused by an earthquake with a 10% chance of exceedance in 50 years. Because the PGAUBE has a longer return period, larger earthquakes and subsequently larger ground motions are associated with it. DSA requires that the more conservative PGAUBE be used to determine a site's susceptibility to liquefaction and the PGADBE be used for structure design.

Liquefaction is the sudden loss of soil shear strength during strong ground shaking, due to increased pore water pressure and decreased *effective stress*, that portion of the total stress on the soil that is borne by the soil grains. As a result, sufficiently liquefied soils can no longer support structures built on them or maintain buoyant structures placed beneath them.

Lateral spreading is a ground failure in which a subsurface layer of soil liquefies, resulting in the overlying soil mass deforming laterally toward a free face.

Using the USGS Earthquake Hazards Program and a specific location of the following areas (Seed et al. 1997), the following PGAUBE and PGADBE are recommended.

- Discuss probabilistic versus deterministic approach. For planning, use probabilistic for hospitals and schools; use deterministic for all else.
- The probability studies focus on seven fault systems within the Bay area. Fault systems are composed of different, interacting fault segments capable of producing earthquakes within the individual segment or in combination with other segments of the same fault system.

SEISMICALLY INDUCED GROUND FAILURES

Ground failures due to seismically induced ground shaking are also referred to as *secondary effects*. This is to distinguish them from the primary movement or displacement (surface fault rupture) that occurs along the fault plane, which in turn generates the earthquake shaking. In contrast to primary fault rupture, whose effects are localized along the fault, secondary-shaking effects can extend many miles from the earthquake fault that generated the shaking. That is why a sizable earthquake on a fault outside of the County can inflict damage within the County. Ground failures can result directly from earthquake shaking, or from liquefaction induced by the shaking. In either case, they are referred to as seismically induced ground failures.

The following represent principal ground failures due to shaking.

- Various types of landsliding.
- Liquefaction, including liquefaction-triggered landslides.
- Ground settlements, including differential settlement.
- Lateral spreads, lurching and ground cracking.

Depending on their severity and location, ground failures can be quite damaging.

EARTHQUAKE GENERATED LANDSLIDING

Landsliding is one the most common types of failure resulting from earthquake shaking. Landsliding triggered by ground shaking occurs in the same types of hilly or mountainous terrain that is also the source area for non-seismically induced sliding. Ground shaking can reactivate dormant landslides, cause new landslides, and accelerated or aggravate movement on active slides.

A number of landslide types can occur as the result of shaking. These include all of the slide types shown in the landslide maps of the County. Rock falls and rock topples probably have a higher incidence during earthquakes than under non-earthquake conditions. A large earthquake occurring when the ground is saturated from winter rains has the potential to trigger a large number of landslides of various dimensions and types of movement, i.e., falls, flows, rotations, translations. Non-earthquake generated landslides are discussed in the *Landslides and Soil Creep* section below. In sum, susceptibility to earthquake-generated landslides can be estimated using probabilistic maps of ground shaking and statistical or deterministic evaluation of landslide susceptibility.

LIQUEFACTION

Liquefaction is the sudden loss of soil shear strength during strong ground shaking, due to increased pore water pressure and decreased *effective stress*, that portion of the total stress on the soil that is borne by the soil grains. As a result, sufficiently liquefied soils can no longer support structures built on them or maintain buoyant structures placed beneath them. Liquefied soils on sloping ground may flow in a semi-fluid or plastic state (a lateral spreading), disrupting the original ground surface and damaging improvements in their path. Liquefaction susceptibility in Napa County is shown in Map 1-10.

Experience gained from large earthquakes throughout the world has revealed that liquefaction effects are not random. They occur in areas underlain by loose, saturated, cohesionless (non-clayey) sand, silt, and gravel. Liquefaction prone deposits of this type are geologically young, relatively unconsolidated materials that are most commonly associated with alluviated valleys with high groundwater levels. The GIS-based maps accompanying this chapter indicate that even within these areas, the liquefaction potential varies from high to low due to various factors, including soil type, soil thickness and groundwater levels. Estuarine areas, and areas comprising unengineered, saturated, cohesionless fill are often considered to have relatively high liquefaction potential.

Relative to the total area of the County, alluviated valleys represent a relatively small percentage; roughly about 20% or somewhat less. Therefore, on a countywide basis, the potential for liquefaction-induced ground failures is relatively low. However, most of the County's improved areas are within parts these valleys. As a result, liquefaction that may occur presents a commensurately higher risk of causing damage. Estuarine (marshlands) areas generally present a uniformly higher potential for liquefaction. The largest contiguous area within the County where liquefaction failures could occur is within the loose saturated estuarine deposits along the Napa River, south of the City of Napa. Other smaller areas with ground failure potential are scattered within valley areas throughout the County. More information on liquefaction and it effects can be found on the USGS Earthquake hazards website, *Shake Maps*. USGS Open File Report (OFR 00-444) shows regional liquefaction susceptibility.

OTHER EARTHQUAKE GROUND FAILURES

LATERAL SPREADING

Lateral spreading is a ground failure in which a subsurface layer of soil liquefies (the liquefaction process has been described above), resulting in the overlying soil mass deforming laterally toward a free face. This is a type of landsliding triggered by shaking. Most of the County is not susceptible to lateral spreading. Limited lateral spreading could occur in alluvial areas adjacent to open stream channels where a bank or terrace face exists.

LURCHING

Ground lurching is a short-term ground failure caused by seismic forces exerted on the soil. Ground lurching can occur in areas underlain with soft, weaker surficial deposits and soils and often results in ground cracking and permanent displacements. The largest known area within the County underlain by soft, weak soils is the lower Napa Valley immediately south of the City of Napa. Weaker surficial deposits in the Napa area typically include the Bay Mud, indicated by the map symbol Qhbm on the Graymer map.

SEISMIC DIFFERENTIAL SETTLEMENT

Differential settlement is the non-uniform densification of loose soils that occurs during strong ground shaking and causes uneven settlement of the ground surface. Soils of this type are likely to occur in numerous locations in the County. The largest of these areas are in valley areas. Differential settlement can also occur under non-seismic conditions. Differential settlement can be quite damaging to structures and other above and below ground facilities.

FAILURE OF LEVEES AND DAMS

The seismically induced failure of levees, earth-fill dams, and other embankments can occur due to the direct failure of the embankment itself or due to seismic failure of the natural foundation materials beneath the embankment, leading to failure of the overlying embankment structure. Due to generally weak foundation materials believed to be present in the southernmost part of the Napa Valley, the risk of levee failure resulting from seismic shaking could be moderate or higher. This is particularly the case for older levees that may not have been constructed to modern standards, including older levees in the Cuttings Wharf area just west of the Napa River.

As of October 15, 2004, 51 dams of various sizes and ages were in the County (California Department of Water Resources 2004). Most of these are believed to be earth-fill structures. Some of these dams are within the jurisdiction of the Division of Safety of Dams of the California Department of Water Resources. Dams that fall within this jurisdiction include (1) dams with structures that are, or will be in the future, 25 feet or more in height from the natural bed of the stream or water course at the down stream at the toe of the barrier or (2) dams that have an impounding capacity of 50 acre feet or more (California Department of Water Resources 2004). These dams are highly regulated during their design and construction phases and routinely inspected during their impoundment life. As such, these jurisdictional dams are monitored and maintained to assure ongoing compliance with seismic stability standards. The remaining dams are either lower or have less impounding capacity. The largest, oldest, and least maintained of these latter dams very likely present the highest risk for seismic failure.

The Division of Safety of Dams report by the California Department of Water Resources (1990) contains a chart showing jurisdictional dam sizes, which correlates dam height in feet to storage capacity. This chart identifies the dam size (jurisdictional versus non-jurisdictional). A first indication of the potential of the underlying geologic materials to fail or cause settlement problems for a dam can be obtained by the various maps that accompany this chapter.

The potential for seismically induced structural failure of large storage tanks must be determined on the basis of site-specific geotechnical design investigation and other engineering investigations.

Differential settlement is the non-uniform densification of loose soils that occurs during strong ground shaking and causes uneven settlement of the ground surface.

GROUND SUBSIDENCE/SETTLEMENT

Subsidence and *settlement* result from the same physical processes. Settlement is usually considered to occur within a relatively short time frame and within a small area, for instance on the project scale. Subsidence takes place over a longer time frame and a broader regional area. Subsidence/settlement can occur differentially; that is, one area or location subsides or settles more than another. The results of subsidence/settlement, especially when it occurs differentially, can be quite damaging.

Gully Erosion

Ground subsidence/settlement has two basic mechanisms: elastic settlement and consolidation. Elastic settlement occurs from structures and other loads that cause deformation of the subsurface soils. Elastic settlement from structures is usually minor and usually occurs during construction or within the first few weeks after construction.

Longer-term ground subsidence requiring months to decades also occurs as a result of the consolidation of natural surficial materials that are compressible. A surficial geologic unit that is known to be quite prone to subsidence is the bay mud that underlies parts of the marsh area in the lower parts of the Napa Valley south of the City of Napa. When fill or structure loads are placed on these muds for development, flood control, or other purposes, significant settlement can result. It is expected that fills previously placed on these deposits are likely undergoing consolidation and settlement of the ground surface. Any new fill or structure loads will induce new settlement in addition to any on-going settlement. Detailed geotechnical investigation is required in order to reduce the amount of settlement to acceptable levels. The time required to complete consolidation of the bay mud depends on the thickness of the bay mud and distance to a drainage layer (underlying sand lenses). The time required to complete settlement can range from a few months to many decades.

Settlement is usually considered to occur within a relatively short time frame and within a small area, for instance on the project scale. Subsidence takes place over a longer time frame and a broader regional area.

Subsidence may result in flooding as ground levels are lowered, including the freeboard of flood control levees. Subsidence can also cause damage to structures, utilities, and roadways from differential settlement. Foundation and walls can crack and the structure tilt out of level. Gravity-based utilities and storm drains can become inoperable due to differential settlement that causes sag in the lines or slope reversal. This potential highlights the need for recognition of the presence of bay mud and similar deposits, and their careful investigation.

Landslides and Soil Creep

The purpose of this section is to provide introductory-level discussion and description of landsliding and related types of slope failures in the County. This, along with appropriate review of the accompanying GIS-based landslide maps and hard copies of referenced, non-GIS landslide maps, is the first step in identifying potential landslide hazards at given a locality and in developing appropriate measures for hazard mitigation.

Ground lurching is a short-term ground failure caused by seismic forces and can occur in areas underlain with soft, weak soils and often results in ground cracking and permanent displacements.

Map Types, Uses, and Limitations

The GIS-based landslide maps and list of referenced, non-GIS landslide maps that accompany this chapter are a countywide compilation selected from sources published over several decades (1976–1999). Various geologic professionals, using similar but not identical mapping and classification techniques, prepared the maps. The principal mapping method used in their preparation was aerial photograph interpretation, supplemented in some cases by varying amounts of field mapping. Each of the selected landslide publications covers only part of the County, and not all of the maps were prepared at the same scale; some at one inch equals 2,000 feet (1:24,000 scale) and others at 1 inch = 1 mile (1:64,500 scale).

As a result published maps vary in several respects, including the landslide classifications selected to depict the slides shown in the maps, the level of graphical detail employed to show the various landslide features, the degree of indicated landslide activity, and the type of indicated movement. Some landslide maps are accompanied by geologic maps of the same scale and area, showing bedrock and surficial deposits; others are not so accompanied. These former maps can be quite useful because they provide an indication of which bedrock and surficial units are most susceptible to landsliding. Using GIS, landslide maps can be compared and even statistically correlated.

In some cases, relative landslide susceptibility maps accompany landslide maps. These are derivative maps; their intent is to show the relative potential for future landsliding throughout the entire area covered by landslide maps and at the same scale. They are interpretive in nature and are based on a number of factors, including variations in bedrock type, degree of slope, slope aspect, and so forth. Typically, a four-value scale, ranging from least to most susceptible, is used.

Although interpretive, and varying in scale and detail, landslide susceptibility maps provide a good planning-level depiction of existing and potential landslide hazards and their variability throughout those parts of the County for which they have been prepared.

Essentially, landslide maps are useful for planning, preliminary environmental assessments, identifying the need for more detailed investigation, and providing an initial indication of the level of detail required in performing on-site geologic evaluations. Proper application includes using the maps early in the planning process to develop an initial indication of the possible degree of landslide hazards and their impact on a project and its surrounding environment. It is important to recognize that the maps are not a substitute for detailed site-specific landslide investigations. They are useful, however, to indicate when such investigation is required or desirable for a particular project; along with the type of proposed project, landslide maps can be used to suggest the extent and detail of the investigation. Although not generally anticipated, these maps may also in some instances incorrectly predict hazards. For instance, a particular landform interpreted to be a hazard (such as a landslide) and indicated as such on a landslide map may, in fact, not be of landslide origin. This can only be revealed by site-specific investigation.

Essentially, landslide maps are useful for planning, preliminary environmental assessments, identifying the need for more detailed investigation, and providing an initial indication of the level of detail required in performing on-site geologic evaluations. Proper application includes using the maps early in the planning process to develop an initial indication of the possible degree of landslide hazards and their impact on a project and its surrounding environment.

Some of the maps were prepared at a scale of 1:24,000 and others at 1:62,500. Electronically enlarging a map beyond its original scale of preparation will not provide additional detail or better information, and may be misleading.

The first two GIS landslide maps in the series are large-area overview maps. By initially referring to these maps or the described landslide susceptibility maps, the user will benefit by gaining a sub regional sense of landslide occurrence and landslide potential in the area surrounding a particular site. Reference should then be made to the relatively more detailed maps (quadrangle sheet) which, focus on delineating specific landslides and their locations relative to a given project, or area of interest.

Importance of Landslide Type

Like other parts of the Coast Ranges, Napa County exhibits a wide variation in landslide types. This variation includes type of movement, size and depth, geometry, degree of activity, rate of movement, and density of landslide development. Based on these variations (generally by type of material and type of movement) landslides are classified and referred to by such terms as *slump*, *earth flow*, *translational*, *fall*, *flow*, and so forth. Not all landslides present the same level of risk to a given project, and different projects may have different levels of risk from the same landslide. Some bedrock formations and surficial deposits are more prone to landslide failure than others, and some slope types can be more prone to sliding or particular types of sliding than others. Information on landslide variation within the County can be obtained by review of referenced landslide maps and their accompanying explanatory text. Additional information is available online and in hard copy from state and federal agencies such as the California Geological Survey and the USGS.

Most landslide types usually present a greater risk of property damage than risk of physical injury or death, because most landslides proceed at a slow rate of movement. However, some types have a higher probability of causing physical injury or death. These latter slides are characterized by their rapid movement (up to several tens of feet per second) and long travel distance (runout) from point of origin. They are most commonly classified as *debris flows* and *debris avalanches* on the landslide maps. When their movement is reported to the public by the media, such failures are often referred to as *mud slides* or *mud flows*. Several but not all of the County landslide maps show the potential for slope failures of this type. Because of the type of risk they present, such slides and the areas within which they are shown to occur should be carefully investigated and, as found necessary, appropriately mitigated. This is especially the case for proposed improvements designated for human habitation, including critical facilities (hospitals, police/fire stations, schools, prisons, main access routes, etc.).

EROSION

Erosion is the general process or group of processes in which materials of the Earth's crust are loosened, dissolved, or worn away and simultaneously moved from one place to another by natural agencies. These agencies include weathering, solution, corrosion, and transportation, but usually exclude mass wasting processes such as landsliding and soil creep. More specifically, erosion is the mechanical breakdown of rock material and the removal of the resultant materials, such as soil and rock particles, by running water, wind, etc. Erosion can be natural or it can be caused or exacerbated by the activities of humankind. Exacerbated erosion is referred to as *accelerated erosion*. Erosion K factor is shown in the map of Map 1-11.

Sandy soils on moderate slopes or clayey soils on steep slopes are susceptible to erosion, especially when subjected to concentrated surface water flow. Weathered rock can also be eroded if the concentrated flows are sufficiently high. The potential for erosion is accelerated when established vegetation is disturbed or removed, particularly on hillside areas. On hillside areas the result can be rilling, rutting, and, without correction, the eventual development of damaging gully systems. The eroded material may be transported to stream courses and cause water quality and other environmental problems.

Along many natural drainage courses on both hillsides and within the valley areas, stream and river flow erodes banks. This results in water siltation and also causes the location of the stream or river to meander (lateral migration of the channel). If the migration is sufficient, it can undermine structures or roadways and cause damage or collapse. These natural processes can be accelerated or initiated by inappropriate or poorly designed/constructed improvements.

The potential for natural and accelerated erosion damage exists at many locations throughout the County. This potential is also common to most of the Bay Area. This potential is due to the large total area occupied by hill and ridge systems in the County relative to gently sloping valley areas. The potential for increasing amounts of accelerated erosion exists due to such activities as continued hillside development, including vineyards and other types of land modification.

If the potential for accelerated erosion is recognized in the project planning process, it can be greatly reduced by the design and installation of adequate erosion control facilities. Alternatively, areas identified as environmentally sensitive or excessively prone to erosion can be precluded from development or greatly scaled back in terms of the amount or type of development. Where erosive soils should be anticipated can be found by referring to the earlier described SSURGO database or the equivalent hard copy U.S. Soil Conservation report by Lamber and Kashiwagi (1978). The soil database contains a list of the soil units that have the potential for accelerated erosion. Referral to GIS-based and hard copy maps of landslides and surficial deposits can also assist in identifying erosion prone areas. The actual potential for such erosion should be confirmed by site-specific, follow-up investigation.

EXPANSIVE SOILS

Certain clay-rich soils can cause considerable damage to structures, streets, and roads as they shrink and swell in response to seasonal changes in their moisture content. Such soils are referred to as *expansive*. In late summer, expansive soil shrinks and cracks (up to 1 to 4 inches wide) as the soil dries and hardens. In the wet season, swelling of the clay closes the cracks, and the soil then is plastic and weak. The forces exerted during expansion and contraction are sufficient to heave and distort buildings and to crack shallow foundations and pavements.

Expansive soils exist at a number of locations in the County. Such conditions are typical of much of the Bay Area. The SSURGO database or the equivalent hard copy report by the U.S. Soil Conservation Lamber and Kashiwagi (1978) are good sources that indicate where such soils should be anticipated.

If expansive soils are initially anticipated through map review, their actual presence or absence should be determined prior to construction by site-specific geotechnical investigation. When this is done, special engineering methods can be used to reduce the stresses on buildings and utility lines. When expansive soils occur on a hill slope, they undergo the slow seasonal down slope movement known as *soil creep*. This down slope process adds to the potential for these soils to damage improvements.

In the event of a large earthquake, the planning area could locally experience some or all of the above-listed ground failures. Such failures can cause damage to structures, breaking of underground utilities, embankment failures, differential settlement of structures, cracking in paved areas, and rising of buoyant buried facilities relative to ground level, such as empty or partially empty storage tanks. The potential for highly damaging failures of this type within the planning area ranges from moderate to low in the unconsolidated deposits of colluvium, alluvium, and marsh/bay mud (hill-front, valley, and near-bay front areas, respectively) to remote in areas underlain by bedrock (primarily hill-slopes). Failure potential is moderate in undocumented fill areas that are or might be subject to development at some future time. Such fills are believed to be primarily present over bay mud and in existing landfill areas (the same areas as those identified in the Modified Mercalli Scale.

GEOLOGIC HAZARDS OF COUNTY SUBREGIONS

Geologic hazards of the BDR study area have been discussed in earlier parts of this chapter. The following provides a summary of the types of hazards particular to the subregions and indicates the order of their importance. Seismic ground shaking will affect all the subregions, but not uniformly.

NAPA VALLEY

Landsliding, amplified seismic ground shaking and related effects, and subsidence are identified as the principal geologic hazards of the Napa Valley subregion. Erosion and expansive soils are significant on a more localized basis. Landslides are non-uniformly present on slopes to either side of the Napa Valley, including large zones of sliding. Most amplified ground shaking is expected in the Napa Valley from the City of Napa southward. Subsidence hazards are primarily located in the larger areas of

Erosion is the general process by which materials are loosened, dissolved, or worn away. There are many natural and human-related causes of erosion. The process of in-stream channel erosion, as shown in this image, includes bank slumping and shearing, channel bed incision, and channel widening.

marshlands located in the southern part of the subregion associated with fault rupture on the West Napa fault.

Interior Valleys

Landsliding is the greatest hazard due to the many very large, continuous zones of massive landslides present throughout the length of the interior valleys subregion. Large areas of expansive soils/rock are suspected due to the presence continuous serpentinite bodies and shales associated with the Great Valley sequence rocks. Erosion hazard are expected to be locally high. Some amplified ground shaking and related effects may occur in the relatively small valleys of the subregion. Earthquake shaking could reactivate some of the large landslide zones. In the interior valley areas most of these hazards are associated with rupture along the Green Valley fault.

Berryessa/Knoxville Area

The type and degree of geologic hazards of the Berryessa/Knoxville subregion are expected to be similar to that of the interior valleys subregion. There are however, fewer large zones of landsliding present, and the risk of massive failures of this sort is lower. Because the areal extent of serpentinite is greater, there is probably increased potential for expansive soils/bedrock. The potential for seiche occurrence in Lake Berryessa has apparently not been evaluated and is beyond the scope of the Baseline Report. In the Berryessa/Knoxville area most of these hazards are associated with rupture along the Hunting Creek fault.

Certain clay-rich soils can cause considerable damage to structures, streets, and roads as they shrink and swell in response to seasonal changes in their moisture content. Such soils are referred to as *expansive*.

Conclusions and Report Update Recommendations

Countywide

There are several regulations, acts, codes, and ordinances, from the federal to the county level, that require geologic or geotechnical study or investigation, and for which the County is required to provide some form of response, regulation or review. These various laws are for the purposes of protecting public safety and welfare, and environmental protection.

The physiography of Napa County is predominantly rugged and consists of a small number of long, linear, northwest-trending, major and lesser valleys, separated by broad, steep, rugged ridge and hill systems of moderate relief that have been deeply incised by their drainage systems. The present geomorphic setting is a result of complex interactions of tectonics that took place over millions of years. The result is a region of unique and varied beauty.

The physiography influences the local climate, the development of soils, and the existence and location of geologic hazards such as landsliding. The combination of physiography, bedrock types, soils, and climate (and micro-climates) has resulted in a County rich in resources and the benefits they offer, including the production of premium wine grapes and other agricultural products for which the County is famous.

The bedrock types of the County are varied and are made up of two principal components: (1) an older set of rocks composed of amalgamated, highly deformed terrenes that have been displaced (at least in part) via plate tectonics, from hundreds to thousands of kilometers from their position of origin and (2) a younger, less deformed set of rocks that overlie the amalgamated terrains and which are roughly in their original position.

The structural geology of Napa County, like all of the Coast Ranges, is complex and continues to evolve due to broadly regional forces acting along the North American and East Pacific plate boundary. However, the overall picture is consistent with the younger Pliocene-Quaternary (about the last 5 million years) compressional deformation superimposed on earlier extensional deformation.

The continued structural evolution of the County occurs as a number of ongoing but deceptively slow, subtle geologic processes. The results of these processes are best identified over long time periods known as *geologic time*. An episodic and more abrupt geologic process that is more obvious to the layperson is the presence of active faulting, which occasionally results in felt and sometimes damaging earthquakes. The most recent damaging earthquake was the Napa Earthquake of 2000.

Important among these younger structures in Napa County, are three active faults: the West Napa fault, the northernmost few miles of the Green Valley fault, and the Hunting Creek fault. While not zoned by the State of California, this chapter also considers the Cordelia fault to be active.

A number of geologic and seismic hazards exist in Napa County.

- Landsliding.
- Structural damage directly caused by earthquake shaking or from ground failures resulting from the shaking.
- Surface fault rupture caused by movement along a fault trace as a result of an earthquake.
- Seismic and non-seismic subsidence and settlement.
- Expansive soils.
- Accelerated erosion.
- Water wave damage by seiche and tsunami.

The losses from these various hazards can be greatly reduced by diligent adherence to the laws, regulations and codes described in this chapter. On a year-in and year-out basis, landsliding is potentially the most damaging hazard. On a longer time frame (decades), greater damage is projected to result from earthquake ground shaking.

It is currently estimated that there is a there is a 67% chance for a magnitude 6.7 or larger earthquake to occur in the Bay Area by the year 2032. Depending on the proximity to the County and actual magnitude of the earthquake, shaking damage in the County could range from nominal to high. Older, unreinforced masonry buildings and other buildings constructed before 1930 that have not been seismically retrofitted are most subject to structural failure/collapse. Worst-case earthquake scenarios indicate that intense ground shaking generated by a very large earthquake (greater than 6.7) on one of the Bay Areas major faults in relatively close proximity to the County could cause loss (structural damage, injury and social/economic dislocation) within the County totaling more than $300 million. As the County becomes more populated and developed, this figure will increase. Smaller or more distant earthquakes could cause loss in the millions to tens of millions of dollars.

The three known active faults listed above have the potential to cause surface fault rupture within the County. Damage from surface fault rupture is relatively low compared to the much wider effects of earthquake ground shaking.

The potential for damage caused by seiches and tsunamis is judged to be low, but further study is necessary for confirmation.

CONCLUSIONS SPECIFIC TO COUNTY SUBREGIONS

NAPA VALLEY

The physiography of the Napa Valley subregion has dominant northwest-southeast trend. Major streams are generally well incised with deep canyons. The Napa Valley is the largest and most significant valley of the subregions. Napa Valley is a major groundwater resource.

Near the south end of Napa Valley the alluvium may be relatively quite thick, possibly as much as about 1.2 miles (2 km). The mouth of Napa Valley and southward to the County line in the subregion contains major marshlands.

Soils of the Napa Valley and those of localized side slopes to either side are a major resource for agriculture.

Landsliding, amplified seismic ground shaking and related effects, and subsidence are identified as the principal geologic hazards of the subregion. Landsliding hazards are distributed non-uniformly throughout the hillside areas of the subregion. There is potential for surface ground rupture along the West Napa fault, with attendant ground shaking. The potential for amplified ground shaking damage appears greatest in the vicinity of the City of Napa and southward. The potential for subsidence is greatest in the marshlands from just south of the City of Napa to the southern boundary of the subregion. On a more localized basis, erosion and expansive soils are significant hazards within the subregion.

INTERIOR VALLEYS

The interior valleys subregion is predominantly hilly with major ridge systems that have a dominant northwest-southeast trend. Major streams are generally well incised with deep canyons. There are several small valleys located from north to south within the subregion.

There are numerous, very large zones of landsliding present within the subregion. Landsliding is the principal geologic hazard within the subregion. Due to their relatively large numbers, earthquake shaking could reactivate some of the large zones of landsliding. Large areas of expansive soils/bedrock are expected to be in existence due to the presence of continuous bodies of serpentinite and shale/mudstone. Erosion hazards are expected to be locally high.

Some amplified ground shaking and related effects may occur in the valley areas. The active Green Valley fault is a localized, potential source for surface ground rupture in the southernmost part of the subregion. The Green Valley fault may be undergoing fault creep. The nearby, active Cordelia fault presents less potential for surface ground rupture than the Green Valley fault.

BERRYESSA/KNOXVILLE AREA

The physiography of this Berryessa/Knoxville subregion is similar to that of the interior valleys subregion. The principal physiographic feature is the former Berryessa Valley that now contains the reservoir of Lake Berryessa. The high, steep, northwest-southeast Blue Ridge that borders the County on the east is a prominent physiographic feature.

Landslide development is locally high, but not as high as in the interior valleys subregion. The type of geologic hazards is similar to that of the interior valleys subregion. The active Hunting Creek fault presents potential for ground surface rupture. The potential for seiche occurrence in Lake Berryessa is not known and its evaluation is beyond the scope of this chapter.

UPDATE RECOMMENDATIONS COUNTYWIDE

The County should continue to provide regulation, review, and other oversight duties of the various acts, codes and ordinances that contain geologic and geotechnical provisions. Some of the more pertinent of these have been described in this chapter.

A formalized geologic peer review process should be developed by the County and implemented for large, complex projects. In particular, peer review should be done for those projects with significant, recognized or potential geologic or seismic hazards.

Part of the peer review development process should include identifying a small number highly qualified geologic and geotechnical consultants experienced in the review process, and developing criteria for avoiding conflict of interest.

If the County decides peer review is required, the reviewer should be selected and should commence to communicate and work with the applicant's consultants. The intent is to provide proactive rather than reactive peer review, resulting in a fair, complete, and expeditious review product.

The various GIS-based and hard copy maps that have been compiled and reviewed for use in the geologic data base should be routinely updated by the County or their consultants. The update search should be formalized and done yearly.

The USGS maps of Graymer et al. 2002 and 2005 (in press) should be referred to as the most recent geologic maps that provide countywide coverage. However, there are also recent (2004) geologic maps that provide partial coverage of the County that is of at least equal detail. These are of 1:24,000 scale maps of the California Geological Survey and are presently only available for the southernmost part of the County. These maps should also be referred to for these southern areas.

Subsidence in all areas of mud levees needs to be evaluated.

A workshop should be conducted by geologists for County personnel responsible for using the many maps and related documents comprising the BDR. The purpose would be to clarify the proper use of BDR by developing use methodology.

When the forthcoming maps for the Seismic Hazards Mapping Program (Seismic Hazards Mapping Act of 1990) become available, the County will be required to comply with the provisions of the Act. The basic responsibilities the County will have can be found in publications (electronic and hard copy) by the California Geological Survey.

Generally, landsliding is the principal geologic hazard in the County. This dictates the need for careful review and investigation of landslide hazards as they relate to public and private improvements.

In the longer term (years to decades), the greatest damage potential will be from earthquake ground shaking.

Generally, landsliding is the principal geologic hazard in the County. This dictates the need for careful review and investigation of landslide hazards as they relate to public and private improvements.

In the longer term (years to decades), the greatest damage potential will be from earthquake ground shaking.

The County should require or continue to require the seismic retrofitting of older, unreinforced masonry buildings used or proposed for use in any form of human occupancy. This should include other older structures built before 1930.

The County should consider further study or investigation for tsunami and seiche potential.

UPDATE RECOMMENDATIONS SUBREGION

NAPA VALLEY

The soils of the Napa Valley subregion are an important resource, particularly the agricultural soils, and they should be protected from erosion. This includes continued implementation of existing erosion control ordinances and regulations for agriculture and facilities development.

Continued research and related field investigation should be done on the surface ground rupture and seismic shaking potential of the West Napa fault.

The potential for amplified ground shaking should be recognized in the southern part of this subregion and be responded to in the investigation and design for new facilities, especially critical facilities and larger multi-story facilities.

Given the greater relative number and long history of communities in the subregion, requirements for seismic retrofitting of older, unreinforced masonry buildings for human occupation should be adopted, or if this requirement already exists, its enforcement should continue. This recommendation should also apply to older structures built before 1930.

Detailed geologic and geotechnical investigation should be required for areas with recognized geologic hazards. These hazards have been discussed in the subsection on subregion hazards. Particular care should be exercised in areas of recognized large landsliding, areas susceptible to subsidence and surface fault rupture. It may be found advisable to limit development in the zones of massive landsliding due to their size and great economic and technical challenges associated with their mitigation.

INTERIOR VALLEYS

The soils of the interior valleys subregion are an important resource, including more localized areas of agricultural soils, and they should be protected from erosion. This includes continued implementation of existing erosion control ordinances and regulations for agriculture and facilities development.

With respect to future development, especially for large or critical facilities, the large number of zones of massive landsliding prevalent within the subregion should be very carefully evaluated for the risk of future movement. It may be found advisable to limit development in these landslide areas due to their size and great economic and technical challenges associated with their mitigation.

Continued research and related field investigation should be done on the surface ground rupture and seismic shaking potential of the Green Valley and Cordelia faults.

While not zoned as active by the State of California, it is recommended that investigation similar to that required by the Alquist-Priolo Earthquake Act be required for the Cordelia fault.

Berryessa/Knoxville Area

The recommendations for this Berryessa/Knoxville subregion are similar to those of the interior valleys.

Continued research and related field investigation should be done on the surface ground rupture and seismic shaking potential of the Hunting Creek fault.

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