Geology of Los Angeles, California, United States of America

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FOREWORD

There is much about Los Angeles that has affected the profession of engineering geology, perhaps more than any other city. The need for infrastructure was evident soon after its founding, given its agreeable climate coupled with the shortage of water; a population boom, with its consequent transportation requirements; and recurring large earthquakes amid the rumble of smaller, stress-relieving tremors. The Los Angeles area is a popular destination, and the historic development of the city recounts a story that highlights the fact that technical expertise is constantly needed to meet the challenges of urban development in an environmentally changing and tectonically active area.

Geologic surprises typically affect the daily lives of Los Angeles residents. Little was known about the geologic history of the area when the University of California at Los Angeles (UCLA) opened its campus in 1928. Engineering geologist Rollin Eckis pieced together the geologic framework of a basin and basement-complex for one of UCLA's first Ph.D. dissertations in 1932. Stratigraphers, structural geologists, and paleontologists became entranced with the sedimentary basin fill, all 30,000 ft (9,100 m) of it, and their findings were used by petroleum geologists to discover and produce huge volumes of oil. Further studies confirmed that the Los Angeles area is located over a deep sedimentary basin with hills composed of folded Miocene and Pliocene sedimentary rocks. The basin is rimmed by the crystalline rocks of the Santa Monica Mountains and the San Gabriel Mountains.

The nearby San Andreas fault and other active faults are a constant reminder of how the power of nature can affect the works of man. Each year, and with each moderate earthquake, we learn more about geologic processes and how they affect urban life in Los Angeles. Newly recognized blind thrust faults provide new challenges to our understanding of the neotectonic evolution of the Los Angeles basin. Although we know more about earthquakes and seismic effects than ever before, most Los Angeles residents still fear "the Big One," an earthquake larger than the 1933, 1971, or 1994 events. We trust that the structural engineers have designed high-rise buildings that will ride through the "Big One" with minimal loss of life and property damage.

Engineering geology as we know it today grew from adolescence to maturity in Los Angeles, from 1950 through the advent of the environmental response era. Post–World War II hillside development and the sustained rainfall in the spring of 1952 led to major slope failures and damage to thousands of homes. As a result of these occurrences, engineering geologists were given new status and responsibilities by the city and county. Today, engineering geology and geotechnical engineering are thoroughly integrated in the Los Angeles area. High-rise and deep-basement architecture are now used as buildings are increasingly taller and basements are deeper to accommodate the ever-present automobile and its occupants. For example, foundation engineering innovations were required to design and construct these buildings, and the development of the tie-back anchor made temporary construction-retention of basement cuts possible in the weak rock that is characteristic of the region.

Los Angeles has suffered numerous environmental setbacks, but it routinely responds with aggressive regulations to mitigate the impact of these events. Air pollution control and regulation were born in Los Angeles, and much of the present hazardous waste management and remediation process grew from examples within and around this city. Los Angeles enters the 21st century with a strong effort to replace its once world-class public transportation network, killed by the post–World War II romance with the automobile, with a new Metro rail system. The city has the heart to meet and survive its urban pressures and environmental constraints, and engineering geology will play an integral role in the development of solutions to problems as they arise.

The Geology of Los Angeles has unique appeal to me as the series editor. Two of the 1781 town-founding, leather-jacketed soldiers of Spain's army were my grandfathers (seven times removed). This is my city of birth and of my early geology education (at UCLA). I am even more enthused than usual about the geologic impacts on this great center of commerce and terminus of America's historic 1847 expansion to the Pacific Ocean.

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Key Terms: ***Geology, Los Angeles, Port of Los Angeles, Pier 400, Oil and Gas Deposits of Los Angeles, La Brea Tar Pits, Asphaltum, Blind Thrust Fault, Earthquake, Landslide, Liquefaction, Floods, Methane Hazard Mitigation, Hazardous Waste, Solid Waste, Seismic Retrofit***

ABSTRACT

The City of Los Angeles is located on the east edge of the Pacific Plate, within the wide transform boundary zone with the North American Plate and near the big bend in the San Andreas fault. Situated just south of this restraining bend, the city is within the Western Transverse Ranges which are undergoing transpressional uplift along active thrust faults. The city has experienced and mitigated the effects of earthquakes on the San Andreas and local faults, floods, fires, droughts, landslides and debris flows.

The natural resources of Los Angeles include vast oil and gas deposits and the La Brea Tar Pits, an important Pleistocene fossil locality. Urbanization over and tunneling through both abandoned and active oil and gas fields have encountered hazardous conditions. Seepage of hazardous gasses has caused explosions within the city and as a result Los Angeles established methane mitigation requirements for construction in methane hazard zones.

Los Angeles has been aggressive in addressing issues of air, soil and water pollution control. A master plan for solid waste management has been implemented, regulating the siting and operation of landfills. Local sources of drinking water are inadequate to support the population. Importation of drinking water via three aqueducts has fueled the city's growth and agricultural prosperity.

The practice of engineering and environmental geology has been greatly influenced by laws, practices and policies that were started in or influenced by the City of Los Angeles. These include the 1915 Los Angeles Flood Control Act, 1929 California Dam Safety Act, 1958 Engineering Geologists Qualifications Board, 1933 Field Act, 1972 Alquist-Priolo Act, 1975 Seismic Safety Act, 1990 Hazards Mapping Act, and modifications to the Uniform Building Code for seismic safety.

INTRODUCTION

Geographic Setting

Los Angeles is located in coastal southern California (Figure 1) and is the second largest city in the United States, with a population of just under four million people. It is the industrial, financial, and trade center of the western United States and is the largest manufacturing center in the country. It ranks first in the production of aircraft- and space-related items. The city's film and television industry are world renowned. The Port of Los Angeles is the nation's busiest port. The city covers 469 square mi (1,215 km^2), being split in the east–west direction by the Santa Monica Mountains, separating the San Fernando Valley from the Los Angeles basin, which extends south to the Port of Los Angeles (Figure 1).

Not surprisingly, many communities within the City of Los Angeles are thought of as separate cities; these include Hollywood, Venice, Century City, and Universal City. Larger communities within the City of Los Angeles south of the Santa Monica Mountains include Bel Air, Boyle Heights, Brentwood, Century City, El Sereno, the Fairfax District, Hollywood, Highland Park, Los Feliz, Marina del Rey, Pacific Palisades, San Pedro, Sawtelle, Silver Lake, Venice, Watts, Westchester, Westwood, and Wilmington. Los Angeles communities in the San Fernando Valley

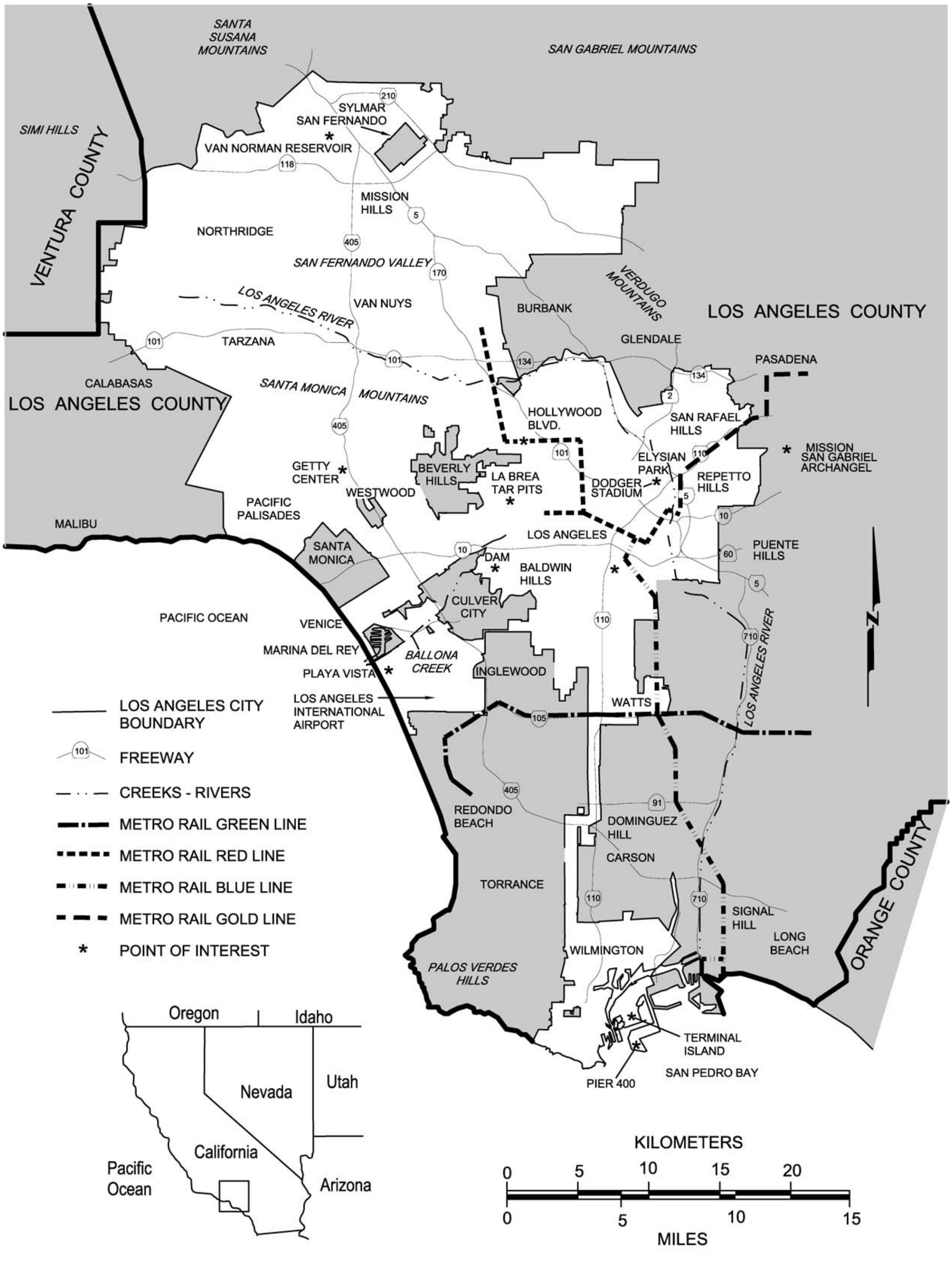


Figure 1. Location map of Los Angeles, CA, showing physical features and points of interest discussed in the text.

include Canoga Park, Chatsworth, Encino, Granada Hills, North Hollywood, Northridge, Pacoima, Reseda, Sherman Oaks, Studio City, Sunland, Sylmar, Tarzana, Tujunga, Universal City, Van Nuys, and Woodland Hills.

Cities sharing borders with Los Angeles include Alhambra, Beverly Hills, Burbank, Calabasas, Carson, Culver City, El Segundo, Gardena, Glendale, Inglewood, Long Beach, Pasadena, Rancho Palos Verdes, San Fernando, Santa Monica, Torrance, and West Hollywood. Many surrounding communities appear so similar that it is often difficult to tell where one city ends and another begins.

Before 1913, Los Angeles depended on the Los Angeles River and local wells for its water supply. On November 5, 1913, the Los Angeles Aqueduct opened, bringing water to the city from Owens Valley, a distance of 233 mi (375 km). Although it continues to be considered controversial, this act of water acquisition was the single most important step toward making Los Angeles into the world-class city it is today. The plentiful water allowed both agriculture and manufacturing to thrive and to support the growth in population that followed.

Climate

The city's latitude and geographic location between the mountains and the sea makes for a temperate "Mediterranean" climate. The average daily temperature downtown in January is 55° F or 13°C, and in July the average temperature is 73°F (23°C). Los Angeles is one of the few cities in the world where one can snow ski in the mountains in the morning and surf ocean waves in the afternoon. The winters are mild, with a rainy season extending from December through March. During the summer the humidity is usually so low that discomfort from the heat is rare. The area is semiarid, with an average, though highly variable, annual rainfall of 15 in. (38 cm). In general, the coastal area receives less rainfall than do the foothill areas adjacent to the mountains. The geographic setting of the Los Angeles basin contributes to its historic and ongoing air pollution (smog) problem. The air becomes trapped against the mountains and a natural inversion layer forms. The Native Americans called the Los Angeles basin the "valley of smoke" because of the haze that filled the air. Today the inversion layer traps the exhaust from motor vehicles, creating smog; however, "smog alerts" have been steadily decreasing in recent years as a result of environmental regulation.

The cycle of hot, dry summers followed by wet winters has led to the growth of drought-resistant native vegetation. The brush-covered hillsides become tinder dry during the summers, creating a significant fire hazard. One of the worst Los Angeles brush fires occurred in 1961, when 496 homes in the Bel Air area were destroyed. Brush fires are difficult to control, especially if "Santa Ana" wind conditions are present. Santa Ana winds are hot, dry winds that blow from the inland desert toward the coast. When sustained winter rains saturate the denuded hillsides after a brush fire, landslides and debris flows are often the result.

Figure 2. Mission San Gabriel Archangel, built in 1771.

History and Founding

The first recorded local American Indian village was Yang-na, along the Los Angeles River. Juan Rodriguez Cabrillo, a Portuguese explorer in the service of Spain, documented the village on a map in 1542. In 1769 a Spanish army captain, Gaspar de Portolá, described the Yang-na village as "a delightful place" and renamed the area Nuestra Señora la Reina de Los Angeles de Porciúncula (Our Lady the Queen of the Angels of Porciúncula; Brunn and Williams, 1983).

The area was chosen as the site for two missions: the Mission San Gabriel Archangel (Figure 2), built in 1771, and the Mission San Fernando Rey, built in 1797. Franciscan monks eventually established 21 missions along the California coast. The missions were placed along trade routes and served to convert the native Indians to Christianity and to provide safe resting and trading posts. The Mission San Gabriel Archangel was originally located along the San Gabriel River, but floods ruined its crops so it was moved approximately 9 mi east to its present site in the city of San Gabriel (Brunn and Williams, 1983).

After the missions were established, Felipe de Neve, the Spanish governor of California, decided to encourage settlement of the area. He offered free land, tools, and animals to anyone who would come and settle. On September 4, 1781, 11 men, 11 women, and 22 children founded the Pueblo de Los Angeles, or the City of the Angels, on high ground along the Rio de Los Angeles (Dash, 1976). The group consisted of Indians, Spaniards, and people of mixed white, black, and Indian ancestry. In 1846 war broke out between the United States and Mexico, and by 1848 California belonged to the United States. On April 4, 1850, Los Angeles was incorporated as a city with a population of 1,610. In 1876 the Southern Pacific Railroad was completed between Los Angeles and San Francisco, providing Los Angeles with a link to the rest of the United States, through San Francisco. By 1885 there were direct railroads between the Midwest and Los Angeles. This allowed Los Angeles to market oranges and other farm products to the Midwest.

By 1890 the population had soared to more than 50,000, and in that year Orange County was created from southeastern Los Angeles County. In the 1890s, rich deposits of petroleum were discovered. The oil industry grew, but so did urbanization, which encroached on or covered many abandoned oil fields. In 1899 Los Angeles began building a huge man-made harbor at San Pedro. The harbor was completed in 1914 and Los Angeles quickly became a major seaport. The 9-mile (15-km)–long breakwater, constructed of huge granite rip-rap barged 26 mi (42 km) from a quarry on Santa Catalina Island, still protects the combined harbors of Los Angeles and Long Beach. The Port of Los Angeles is the largest cargo port in the nation and one of the nation's chief fishing ports.

In the 1920s tourism increased and the motion picture industry flourished. At the same time the city also became a center for aircraft manufacturing, with the presence of Douglas, Hughes, and Lockheed. By 1945 the population of Los Angeles had reached one and a half million people. Rapid growth, especially in the new bedroom suburbs, followed the end of World War II as many service men and women chose Los Angeles as a place to settle and raise their families.

REGIONAL GEOLOGY

Geologic Setting

Los Angeles is the only city in the United States that is divided by a mountain range, the Santa Monica Mountains (Figure 1). The city, which is located at the convergence of two major physiographic provinces, the Transverse Ranges and the Peninsular Ranges, includes rugged mountains, hills, valleys, and alluvial plains.

The east-west–trending Transverse Ranges are anomalous to the prevailing northwest structural grain of California. Starting about six million years (Ma) ago, the Transverse Ranges were uplifted along east-west–trending thrust faults and folds (Crowell, 1976; Wright, 1991; and Ingersoll and Rumelhart, 1999). The city is bisected by the southernmost of the Transverse Ranges, the Santa Monica Mountains. The dominant structural element in the area is the north-dipping Santa Monica–Hollywood–Raymond fault system, the southern boundary of the Transverse Ranges.

The Los Angeles basin is part of the northern Peninsular Ranges, which extend southeastward into Baja California, Mexico. These ranges are composed of mildly metamorphosed sedimentary and volcanic rocks of Jurassic age that have been intruded by mid-Cretaceous plutonic rocks of the southern California batholith and rimmed by Cenozoic sedimentary rocks (Gastil et al., 1981; Schoellhamer et al., 1981). The Los Angeles basin is also part of the onshore portion of the California continental borderland, characterized by northwest-trending offshore ridges and basins, formed primarily during early and middle Miocene time (Legg, 1991; Wright, 1991; and Crouch and Suppe, 1993). Major northwest-trending strike–slip faults such as the Whittier, Newport–Inglewood, and Palos Verdes faults dominate the basin. The thickness of the dominantly Neogene sedimentary fill in the central trough of the Los Angeles basin, a structural low between the Whittier and Newport–Inglewood faults, is estimated to be about 30,000 ft (9,100 m) (Yerkes et al., 1965).

Tectonic Setting

Los Angeles is located at the intersection of two major active fault systems, the northwest-trending, right-lateral strike–slip San Andreas–type faults and the east–west faults, mostly left-lateral or thrust faults that bound the Transverse Ranges (Figure 3). Situated on the eastern edge of the Pacific plate, and within the active transform boundary zone with the North American plate, Los Angeles is in the middle of a wide zone of deformation (Yerkes, 1985). The present plate margin is delineated by the San Andreas fault, 35 mi (56 km) northeast of downtown Los Angeles. The Pacific plate is moving northwest at an average rate of 48–52 mm/yr relative to the rest of North America east of the San Andreas fault (DeMets et al., 1990; Atwater and Stock, 1998; and DeMets and Dixon, 1999).

Although Precambrian igneous and metamorphic rocks are found in the San Gabriel and Verdugo Mountains north and east of Los Angeles, the present tectonic regime is related to plate interactions that began in the Mesozoic. The geologic and tectonic history of the area since Mesozoic time can be divided

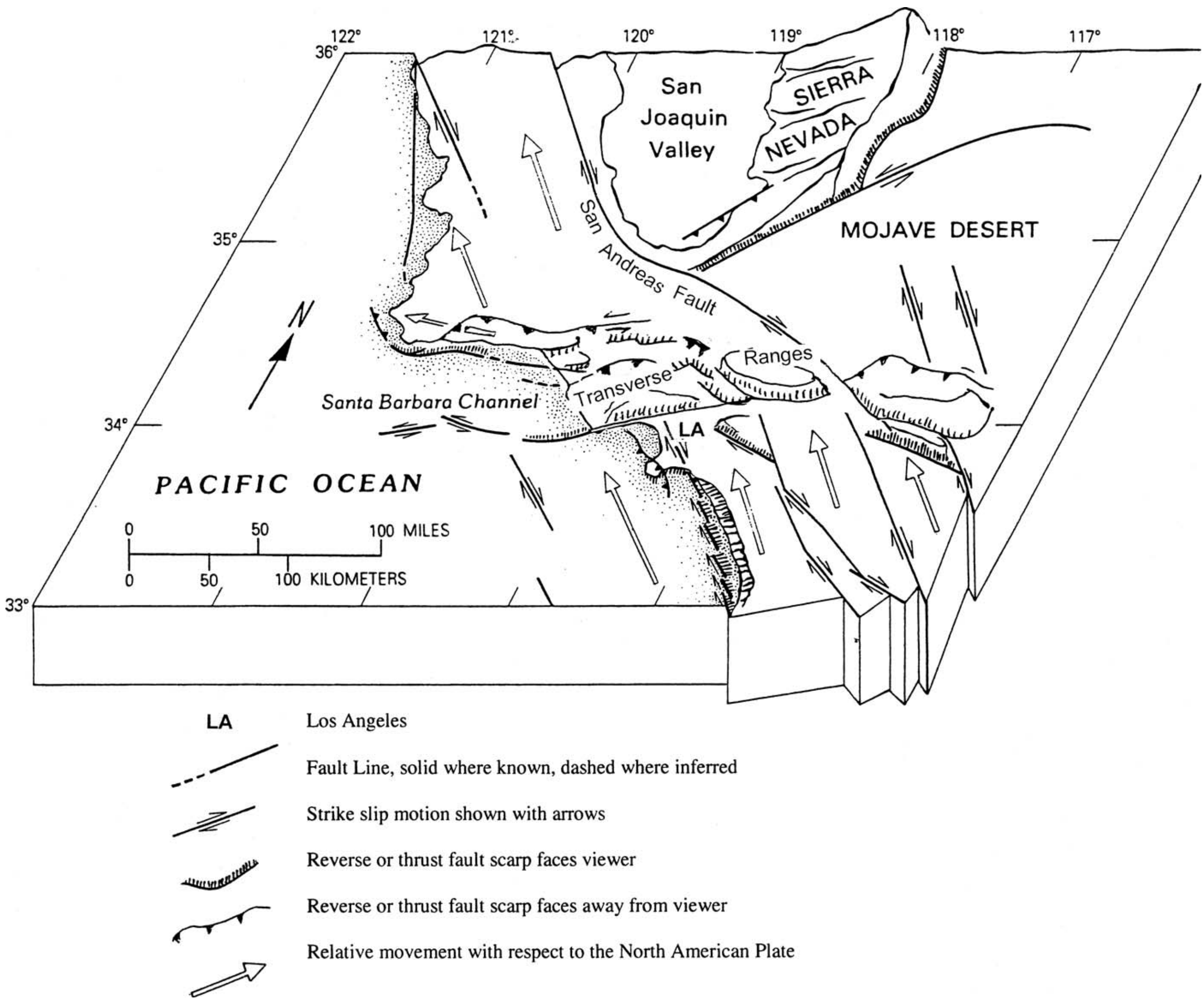


Figure 3. Schematic diagram of relative motions of crustal blocks around Los Angeles. Blocks in the foreground move northwest with the Pacific plate. The Transverse Ranges are shown bounded by reverse and thrust faults with prominent scarps (after Yerkes, 1985).

into three phases. The first phase began in the Mesozoic (ca. 150–145 Ma) with the formation of a continental margin subduction zone along the western boundary of the North American plate. During this phase various Cretaceous–Paleogene rocks were deposited or emplaced within the magmatic arc–trench system, either as sediments (forearc basin), granitic rocks (magmatic arc), or blueschist and greenschist metamorphic rocks (accretionary prism) (Dickinson, 1981; Wright, 1991; Crouch and Suppe, 1993; and Ingersoll, 2001).

The second phase began in the early Miocene (ca. 20–18 Ma), when the ongoing collision of the East Pacific Rise with the subduction zone reached the Los Angeles area, changing the local plate boundary from subduction and oblique convergence to transform (lateral) motion (Atwater, 1989; Atwater and Stock, 1998). This change in plate margin tectonics formed several subparallel right-slip faults within and west of the Los Angeles area, breaking crustal blocks off the edge of the North American plate and adding them to the Pacific plate in a process called microplate capture (Nicholson et al., 1994; Dickinson, 1996; and Atwater and Stock, 1998). Large-scale crustal block rotation and rifting, culminating in the more than 90° clockwise rotation of the western Transverse Ranges, characterized the transrotational and transtensional tectonic development of this phase (Luyendyk, 1991; Wright, 1991; Crouch and Suppe, 1993; Nicholson et al., 1994; Dickinson, 1996; Fritsche, 1998; and Ingersoll and Rumelhart, 1999). The Miocene basin and range extensional structures (including low-angle normal or detachment faults) of the continental borderland and the Los Angeles basin were formed at this time in the wake of the clockwise-rotating blocks of the western Transverse Ranges (Legg, 1991; Crouch and Suppe, 1993; Dickinson, 1996; and Ingersoll and Rumelhart, 1999). Most sediments filling the Los Angeles basin were deposited during this period of tectonic subsidence and transrotation of the western Transverse Ranges (Mayer, 1991; Yeats and Beall, 1991; Rumelhart and Ingersoll, 1997; and Ingersoll, 2001).

The transition to phase three began in the Miocene–Pliocene time (ca. 6–4 Ma) with the opening of the Gulf of California and the eastward relocation of the Pacific–North American plate boundary in southern California to its present configuration as the system of dominantly right-slip faults of the San Andreas transform system (Wright, 1991; Powell, 1993; and Ingersoll and Rumelhart, 1999). Near Palm Springs, the San Andreas fault bends to the left (west–northwest) from the otherwise-linear northwest-trending fault trace. This bend results in strain partitioning between the right-slip San Andreas and the north–south compressional stress regime that has produced major uplift and crustal shortening along an east–west trend in southern California, resulting in the Transverse Ranges. Known locally as the Pasadenan deformation (Yerkes et al., 1965; Wright, 1991), this Plio–Pleistocene transpressional deformation apparently reactivated many Miocene detachment faults as low-angle thrusts (Crouch and Suppe, 1993). These thrust systems created most of the modern topographic relief in the Los Angeles area, including the San Gabriel and Santa Monica Mountains and the Elysian Park, Repetto, and Puente Hills. Transpressional strike–slip tectonic stresses are now forming other Los Angeles area topographic features, such as the Palos Verdes, Baldwin, and Dominguez Hills (Figure 1).

Stratigraphy

Beside the granitic and metamorphic basement rocks in the San Gabriel Mountains and a small part of the Santa Monica Mountains, the stratigraphic sequence of the Los Angeles area consists of Upper Cretaceous marine clastic sedimentary rocks; a thick section of Tertiary, mostly marine sedimentary and volcanic rocks; and clastic marine and nonmarine Quaternary deposits (Figures 4 and 5).

Basement Rocks

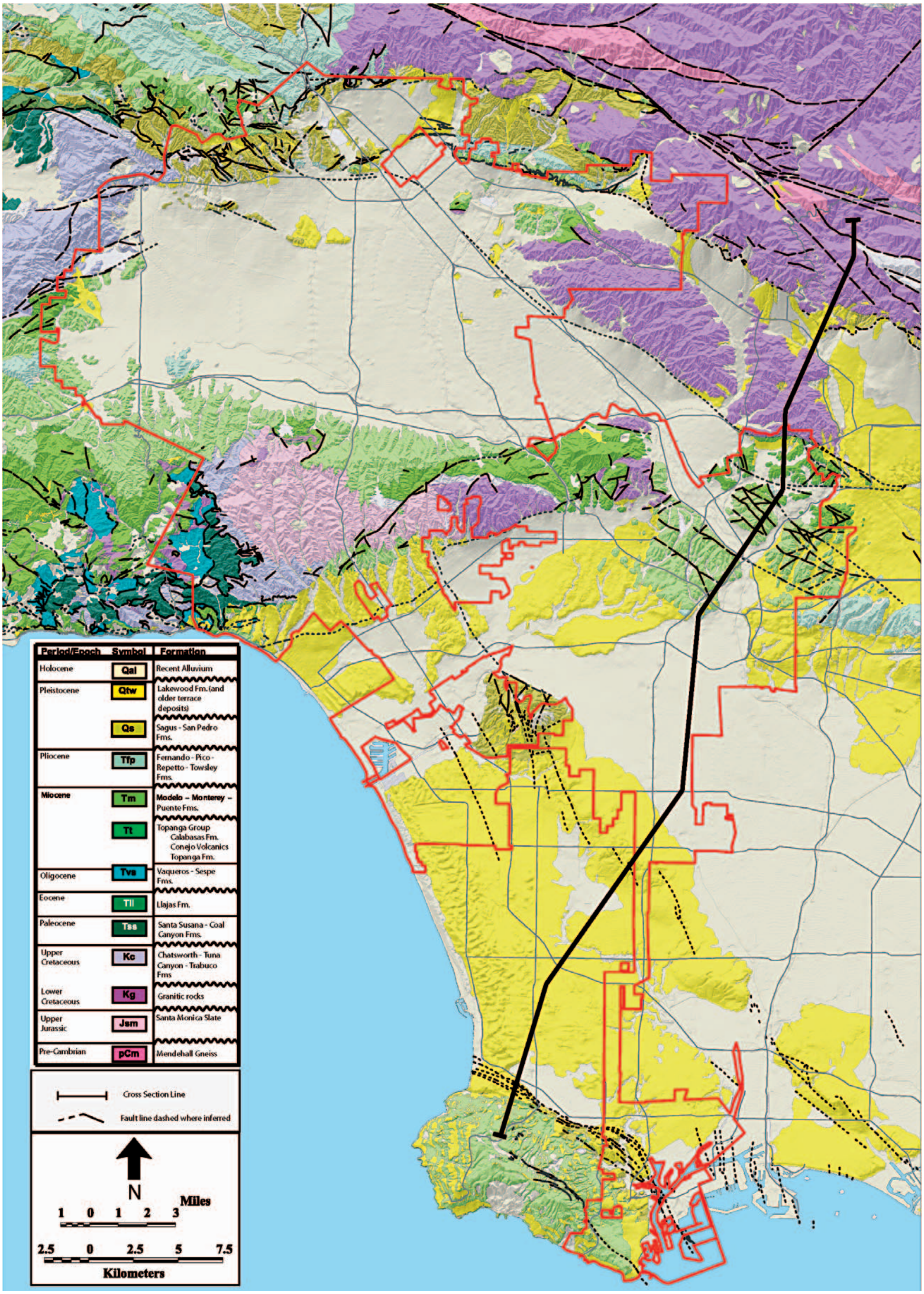
The basement rocks of the Los Angeles area are separated at the Newport–Inglewood fault zone into two distinctly different types on the basis of contrasting lithology and mineralogy. Mesozoic rocks of the Catalina Schist occur southwest of the fault zone, and Precambrian gneiss intruded by Mesozoic granitic rocks crop out to the northeast in the San Gabriel Mountains, San Rafael Hills, and Verdugo Mountains (Yerkes et al., 1965; Lamar, 1970; Dibblee, 1989a; and Wright, 1991).

The Catalina Schist is dominated by blueschist-facies metagraywacke and metavolcanic rocks mixed with lesser amounts of greenschist- and amphibolite-facies rocks that generally correlate with the Franciscan assemblage accretionary prism or subduction complex (Sorensen, 1986; Vedder, 1987; and Sorensen et al., 1991). K-Ar dates indicate that the minimum age of metamorphism (cooling age) for the schist is 90–70 Ma (Suppe and Armstrong, 1972). The Catalina Schist is exposed in the Palos Verdes Hills and on Catalina Island (Woodring et al., 1946). Basement rock exposures in the eastern Santa Monica Mountains, north of the Newport–Inglewood fault zone, reveal slate and schist (Upper Jurassic Santa Monica Slate) intruded by Cretaceous granitic rocks (Hoots, 1931; City of Los Angeles, 1960–1970; Dibblee, 1982, 1991; and Ingersoll, 2001). These distinctive rocks also have been encountered in drill-cores beneath parts of the Los Angeles and San Fernando basins (Wright, 1991; Tsutsumi and Yeats, 1999).

Cretaceous Sedimentary Rocks

The oldest sedimentary rocks in the Los Angeles area are Upper Cretaceous, mostly marine clastic sedimentary rocks of the Calabasas and Trabuco Formations, the unnamed Upper Cretaceous strata of Dibblee (1991), and the Chatsworth Formation in the Simi Hills (Link et al., 1981) (Figure 4). A thin sequence of these strata unconformably overlies basement-complex quartz diorite in the eastern end of the Santa Monica Mountains but thickens to the west in the Santa Monica Mountains and northwest under the San Fernando Valley into the Simi Hills (Dibblee, 1982, 1991). The section in the eastern Santa Monica Mountains is mostly nonmarine, poorly sorted pebble to cobble conglomerate with some reddish sandstone and claystone and is about 1,000 ft (305 m) thick. However, where it thickens to the west–northwest, it is marine pebble to cobble conglomerate, coarse-grained feldspathic sandstone, and argillaceous, sometimes micaceous, siltstone and shale (Yerkes et al., 1965; Yerkes and Campbell, 1979; and Dibblee, 1982). In the Simi Hills, the Chatsworth Formation is over 4,600 ft (1,400 m) thick and is interpreted to be submarine fan turbidites (Link et al., 1981; Tsutsumi and Yeats, 1999).

In the subsurface of the northern Los Angeles basin, Upper Cretaceous sedimentary rocks are


Period/Epoch
Symbol
Formation
Holocene
Qal
Recent Alluvium
Pleistocene
Qtw
Lakewood Fm. (and older terrace deposits)
Qs
Sagus - San Pedro Fms.
Pliocene
Tfp
Fernando - Pico - Repetto - Towsley Fms.
Miocene
Tm
Modelo – Monterey – Puente Fms.
Tt
Topanga Group Calabasas Fm. Conejo Volcanics Topanga Fm.
Oligocene
Tvs
Vaqueros - Sespe Fms.
Eocene
Tll
Llajas Fm.
Paleocene
Tss
Santa Susana - Coal Canyon Fms.
Upper Cretaceous
Kc
Chatsworth - Tuna Canyon - Trabuco Fms
Lower Cretaceous
Kg
Granitic rocks
Upper Jurassic
Jsm
Santa Monica Slate
Pre-Cambrian
pCm
Mendehall Gneiss
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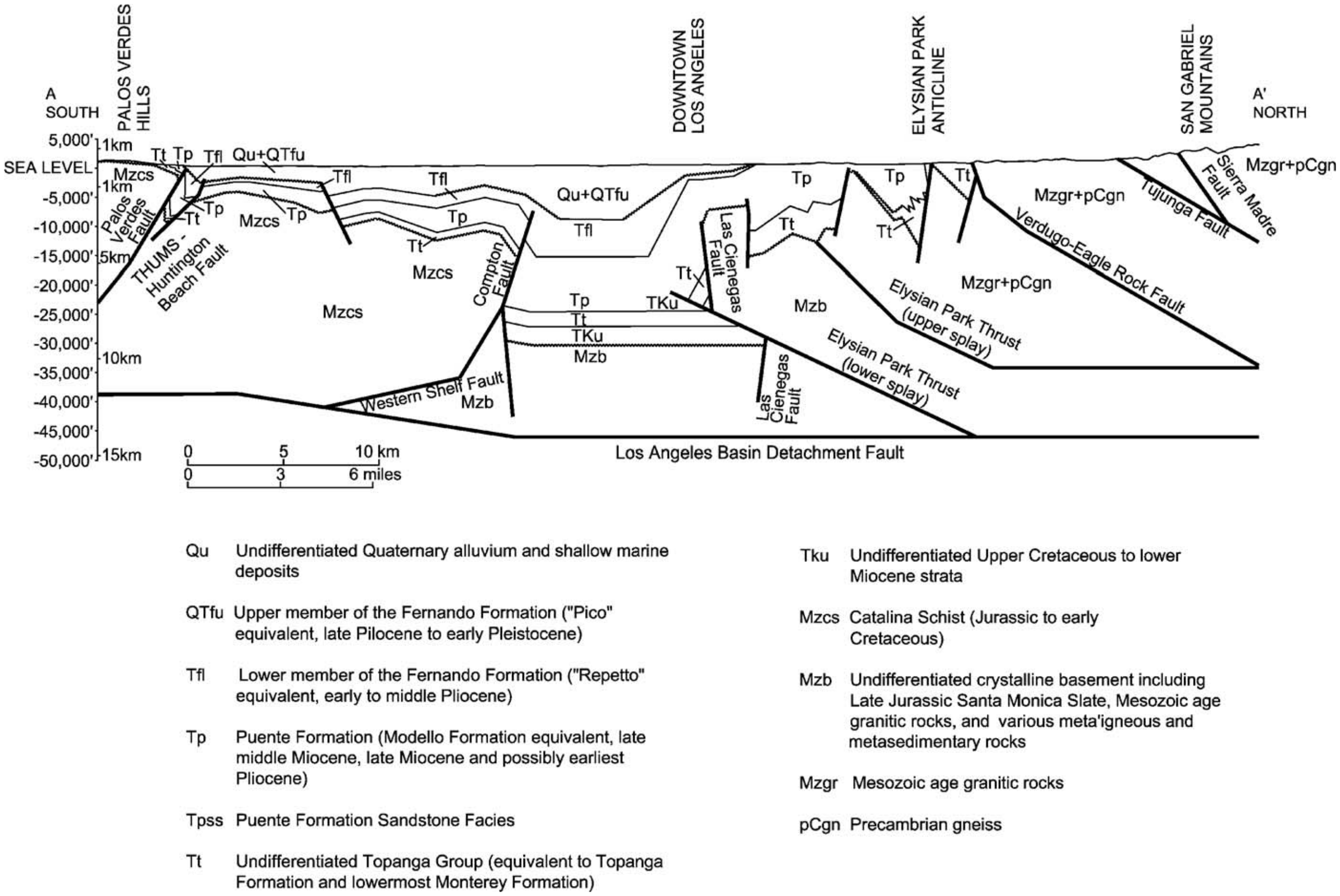

Figure 5. Basin cross section showing faults and basin detachment fault (after Davis and Namson, 1998). Section line shown on Figure 4.

probably thin or indistinguishable from the conglomerates of the younger Topanga Formation. The Cretaceous section is thick in the subsurface of the southern Los Angeles basin and in the Santa Ana Mountains to the east (Wright, 1991).

Paleogene Rocks

The Paleogene or lower Tertiary sedimentary sequence consists of marine and nonmarine clastic rocks, of which only a thin section, about 300 ft (91 m) thick, overlying the thin Cretaceous section, is exposed in the eastern Santa Monica Mountains. The Paleocene Santa Susana Formation is mostly marine sandstone and micaceous silty claystone with a basal conglomerate (Simi Conglomerate Member) that has a few thin, interbedded reddish, possibly nonmarine, sandstone and claystone layers. This formation thickens to the west and northwest, away from the Los Angeles area (Yerkes and Campbell, 1979, 1980; Dibblee, 1982, 1991).

Paleogene strata have not been identified in the subsurface of the northern Los Angeles basin but occur beneath the western part of the San Fernando Valley, in the Santa Monica Mountains and in the southern Los Angeles basin. These sediments also include the marine Eocene Llajas Formation, the nonmarine Sespe Formation of Oligocene–early Miocene age, and the age-equivalent but marine Vaqueros Formation (Figure 4) (Yerkes and Campbell, 1979, 1980; Dibblee, 1982; Wright, 1991; and Fritsche, 1993).

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Figure 4. General geologic map of the Los Angeles area (after Saucedo et al., 2003; Yerkes and Campbell, 2005). City boundaries are outlined by red line; cross section is depicted in Figure 5.

Miocene Rocks

Miocene rocks of the Los Angeles area are divided into generally lower, lower–middle, and upper Miocene sequences (Yerkes and Campbell, 1979; Fritsche, 1993). The lower Miocene rocks comprise the uppermost strata of the Sespe and Vaqueros Formations, which are mostly Oligocene in age (Figure 4). The lower–middle Miocene is represented by the Topanga Formation and the upper Miocene by the Modelo, Monterey, and Puente Formations (Dibblee, 1982, 1991; Wright, 1991).

The Topanga Formation is a mostly marine clastic unit that crops out in the Santa Monica Mountains and San Rafael Hills (Dibblee, 1989a, 1991). It consists of a thin lower member of marine sandstone; a middle member of marine sandstone, siltstone, and basaltic volcanic rocks correlative with the Conejo Volcanics exposed in the Santa Monica Mountains to the west and the Glendora Volcanics to the northeast; and an upper member of marine conglomerate, sandstone, siltstone, and shale correlative with the Calabasas Formation (Figure 4) (Yerkes and Campbell, 1979; Dibblee, 1982, 1989a, 1991; Fritsche, 1993; and McCulloh et al., 2002). Isotopic ages for the Conejo Volcanics and Glendora Volcanics are generally between about 17.4 and 15.3 Ma (McCulloh et al., 2002). The Topanga Formation was deposited mostly as a shallow- to moderately deep-water submarine fan channel system (Redin, 1991). Topanga Formation rocks, encountered in wells drilled around the margins of the Los Angeles basin, generally thicken toward the axis of the basin. Beneath the central trough of the Los Angeles basin, the Topanga Formation may be overlain by 16,000–24,000 ft (4,900–7,300 m) of younger strata; and the formation has yet to be penetrated by drilling (Figure 5) (Wright, 1991).

Upper Miocene strata include the stratigraphically equivalent Modelo and Monterey Formations and an unnamed shale unit of the Santa Monica Mountains and the Puente Formation of the Puente Hills (Figure 4) (Lamar, 1970; Dibblee, 1982, 1989b, 1991). This sequence of siliceous shale and sandstone is up to 8,500 ft (2,600 m) thick along the Los Angeles River in the Elysian Park–Repetto Hills of the north–central part of the city. The sand-dominated parts of this sequence were deposited by two submarine fan systems that fed sediment southward into the developing Los Angeles basin. These two fans are designated the "Tarzana" and "Puente" fans (Redin, 1991; Wright, 1991).

Pliocene Rocks

Pliocene units, repetitiously interbedded fine- to coarse-clastic marine strata variously referred to as the Fernando, Pico, and Repetto Formations (Figure 4), underlie the northern Los Angeles basin and are exposed in the Repetto Hills in east Los Angeles. These strata also have been exposed in downtown Los Angeles during excavation for streets, high-rise buildings, and the new Metro Rail subway line (Lamar, 1970; Dibblee, 1982, 1989b, 1991). In the Repetto Hills, 4,300 ft (1,310 m) of soft, gray marine mudstone and siltstone, with thin interbeds of soft, silty sandstone, are overlain by 2,500 ft (760 m) of friable sandy siltstone, sandstone, and pebble conglomerate (Yerkes et al., 1965; Dibblee, 1982). The Pliocene sequence thickens southward in the Los Angeles basin to about 14,000 ft (4,270 m) and is a part of the submarine fan depositional system that began in the Miocene (Yerkes et al., 1965; Redin, 1991). Sandstones within these submarine fan deposits are the reservoir rocks for most oil extracted from the Los Angeles basin during the last century.

Pleistocene Deposits

Pleistocene surficial sedimentary units cover much of Los Angeles and consist of uplifted and dissected marine strata, coastal floodplain, and alluvial fan deposits. These deposits include marine silt, sand, and gravel of the lower Pleistocene San Pedro Formation and the upper Pleistocene Lakewood Formation (Figure 4). The Lakewood Formation has been mapped by Dibblee (1989b, 1991) as older alluvium and alluvial fan deposits that interfinger with marine sands near the coast. The thickness of these deposits is highly variable, with the marine deposits (combined lower and upper Pleistocene) being as much as 415 ft (126 m) thick in the hills along the Newport–Inglewood fault zone and the marine and alluvial deposits as much as 4,300 ft (1,310 m) thick in the central part of the Los Angeles basin (Yerkes et al., 1965). The major groundwater aquifers in the basin (such as the Exposition, Gage, Lynwood, Silverado, and Sunnyside aquifers) occur within the Pleistocene deposits (California Department of Water Resources, 1961).

The Pleistocene filling of the Los Angeles basin occurred in response to worldwide climate and eustatic sea-level change. During glacial periods, the sea level dropped as much as 425 ft (130 m), exposing broad expanses of the continental shelf. Concurrently, a wetter climate in the Los Angeles area led to incision of fluvial channels across the newly exposed coastal plain. As the glaciers melted, sea level rose, and the stream valleys began to backfill in response to the new base level. Most aquifers consist of coarse clastic sediments deposited during low stands, whereas the aquitards are generally fine-grained marine and estuarine sediments deposited during sea-level rises.

Elevated marine terraces are common along the coast of southern California. These terraces reflect interglacial sea-level highstands that are now preserved because of local tectonic uplift of wave-cut platforms. The most extensive marine terraces are preserved in the Palos Verdes Hills and in the Malibu–Pacific Palisades region. Presently, at about 100–200 ft (30–60 m) in elevation, the 125 thousand years (ka) old (oxygen-isotope Stage 5e) marine terrace formed when sea level was 20 ft (6 m) higher than it is today (Shaller and Heron, 2004).

Holocene Alluvium

The youngest surficial deposits are Holocene sediments of modern alluvial fans, stream channels (i.e., Los Angeles and San Gabriel Rivers), and their flood plains. These debris-flow, sheetflood, and fluvial deposits consist of boulder, cobble, and pebble gravel lenses and sheets, interbedded with sand, silt, and clay derived from the surrounding highlands. Although the thickness of these sediments is usually less than 100 ft (30 m), they are locally as thick as 200 ft (60 m), and the fluvial sediments are roughly graded, with the lower parts containing coarser material. A narrow zone of well-sorted, fine- to medium-grained, dune sand, as thick as 70 ft (21 m), is located near the coast between Santa Monica and the Palos Verdes Hills (California Department of Water Resources, 1961; Yerkes et al., 1965). Since about 6 ka ago, when postglacial sea level had risen to near its present level, coastal estuaries and tidal marshes formed and became filled with organic-rich, fine-grained sediment that extended as far as 4 mi (6.4 km) inland from the mouths of the streams (Yerkes et al., 1965). Real estate development has now transformed most of these estuaries and marshes into marinas and residential areas.

NATURAL RESOURCES

Oil and Gas

Petroleum deposits in the Los Angeles area were recognized and used by the indigenous Chumash Indians long before the founding of the city. The "tar" (actually asphalt) pits at Rancho La Brea and other asphaltum deposits were used by the local Native Americans as sealant for their canoes and as trading goods. As early as 1865, a well was excavated to a depth of 390 ft (119 m), near downtown, in the Pliocene section (McLaughlin, 1914). Although not a true oil-producing well, it did produce some natural gas and water. The first producing oil well in the City of Los Angeles was excavated with a pick and shovel by Edward L. Doheny, a down-on-his-luck mining prospector, and Charles A. Canfield, his mining partner, in 1892 at the corner of Colton Street and Glendale Boulevard (near present-day Dodger Stadium). This well hit oil at 46 ft (14 m). By the end of 1895 there were more than 300 wells in the city, with an estimated annual production of 730,000 barrels, with the price as low as 60 cents per barrel (McLaughlin, 1914; Rintoul, 1991). During construction of many of the high-rise building basements, constructed for vehicle parking space, workers encountered nonflowing asphaltum in the vertical excavation walls.

Development of the Salt Lake oil field, west of downtown and surrounding the La Brea Tar Pits, began in 1903. In 1904 there were about 1,150 producing wells in the Los Angeles City oil field, but production declined, and the number dwindled to 416 by the end of 1910. This decline reflected poor development, as the wells had been placed too close together on individual city lots. Whole city neighborhoods were overgrown with forests of wooden oil derricks (Figure 6). Today there are 43 active fields in the Los Angeles basin (onshore and offshore) and about 4,000 producing wells. Many of these oil fields were discovered between 1892 and 1936. Annual production of these fields has declined from 49.2 million barrels in 1990 to 30.2 million barrels in 2004 (California Division of Oil, Gas and Geothermal Resources, 2005). When the major oil companies began departing Los Angeles in the 1980s during the worldwide downturn in oil prices, most fields were sold to smaller, independent oil companies. Through the use of new technology and drilling techniques, these companies found new oil and revitalized many of the old fields. Development in the urban oil fields of Los Angeles is a challenging prospect, considering the strict environmental and noise requirements levied on the operators (Rintoul, 1991; Sever, 2005). Figure 7 shows the oil and gas fields located within the Los Angeles area. Figure 8 shows a cross section of directional wells used to extract oil and gas with less disruption of the surface. More than six million barrels of oil and condensate were produced from 15 local oil and gas fields in 2005. Table 1 summarizes the current oil and gas production from fields with significant production within the Los Angeles city limits (California Division of Oil, Gas and Geothermal Resources, 2006).

La Brea Tar Pits

The tar pits at Rancho La Brea are one of the world's most valuable fossil sites and contain one of the earliest geological resources in Los Angeles,

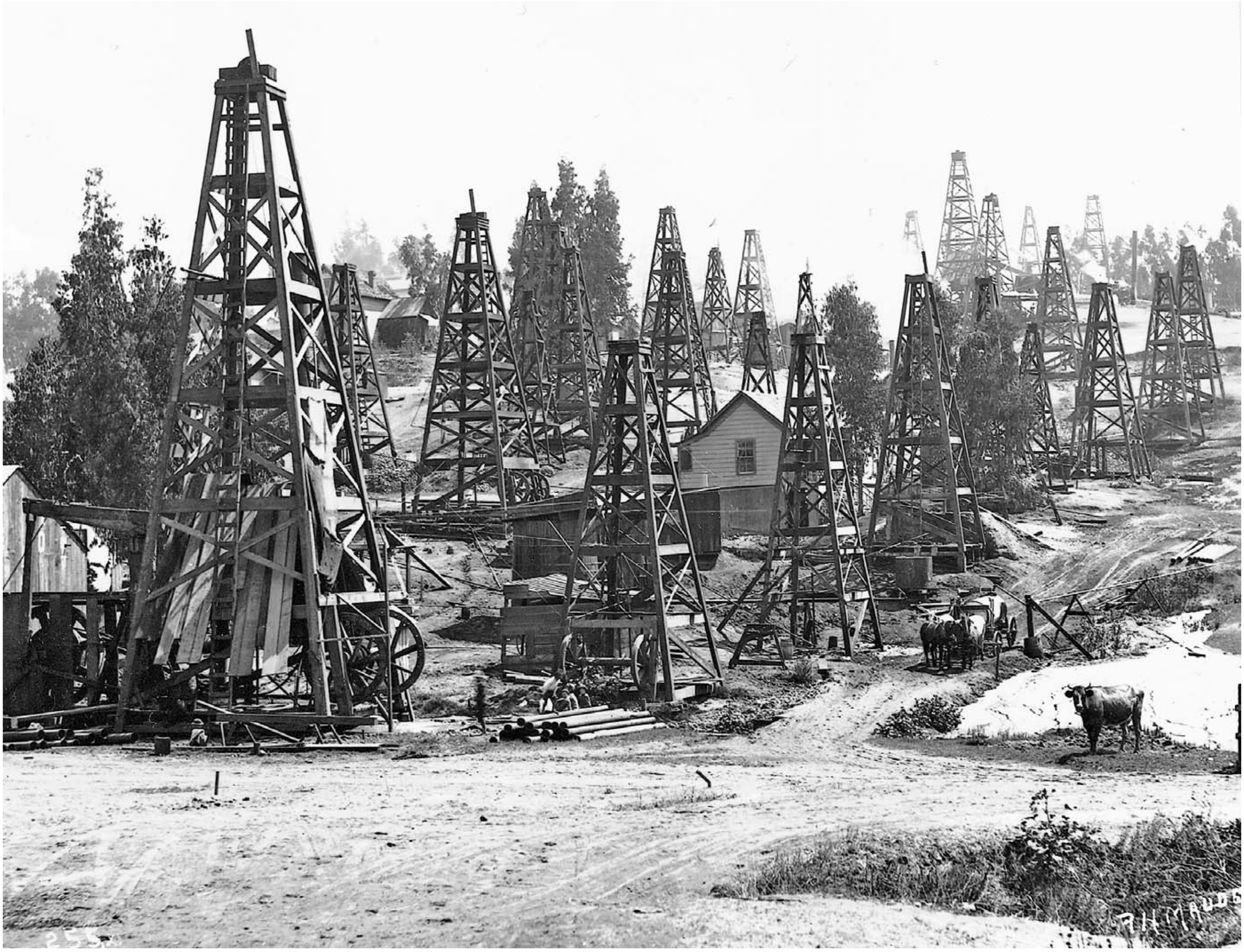

Figure 6. Photo of Los Angeles City field, circa 1900, showing the proximity of oil wells. Photo from the History Collections, Los Angeles County Museum of Natural History.

"pitch," or asphaltum (Figure 1). They have yielded a tremendous variety of fossils from the Pleistocene and Holocene epochs. Paleontologists have recovered almost 1.5 million vertebrate and 2.5 million invertebrate fossils from the deposits. These fossils represent 140 species of plants and more than 420 species of animals up to 40,000 years in age (Natural History Museum of Los Angeles County, 1988).

Gaspar de Portolá first recorded the tar seeps as "springs of pitch," in his diary on August 3, 1769. In 1792, Jose Longines Martinez reported that near the Pueblo de Los Angeles there were more than 20 springs of liquid petroleum and pitch. He described a great lake of pitch, with many bubbles continually forming and breaking. The native inhabitants used the black pitch or tar as an adhesive, for waterproofing materials and caulking boats. In hot weather, animals were observed to sink into the lake. Bones later came up out of the pitch petrified (Stock, 1956).

The method of entrapment was relatively simple. An animal, bird, or insect would be attracted to the area by the water floating on top of the tar deposit. When the creature came close to drink, it would get mired in the tar, find itself unable to escape, and then die of hunger or thirst. Once it was trapped and dying, carnivorous animals would be drawn to the area to feed on it and they, in turn, would also get trapped. The pitch preserved the bones virtually intact. This makes the deposit even more valuable, because so many skeletons are complete and undamaged. The most striking aspect of the mammalian assemblage is the dominance of predatory forms. This is a result of entrapment of carnivores attracted to the pits by dead or dying herbivores. The remains of only one human, the so-called "La Brea Woman," who

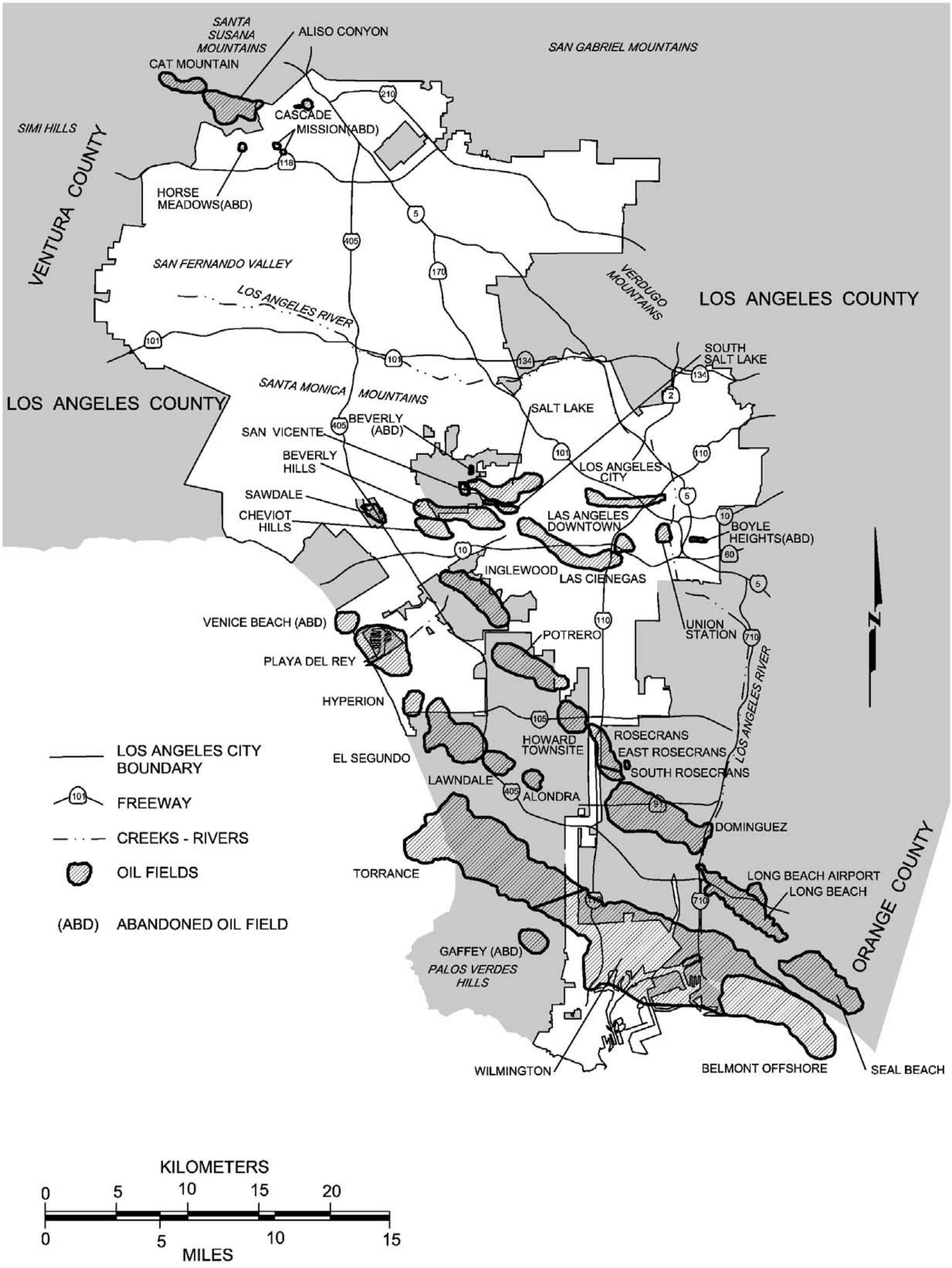

Figure 7. Major oil and gas fields in the Los Angeles area (from the City of Los Angeles and Munger, 2001).

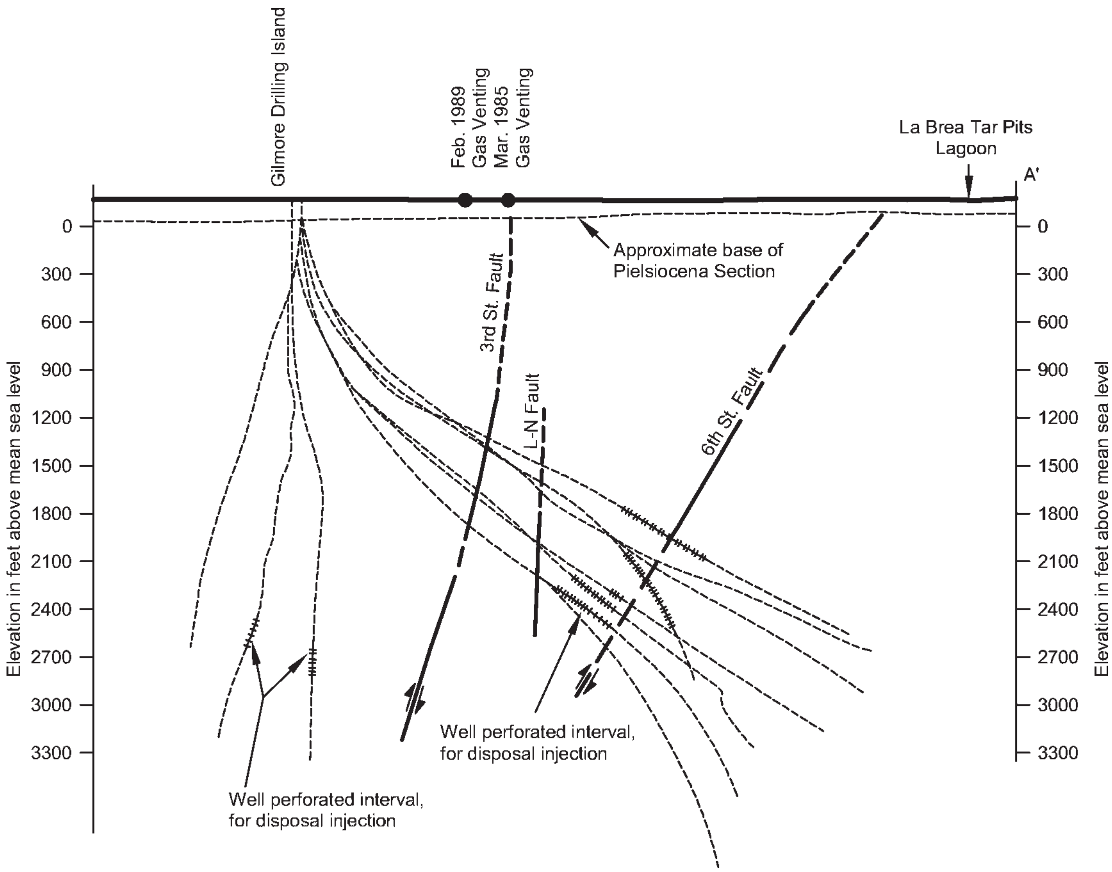

Figure 8. Cross section of directional wells used in Fairfax District to extract oil and gas from the subsurface with minimal disturbance to surface commerce (after Hamilton and Meehan, 1992).

Table 1. *Oil and gas field production in the Los Angeles area, 2005.*

Field Name	Location by Township and Range	Cumulative Oil and Condensate (bbl)	Cumulative Gas (Mcf)	Number of Producing Wells
Beverly Hills	T1S R14-15W	1,110,000	1,950,000	92
Cascade	T3N R15W	411,000	490,000	20
Cheviot Hills	T1S R15W	74,000	73,300	11
Hyperion	T3S R15W	9,870	0	1
Las Cienegus	TIS R14W	420,000	243,000	48
Los Angeles, city	TIS R13W	1,920	0	8
Los Angeles, downtown	TIS R13W	88,700	212,000	19
Playa Del Rey	T2S R15W	32,600	11,500	5
Rosecrans	T3S R13W	193,000	172,000	47
Salt Lake	TIS R14W	57,100	90,100	6
Salt Lake, south	TIS R14W	53,600	114,000	10
San Vicente	T1S R14W	594,000	1,020,000	40
Sawtelle	T1S R15W	208,000	139,000	11
Union Station	TIS R12W	4,110	0	5
Wilmington (onshore)	T4-5S R13W	3,210,000	546,000	408
Totals		6,467,900	5,060,900	731

bbl = barrels of oil and condensate; Mcf = thousands of cubic feet of gas; T2S R14W = Township 2 South, Range 14 West.
Data are from California Division of Oil, Gas and Geothermal Resources (2006).

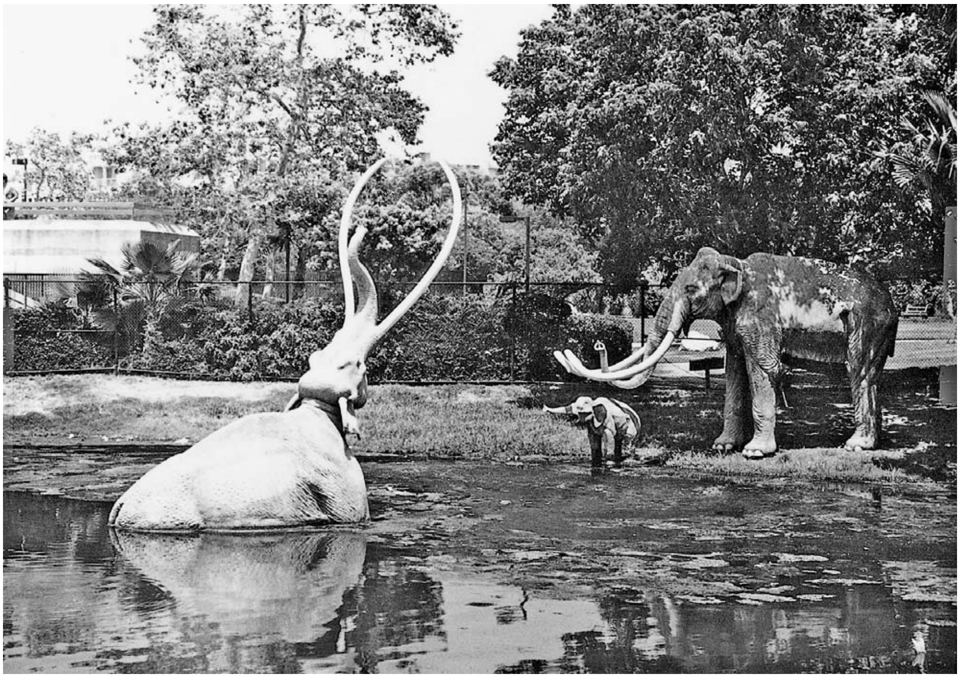

Figure 9. Scene depicting entrapment of mammoths in front of the George C. Page Museum at the La Brea Tar Pits.

lived about 9,000 years ago, have been found in the deposits. She was approximately 4 feet 10 inches (1.5 m) tall and 20–25 years old (Natural History Museum of Los Angeles County, 1988).

The fossil bones were first discovered in 1875. In 1906, permission was granted to the University of California to excavate the fossils. In 1915, landowner G. Allan Hancock generously gave the 23-acre (9.3-hectare) tract of land on which the fossils appear to Los Angeles County, with the stipulation that the scientific features of the deposits be adequately displayed and exhibited. A unique public park (Hancock Park) and an exceptional museum (George C. Page Museum) are now located on the site. Life-sized statues of Pleistocene animals are present in different areas of the park, and a family of mammoths is depicted becoming trapped in the asphaltum (Figure 9).

Aggregates

The term aggregate includes materials composed of natural or crushed, hard, sound and durable particles of nonreactive minerals (sand, gravel, and crushed rock). Aggregate is a bulk commodity with a low unit value at the quarry or pit site. Its cost primarily depends on transportation. The maximum distance at which that aggregate can be transported to the consumer and allow the owner to still remain competitive in the market is about 20 mi (Williamson, 1990). With 20 active gravel pits and rock quarries, the Los Angeles area is one of the largest consumers of construction aggregate in the world. A typical 1,500 ft^2 (139 m^2) house requires over 114 tons of aggregate to construct. Aggregate production and consumption in the Los Angeles metropolitan area was more than 35 million tons in 1997 (Beeby et al., 1999).

Most Los Angeles aggregate production comes from stream deposits washed down from the San Gabriel Mountains (Goldman, 1968). Stream channel deposits are desirable sources of aggregate because the natural abrasive action of stream transport has rounded the predominantly hard, crystalline rock particles and removed the weaker rock types. Various methods of excavating sand and gravel deposits are employed in the Los Angeles area. The most common method is to use a dragline or electric shovel and then conveyor belts or trucks to move the material from the pit to the processing plant.

Reserves include material within aggregate-producing property boundaries believed to be acceptable for commercial use. Resources are deposits that are located on company-owned or company-leased land but that are not actively mined because no use permit has been granted or because technological or economic conditions prevent development. The presently identified reserves could provide up to 50 years of additional aggregate, assuming these reserves are put into production.

Urban expansion in the Los Angeles area has caused some pits to close and has prevented expansion of existing sites to exploit adjacent deposits. The buildings and roads in Los Angeles and the San Fernando Valley were built mostly from sand and gravel from the Irwindale and Sun Valley pits. Extensive gravel deposits still remain beneath the San Gabriel Valley, an area now covered by subdivision homes. No new pits have opened in the Los Angeles area since the mid-1970s. Several options have been identified to meet the projected future demand for aggregate. One is to continue a strong land-use program to prevent urbanization over known deposits. Another is to evaluate the economic and environmental impacts of mining the nearby offshore aggregate deposits. A third is to mine the sediments that have accumulated behind flood-control debris basins along the southern flank of the San Gabriel Mountains. Lastly, recycling of construction and demolition debris, including concrete aggregate, is now mandated in Los Angeles County (Construction and Demolition Debris Recycling and Reuse Ordinance, enacted January 4, 2005) to help meet the 50 percent reduction in solid waste entering disposal facilities required by the California Integrated Waste Management Act of 1989. The City of Los Angeles strongly supports the recycling and reuse of construction and demolition debris and in March 1995 passed a motion requiring that road base in all city projects include "crushed miscellaneous base" with 100 percent recycled asphalt, concrete, and other inert material where possible.

GEOLOGIC CONSTRAINTS

Historic Earthquakes

Catalogs of earthquake activity for southern California extend back to the earliest reported event, recorded on July 28, 1769, by the first Spanish exploration party, the Portolá expedition, as they camped beside the Santa Ana River in Orange County, about 31 mi (50 km) southeast of Los Angeles (Townley and Allen, 1939; Toppozada et al., 1981; and Ellsworth, 1990). The earliest chronicles of earthquake activity are from subjective personal accounts. Systematic calculations of earthquake epicenters and the compilation of ongoing earthquake activity in southern California began in 1932 with the establishment of a seismographic instrumentation program at the California Institute of Technology (Caltech). This program comprised a network of six Wood–Anderson torsion seismographs installed around southern California and the routine publication of a station bulletin.

Los Angeles lies within a highly active tectonic area and has been the victim of several major earthquakes in the past 150 years (Figure 10). These earthquakes are described in the following paragraphs.

July 11, 1855: The earthquake was felt locally as a strong shock, with Modified Mercalli Intensities as high as VIII, with an estimated magnitude of M6.0 (Toppozada et al., 1981; Toppozada, 1995). Many buildings were damaged, bells were downed at the San Gabriel Mission, and an adobe dwelling was destroyed in an area now occupied by the Los Angeles County Arboretum in Arcadia. The earthquake was probably located on one of the faults bordering the Los Angeles basin, possibly the Raymond fault (Yerkes, 1985).

January 9, 1857—"Fort Tejon Earthquake": Just 7 years after California gained statehood, southern California experienced the great Fort Tejon Earthquake (M7.9). Surface rupture, along the south–central portion of the San Andreas fault, extended for at least 220 mi (350 km) southeast from Parkfield (location of the earthquake's epicenter) in San Luis Obispo County to near Wrightwood in San Bernardino County (Ellsworth, 1990; Toppozada, 1995). In Los Angeles, the reported damage was less than reported in the 1855 earthquake, although there was a very strong, long-duration swaying motion, and water from the Los Angeles River was thrown from its channel. Houses were reportedly knocked down in the San Fernando Valley (Agnew and Sieh, 1978). The loss of only two lives is attributed to the fact that the most heavily shaken areas were sparsely populated. A potential repeat of an earthquake of this magnitude on the San Andreas fault is loosely known as "The Big One."

March 10, 1933—"Long Beach Earthquake": One of the most destructive earthquakes (M6.4) in the history of southern California occurred on the southern segment of the Newport–Inglewood fault zone (Figure 10). The epicenter was located 3 mi (5 km) south of Huntington Beach, and considerable damage, along with the loss of 115 lives, occurred in Long Beach and surrounding areas (Ellsworth, 1990).

The 1933 Long Beach Earthquake showed that Los Angeles basin alluvial deposits are particularly subject to liquefaction and earthquake-induced ground settlement. As noted by Wood (1933), "… along the shore between Long Beach and Newport Beach, and in a few localities a short distance inland, road fills across marshy land, and similar earth construction resting in wet sand or mud, settled, shook apart, or moved laterally, causing considerable damage to concrete highway surfaces and to approaches to highway bridges." Similar phenomena occurred to piers and landings in the harbor area. Consolidated terrace deposits, compacted man-made fill, hilly ground such as Signal Hill, and even areas underlain

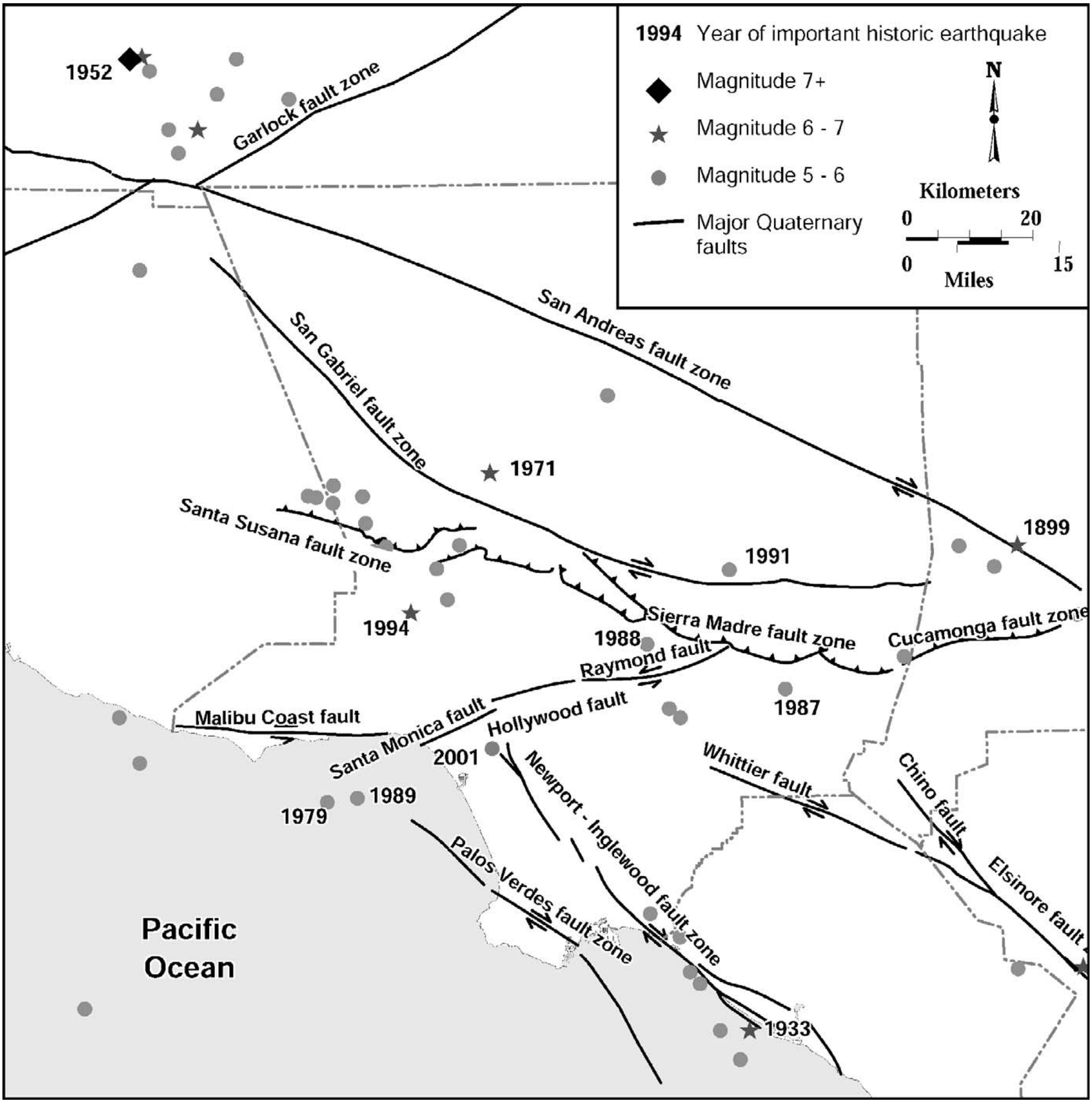

Figure 10. Major Quaternary faults and earthquake epicenters within the Los Angeles area (after Jennings, 1994; Southern California Earthquake Center [SCEC], 2006; and U.S. Geological Survey [USGS]/National Earthquake Information Center [NEIC], 2006).

by sedimentary rock were less damaged, although subject to intense shaking. Well-constructed buildings in even the most vigorously shaken areas suffered relatively little damage, especially when sited on "well chosen or well-prepared foundations" (Wood, 1933). Major structural damage to public schools led to the prohibition of new unreinforced masonry (URM) buildings and to the enactment of a landmark school building design and retrofit law, the Field Act. Notable studies of the Newport–Inglewood fault zone (NIFZ) have been made by Barrows (1974), Freeman and others (1992), Toppozada and others (1988), and Yeats (1973). Seismic studies of recent earthquakes on the NIFZ show right-lateral strike–slip focal mechanisms similar to the 1933 Long Beach Earthquake focal mechanism (Hauksson, 1990, 1992).

February 9, 1971—"San Fernando Earthquake": Prior to 1971, the San Fernando Valley area

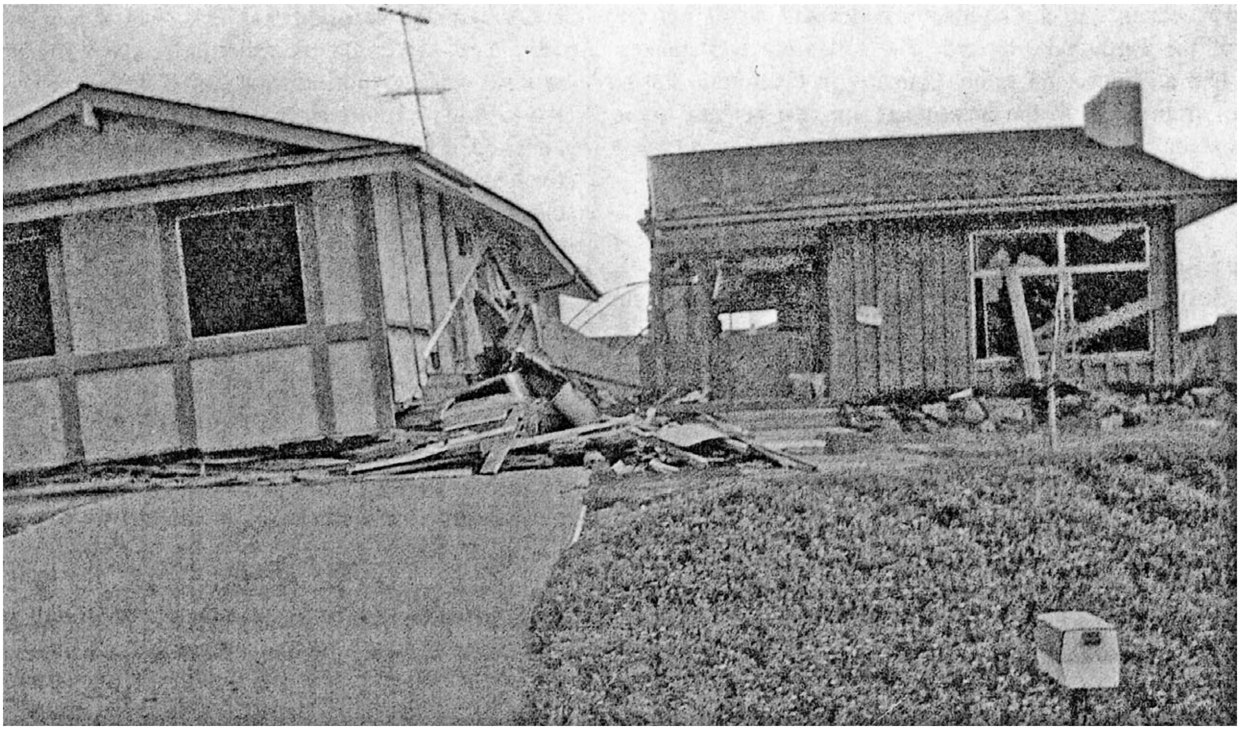

Figure 11. True split-level house in Sylmar after the 1971 earthquake. The heavier bedroom collapsed into the two-car garage during the strong ground shaking.

(Figure 1) was characterized by low to moderate seismicity. The area experienced about 10 earthquakes of magnitude 3.0 between 1934 and 1971. Because of the lack of instrumental data, the only pre-1934 earthquake reported for the valley occurred in 1893 (Wentworth and Yerkes, 1971; Richter, 1973). The 1971 San Fernando (or Sylmar) Earthquake (M6.7) occurred on north-dipping thrust faults at a depth of 5.2 mi (8.4 km). This was surprising because the area was essentially seismically quiescent prior to the event. The main shock claimed 58 lives and caused over $500 million in damages ($3 billion in 2005 dollars) (Steinbrugge et al., 1975; Ellsworth, 1990). The maximum Modified Mercalli Intensity rating was IX in the epicentral area.

The San Fernando Earthquake was the first test for new urban developments with regard to the damaging effects of a moderate-size earthquake. Most economic loss resulted from a combination of intense ground shaking and severe ground rupture (Figure 11) (Slosson, 1975). Principal fault rupture was distributed along the San Fernando and western Santa Susana fault zones for 9.5 mi (15 km) in an area as wide as 1.8 mi (3 km) (Proctor et al., 1972; Weber, 1975). Surface ruptures damaged many buildings, and as a consequence, the Alquist–Priolo Earthquake Fault Zoning Act of 1972 was implemented in California to preclude construction over active fault traces. Also contributing to the high property losses were widespread ground lurching, liquefaction, lateral spreading, and differential settlement of nonengineered fills and loose alluvium (Slosson, 1975; Steinbrugge et al., 1975). As a result, previously accepted Uniform Building Code (UBC) standards and construction techniques common to southern California were reassessed (e.g., Scullin, 1983). The highly popular "soft-story" construction was deleted from the code, and popular "tilt-up" commercial buildings were redesigned to strengthen the roof joist connectors. However, thousands of these pre-1971 buildings, as well as URM structures, still remain in Los Angeles and are the largest threat to life from future earthquakes.

October 1, 1987—"Whittier Narrows Earthquake": The Whittier Narrows Earthquake (M5.9; Modified Mercalli Intensity VIII) occurred on a previously unknown blind thrust fault underlying the Elysian Park–Montebello Hills at a depth of 5.9 mi (9.5 km) (Davis et al., 1989; Hauksson and Jones, 1989; and Hauksson, 1992). Although blind thrust faults were known to exist, this earthquake caused geologists, seismologists, and planners to reevaluate the seismic risk of these structures. Newly recognized blind thrust faults have increased previously accepted annual probabilities for damaging earthquakes and pose the risk of generating a large-magnitude earthquake directly below Los Angeles (Davis et al., 1989).

Figure 12. Building collapse from the 1994 Northridge Earthquake.

The Whittier Narrows Earthquake did not rupture the ground surface; nevertheless, structural and nonstructural property damage was extensive. The damage, an estimated $360 million, particularly affected pre-1933 URM buildings, pre-1950 single-family homes built on raised foundations, and multistory parking structures (Weber, 1987). The earthquake also tested the Federal, state, and local earthquake mitigation, emergency response, and preparedness programs that had evolved since the 1971 San Fernando Earthquake.

June 28, 1991—"Sierra Madre Earthquake": This early-morning earthquake (M5.8; Modified Mercalli Intensity VIII) occurred 6.5 mi (10.5 km) beneath the San Gabriel Mountains and reconfirmed the seismogenic potential of the 68-mi (110 km)–long, north-dipping Sierra Madre thrust fault system (Crook et al., 1987). Prior to this earthquake, the Sierra Madre fault zone had been seismically quiet, and the fault was considered as only potentially active under the state criteria. The earthquake caused extensive landsliding in the San Gabriel Mountains and damaged many older homes and structures in the foothills communities. Only one death was attributed to the earthquake, but the implications of a seismically active frontal fault are major and portend much greater losses in the future.

January 17, 1994—"Northridge Earthquake": The Northridge Earthquake (M6.7; Modified Mercalli Intensity IX) shook the San Fernando Valley and surrounding regions of the Los Angeles area at 4:31 AM (Pacific Standard Time) (Figure 12). The timing was fortunate because most people were still in bed and the freeways were not crowded. The estimated losses of $20–40 billion make this the costliest earthquake in U.S. history. Even so, only 57 deaths were attributed to the earthquake, and the majority of these resulted from the collapse of a single apartment building (a pre-1971 soft-story structure) in Northridge. Over 9,000 injuries were attributed to the earthquake, and 20,000 people were displaced from their homes. During the 10–20 seconds of strong shaking, thousands of buildings were damaged, with over 1,600 of them "red-tagged" as unsafe to enter and 7,300 of them "yellow-tagged" for limited entry (U.S. Geological Survey, 1996). Many buildings were the same pre-1971 soft-story (including several large buildings at California State University, Northridge), pre-1950 single-family homes, tilt-up warehouses, and URMs (especially in Santa Monica) damaged in previous earthquakes.

The collapse of seven freeway structures and damage to 230 other bridges caused major disruption to the transportation system in the Los Angeles area (Yashinsky, 1995). Particularly significant were the State Highway 14 collapse onto the Interstate 5 Freeway just north of Sylmar and, 15 mi (24 km) south of the epicenter, the Interstate 10 collapse onto La Cienega Boulevard west of downtown Los Angeles. After the 1971 San Fernando Earthquake, the California Department of Transportation (Caltrans) began a modest seismic retrofit program for highway bridges to strengthen the connection between the bridge deck and its supports. Several collapsed highway bridges had a post–San Fernando earthquake seismic retrofit. The Highway 14 overpass had also collapsed in the 1971 earthquake and had been rebuilt using the same design plans with minor connector strengthening. After the 1989 Loma Prieta Earthquake, which severely damaged highway bridges in the San Francisco area, Caltrans began a more robust seismic retrofit program that also strengthened bridge footings, columns, and abutments. None of the collapsed bridges had undergone the post–Loma Prieta seismic retrofit, and none of the 63 highway bridges in the area that had post–Loma Prieta retrofits suffered major damage (Yashinsky, 1995).

Although steel-framed buildings did not collapse, the Northridge Earthquake cracked welds in more than 120 structures, a major surprise to the engineering community (Chittenden, 1995). Much of this damage was not identified until several weeks after the quake, particularly in many buildings previously "green-tagged" as structurally sound. In almost all cases, the damage to the steel framing was hidden behind undamaged architectural elements that did not permit direct visual inspection of the structural member. The structural failures included buckling of frame braces and brittle-fracturing of brace connections and column base plates. The most common failure was to welded beam-to-column connections. This unexpectedly poor performance of steel structures brought into question accepted seismic design standards for behavior of steel frames in high-rise buildings during moderate or large earthquakes (Bertero et al., 1994; Heaton et al., 1995) and has thus led to several structural code changes (Chittenden, 1995; U.S. Geological Survey, 1996).

The strong ground motions that caused the widespread damage were recorded on a regional network of over 200 accelerographs maintained by the California Strong Motion Instrumentation Program, U.S. Geological Survey, and University of Southern California (USC). This array, and smaller groups of stations maintained by Caltech, Southern California Edison, the Los Angeles Department of Water and Power, and the California Department of Water Resources, produced one of the best strong-motion data sets ever compiled from an earthquake (Chang et al., 1994; Stein et al., 1994; and Darragh et al., 1995). Peak accelerations of over 1.0 gravity (g) were recorded at several sites near the epicentral area, decreasing to 0.1 g at about 31 mi (50 km) from the epicenter. In downtown Los Angeles, 22 mi (36 km) from the epicenter, peak accelerations approached 0.5 g. The largest free-field acceleration, 1.82 g horizontal and 1.18 g vertical, was recorded about 4 mi (7 km) south of the epicenter in Tarzana, on approximately 33 ft (10 m) of alluvium over siltstone (Chang et al., 1994; Moehler, 1994). Although there were localized areas of surface cracking, there is no evidence that the Northridge fault displacement extended to the ground surface.

The earthquake was also notable because of the orientation of the fault plane. In contrast to the San Fernando, Whittier Narrows, and Sierra Madre Earthquakes, the inferred subsurface rupture occurred on a south-dipping, as opposed to a north-dipping, blind thrust fault. The rupture surface, delineated by the aftershocks, extended from the hypocenter at 11.3 mi (18.2 km) upward, to a depth of about 3.1 mi (5 km). In the aftershock region, resurveys of Global Positioning System (GPS) benchmarks showed vertical uplifts of 16–20 in. (40–50 cm) and horizontal movements of 0.8–8 in. (2–20 cm). Modeling of these data indicates that the fault slipped 8.2–11.5 ft (2.5–3.5 m) on a 6.2 × 6.2–mile (10 × 10 km) portion of the fault below a depth of 3.7 mi (6 km) (Wald et al., 1995).

Earthquake Hazards

Los Angeles is earthquake country. Thousands of earthquakes are recorded every year in southern California; fortunately, very few of them are felt by the residents. "Earthquakes are as southern Californian as waves at the beach and traffic on the freeways" (Southern California Earthquake Center, 2005). As the recent earthquake history of southern California shows, large earthquakes can cause severe damage and loss of life. In the last 100 years, only one earthquake, the 1971 San Fernando Earthquake, caused damage in the Los Angeles area due to fault displacement of the ground surface. The most significant damage in all of the recent earthquakes, including the 1971 earthquake, was caused by intense ground motion (i.e., shaking). This ground motion was amplified and focused by local geological conditions and deep geological structures and produced ground failures such as liquefaction and landslides.

Dolan and others (1995) sounded the wake-up call for Los Angeles by postulating a serious deficit in the number of "Northridge-type" earthquakes in the Los Angeles basin. Their conclusions are alarming: either the Los Angeles area could experience 15 additional M6.7 earthquakes over the next 30 years just to catch up to unreleased strain accumulation, or Los Angeles should expect significantly larger earthquakes (M7.2–7.6) in the future. Southern California Earthquake Center (SCEC) researchers are studying the question

Table 2. *Late Quaternary faults in the Los Angeles region.*

Fault Name	Activity Status[1]	Segment Length (km)	Segment Length (mi)	Maximum Credible EQ (M)
Cabrillo	Active	18	11	6.2
Charnock	Potentially active	>10	>6	6.2
Clamshell–Sawpit	Active	13	8	6.4
Clearwater	Potentially active	33	20	6.9
Hollywood	Active	17	11	6.4
Malibu Coast	Active	>27	>17	6.9
Mission Hills	Active	10	6	6.3
Newport–Ingelwood	Active	>43	>27	6.9
North Hollywood	Active	2	1	?
Northridge	Active	15–21	9–13	6.6
Palos Verdes	Active	>77	>48	6.7
Raymond	Active	22	14	6.7
San Andreas	Active	>120	>74	8
San Antonio	Active	18	11	6.2
San Fernando	Active–potentially active	17	11	6.5
San Gabriel	Active–potentially active	130	81	>7.0
San Jose	Active	14	9	6.7
San Pedro basin	Potentially active	70	43	>7.0
Santa Felicia	Potentially active	8	5	6.1
Santa Monica	Active	>40	>25	6.7
Santa Susana	Active	28–38	17–24	6.9
Sierra Madre	Active	62	38	>7.0
Verdugo	Active	21	13	6.7
Whittier	Active	>40	>25	>7.0

[1]The term potentially active is used here to classify those faults for which there is evidence for Pleistocene age offsets but for which evidence for or against Holocene activity has not (yet) been developed. The term active is used here to indicate a fault for which there is geologic or geomorphic evidence to infer Holocene offset or for which there is current seismic activity on the fault structure.
EQ = earthquake; M = magnitude.
Source: Ziony (1985), and updated based on preliminary research by the Southern California Earthquake Center.

of temporal clustering of moderate (M6–7) earthquakes or cascade events linking multiple faults or fault segments into larger quakes. Most of the following discussion of the ground response to earthquakes in Los Angeles stems from the work of Dolan and others (1995) and Yeats (2005).

Fault Rupture

Many active (Holocene) faults cross or underlie the Los Angeles area. The designation of fault activity depends on the classification system used and the purpose of the definition. An "active" fault considered to assess seismic risk in siting and designing critical facilities, such as nuclear plants, dams, hospitals, or other critical facilities, may not be considered "active" in building conventional residential or commercial developments. Following the severe damage sustained during the 1971 San Fernando Earthquake, the California legislature adopted the 1972 Alquist–Priolo Earthquake Fault Zoning Act (called the Geologic Hazard Zones Act prior to 1975 and the Special Studies Zones Act from 1975 to 1994) to prohibit the development or construction of buildings meant for human occupancy across active faults (Hart and Bryant, 1997). The Alquist–Priolo Act technically applies only to subdivision developments of four or more residences, although it has been more conservatively interpreted by some to include public buildings and even individual custom homes.

The Alquist–Priolo Act includes a definition of what constitutes an "active" fault. The definition uses geologic evidence to prove or disprove Holocene surface displacement on mapped faults. If a fault has had Holocene surface rupture, it is considered to be active; if it has not, and that can be proven, then the fault is not active. If a fault has demonstrated Quaternary displacement but Holocene activity cannot be either confirmed or precluded because of limitations of the study or site conditions, then the fault is defined as potentially active and professional geologic judgment is required to assess the fault hazard (Hart and Bryant, 1997). Note that the surface rupture requirement in the active fault definition excludes blind thrust faults, some of which are "seismogenically" active. These faults will be addressed in the following section.

Shown in Table 2 are faults either suspected or proven to have experienced surface rupture during

Holocene time. Potentially active faults that are listed need more study but appear to have had activity in at least the last half of Quaternary time. Faults showing no evidence of movement within the Quaternary are considered inactive for most development purposes. The more prominent active faults in the Los Angeles area are depicted on Figure 10.

Blind Seismic Structures

As illustrated by the well-dispersed pattern of earthquake epicenters (Hauksson, 1990), essentially the entire Los Angeles area is underlain by microseismogenic structures. Prior to the 1987 Whittier Narrows and 1994 Northridge Earthquakes, large, damaging earthquakes have been concentrated near major known Quaternary faults mapped at the surface. The thrust fault mechanism identified by seismologists as causing these most recent earthquakes indicates that many other unknown seismogenic faults may lie below the surface (Shaw and Suppe, 1996; Shaw and Shearer, 1999).

Recent research has focused on the seismic hazards associated with "blind" thrust faults, one of which lies directly beneath downtown Los Angeles (Dolan et al., 2003). Since most damage caused by earthquakes is a result of intense shaking and not ground rupture, the seismic risk due to hidden "blind" structures (e.g., the Northridge Earthquake) is very real. Six major faults in and near Los Angeles have been identified as having the potential to generate M7.2–7.6 earthquakes, with a recurrence interval of less than 150 years (Figure 13). Subhorizontal thrust sheets are postulated to underlie the entire Los Angeles basin, accommodating up to 0.53 in./yr (13.5 mm/yr) of north–south shortening between the offshore continental borderland and the San Andreas fault (Davis et al., 1989). Consistent with thrust fault mechanics, upward-verging blind thrust tips produce fault propagation folds manifested at the surface by anticlinal fold belts with topographic relief, such as the Elysian Park, Repetto, and Puente Hills. Shear displacement along the thrust ramps converts to ductile deformation (folding) in the overlying anticlinal structures (Figures 5 and 13).

Two blind seismic structures in the Los Angeles metropolitan area are of specific concern. Detailed borehole studies of young sedimentary beds folded above the Puente Hills blind thrust just east of downtown Los Angeles document at least four large paleoearthquakes with moment-magnitudes of 7.2–7.5 that have occurred on this fault within the past 11,000 years (Dolan et al., 2003). Just north of downtown Los Angeles, the actively growing Elysian Park anticline underlies the Elysian Park and Repetto Hills. Borehole and exploratory trench studies across parasitic folds on the forelimb of this anticline through downtown and east Los Angeles indicate that the Elysian Park anticline is a south-verging, fault-propagation fold above the tip of the Elysian Park fault, a blind thrust fault (Figure 5). This fault is estimated to produce an earthquake of M6.2–6.7 every 500 to 1,300 years, an event roughly comparable to the 1971 San Fernando and 1994 Northridge Earthquakes (Oskin et al., 2000).

Strong Ground Motion

Based on SCEC research, seismic shaking within the Los Angeles area is better modeled than shaking in any other seismogenic area in the world (Field, 2000). Seismic shaking in the Los Angeles basin is controlled by the shape and geology of the basin. Using a three-dimensional finite-element mathematical model of the basin, combined with the geologic units and shear wave velocity profiles of those units, a map of theoretical shaking amplification has been prepared for the Los Angeles area (Figure 14A) (Field, 2001). Built into this model are two of the most important geologic factors that influence the amount of shaking: thickness of sediments above bedrock and relative softness of the surface and near-surface materials (Figure 14B). With this new model of shaking amplification, scenario earthquakes (Figure 15) can be developed using path effects through the basin to more precisely estimate potential earthquake effects on the surface environment, particularly to human-built structures (Field et al., 2001). In response to the Seismic Hazards Mapping Act of 1990, the California Geological Survey has prepared Ground Motion Maps that show the maximum horizontal accelerations having a 10 percent probability of being exceeded in a 50-year period (corresponding to a 475-year return period), in keeping with the UBC level of hazard.

Liquefaction

The 1933 Long Beach, 1971 San Fernando, and 1994 Northridge Earthquakes were accompanied by costly damage from earthquake-induced ground failure. In 1971, liquefaction caused the partial failure of the hydraulic fill embankment of the Lower San Fernando Dam (see discussion of local dam failures, below). The destruction of the Juvenile Hall facility in the San Fernando Valley in 1971 was caused by lateral spreading, a form of liquefaction that results in shallow flow failures on gently sloping ground. The Juvenile Hall landslide was reactivated during the 1994 Northridge Earthquake, resulting in minor

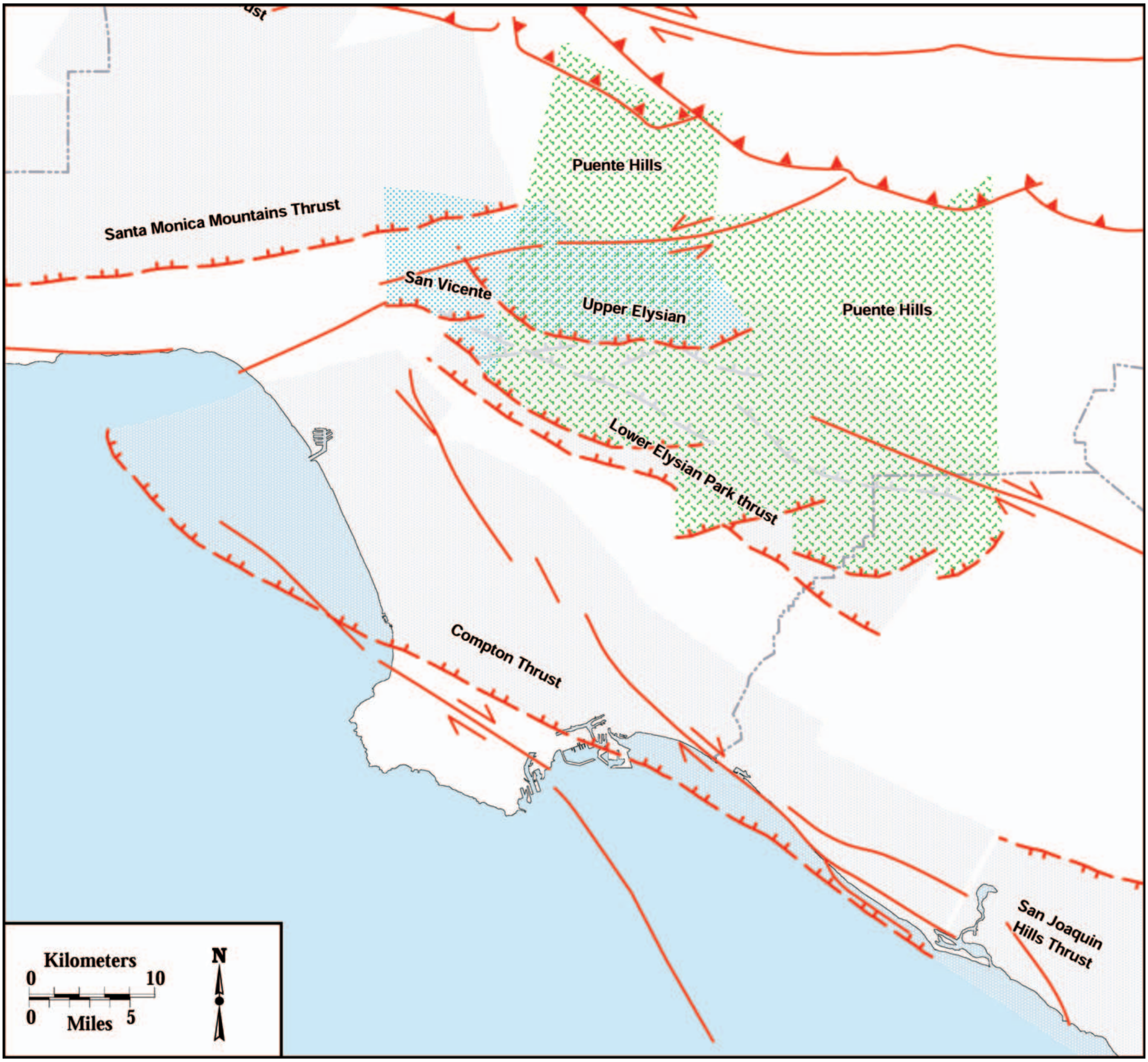

Figure 13. Blind thrust fault ramps (after Jennings, 1994; Shaw et al., 2002).

downslope movement marked by 6-in. (15-cm)–offset curbs. Although there were localized areas of liquefaction and lateral spreading, the amount of liquefaction caused by the 1994 Northridge Earthquake was less than expected. This is explained by relatively low groundwater levels in the San Fernando Valley (Wald et al., 1995). Ground failure of poorly compacted artificial fill in all three earthquakes also caused damage to bridge approaches and roadways.

Since the early 1900s, the growing agricultural use of groundwater in the coastal lowland and valleys of Los Angeles has caused regional lowering of groundwater levels. In general, this depletion of groundwater can be credited with reducing the liquefaction hazard. However, the reduction in agricultural land use in the basin, coupled with high residential landscape watering, has resulted in the reestablishment of some of the previous historically high groundwater levels (Youd and Perkins, 1978; Tinsley et al., 1985). Where groundwater is present at less than 10 ft (3 m) below the ground surface, the liquefaction potential is high; conversely, where water is below 30 ft (9 m), the liquefaction potential is judged to be low (Youd and Perkins, 1978).

The most comprehensive liquefaction studies conducted in Los Angeles County (Tinsley et al., 1985)

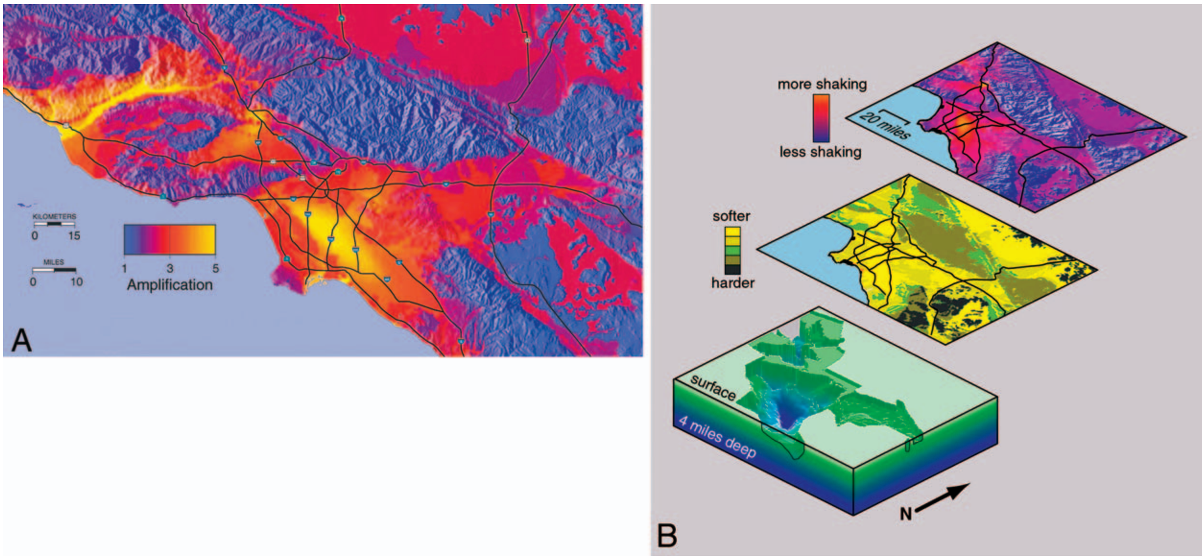

Figure 14. (A) Seismic shaking amplification in southern California (from Field, 2001). The yellow areas are "hotspots," where amplification is predicted to be the highest. (B) The lower block diagram shows sediment thickness and the middle layer illustrates relative softness of the surficial materials underlying the region (from Field et al., 2001).

utilized soil profile development and patterns of historical flooding and flood deposits as mapping criteria to delimit Quaternary units. Cone penetrometer data from selected boreholes provided textural control for these mappable geomorphic units. This study also separated the relative susceptibility into three units: sediments deposited within the past 1,000 years—the most susceptible; sediments deposited during the preceding 10,000 years—highly to moderately susceptible, depending upon sorting; and Pleistocene deposits—unlikely to liquefy.

Tinsley and Fumal (1985) measured shear-wave velocity at 84 sites in the Los Angeles area to correlate velocity with the age and textural characteristics (grain size, sorting, relative density) of alluvial sediments. The age and textural characteristics of the surficial geologic materials were used with the liquefaction units defined by Tinsley et al. (1985) to classify the relative liquefaction susceptibility for the Los Angeles area (Leighton and Associates, 1990). In response to the Seismic Hazards Mapping Act of 1990, the California Geological Survey prepared guidelines for evaluating and mitigating seismic hazards, including liquefaction (California Geological Survey, 1997). Maps delineating the seismic hazard zones, as defined by the State of California, are now available for download from the Californian Geological Survey website and are the basis for Figure 16, which shows liquefaction-prone areas in the Los Angeles region. These maps show areas of either historic occurrence of liquefaction or local geological, geotechnical, and groundwater conditions that indicate a potential for liquefaction.

Tsunami Hazard

Tsunamis are long-wavelength sea waves produced when sudden vertical movement of the seafloor displaces ocean water. The seafloor motion can be caused by faulting, volcanic eruptions, or large submarine slope failures. Tsunamis can travel thousands of miles without a reduction in size, at speeds as great as 500 mi (800 km) per hour. The coastline geomorphology and sea-bottom topography may accentuate the wave by focusing tsunami energy into narrow inlets, harbors, embayments, or other low-lying areas (Urban Regional Research, 1988). Tsunami approach is typically preceded by nearshore water withdrawal followed by a series of shoreward surges as the wave crests come ashore.

Two areas along the Los Angeles coastline particularly vulnerable to tsunami inundation and major damage are the Los Angeles/Long Beach Harbors and Marina del Rey. The coastline is subject to tsunami risk both from distant Pacific-wide (far-field) and local near-field sources. The 1960 M9.5 Chile and 1964 M9.2 Alaska Earthquakes generated the largest far-field tsunamis recorded in southern California. The Chile event resulted in a 5-ft (1.5-m) wave height that caused little structural damage in Los Angeles Harbor but that destroyed over 300 small pleasure boats and created a potential fire threat from spilled gasoline. The 1964 tsunami produced wave heights of less than 4 ft (1.2 m) in tide-gage records in Los Angeles Harbor and caused about $500,000 damage to several small boat docks, pilings, and the Union Oil Company fuel dock (Lander et al., 1993).

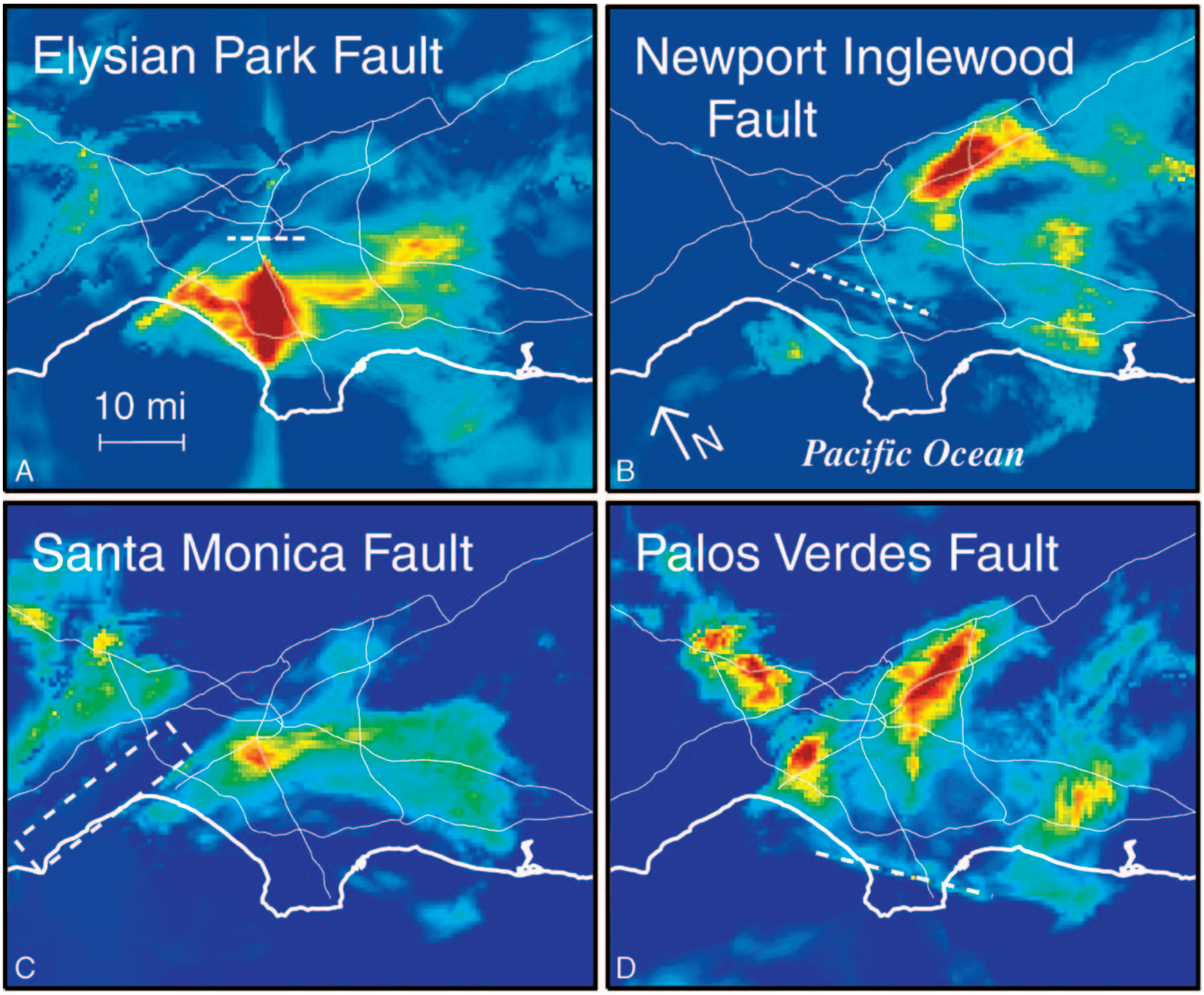

Figure 15. Earthquake shaking intensities for modeled earthquakes on four separate faults in the Los Angeles area. The Elysian Park fault (A), Newport–Inglewood fault (B), Santa Monica fault (C), and the Palos Verdes fault (D) were chosen because they have sufficient data to model and are the likely causative faults for damage in Los Angeles (from Field et al., 2001).

There is a distinct possibility that a hazardous near-field tsunami could be generated off the coast of Los Angeles (Borrero et al., 2005; California Seismic Safety Commission, 2005). The 1812 Santa Barbara Earthquake reportedly produced tsunami run-up heights along the Santa Barbara coastline of approximately 7–12 ft (2.1–3.7 m). The better-documented 1927 Point Arguello Earthquake (M7.3) produced tsunami wave heights of 6 ft (2 m) (McCulloch, 1985; Lander et al., 1993; and Borrero et al., 2001). The offshore 1933 Long Beach Earthquake (M6.4) had a strike–slip focal mechanism and did not generate a tsunami. The 1930 Santa Monica Bay Earthquake (M5.2) produced unusual waves in Santa Monica Bay and may have triggered a submarine landslide, but no tsunami was recorded (Lander et al., 1993; Legg et al., 2004; and Borrero et al., 2005). Recent work at the USC Tsunami Research Center has modeled potential tsunami wave run-up along the southern California coast from both offshore faulting (with associated M7+ earthquakes) and submarine slope failures (Borrero et al., 2004, 2005; Legg et al., 2004). These studies indicate that tsunami wave run-up from near-field sources could range from 1.6 to 20 ft (0.5–6.0 m). The USC Tsunami Research Center has also produced tsunami inundation maps for the California Office of Emergency Services (Eisner et al., 2001). Borrero and others (2005) estimate that potential economic losses from a major tsunami could range from \$7 billion to \$42 billion, depending on how much damage occurs to the Los Angeles/Long Beach port infrastructure.

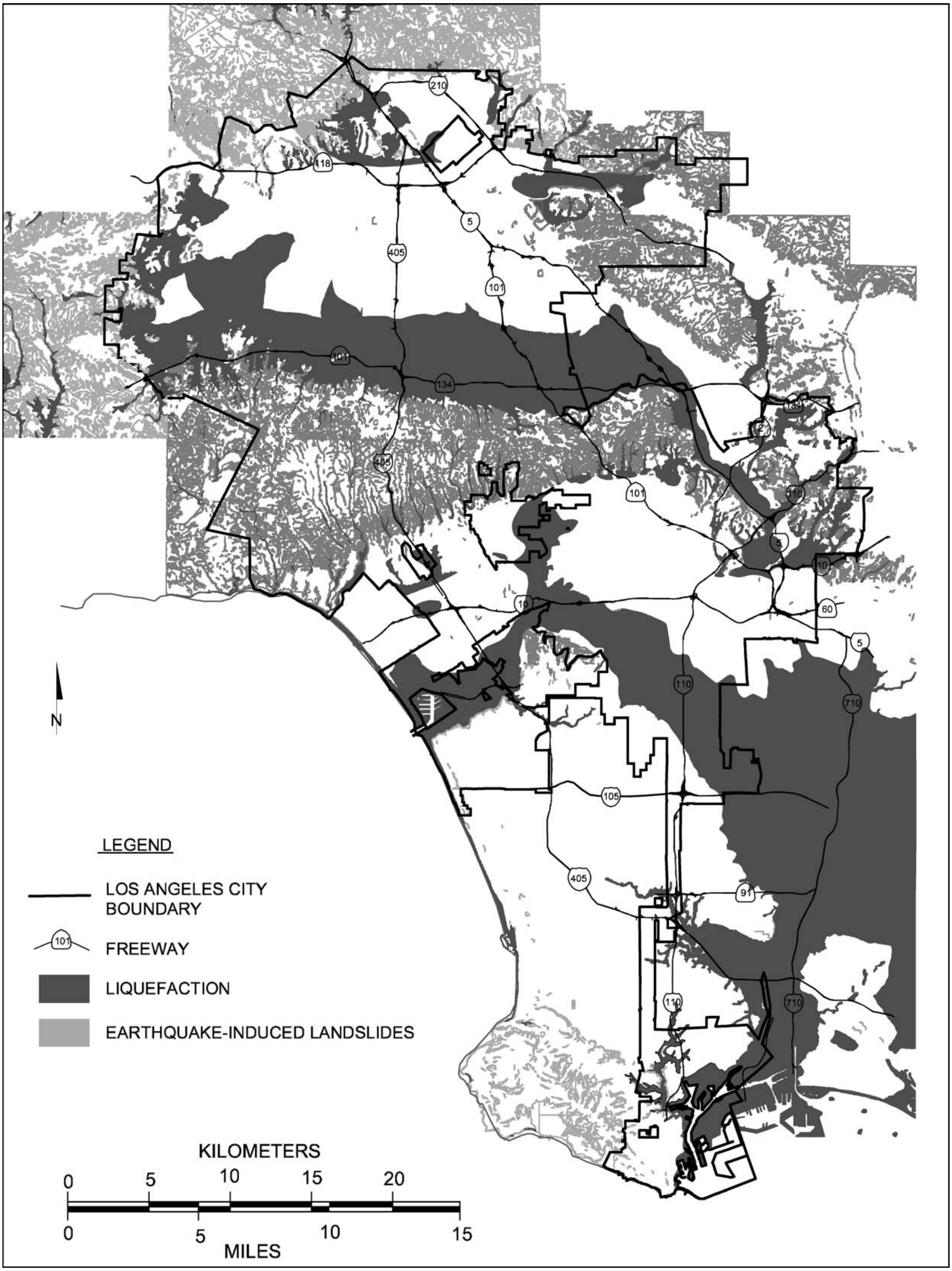

Figure 16. Landslide and liquefaction hazards in Los Angeles, as depicted on city engineering maps (from the City of Los Angeles).

Table 3. *Major Los Angeles landslides since 1956.*

Year and Identification	Cost (in 2000 dollars, unless otherwise noted)	Summary
1956 Portuguese Bend	$14.6 million	Expensive, single-family houses were constructed with individual septic systems, generally consisting of septic tanks and seepage pits. Landslides have been active here for thousands of years, and modern landslide activity initiated in August 1956
1958–1971 Pacific Palisades	$29.1 million	Damaged California Highway 1 and one house
1961 Mulholland Cut	$41.5 million	Damaged Interstate 405, 11 mi north of Santa Monica
1963 Baldwin Hills Dam failure	$50 million (1963 dollars)	The December 14 landslide caused the dam to fail and sent 360 million gallons of water into the community below. Five people were killed
1969 Seventh Ave., Los Angeles County	$14.6 million	Damaged Highway 60
1971 Upper and Lower Van Norman Dams, San Fernando	$302.4 million	Earthquake-induced landslides due to the February 9, 1971, magnitude 6.5 San Fernando Earthquake. Severely damaged the dams
1971 Juvenile Hall, San Fernando	$266.6 million	Landslides caused by the February 9, 1971, San Fernando Earthquake. Damaged the San Fernando Juvenile Hall. The 1.2 km–long slide also damaged trunk lines of the Southern Pacific Railroad; San Fernando Boulevard; Interstate Highway 5; the Sylmar, CA, electrical converter station; and several pipelines and canals
1977–1980 Monterey Park and Repetto Hills	$14.6 million	100 houses damaged in 1980 as a result of debris flows
1979 Big Rock landslides	Approximately $1.08 billion	California Highway 1 rockslide in Malibu
1980 Southern California slides	$1.1 billion in damage	Heavy winter rainfall in 1979–1980 triggered landslides in six Southern California counties
1983 Big Rock Mesa landslides	$706 million	Cost in legal claims, condemnation of 13 houses and 300 more threatened; rockslide triggered by rainfall
1994 Northridge Earthquake landslides	Cost not calculated	As a result of the magnitude 6.7 Northridge Earthquake, more than 11,000 landslides occurred over an area of 10,000 km^2. Most were in the Santa Susana Mountains and in mountains north of the Santa Clara River Valley. Destroyed dozens of homes, blocked roads, and damaged oil-field infrastructure. Caused deaths from Coccidioido-mycosis (valley fever), the spore of which was released from the soil and blown toward the coastal populated areas. The spore was released from the soil by the landslide activity
March 1995 Los Angeles and Ventura Counties	Cost not calculated	Above-normal rainfall triggered damaging debris flows, deep-seated landslides, and flooding. Several deep-seated landslides were triggered by the storms. There also was widespread debris-flow and flood damage to homes, commercial buildings, and roads and highways in areas along the Malibu coast that had been devastated by the 1993 wildfire

Source: City of West Covina (2004).

Slope Stability

Landslides and debris flows have been a recurring problem in the Los Angeles area (Leighton, 1966; Wilson and Pike, 2005) (Table 3). The city encompasses wide-ranging geologic terrains, with several formations that are notable for landslides. Most of the landslide-prone bedrock formations are Neogene marine deposits that contain interbeds of low-strength clayey shale. The Miocene marine formations, notably the Modelo, Puente, and correlative Monterey Formations, contain interbeds of tuff and tuffaceous shale that have altered to bentonitic clay. These bentonite beds have very low shear strength and form the failure planes for landslides, such as the Pt. Fermin and Portuguese Bend landslides in the Palos Verdes Hills. The larger Portuguese Bend landslide (considered a mega-landslide) was active in late Quaternary time, when precipitation was much greater, groundwater levels were higher, and local base level (sea level) was lower, and this landslide has been reactivated following urban development (Ehlig, 1992).

The Jurassic Santa Monica Slate, which underlies a great portion of the eastern Santa Monica Mountains, is also prone to slope failure. The Santa Monica Slate is a deep marine deposit metamorphosed, sheared, and fractured within a subduction zone. The slate exhibits foliation parting surfaces at an orientation commonly subparallel to relict bedding. This structural character leads to unpredictable slope stability. Landslides can occur along shear

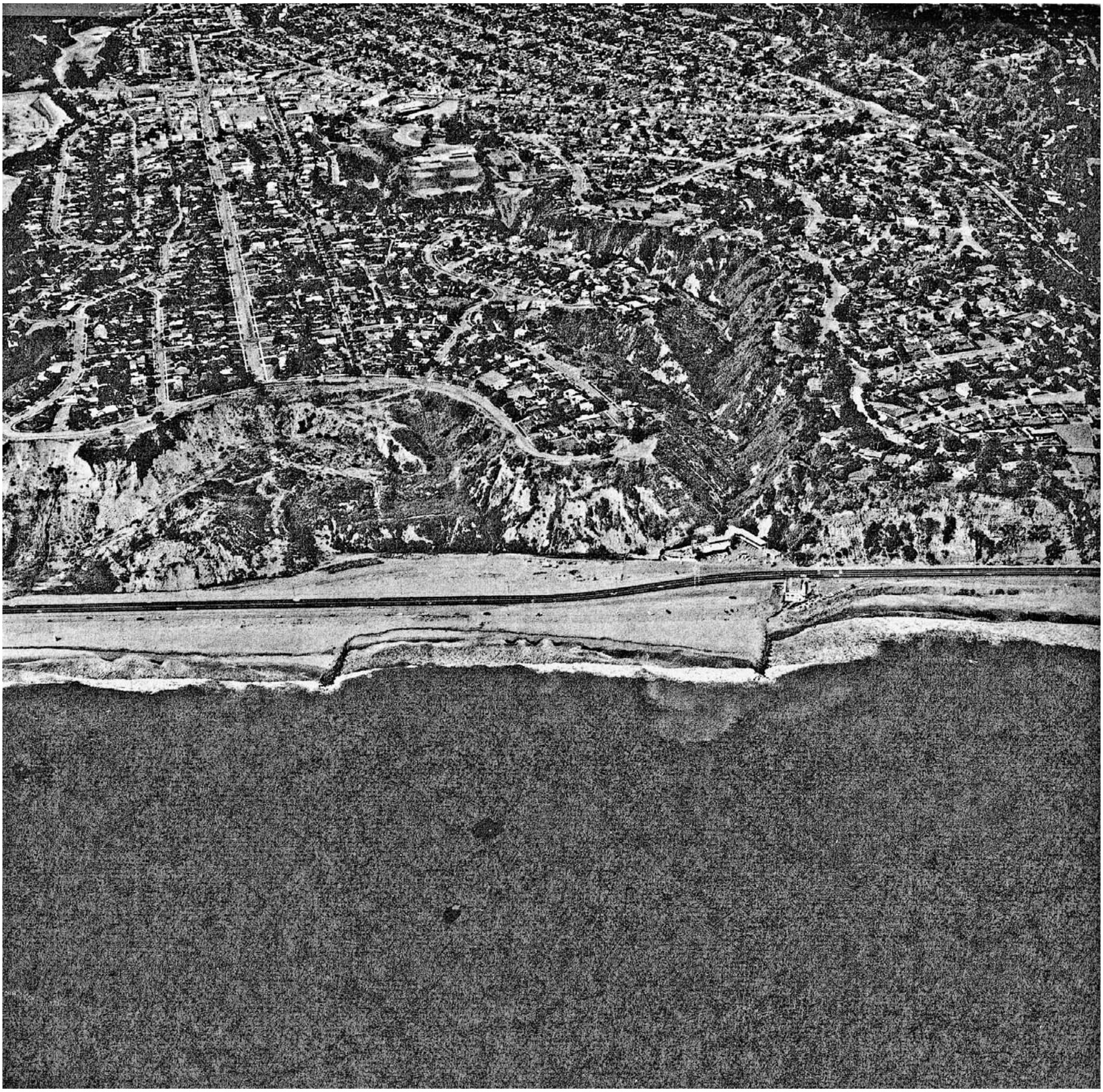

Figure 17. Pacific Palisades landslide along Pacific Coast Highway following heavy rains in 1952 (Division of Highways photo, May 1960).

surfaces, joints, foliation, or a combination of these features.

Uncontrolled grading in hillside areas of Los Angeles beginning at the turn of the century included the practice of placing uncompacted fill over surficial soil deposits, adversely oriented bedrock structure, and on ancient landslides. Slope failures in Los Angeles are exacerbated by the periodic fires that denude the hill slopes and are followed by heavy rainstorms that erode and mobilize earth materials that are no longer anchored by vegetation (Figure 17). Table 3 lists notable slope failures that have occurred in Los Angeles and the approximate costs associated with them. The destruction of personal and public property resulting from slope failures influenced the city of Los Angeles to be one of the first municipalities in the nation to adopt hillside-grading ordinances (Scullin, 1983).

Slope failures are an ongoing problem in hillside areas, where rainfall and overwatering of landscaping combine to soften and saturate steep slopes. Several years have been particularly damaging, but the rains

Figure 18. Santa Monica Palisades landslide after the 1994 Northridge Earthquake.

of 1938 stand out as the most devastating. The onslaught of storms during that winter culminated in widespread flooding and thousands of shallow debris flows. In 1969, debris flows caused more than 10 deaths in Los Angeles County (Weber, 1980) and at least $6 million in property damage (Campbell, 1985). In 1978 major rainstorms triggered destructive debris flows from burned hillside areas in the San Gabriel Mountains and from unburned slopes in the Santa Monica Mountains and Baldwin Hills. These debris flows resulted in property damage estimated at $100 million (Slosson and Krohn, 1982). In February 1980 six closely spaced rainstorms caused major landslides and debris flows that killed several people, blocked roads, destroyed 111 homes, and damaged more than 1,350 others (Weber, 1980). Public and private property damage from the February 1980 storms was estimated at $140 million (Slosson and Krohn, 1982). Similar widespread rain-induced landslide activity occurred in 1993, 1995, and 2005, again resulting in tens of millions of dollars in property losses.

Earthquake-induced landslides are also a problem in the Los Angeles area. The 1971 San Fernando Earthquake triggered more than 1,000 landslides in the hills and mountains north of San Fernando Valley (Morton, 1971). In 1994, the Northridge earthquake generated over 11,000 landslides and slope failures (Figure 18), most within the Neogene sedimentary rocks of the Santa Susana Mountains north of Los Angeles (Harp and Jibson, 1995). Dust released by these failures contained fungal spores that resulted in 150 cases of the endemic lung disease ‘‘valley fever,’’ three of which proved fatal.

In recognition of the economic losses caused by earthquake-induced landslides, the state legislature passed the Seismic Hazards Mapping Act in 1990, which required the California Department of Conservation, Division of Mines and Geology (now the California Geological Survey, CGS) to prepare guidelines for evaluation of seismic hazards other than surface fault rupture and to recommend mitigation measures. In response, the CGS published Special Publication 117, which provides guidelines to practicing geologists and engineers for evaluation of seismic hazards, especially liquefaction and landslides (California Geological Survey, 1997). CGS created a state-wide seismic hazard mapping and technical advisory program to assist cities and counties in fulfilling their responsibilities for protecting public health and safety from the effects of seismic hazards caused by earthquakes, including landslides.

The general engineering practice in the city of Los Angeles is to provide static and, where needed, seismic slope stability analysis. Static slope stability analyses use static-limit equilibrium-stability analysis methods, with appropriate representations of the site conditions, such as slope configuration, distribution of earth material, material strength, and groundwater conditions. The determination of adequate slope stability has traditionally been made by calculation of the slope stability ‘‘factor-of-safety,’’ which is the ratio of the driving forces to the resisting forces. A factor-of-safety of 1.0 indicates a condition of balanced forces, and, thus, a factor-of-safety of 1.5 insures an adequate safety margin. Traditionally, the City of Los Angeles has required that slopes potentially affected by seismic shaking be analyzed by the pseudo-static method.

Geotechnical investigations for hillside development in the Santa Monica Slate are very complex. For example, sampling and testing a paper-thin clay seam along a shear or foliation plane is problematic. Methods used for determining the shear strength of the slate include remolding samples, carving samples from blocks, and repeated shearing of samples to try to create planes of weakness similar to those observed with *in situ* conditions. Ultimately it becomes a matter of engineering judgment to select representative strengths based on laboratory results, geologic observation, and experience.

The Los Angeles Section Geotechnical Group of the American Society of Civil Engineers and several municipalities, including the City of Los Angeles, formed a committee of experts to provide guidelines for implementation of the requirements of the Seismic Hazards Mapping Act. The committee spent several years researching the state of current professional practice and published guidelines for analyzing and mitigating landslide hazards in California (Blake et al., 2002).

Expansive Soils

Expansive soil contains clay minerals, such as montmorillonite, that significantly increase in volume when wetted and decrease in volume when dried. The pressures caused by expansive clay can crack foundations and walls. Structures built on expansive soil typically exhibit cracks in stucco, plaster, sheetrock, and driveways, as well as doors and windows that stick. Expansive clay is present within alluvial fans in the Los Angeles basin and the San Fernando Valley, within portions of the Santa Monica Mountains, in the Palos Verdes Hills, and within fault and fracture zones. Soils derived from volcanic rocks commonly contain expansive clay minerals. Expansive clay may also be incorporated within engineered fill.

Expansive soils are identified through a shrink–swell test. To mitigate the effects of expansive soils, they can be removed, replaced, or blended with nonexpansive material. In addition, foundations can be designed for isolation from the expansive elements or to withstand the expansive pressures. The Los Angeles Municipal Code (section 91.1804.4) identifies the requirements for foundations for single-family dwellings on expansive soils. A critical element for the management of structures built on expansive soils is to maintain constant moisture, thus halting the shrink–swell cycle.

Flooding

Los Angeles is vulnerable to a wide range of flood hazards, including intense winter storms and failure of man-made structures. In most years, Los Angeles receives only enough rain to turn the hills green for a few weeks, but every few years the region is subjected to intense and prolonged rainfall that causes flooding. Intense storms present a flood hazard for developments located in narrow canyons in hillside areas, as well as for those on alluvial fans and valley floors. A particularly dangerous combination, intense storms coupled with burned watersheds, places developments located at the base of steep mountainous terrain at extreme risk from mudflows and debris flows (California Department of Water Resources, 1980; Davis, 1982; and Los Angeles County Department of Public Works, 1986). Extremely rapid flash floods—those that are beyond the design capacity of the flood control system—can also cause failure of dams, levees, and channels, as has occurred several times in many parts of Los Angeles County. Such failure is most likely to occur when rain falls at rates of 1 in./hr (2.5 cm/hr) or greater (California Department of Water Resources, 1980).

Historic documentation of flooding goes back to 1770, when Franciscan priests recorded flooding that changed the course of the Los Angeles River (Alfors et al., 1973). Since 1811 the Los Angeles River has flooded 30 times. Until 1825 the Los Angeles River channel extended westerly from present-day downtown to the now mostly dry Ballona Creek bed, which empties into the Pacific Ocean near Marina del Rey (Figure 1). The flood of 1825 caused the Los Angeles River to change channels to a southerly route, with its present mouth in what is now Long Beach Harbor on San Pedro Bay.

In the 1920s and 1930s, following the destructive floods of 1914, the Los Angeles County Flood Control District (now part of the County Department of Public Works) built five large catchment dams for flood control (Table 4). Then, in the 1940s and 1950s, after the flood of 1938, the U.S. Army Corps of Engineers built five additional large catchment dams and flood control channels along the major rivers (Table 4). Despite the high level of protection that the system provides against flood hazards in Los Angeles, some areas may still be at risk. After the 1978 and 1980 storms (Garza and Peterson, 1982; Chin et al., 1991), high runoff resulting from increased urbanization required upgrading of the major downstream flood control channels, designed and built to older Corps of Engineers standards. Because of such deficiencies, the Corps developed new "flood frequency standards" to identify areas susceptible to flood damage. Preliminary

Table 4. *Major flood control dams in Southern California.*

Owner Name of Dam	Year	Size (acre-ft)	Size (m^3)	Type
Los Angeles County				
Big Tujunga	1931	4,000	4,934,000	Arch
Cogswell	1935	8,000	9,868,000	Rockfill
Pacoima	1929	4,000	4,934,000	Arch
Puddingstone	1928	17,000	20,969,500	Earth
San Gabriel No. 1	1938	44,000	54,274,000	Earth
U.S. Corps of Engineers				
Hansen	1940	27,000	33,304,500	Earth
Prado	1941	314,000	387,320,000	Earth
Santa Fe	1949	32,000	39,472,000	Earth
Sepulveda	1941	17,000	20,969,500	Earth
Whittier Narrows	1957	67,000	82,644,500	Earth

1-in-100-year and very conservative 1-in-500-year flood limits have been prepared for several main drainages, including the Los Angeles River. These maps are based on a much more severe flood hazard criterion than the flood limits used by the National Flood Insurance Program, which is based on the 1974, 1-in-100-year flood standards.

California's Worst Flood—1861–1862

The "Great Flood" of 1861–1862 affected the entire west coast of the United States and Baja California, Mexico. Except for two clear days, rain began on December 24, 1861, and didn't stop until January 12, 1862. It was estimated that 35–50 in. (89–127 cm) of rain fell. The entire Sacramento and San Joaquin Valleys became a shallow inland sea. Another inland sea formed in Orange County, with water covering farmlands and homes for as far as 4 mi (6.4 km) on either side of the Santa Ana River. The Los Angeles River overflowed its channel, forming a large lake that filled the entire valley area from downtown to the ocean, toward both San Pedro and Marina del Rey along Ballona Creek (Newmark, 1916; Troxell, 1942; and Gumprecht, 1999). The 1861–1862 flooding was followed by California's most severe drought, in which much of the state's cattle perished.

The Flood of 1938

The second worst flood in southern California occurred between February 27 and March 4, 1938, when 22.5 in. (57 cm) of rain fell. One and one-half times the annual precipitation fell in just 6 days. As in the flood of 1861–1862, the Los Angeles and Santa Ana Rivers overflowed (Figure 19), causing 87 deaths and $79 million in damage (Troxell, 1942). As a consequence of this flooding, the U.S. Army Corps of Engineers built five additional large flood control dams downstream from the previously constructed dams to help prevent future flooding (Table 4). In addition, more than 130 debris basins have been built at the mouths of canyons, and more than 1,000 miles (1,600 km) of lined channels have been built by the Corps of Engineers and the Los Angeles County Department of Public Works.

Hazardous Gases

Oil and gas seeps have been evident in Los Angeles since its founding. Generation of oil and thermogenic methane from thick Neogene-source rocks in the Los Angeles basin and San Fernando Valley continues today. Seepage of natural gas is particularly hazardous because of its explosive character and the presence of highly toxic hydrogen sulfide. Safety issues have spurred the City of Los Angeles to establish methane mitigation requirements for construction in methane hazard zones throughout the city.

San Fernando Tunnel Explosion

On June 24, 1971, a fatal natural gas explosion occurred in a tunnel under construction beneath the community of Sylmar, in the northern San Fernando Valley (Figure 1). Of the heading crew, 17 workers died and one survived. The tunnel was being built for the Metropolitan Water District (MWD) as part of their distribution system for California Aqueduct water. Before the explosion halted work for 2 years, the 22-ft (6.7-m)–diameter tunnel had been excavated for 5 mi (8 km) of the total 5.5-mi (8.8-km) length.

Factors that may have contributed to the disaster were (a) inadequate ventilation; (b) a malfunctioning

Figure 19. The Los Angeles River destroying a railroad bridge during the March 1938 flood (Troxel, 1942).

gas detector and/or an improperly trained "sniffer" operator; (c) allowing welding and smoking at the face, despite a minor gas explosion the previous night that hospitalized four workers; (d) the lack of spark-preventative safeguards on the tunnel boring machine; and (e) the lack of breathing packs in the tunnel. Of these factors, abundant ventilation is most critical to dilute the gases. The most common underground gas is methane, which is explosive only when mixed with air in concentrations between 5 percent and 15 percent. At less than 5 percent methane, the lower explosive limit (LEL), methane merely burns, and above 15 percent it is not an explosive hazard. Therefore, one purpose of tunnel ventilation is to supply enough air to keep methane below the LEL. Modern tunnels in gassy ground are provided with detectors that audibly warn if methane exceeds 20 percent of its LEL. Because of this explosion, higher tunnel safety standards have been written; thus, the lessons learned at Sylmar may have prevented other disasters (Proctor, 2002).

Fairfax District Methane Explosion

Surface gas and tar seeps led to the 1902 discovery of the Salt Lake oil field (Figure 7) in the Fairfax District. The area is underlain by approximately 100 ft (30 m) of unconsolidated alluvial deposits that overlie the San Pedro Formation and the oil-bearing sandstone and shale of the Repetto and Pico Formations. The bedrock is folded into west- and northwest-plunging anticlines bounded by faults to the north and south. The 1,200-acre (486-hectare) Salt Lake field was developed with over 500 wells (Cobarrubias, 1992).

Approximately 50 million barrels of oil were produced from the field. Most wells were abandoned in the 1930s, and although records are sparse, the standard practice of the day was to remove the top 6–8 ft (1.8–2.4 m) of casing and backfill the well boring with timber, soil, or other waste. Most wells were abandoned in this manner and therefore can provide a conduit for liquids or gases to migrate vertically.

Only a few of the wells were properly plugged with cement, in accordance with present standards for well abandonment.

Urbanization of the area increased in the 1930s. Installation of pavement, building foundations, and other impervious features affected the natural process of gas venting that had been occurring throughout the field. Today, the La Brea Tar Pits continue to vent gas bubbles in the asphaltic "tar." The potential for natural gas accumulation in this area was further indicated by the seepage of oil and methane into several basements in the surrounding area (Richards, 1973).

Renewed drilling activity began in the field around 1961. To enhance recovery and to dispose of saltwater produced along with the oil, the water was reinjected into the field from the Gilmore Drilling "Island," just north of the La Brea Tar Pits. This "island" includes 43 wells and covers about 1 acre (0.4 hectare) of land. Use of directional-drilling methods on the "island" allowed for new production within a 1 mi^2 (2.6 km^2) subsurface area while affecting a very small surface area (Figure 8). The saltwater injection may have caused local overpressured zones and pressure-induced hydrofracturing of the Third Street fault. This newly created fracture porosity could provide a conduit for methane gas to reach the surface along the fault (Hamilton and Meehan, 1992).

Employees and patrons of the Ross "Dress for Less" clothing store, located just four blocks from the La Brea Tar Pits, had noted an odor of burned coffee and sewage throughout the day on March 24, 1985. Late in the afternoon, an explosion and fire blew out the windows of the store and caused partial collapse of the roof. Of the 75 people in the store, 23 required hospital treatment for injuries (Hamilton and Meehan, 1992). Four surrounding blocks were closed off, and small fires were evident in the store, in landscaping planters, from cracks in the pavement, and from storm-drain vaults. The fires were allowed to burn in the hope that gas pressure would be relieved.

Analysis of the gas revealed that it was composed of almost pure methane. There were no traces of the chemicals that are added to commercial gas prior to sale or transportation. Seepage from numerous abandoned oil wells in the area or the Third Street fault was the most probable source of the gas (Figure 8). The Los Angeles City Council formed a task force to investigate the cause of the explosion and to present recommendations necessary to protect health and safety in the area. The task force included representatives from city and state agencies along with engineering geologists, petroleum geologists, and landfill engineers. Acting on recommendations in the task force report, the City Council added the first "methane mitigation ordinance" to the Los Angeles Municipal Code (Cobarrubias, 1992).

The methane mitigation ordinance requires new construction in "methane gas potential risk zones," as delimited in the task force report, to have subslab membrane barriers, vent piping, methane detection systems and alarms, interior ventilation, and venting of paved parking areas. Existing buildings must be retrofitted with detection systems to give warning of methane presence prior to an accumulation of an explosive level. Gas is monitored on a 24-hour basis (Cobarrubias, 1992).

Hydrogen Sulfide Hazard, Los Angeles Metro Route

Following the 1985 methane gas explosion in the Fairfax District, congressional legislation was enacted that prohibited federal funding for subway construction in the "methane gas potential risk zones." Because of this, the original Los Angeles Metro Rail subway route that extended west of downtown was changed to a new alignment routed south of the Fairfax District (Mid-City route) (Proctor et al., 1985). In the early 1990s, workers boring along this new route encountered concentrations of hydrogen sulfide gas at concentrations of up to 15,000 ppm (Elioff et al., 1995). Unlike methane, hydrogen sulfide is highly toxic. Concentrations of this gas as low as 100 ppm can cause loss of smell, lung irritation, and temporary blindness. Gas concentrations of 500 ppm can be fatal, as a result of respiratory paralysis (Doyle, 2001).

In response to finding abundant hydrogen sulfide gas, the Metropolitan Transportation Authority (MTA) created a consulting board to reassess the Mid-City subway route (Engineering Management Consultants, 1994). The board consisted of seven civil engineers and an engineering geologist. The board advised MTA to avoid the hydrogen sulfide gas area by routing the subway even farther south. This western extension of the Mid-City route has not been constructed, although the Mid-City Exposition light rail (aboveground) transit project is moving forward along this alignment (Metropolitan Transportation Authority, 2005). In 2006, after new tunneling safety evaluations of the methane gas potential risk zones, congressional legislation (H.R. 4653–Waxman) was introduced to repeal the subway prohibitions from federal law, and the MTA is once again considering the westbound subway route through the Fairfax District (Metropolitan Transportation Authority, 2006).

Gases at the Belmont Learning Center

The Los Angeles Unified School District (LAUSD) acquired a 35-acre (14.2-hectare) site near downtown in 1996 for the Belmont Learning Center, a proposed high school site. The property is located within the Los Angeles City oil field (Figure 7), and one inactive oil well was found onsite. During site grading, hydrocarbon-rich soil from former oil-field operations was exposed. The California State Department of Toxic Substances Control (DTSC) required comprehensive environmental investigations to identify and evaluate potential health and safety risks. These investigations showed that the site had gas emissions of methane (explosive) and hydrogen sulfide (toxic and explosive). Part of the learning center structure had already been built when construction was halted by the LAUSD in 1999. Mitigation measures for potential health and explosion risk from emissions had not been required at the initial stages of site construction. This necessitated that the buildings already constructed be retrofitted with venting systems. These added costs and the newly revealed safety risks received extensive coverage in local newspapers and became an issue of great political controversy.

On October 14, 2001, the California legislature passed Assembly Bill 1301, which required LAUSD to prepare and submit to the DTSC a remedial investigation and feasibility study report for the Belmont Learning Center. In 2002 site development was further complicated by the discovery of a fault zone in part of the site. In 2003 and 2004 the development was redesigned, buildings were demolished and reconstructed, and a gas venting and monitoring system was installed. A park (Vista Hermosa Park) is planned for the portion of the site where the fault zone was identified. Because of the stigma now attached to the name Belmont, as a result of the controversy and cost overruns, the development has been renamed Central Los Angeles High School #11–Vista Hermosa Plan. The gas emission issues at the Belmont Learning Center and the Fairfax District reaffirm the potential hazards associated with development in Los Angeles above former oil fields (Gamache and Frost, 2003; Department of Toxic Substance Control, 2005).

Methane Gas at Playa Vista

Playa Vista is a large, mixed-use residential development project in west Los Angeles, next to Marina del Rey and Ballona Creek (Figure 1), that includes part of the former Hughes Aircraft facility. The development is located on the coastal plain of the Los Angeles basin in a small valley referred to as Ballona Gap. Prior to 1825, the Los Angeles River flowed through this area, depositing fluvial sediments that interfinger seaward with deltaic and marsh deposits. Following the 1825 flood, the Los Angeles River shifted southward to its present outlet at the Long Beach Harbor. Ballona Creek now follows the former westward river course through Ballona Gap to Santa Monica Bay. The present-day coastal environment includes a wetlands area that is being restored as part of the redevelopment process.

A portion of the development project lies on the eastern fringe of the administrative boundary of the Playa del Rey oil field, which produces from an anticlinal trap in Neogene sedimentary rocks. Five wells (dry holes) were drilled on the project site in the 1930s during exploration of the Playa del Rey oil field. In 1942, a depleted portion of the oil field, adjacent to Playa Vista, was turned into an underground natural gas storage facility and is presently operated by The Gas Company (formerly the Southern California Gas Company) (Barnds, 1968).

As the Playa Vista project proceeded through the environmental impact analysis, geotechnical investigations, and agency review process, the potential hazard of methane gas seepage became a point of controversy and concern to the City of Los Angeles and the surrounding community. Requirements for investigation and mitigation of potential gas seepage hazards were incorporated into the development plan. During the Playa Vista development design and review process, the city proposed new regulations to update the 1985 methane mitigation ordinance contained in the Los Angeles Municipal Code. As part of this revision of the ordinance, new boundaries were designated for methane zones and methane buffer zones throughout the city where gas potential has been identified (Ordinance No. 175790, adopted by the Los Angeles City Council in February 2004). This ordinance establishes city-wide requirements for expanded testing and installation of state-of-the-art methane mitigation systems.

MAJOR ENGINEERED STRUCTURES

The modern high-rise buildings, utility lines, dams, freeways, subways, and port facilities in Los Angeles are major engineered structures. Those discussed below represent large-scale structures that employed significant application of engineering geology in their development and construction.

Los Angeles Metro Rail System

Los Angeles is one of the world's largest and most motorized cities, with the automobile accounting for 90 percent of all transportation. Even so, Los Angeles has developed one of the world's largest bus fleets. Traffic congestion and related air pollution problems

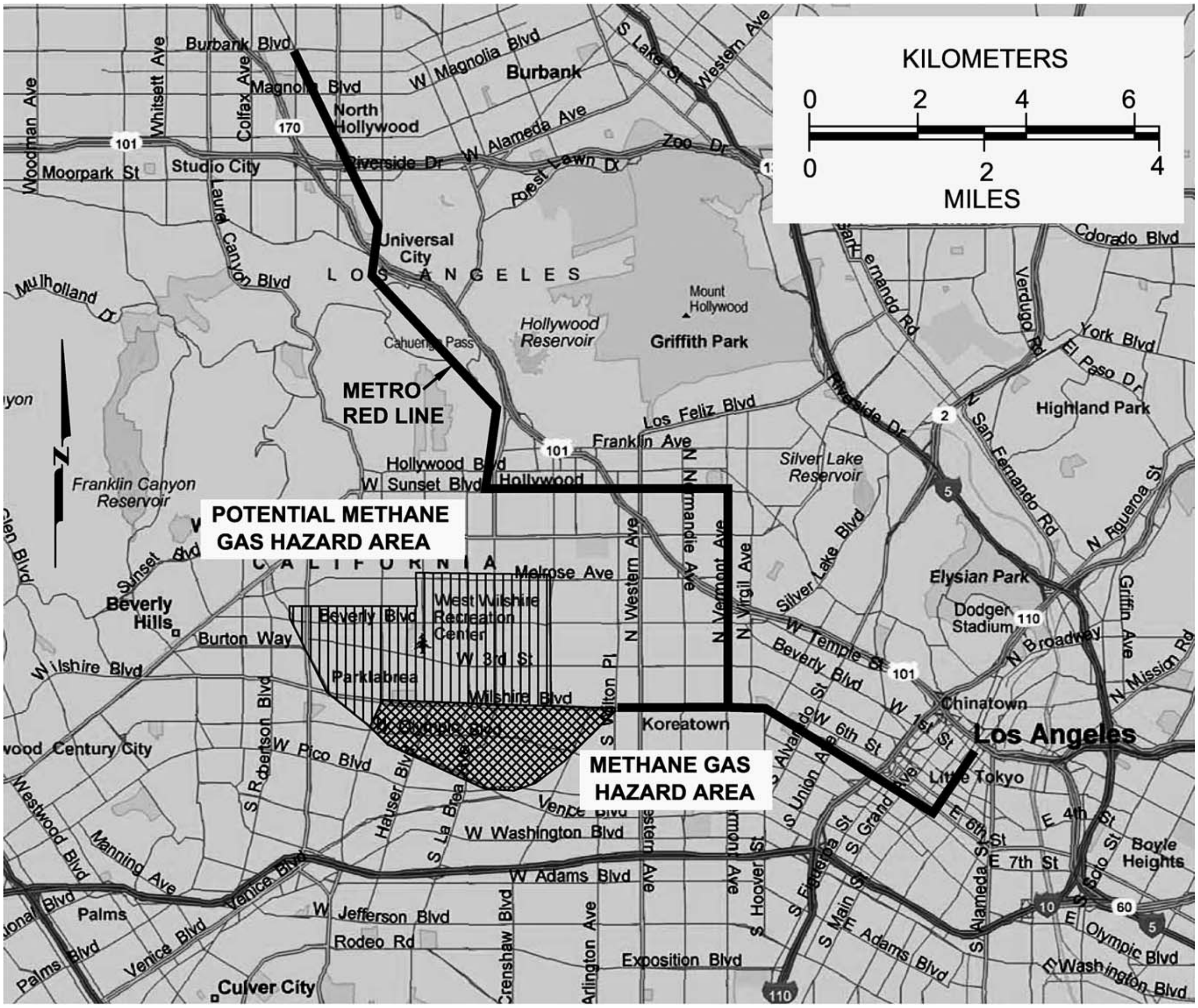

Figure 20. Route of the Los Angeles Metro Red Line, changed in 1987 to avoid methane gas hazard zones in the Fairfax District. Los Angeles central business district to the right and San Fernando Valley to the top left.

have brought worldwide attention to a city in love with the automobile. Current projections indicate that the average rush hour speed is expected to drop to 16 mph (26 km/hr) by the year 2025 (Metropolitan Transportation Authority, 2001).

In the early 1950s, the world's most extensive trolley network (1,100 mi [1,770 km] of rails), the Pacific Electric "Red Cars," was abandoned. City engineers began planning for a modern replacement rail system and other forms of mass transportation to ease automobile congestion. The Los Angeles Metro Rail system was conceived in 1978 under the auspices of the Southern California Rapid Transit District (SCRTD). At that time the Metro Rail Geotechnical Consulting Board was formed; this board comprised three civil engineers, three engineering geologists, and a seismologist. The geology and seismology of the proposed rail routes are discussed in Converse Consultants and others (1981, 1983). In 1993 the SCRTD name was changed to the Los Angeles County MTA.

In 1987, with substantial Federal funding, construction commenced on the first section of the heavy-rail Metro Red Line subway. The initial 9 mi (14.5 km) of the Red Line was opened in 1992, and when completed in 2000 it extended 17.4 mi (28 km), from Union Station in downtown Los Angeles to North Hollywood in the San Fernando Valley (Figure 20). Its excavated diameter measures approximately 21 ft (6.4 m), and it contains twin-tube tunnels and 16 underground stations (Escandon et al., 1992; Stirbys et al., 1998). The first above-ground light-rail portion of the system, the Metro Blue Line, a 22-mi (35.4-km) route between downtown Los

Angeles and Long Beach, was opened in 1990 (Figure 1). Since then, two other light-rail lines have been constructed: the Green Line between downtown and Redondo Beach and the Gold Line between Union Station and Pasadena.

Creation of Metro Red Line Segment 3 required tunneling 2.4 mi (3.9 km) through the Santa Monica Mountains. The twin tunnels are located as deep as 900 ft (274 m) below the surface. This segment traverses Cenozoic shale, sandstone, and volcanic rocks as well as Mesozoic conglomerate and granodiorite. The subway crosses the active Hollywood fault (predominantly reverse-slip), where the tunnel was enlarged from 20 to 29 ft (from 6.1 to 8.8 m) in diameter. This increase in width accommodates subway offset in the event of fault displacement.

Most tunneling in Los Angeles occurs in weak sedimentary rock ("soft ground"), which is ideal for rapid excavation by tunnel-boring machines. However, the Metro designers and constructors were aware of many natural hazards, such as collapse-prone alluvial soil, active faults to be crossed, gassy (natural gas) ground, abandoned oil-well casings, hazardous substances, and locally high groundwater. Because of these conditions, many special procedures have been added to the design, construction, and operational phases of the Metro Rail project (Association of Engineering Geologists, 1981; Desai et al., 1989; and Escandon et al., 1992). To help prevent gases and groundwater from entering the tunnels, a 1/10-in.–thick high-density polyethylene plastic membrane lining was used in certain stretches of the subway (Navin, 1991).

The originally planned Metro alignment crossed the Salt Lake oil field in the Fairfax District. A gas explosion in 1985 at the Ross "Dress for Less" store (discussed in "Hazardous Gases" section) along the planned alignment in the Fairfax District resulted in congressional legislation stipulating that Federal funds could not be used for tunneling in an area identified as a "methane gas potential risk zone" (Figure 20).

The possibility of encountering abandoned well casings is high in major oil-producing areas, such as the downtown Los Angeles City oil field. Such well casings might contain residual gas and if punctured during excavation could rapidly fill a tunnel, creating an explosive or asphyxiating atmosphere. During tunnel excavation for the Red Line, magnetometer surveys in the tunnel warned the contractor of any casings. Later, the ground-penetrating radar technique replaced the magnetometer surveys. This technique is unique in that it can be used to identify all types of well casings, including those made of wood. When old casings were encountered, specific procedures were followed to cut safely through the casings (Stirbys et al., 1998).

Some of the geotechnical instruments used to monitor the tunnel construction activities included inclinometers to monitor the wall deflections in access shafts and station excavations; observation wells to monitor water levels along the tunnel alignments and station excavations; load cells to monitor the stability of tieback anchors used in station support elements; strain gauges installed circumferentially around support struts to monitor load build-up during excavation; borehole extensometers placed along the tunnel alignments to monitor ground and surface movements; tape extensometer anchors at intersections of tunnel and cross passages to monitor convergence; and surface/building survey reference points to monitor settlement (Stirbys et al., 1998).

During Los Angeles Metro Rail tunnel excavation, at 5:00 AM on June 15, 1995, a portion of Hollywood Boulevard collapsed. Seventy feet (21 m) below street level, as the tunnel was being widened, miners heard creaking and ran to safety prior to the collapse. The ensuing sudden inflow of alluvium, broken utility pipes, pieces of street pavement, chunks of Puente Formation shale, and water partially filled the tunnel for several hundred feet. At the surface, a survey crew happened to notice the enlarging sinkhole and halted traffic. The hole enlarged to a width of 80 ft (24 m). About 1 mi (1.6 km) west of the sinkhole, the surface of Hollywood Boulevard subsided as many as 10 in. (25 cm). This caused cracks in the adjacent sidewalk, the famous Hollywood Walk of Fame, and in the facades of the adjacent buildings. A multi–billion dollar lawsuit was brought by the owners of the buildings against the MTA, the City of Los Angeles, and the tunnel contractor. The MTA reached settlements with the property owners totaling over $11 million, all of which was covered by insurance. Ultimately the street was raised and underlying soil consolidated by compaction grouting (Proctor, 1998).

Los Angeles Dodgers Stadium

Chavez Ravine is a large arroyo immediately north of downtown Los Angeles in the Elysian Hills (Figure 1). In the late 1950s, the Brooklyn Dodgers organization moved to Los Angeles and chose this site for a ballpark. The area was sparsely settled because of the rugged hills and deep, narrow gullies. Excavation required removal of a hill 125 ft (38 m) high to form a horseshoe-shaped stadium. The foundation rock of the stadium is Puente Formation sandstone and shale of Miocene age. Figure 21 shows strata dipping favorably 45–50° into the cut. Deep canyons beneath the side portions of the stadium,

Figure 21. Excavation of Dodgers Stadium in 1960 showing dipping beds of the Puente Formation.

previously used for the dumping of trash and debris, were removed and backfilled with on-site excavated sandstone and shale. Locally the sandstone was too hard for normal excavation and had to be drilled and blasted. The stadium is located 3 mi (4.8 km) from the active Raymond fault. The structure is designed for the maximum acceleration this fault would generate, with columns designed for total loads, including seismic loads. Built on bedrock, the stadium, which opened in 1962, has fared better during earthquakes than have many structures built on the alluvium of the Los Angeles basin (Smoots and Melickian, 1966).

J. Paul Getty Center

The J. Paul Getty Center in Los Angeles (the second Getty Foundation art museum in the area) opened to the public in December 1997. The $733 million, 24-acre (9.7-hectare) complex, which contains a museum and research institute for art and the humanities, sits atop hills in the exclusive Brentwood neighborhood of Los Angeles. Construction of the travertine-clad buildings began in 1989 and had to overcome many geological engineering challenges. Foundations for the six major buildings consist of 40–50-ft (12–15-m)–deep drilled caissons and spread footings. The biggest challenge was the inactive Benedict Canyon fault that runs under the museum, where 8-in. (20-cm), up to 200-ft (61-m)–long seismic-absorption joints were required in the floor slabs. Deep caissons anchor the building to the sedimentary bedrock, and shallow footings were used to accommodate movement in the gouge zone of the fault. Any anticipated movement would be sympathetic slip caused by an earthquake on some other "active" fault. During the 1994 Northridge earthquake, welds cracked in the steel framing of one of the three Getty buildings under construction. Subsequent repairs were made based on rapidly initiated, Getty-sponsored research with the American Institute of Steel Construction. The new construction methods suggested by the research were incorporated into the rest of the buildings. During grading, a canyon was filled in with 400,000 yd^3 (305,840 m^3) of earth to support the museum and the air conditioning cooling tower. While preparing the canyon for the fill, an old landslide was encountered, and 75,000 yd^3 (57,345 m^3) of material was moved to stabilize the slope. Seismic safety engineering was a priority for all the buildings, not just the main museum building (Post, 1994).

Los Angeles City Hall Seismic Renovation

Los Angeles City Hall, constructed in 1926, was the tallest building in the city, at 460 ft (140 m) (32 stories), until the 1960s, when the 150-ft (46-m) height limitation ordinance was lifted. The ordinance was removed when structural engineers, using seismic shaker-table modeling from Caltech, convinced the city that skyscrapers could be safely built in earthquake country. City Hall has survived hundreds of earthquakes with the foundation, base, and structural steel frame remaining essentially intact. Unfortunately, the 1971 San Fernando, 1987 Whittier, and 1994 Northridge Earthquakes damaged the masonry walls of the building, causing significant cracks in the exterior terra-cotta tiles and the interior plaster. To strengthen the building against future earthquakes, City Hall has recently undergone a seismic retrofit using base isolation with supplemental damping. Finished in 2001, the seismic renovation included installation of over 500 isolators and sliders, 52 nonlinear viscous dampers under the existing basement, and 12 nonlinear viscous dampers between the 26th and 27th floors to decouple the building from ground motion caused by an earthquake. In addition, 3,000 tons of structural steel and an integrated shear wall structure were added to the core of the building to strengthen its structural integrity (Youssef and Hata, 2005).

Port of Los Angeles and Pier 400

The Port of Los Angeles (POLA), founded in 1907, is the nation's busiest port. Located on San Pedro Bay, the 7,500-acre (3,035-hectare) harbor is about 20 mi (30 km) south of downtown (Figure 1). Along the 43 mi (69 km) of waterfront, POLA has 26 cargo terminals, with a total wharf length of about 5 mi (8 km). Traditionally, POLA wharves are supported on piles driven into the dense alluvial sand and gravel of the ancient (early Holocene) Los Angeles River channel, which is typically encountered at about 60 ft (18 m) below sea level. The wharves are constructed along underwater slopes that are either cut or dredged into the natural silt deposits overlying the alluvial sand and gravel or they are formed by rock rip rap–bounded containment dikes containing hydraulically placed fill (Roth et al., 1992).

Earlier multilift dike construction methods have been replaced by full rock dikes that are more resistant to earthquake shaking. Wharves were traditionally supported by timber piles until the mid-1920s, when precast concrete piles were introduced. From the early 1960s to about 1982, 16–18-in. (41–46-cm) octagonal prestressed concrete piles were used. In 1982, POLA abandoned batter piles for lateral wharf support in favor of a design with 24-in. (61-cm)–diameter vertical piles. The increased lateral flexibility of this new design is intended to minimize earthquake shaking damage through creation of a unitized mass below each wharf (Roth et al., 1992).

Building on the Port's older hydraulic fill, or using these areas for storage of bulk or container freight, often requires that the fill soil be improved. The most common improvement technique involves surcharging with temporary fill, the weight of which is equivalent to or exceeds the expected live load. This drives out pore water and hastens densification by consolidation. After initially allowing settlements of 2 ft (0.6 m) or more under a 10–30-ft (3–9-m)–high fill, subsequent live-load–induced settlements are then reduced to a few inches (or centimeters) over a period of many years. For very fine-grained fill, a consolidation time of a few months may be shortened to a few weeks by installing vertical wick drains, a technique now widely employed for thick embankments (Roth et al., 1992).

Pier 400, which began operations in 2004, is built on one of the largest artificial fill structures constructed in Southern California. Its construction replaced 25 percent of the water in Los Angeles Harbor with a massive compacted earth fill. The earth fill covers 484 acres (196 hectares), and sediment dredged during deepening of the existing ship channels provided the majority of the material for construction. The Pier 400 container terminal is currently the largest single container-handling facility in the world. Owing to the large size of the project and the potential for negative environmental impact, innovative solutions were employed to mitigate potential problems such as air pollution, wildlife impact, and sediment management. Physical modeling of the pier/landfill design and evaluation of resulting wave effects were carefully studied, following techniques pioneered by the Waterways Experiment Station of the Army Corps of Engineers (Vicksburg, MS). Conservative tracer tests were also conducted to determine water migration and particle dilution patterns in the harbor (Shibao, 2004).

To minimize air pollution, most dredging employed electric-powered machinery. In addition, an on-site concrete plant was constructed, reducing the number of vehicle trips needed to supply the site. Over 10 million metric tons of quarried rock were used to construct the retaining dikes and to protect the landfill's perimeter. The rock material, which included individual pieces weighing more than a ton, came from a quarry on Santa Catalina Island, 26 mi (42 km) away. By bringing the rock material from this nearby island, vehicle long-haul trips were omitted. The complex geology and ecology of the pier area required extensive investigation, mitigation, and management throughout construction. Dredged material with unsuitable engineering qualities for the earth fill, such as silt and clay, which tend to sequester pollutants, was used to form permanent, constructed shallow-water habitats for fish and terrestrial flora and fauna. Environmental concessions were made as part of the construction plan; three shallow-water habitats were created, as was a 15-acre (6-hectare) designated nesting site for the endangered California Least Tern (Shibao, 2004).

Local Dams

The more than 20 dams with large reservoirs in southern California are major engineered structures that must be sited and designed to withstand the variety of hazards that exist in the area. Three dam failures in southern California are worth noting—one was caused by earthquake shaking and two were caused by unsuitable foundation conditions.

St. Francis Dam Failure—1928

St. Francis Dam, 45 mi (72 km) north of Los Angeles and built by the City of Los Angeles, failed suddenly during initial filling in 1928, drowning more than 400 people (Figure 22). This failure led to the requirement for thorough geologic investigations prior to dam siting and led, in part, to the development of engineering geology. The dam failure also prompted the California legislature to regulate the construction and operation of dams in the state by passing the 1929 Dam Safety Act. The dam was sited on a fault that separates two strikingly different foundation materials, sandstone and adversely dipping schist. Many prominent engineers and geologists investigated the failure, and several books have been written about it. It was suggested that the fault provided a conduit for piping of water under the dam, resulting in erosion of the foundation. However, Rogers (1992) found and published previously unknown original drawings of the dam and conducted an in-depth analysis of its failure. He determined that the most probable cause of failure was a foliation plane landslide in the adversely dipping schist at the left abutment. Also, air photos, unavailable at the time of dam construction, show existing geomorphic evidence that the left abutment was part of a large preexisting, ancient, quasi-stable slide mass.

Baldwin Hills Dam Failure—1963

The Baldwin Hills Dam, an earthfill dam that created a 19-acre (7.7-hectare) reservoir, was constructed on a hill in Los Angeles by excavating the hilltop and creating a dam by filling a ravine (Wilson, 1949; Figure 23). The Baldwin Hills are the neotectonic expression of transpressional movement along the active Newport–Inglewood fault zone, splays of which cross the reservoir. The 1963 failure of the dam probably stemmed from both poor site location (it was located on a fault) and deficient dam-lining design. Differential subsidence along the fractured fault zone likely was caused by local petroleum withdrawal (by pumping) and the weight of the reservoir water on the lining overlying the fault. Leaking reservoir water entered and traveled along the fault surface and was largely undetected by the subdrain monitoring system. The resultant piping caused failure of the northeast corner of the dam embankment, and five people drowned (Kresse, 1966; James, 1968; and Hamilton and Meehan, 1971).

Lower San Fernando Dam Partial Collapse—1971

A disaster was narrowly averted when 80,000 people were evacuated for 3 days following the partial collapse of the Lower San Fernando Dam during the 1971 San Fernando Earthquake. The nearest surface-rupture traces in 1971 were only a few hundred feet (about 100 m) east of the dam on the Mission Wells fault segment, though the epicenter of the earthquake was approximately 17 mi (27 km) northeast. The dam

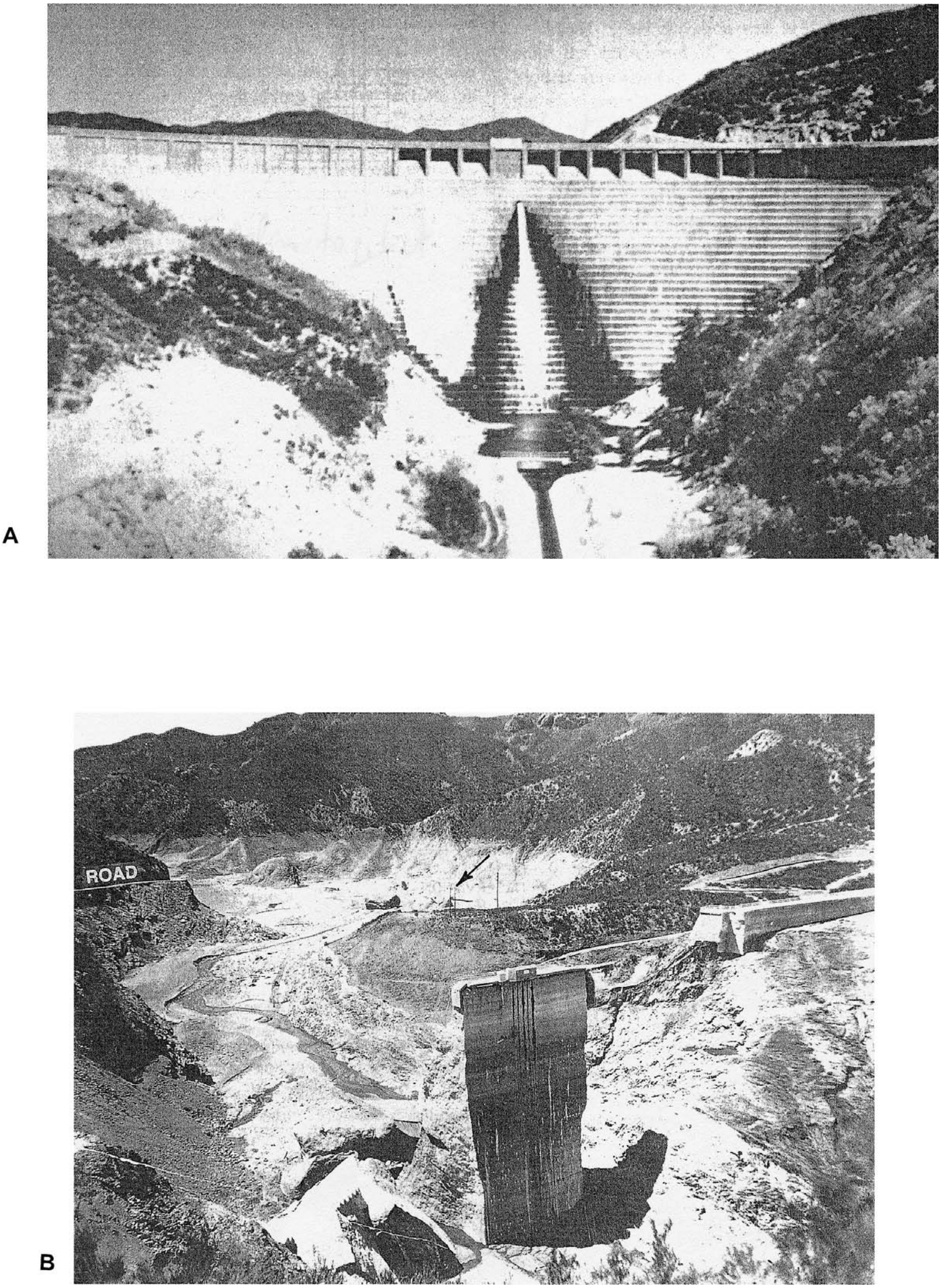

Figure 22. (A) St. Francis Dam as viewed from the north, as it appeared just after its completion in May 1926. The dam was 200 ft (61 m) high and is situated on a fault that separates sandstone from schist. (B) St. Francis Dam, viewed from the north, after the collapse and resulting flood. (Photos courtesy of Ventura County Museum of History and Art.)

Figure 23. Baldwin Hills Reservoir 1963 failure (after Hamilton and Meehan, 1971).

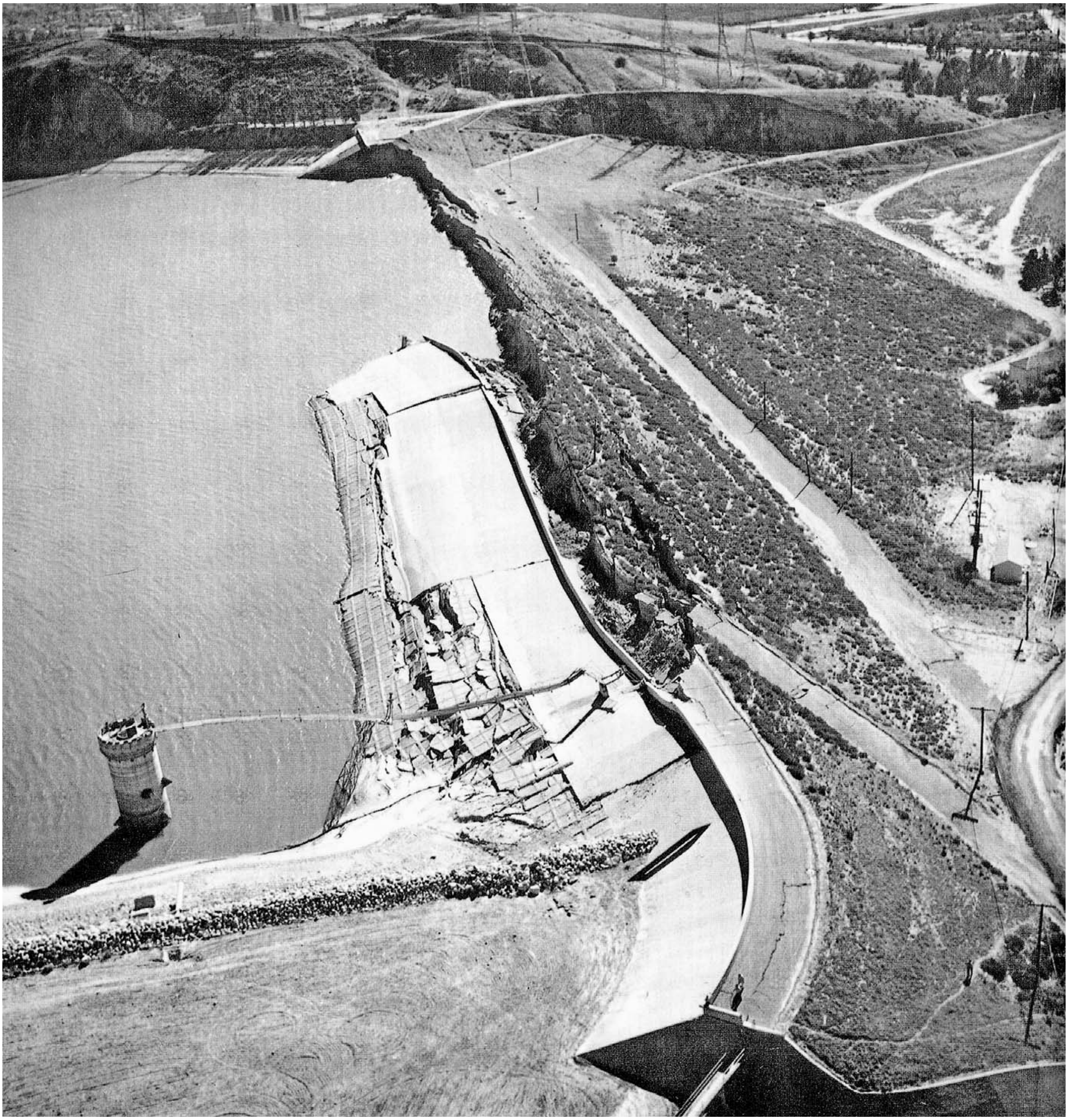

Figure 24. Lower San Fernando Dam and Lower Van Norman Reservoir after the 1971 San Fernando Earthquake. Slumping of the concrete lining was caused by liquefaction of the earthen dam's hydraulic fill during the earthquake. (Photograph by R. E. Wallace, from U.S. Geological Survey, 1971.)

was constructed to create the Lower Van Norman Reservoir. It was built in 1918 using the hydraulic-fill method of consolidating earthfill by ponding, a technique common in its day. During the strong ground shaking associated with the M6.7 quake, much of the embankment slid into the reservoir (Figure 24). The reservoir water level was just 4 ft (1.2 m) below the top of the headscarp of the embankment slide mass, thus preventing instantaneous overtopping. Fortunately, the reservoir level was 14 ft (4.3 m) lower than normal when the earthquake occurred, and a disaster was narrowly averted. The reservoir was emptied, the embankment reshaped, and a new, smaller dam, called the "Los Angeles Dam," was constructed in 1977 within the old reservoir (Scott, 1971; Yerkes et al., 1974; Seed, 1975; and Mayeda and Weldon, 1978).

USE OF UNDERGROUND SPACE

More than 70 tunnels, with a total combined length of over 50 mi (80 km), have been bored within the city limits. The two oldest tunnels still in use were constructed in 1876 by Chinese laborers who moved down from the Mother Lode goldfields; one is a railroad tunnel and the other is a water conduit in which redwood staves were used for lining. The largest diameter tunnel (56-ft [17-m] half-circle) is part of the Pasadena Freeway (Proctor, 1973, 1992b).

In the Los Angeles area, more tunnels have been built to supply water than for the most common purpose in most other large cities of the world: heavy-rail subways. The need for extensive importation of water by aqueducts exists because Los Angeles is in a semiarid region, and tunnels are required because the Los Angeles basin is surrounded by hills and mountains (Yerkes et al., 1977).

Three major aqueducts, the largest water-conveyance system in the world, bring water to southern California. These aqueducts are described later in the "Water Supply" section. Each aqueduct has tunnel segments. The Owens Valley, or Los Angeles City, Aqueduct was completed in 1913. Its headwaters are in the Sierra Nevada, 350 mi (563 km) to the north, and it includes 76 mi (122 km) of tunnels. The Colorado River Aqueduct, completed in 1939, brings water from Lake Havasu on the Colorado River, 300 mi (483 km) to the east, and includes 92 mi (148 km) of tunnels. The California Aqueduct of the State Water Project, completed in 1974, pumps water from the Sacramento River Delta 400 mi (640 km) to the north and includes 19 mi (30 km) of tunnels. Consequently, potable water delivered to the Los Angeles area probably spends 4 days traveling more than 300 mi (480 km) through one of the three man-made rivers to reach the final user.

In addition to aqueduct tunnels, there are 27 mi (43 km) of sewer tunnels and 19 mi (30 km) of flood control tunnels in the Los Angeles area. Presumably, future tunnels for the Los Angeles area will continue to be built for water supply, sewers, and storm drains as well as for transportation and should total about 60 mi (96 km) in the next 15 years. Two unique transportation plans include proposed 12–15-mi (19–24-km) tunnels through the San Gabriel Mountains for high-speed trains linking San Diego and San Francisco and a high-speed train from Los Angeles to Las Vegas. Of the 110-mi (177-km), five-corridor rapid transit routes proposed by the MTA, most are proposed to be subways. Subways are planned here partly because of the favorable geologic conditions present in most of the Los Angeles basin, specifically, firm soils and deep groundwater levels (Walton and Proctor, 1976).

PROFESSIONAL PRACTICES

Exploration Methods

The American Society for Testing and Materials has published standards for the completion of geotechnical explorations, which are typically called Phase I or Phase II investigations. An investigation of any real property identified for transfer or development normally begins with review of the geologic and geotechnical literature, followed by interpretation of aerial photographs, and, if warranted, concludes with surface and subsurface site investigations and laboratory testing of materials.

Excellent sources of aerial photographs are available for Los Angeles. The Fairchild Aerial Photography collection is located at Whittier College; the Spence Air Photo collection (and copies of the Fairchild collection) at the University of California, Los Angeles; and additional air photos are at the Alexandria Digital Library, University of California, Santa Barbara. In addition, several commercial collections are available for specific searches for a fee. These photographic collections date back to 1927 and are invaluable for site-specific geologic analysis. Historical aerial photos are particularly useful for detecting and mapping land-use changes through time and for identifying geomorphic evidence of adverse geologic features such as landslides, active faults, infilled gullies, or other former topographic depressions.

Rotary bucket, frequently referred to as bucket auger, is the preferred method for conducting geotechnical investigations in soil and soft rock. During drilling, the bucket, which is typically 24 in. (61 cm) in diameter, is advanced about 6–12 in. (15–30 cm) each run. A significant advantage of rotary bucket is the ability of the geologist to enter the 24–36-in. (61–91-cm)–diameter boring in a metal safety cage for detailed logging. "Downhole" logging in this manner provides a means of directly observing, measuring, and sampling subsurface geologic features and materials. This procedure is common in southern California. The California Occupational Safety and Health Administration (CAL-OSHA) has imposed stringent safety requirements on this type of downhole geological logging. Workers are required to ventilate the boring using an air-blower connected to a long hose and to have two-way communications. Rotary bucket drilling is, however, inherently limited to depths above local groundwater levels.

Soil and rock sampling traditionally employ the Standard Penetration Test (SPT) Sampler and the California Drive Sampler. The SPT consists of a 2-in. (5-cm)–outside diameter, 1.375-in. (3.5-cm)–inside diameter, 18-in. (46-cm)–long split-spoon. The sampler is driven into the ground by a 140-lb (63.6-kg) hammer falling 30 in. (76 cm). The number of blows necessary to drive the SPT sampler the last 12 in. (25.4 cm) of a total 18-in. (46-cm) interval is the SPT blow count or N-value. This N-value is a quantitative means to determine the relative density of in-place material.

The California Drive Sampler is a cylinder, approximately 2 ft (61 cm) long, lined with twelve 1-in. (2.54-cm)–high removable brass or stainless-steel rings or sleeves. The inside diameter of the device is typically 2.5 in. (6.35 cm). The unique sampling feature of this device is that its sampling rings fit standard geotechnical lab test instruments, allowing removal of the sample without disturbing the contained soil. The driving weight for the sampler is highly dependent on the type of drill rig used. Whereas the drop weight on a hollow-stem rig is 140 lb (63.5 kg), a rotary-bucket drop weight can range from several hundred pounds to as many as 4,000 lb (1,814 kg), based on the rig's kelly bar weight and the sampling depth. This method of sampling is effective for obtaining samples so that moisture content, dry density, soil type, and chemical composition can be determined. A thin-walled 3-in. (7.6-cm)–diameter sampling tube is better suited to sample loose sand or soft clays. This device is sometimes pushed into soft or loose sediments to obtain a relatively undisturbed sample for liquefaction evaluation.

The electronic cone penetrometer test (CPT) is best used in ground that is free of alluvial cobbles and boulders. The device uses empirical relationships based on the ratio of tip resistance to sleeve friction to identify the lithology, to provide *in situ* strength information, to measure permeability, and to collect water samples. There are several advantages to the cone penetrometer method: no soil cuttings are generated, the borehole is very small, numerous holes can be advanced at a relatively low cost, and when verified with other traditional subsurface information, the data are generally acceptable for planning and design purposes. Increasingly CPTs are being used to correlate subsurface sediments between holes. The procedures are particularly valuable to assess fault offset of subsurface stratigraphy below regional groundwater levels. Combined with other relative dating techniques, CPT analysis may well produce slip rate information useful to judge the relative motion on faults.

Exploratory backhoe trenches are employed to determine the geologic structure where outcrops are lacking but faulting is suspected. Trench excavations are frequently used to evaluate the surface rupture potential of faults in order to provide appropriate building setbacks from active faults. Trenches deeper than 5 ft (1.5 m) require shoring and/or benching, as required by CAL-OSHA regulations. In areas of thick Holocene alluvium, space permitting, trenches up to 33 ft (10 m) deep are commonly excavated.

Los Angeles has a special place in the development of the maximum dry density test, as it was the invention of Ralph R. Proctor (no relation to a co-author) in 1932; Proctor was a civil engineer and director of the soils laboratory of the Los Angeles Department of Water and Power. Proctor's development of engineering soils test methods led to the formation of the U.S. Bureau of Reclamation Earth Materials Laboratory in 1933 in Denver, CO. This development also led to Dr. Arthur Casagrande initiating, at the request of Professor Karl Terzaghi, the first U.S. university course in soil mechanics laboratory test theory and procedure at Harvard in 1933.

Grading Codes

Urban expansion into the hillside areas of Los Angeles greatly accelerated after World War II. Heavy rains in 1951–1952 caused an estimated $7.5 million in public and private property damage, with eight deaths resulting from the associated mudflows. The public outcry caught the attention of the politicians and building officials, who at that time mainly considered only the needs of developers. In turn, these officials held public hearings, which led to adoption by the city of the first grading ordinance for a U.S. municipality on October 25, 1952. This initial code, however, stressed only supervision of compaction and excavation by a civil engineer experienced in erosion control. The code did not recognize, nor did anyone involved fully understand, the geological processes active in hillside areas. It was, however, a start that was improved upon by the issuance of periodic grading bulletins from the City of Los Angeles Department of Building and Safety (Scullin, 1983).

The Los Angeles Engineering Geologist Qualification Board, created in 1952, established minimum requirements for geologists submitting reports to the city. This was the first such board in the nation. The

Board later served as a Technical Advisory Committee to the Board of Building and Safety Commission, dealing with technical disputes between the Department of Building and Safety staff and private geological consultants.

On October 27, 1960, the city adopted a grading bulletin that addressed geologic factors. This bulletin limited cut slopes to a 1.5H:1V (horizontal to vertical) gradient when the cut exposed Santa Monica Formation (phyllite, slate, and schist) or other rock formations lying westerly and southerly of these metamorphic rocks (which includes bedrock from the Calabasas, Trabuco, Santa Susana, Llajas, Sespe, Vaqueros, and Topanga Formations). By this point it had become clear that the erosion and slope failures in hillside areas were geological in nature. However, these geomorphic processes only become destructive when urban growth is placed in their path or when a natural "hazard" poses a "risk" to people or property. On April 25, 1963, with this wisdom in mind, the city developed the first "modern concept" grading code, with direct emphasis on minimum acceptable design standards and technical input from both a soil engineer and a geologist (Scullin, 1983).

In the City of Los Angeles, a staff of engineering geologists and geotechnical engineers now routinely review consultant reports for hillside developments, subdivisions, and fault study zones. Geologists serve as regular members on the Advisory Agency of the Department of City Planning and the Environmental Review Committee. Grading inspections for permit compliance are performed by technician-level staff grading inspectors or full-time project deputy inspectors. The grading code, therefore, attempts to provide supervision and control for every aspect of grading and hillside construction. Other geology-based ordinances have been adopted to authorize withholding of permits for habitable structures that are suspected to lie astride an active fault or within a designated Potential Methane Zone (as in the Fairfax District).

Seismic Design Provisions

The 1933 Long Beach Earthquake severely damaged schools and URM buildings. This led to passage of the Field Act and the Riley Act by the California state legislature. The Field Act focused on school buildings and the Riley Act addressed multifamily dwellings. Both acts were instrumental in changing building codes and construction practices so as to greatly improve the seismic resistance of buildings in California.

The fault rupture associated with the 1971 San Fernando Earthquake, and the resultant structural damage, prompted the passage of the Alquist–Priolo Act. This act included the development of statewide maps depicting "Special Studies Zones" (now called Earthquake Fault Zones) along active fault traces. It also included a requirement for cities to incorporate a seismic safety element into their state-mandated master plans. The focus of the act was to recognize active faults and to avoid locating structures in zones of likely ground rupture (Hart and Bryant, 1997).

With the passage of the Seismic Safety Act in 1975, California established the Seismic Safety Commission to investigate earthquakes, review earthquake-related issues, and advise state government on earthquake-hazard mitigation and earthquake-related legislation. The Seismic Hazards Mapping Act of 1990 authorized the California Geological Survey (then the Division of Mines and Geology) to produce 24,000-scale maps of the Los Angeles area that delimit liquefaction- and landslide-prone areas. These maps are used by city government to regulate development (Figure 16).

The 1994 Northridge Earthquake also spurred changes in the seismic design provisions of the UBC and development of these provisions in the International Building Code, first published in April 2000. The building code changes were stimulated by the significant damage incurred by moment-resisting, steel-frame buildings. Before the earthquake, this type of structure was thought to be one of the most seismically resistant structural design concepts (Bertero et al., 1994; Chittenden, 1995).

ENVIRONMENTAL CONCERNS

Water Supply

Water is the single most important commodity in semiarid southern California. Seven local public water agencies store and supply potable water to 18 million people, more than half of California's population. Three aqueducts each bring water more than 300 mi (480 km) from three different sources to the greater Los Angeles metropolitan area (Proctor, 1992a, 1998).

The oldest aqueduct is the City of Los Angeles' Owens Valley Aqueduct, completed in 1913 and enlarged in the 1960s, with more than 30 reservoirs on line. Next is the Colorado River Aqueduct of the MWD of Southern California, the construction of which was completed in 1940 and enlarged in the 1960s, with 11 reservoirs on line. The California Aqueduct of the State Water Project was completed in 1972, with four major reservoirs in southern California. Present total water importation is more than 3 billion gallons (11.4 billion liters) per day.

Diamond Valley Lake in Riverside County is the largest reservoir in southern California, with 810,000 acre-ft (999 million m^3) of storage capacity. The reservoir consists entirely of imported water, since there is essentially no natural drainage into the reservoir. Completed in 1999 by the MWD, this reservoir can store as much water as the more than 20 existing major reservoirs in southern California. It is designed to receive and distribute both Colorado River Aqueduct water and State Water Project water to Los Angeles and San Diego metropolitan areas.

The City of Los Angeles prohibits the use of most private water wells and the construction of new wells within the city limits. This was necessary because of the poor water quality in most existing aquifers. Additionally, some neighboring cities along the coast have pumped down the water levels to below sea level, thus allowing intrusion of seawater (Bean and Brown, 1992).

The use of reclaimed water to recharge local aquifers in the Los Angeles region is one of the largest such operations in the United States. Three treatment plants produce reclaimed water for replenishment of local groundwater supplies. Health studies have repeatedly shown that there have been no undesirable health effects on people using well water that included recharged, treated wastewater. Reclaimed water is regulated by the California Regional Water Quality Control Board and the California Department of Health Services. Groundwater use in the City of Los Angeles currently represents less than 20 percent of the total water used.

Los Angeles City Aqueduct

Often referred to as the Owens Valley Aqueduct, this system comprises more than 350 mi (560 km) of pipelines, tunnels, and reservoirs and is the lifeblood of Los Angeles. The aqueduct is an engineering marvel. Construction lasted from 1906 to 1913, and mules were used to haul steel pipe across the desert. On November 5, 1913, water from the Owens River first arrived in Los Angeles. This new source of water came online at the same time that the San Fernando Valley (except for the cities of San Fernando, Glendale, and Burbank) was annexed to the City of Los Angeles (Blevins and Mann, 1994). Major water-storage reservoirs, such as the St. Francis Dam in 1926 and the Bouquet Canyon Dam in 1934, both in the Sierra Pelona range north of Los Angeles, were later constructed (Wilson and Mayeda, 1966). The catastrophic failure of the St. Francis Dam in 1928 during its initial filling was discussed above.

The Los Angeles Aqueduct supplies the city with most of its water, with supplementary water purchased from the MWD and the California Department of Water Resources, usually in the peak-demand summer months.

Colorado River Aqueduct

Completed in 1940, this aqueduct brings water 244 mi (393 km) from the Colorado River near Parker, AZ, to Lake Mathews reservoir near Riverside. Ninety-two miles (148 km) of the 244 miles are traveled through tunnels. The Colorado River Aqueduct was built and is operated by the MWD, a six-county governmental body created in 1928 by the state legislature. The MWD operates the world's largest water distribution system, supplying two billion gallons (7.6 billion liters) of water per day to 220 cities. In 1955, this aqueduct was named one of the original "Seven Civil Engineering Wonders of the United States" by the American Society of Civil Engineers (Proctor, 1966).

California Aqueduct—State Water Project

The California Department of Water Resources (DWR) owns and operates the California Aqueduct of the State Water Project. The DWR began supplying water to MWD and other public agencies in 1974. The aqueduct, beginning in the Sacramento–San Joaquin River delta, divides into two branches just north of the San Andreas fault in the westernmost Mojave Desert. The West Branch supplies water to the Los Angeles metropolitan area, and the East Branch supplies water to the counties of San Bernardino, Riverside, and San Diego (Arnold, 1966). State Water Project water also enters the Colorado River Aqueduct near Perris Reservoir; thus, an additional major source of water enters MWD's terminal reservoir, Lake Mathews, from the east for distribution into the Los Angeles metropolitan area.

Water Supply South of the San Andreas Fault

Water-supply engineers and planners realized long ago that emergency reservoir storage was needed south of the San Andreas fault, because all three aqueduct sources are north and east of the fault. Statistically, a major earthquake is almost certain during the life of these aqueducts. As a result, 14 reservoirs with a storage capacity of approximately 1,900,000 acre-ft (2.3 billion m^3) are available should future movement on the San Andreas fault disrupt one or more of the aqueducts (Table 5). This contingency provides approximately a 6-month water supply while the aqueducts are being repaired.

Table 5. *Major reservoirs south of the San Andreas fault.*

Owner Name of Reservoir	Year	Size (acre-ft)	Size (m^3)	Type
California Department of Water Resources				
Castaic	1973	350,000	431,730,000	Earth
Cedar Springs (Silverwood)	1973	131,000	161,590,000	Earth
Perris	1973	179,000	220,800,000	Earth
Pyramid	1973	78,000	96,213,000	Earth
Los Angeles Department of Water and Power				
Bouquet Canyon	1936	36,000	44,406,000	Earth
Encino	1924	10,000	12,335,000	Earth
Los Angeles	1977	10,000	12,335,000	Earth
Lower San Fernando	1918/1977	10,000	12,335,000	Hydraulic
Mulholland (Hollywood)	1924	4,000	4,934,000	Gravity
Stone Canyon	1924	10,000	12,335,000	Hydraulic
Metropolitan Water District				
Diamond Valley	1999	810,000	999,135,000	Earth
Mathews	1938/1961	182,000	224,500,000	Earth
Morris	1935	34,000	41,939,000	Gravity
Skinner	1973	43,000	53,040,500	Earth

The three aqueduct owners (MWD, City of Los Angeles, California DWR) have detailed contingency plans (emergency response plans) to mitigate any outage along their distribution pipelines and facilities after a major earthquake. These plans include microwave and radio communications (to allow for loss of telephone service) and dispersal and redundancy of emergency personnel to operate critical valves and generators should access routes be blocked to emergency workers.

It is estimated that about 40 percent of the water wells in the greater Los Angeles area will be unusable as a result of a major earthquake (Dames and Moore, 1991). Those wells that can still pump will supply potable water to fill water trucks for local distribution, as was done in parts of the San Fernando Valley after the 1971 and 1994 Earthquakes.

Groundwater

Los Angeles is underlain by several regionally extensive aquifers (e.g., Poland et al., 1959). These aquifers (Figure 25) are interspersed within the alluvium and the Lakewood and San Pedro Formations. Gaspur, Lynwood, Silverado, and Sunnyside Aquifers comprise the principal producing Aquifers under the Los Angeles coastal plain, with the Silverado Aquifer being by far the main source of production. Groundwater is present in five major groundwater basins: Central, West Coast, Santa Monica/Hollywood, San Fernando, and Sylmar basins. The basins are separated from each other by groundwater barriers such as topographic highs, faults, or nearly impermeable subsurface geologic structures.

Groundwater provides about 15 percent of the city's total supply. The San Fernando groundwater basin accounts for about 80 percent of the total groundwater. The city holds water rights in four groundwater basins: the San Fernando, Sylmar, Central, and West Coast basins. The City's annual entitlement in these basins is as follows: San Fernando, 87,000 acre-ft (107 million m^3); Sylmar, 3,255 acre-ft (4 million m^3); Central, 15,000 acre-ft (18.5 million m^3); and West Coast, 1,503 acre-ft (1.9 million m^3) (Los Angeles Department of Water and Power, 2005).

Between 1981 and 1987, a groundwater monitoring program showed that over 50 percent of the water-supply wells in the eastern portion of the San Fernando Valley were contaminated with industrial solvents. The wells were shut down, necessitating the purchase of more expensive imported water and drilling of deeper water-supply wells to reach uncontaminated, potable groundwater. Water from some of the wells with low levels of contamination is blended with clean water to supplement the water supply.

As Los Angeles and the surrounding metropolitan area are extensively developed, much of the land surface is paved. For this reason Los Angeles County operates 2,436 acres (986 hectares) of spreading grounds and soft-bottomed, permeable flood-channel spreading areas for groundwater recharge (Los Angeles County Department of Public Works, 2005). The City of Los Angeles, in cooperation with the Los Angeles County Department of Public Works, concentrates its groundwater recharge in the San Fernando basin, where five spreading grounds spread an average of 25,390 acre-ft (31.3 million m^3) of captured

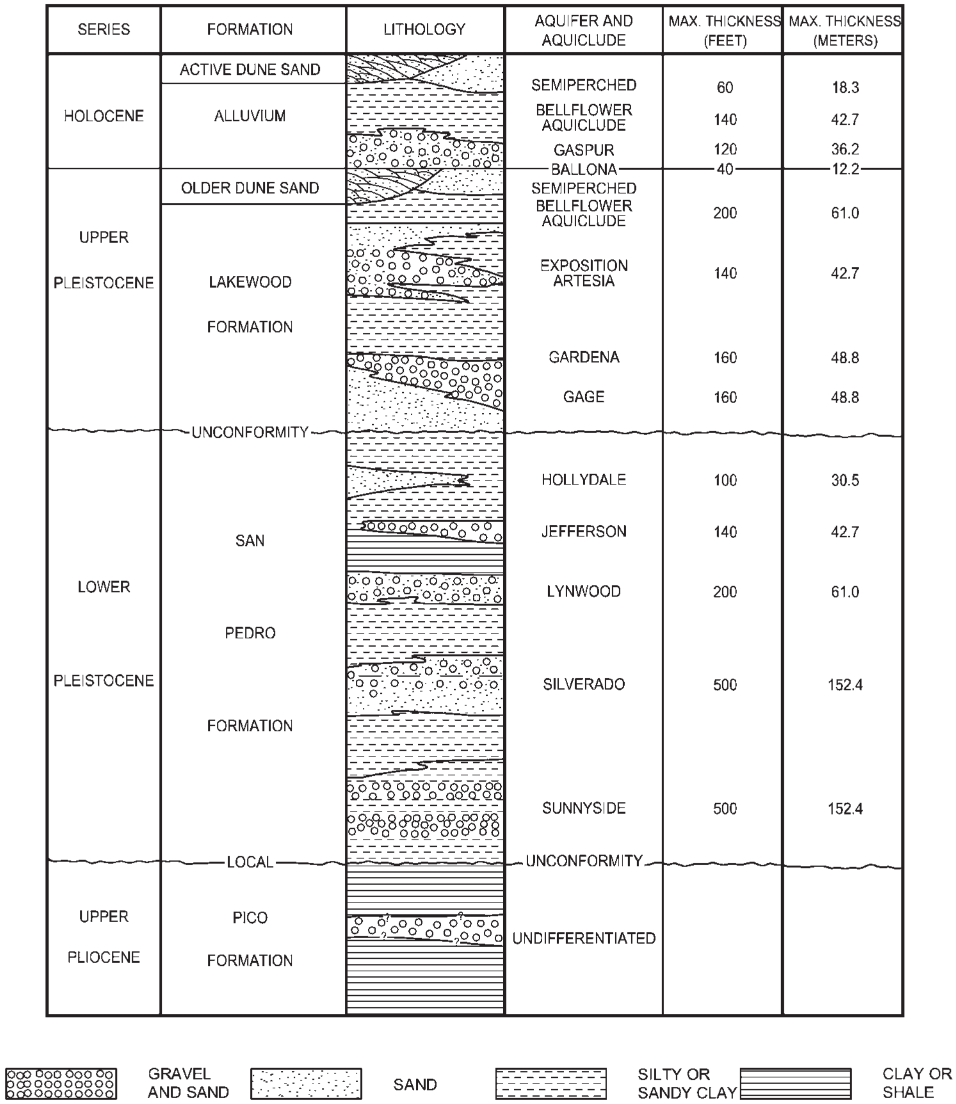

Figure 25. Aquifers in the Los Angeles basin and their corresponding formations (after California Department of Water Resources, 1961).

stormwater and/or imported water per year (Los Angeles Department of Water and Power, 2005).

To protect the groundwater in the West Coast and Central basins from seawater intrusion, the Los Angeles County Department of Public Works operates three saltwater-intrusion barrier systems (Figure 26). The barriers consist of freshwater pressure ridges created by injecting freshwater along a line of injection wells approximately parallel to the coastline (Johnson, 1992; Lipshie and Larson, 1995). During 2002–2003, approximately 30,000 acre-ft (37 million m^3) of water was injected through the barrier projects: 74 percent imported water and 26 percent reclaimed water (Los Angeles County Department of Public Works, 2005).

The Los Angeles Department of Water and Power (LADWP) has instituted a very successful water conservation program. The cornerstone of the program is installation of ultra–low-flush toilets. The program has resulted in annual water conservation of more than 15 percent. The LADWP has initiated programs to encourage commercial/industrial and institutional customers to replace their toilets by providing incentives that greatly reduce or eliminate the cost of installing the low-flush toilets (Los Angeles Department of Water and Power, 2005).

Wastewater

In 1891 sanitation districts were established by law at the county level in California. Prior to this period, sewage in Los Angeles was typically discharged directly into the ground or into rivers and streams that ultimately discharged into Santa Monica Bay. By 1902 Los Angeles had its first primitive sewage treatment plant, the Hyperion Works, at El Segundo, on the Pacific coast. In 1928 construction was completed for the Bixby Plant in Long Beach. This was the first modern sewage treatment plant in California, and it employed the activated sludge process. During and after World War II the population increased dramatically. Groundwater levels were recognized as declining, and groundwater quality was becoming impaired in the county areas without sewers. This population growth, and the increase in industrial discharges, overtaxed the capabilities of many sewage treatment plants. In 1944 the Los Angeles Municipal Code was amended to limit discharges to sewers and storm drains. Temperature and pH were regulated, and disposal of explosives and flammable liquids was prohibited (Randell et al., 1983). Presently the city's wastewater collection system consists of over 6,500 mi (10,460 km) of sewers, 100 diversion structures, and 54 sewage pumping plants within a 600-mi^2 (1,554-km^2) service area. The city also operates four wastewater treatment and reclamation plants, the Hyperion and Terminal Island treatment plants and the Tillman and Los Angeles/Glendale water reclamation plants.

The North Outfall Sewer (NOS) was constructed in 1925 to convey wastewater to the original Hyperion Treatment Plant at El Segundo, just south of the Los Angeles International Airport (LAX). Following World War II, the Hyperion Treatment Plant was reconstructed, and secondary treatment and biosolids processing were used to produce a heat-dried fertilizer. In 1957 two ocean outfalls were built to discharge a blend of secondary and primary effluent and digested sludge.

In the 30 years after World War II, the environment of Santa Monica Bay was severely affected by the discharge of 30 million lb (13.6 million kg) of wastewater solids per month. In the mid-1980s, under pressure from the Environmental Protection Agency (EPA), the City launched the Sludge-Out Program and the Full Secondary treatment program to clean up Santa Monica Bay. The new full secondary Hyperion Treatment Plant, completed at a cost of $1.6 billion, began operation in 1998. The plant continuously treats 350 million gallons (1,591 million liters) per day and exceeds all National Pollutant Discharge Elimination System permit requirements. The Hyperion Treatment Plant was named as one of the American Public Works Association's Top Ten Public Projects of the Twentieth Century, keeping company with such projects as the Panama Canal, Hoover Dam, and the Golden Gate Bridge.

The city design plan calls for the replacement of the aging NOS sewer to keep pace with population growth. This newer sewer line extends from the eastern end of the Santa Monica Mountains through the Los Angeles River Narrows and across the northern Los Angeles basin to the Hyperion Treatment Plant. The route mainly involves travel through gravity-flow tunnels. The North Outfall Replacement Sewer (NORS) has played a major role in upgrading the sewer and treatment facilities for the City of Los Angeles. Completed in 1992, the NORS tunnel extends 8 mi (13 km) from the northern end of the Baldwin Hills to the Hyperion Treatment Plant (Figure 26). The two other sewage trunk lines, the 11-mi (18-km) East Central Interceptor Sewer, completed in 2004, and the 9-mi (14.5-km) Northeast Interceptor Sewer (NEIS), completed in 2006, join NORS in conveying sewage to the treatment facility (Figure 26). The design consisted of a 7.5-ft (2.3-m)–diameter sewer line placed within a 12-ft (3.7-m)–diameter tunnel bore. The annular space is filled with lightweight compressible concrete. A major construc-

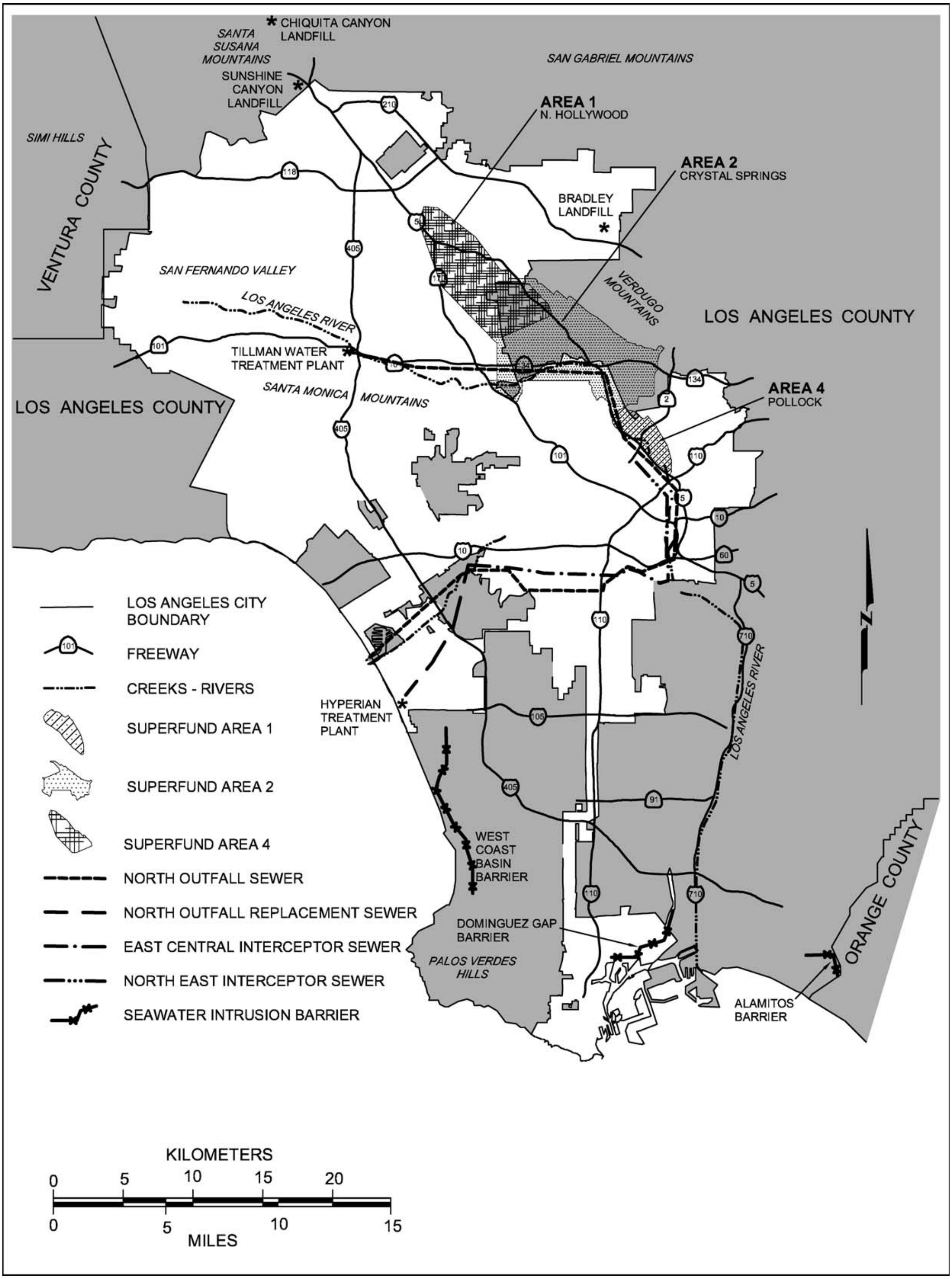

Figure 26. Major sewer tunnels, seawater intrusion barriers, and Superfund and landfill sites in the Los Angeles area (from the City of Los Angeles and Lipshie and Larson, 1995).

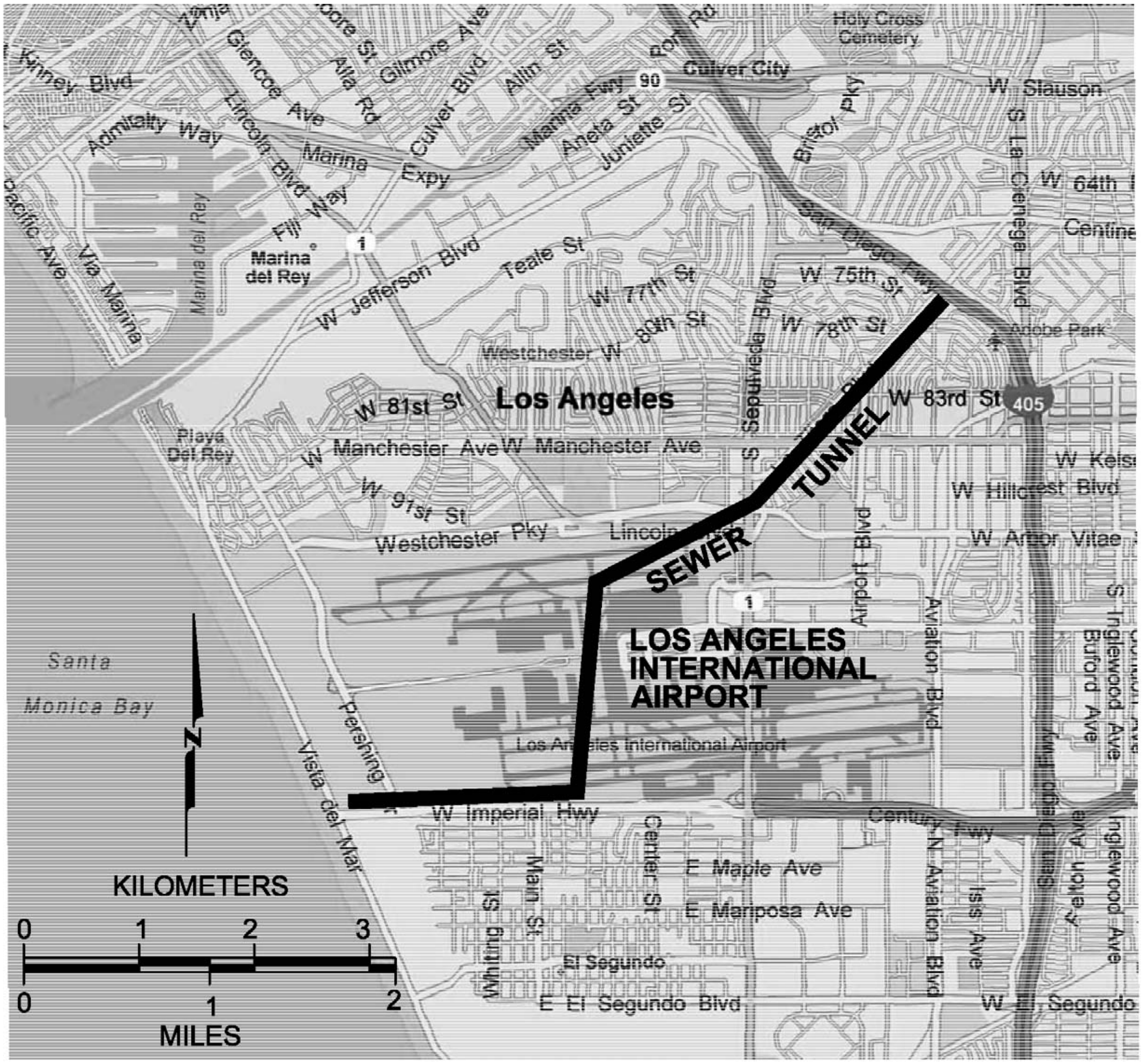

Figure 27. Route of NORS tunnel under the LAX runways and taxiways.

tion challenge in the northern Baldwin Hills was saturated alluvium containing floating gasoline (Proctor, 1998).

Geologic units along the NORS alignment include Pleistocene San Pedro Formation, Pleistocene and Holocene dune sand, Holocene alluvium, and man-made fill. The main structural feature crossed is the active Newport–Inglewood fault zone. As was done with the Metro tunnel where it crosses the Hollywood fault, a 300-ft (91-m) section of oversized tunnel was specially designed at this crossing to accommodate future fault movement (Latiolait et al., 1992). Additional engineering challenges for the NEIS sewer tunnel included crossing the tectonically active (rising) Elysian Park anticline and the Coyote Pass Escarpment, an active monocline.

Geotechnical studies for NORS were conducted from 1987 to 1989, based upon recommendations of a Geotechnical Consulting Board consisting of four civil engineers and one engineering geologist. One major challenge of the project was that the chosen route for the sewer tunnel would cross under LAX (Figure 27). The geologic, soil, groundwater, and contaminant conditions along the tunnel alignment were sampled and defined by 144 borings (LeRoy Crandall and Associates, 1989). Tunneling through the weakly cemented dune sand under LAX was performed with an open-faced excavator shield. Because of excessive ground loss at the face, the tunnel shield eventually was equipped with two breasting tables to help hold the part of the face not actively being excavated. This modification was implemented after the dune sand had caved or "chimneyed" up to the ground surface, creating several sinkholes in a taxiway. One night an alert airport worker noticed the holes forming, and the

Figure 28. Sinkhole in LAX taxiway; NORS tunnel is 90 ft (27 m) below ground surface.

airport was closed for 2 days while drilling was performed to locate voids under the runways and taxiways (Figure 28). A dense pattern of grouting from the surface was employed to fill the voids above the tunnel alignment. The costs of these grouting and other tunneling problems are discussed by Roth and Kamine (1997).

Hazardous Waste

California is credited with being either directly or indirectly responsible for the enactment of the majority of hazardous waste laws and regulations in the United States. Health departments are traditionally the first governmental agencies involved in the response to effects resulting from hazardous waste releases. The California State Health Department was created in 1870 and was the second formed in the United States (after that formed in Massachusetts). The first major waste-producing industry in Los Angeles was James Walsh's Manufactured Gas Works, located across the street from the famous Pico House, the city's first hotel. This industry was cited in 1872 for being a public nuisance and was ordered not to discharge the tar-laden plant wastes into the public sewer (Hatheway, 1992).

Los Angeles felt the pinch of groundwater contamination early. In 1917, the "iodoform" taste of phenols and cedar oils was detected in the chlorinated public water supply of the Vernon–Huntington Park area, which led to abandonment of the affected wells. The source has not been identified, but it is likely that it had something to do with Bakelite (a celluloid backing board developed in 1909), which figured prominently in the fabrication of some automobile storage battery casings (Hatheway, pers. comm., December 2005).

The legislation that caused Californians to begin to address water pollution in the state was the Dickey Water Pollution Control Act of 1949. This act created a State Board of Water Pollution Control and first seven, and then nine, regional Water Pollution Control Boards (now called Water Quality Control Boards). The purpose of the Regional Boards was to coordinate clean-up actions, control water pollution, and develop long-range plans to protect the waters of the state. The Dickey Act has become a landmark in state legislation because it was enacted when no other state had a comprehensive water pollution control act. This act also recognized that surface water and groundwater were unique within the different watersheds and that the boundaries between the regions had to be hydrologic boundaries, not political ones (Hatheway, 1992). In 1972, the Porter–Cologne Water Pollution Control Act, the successor to the Dickey Act, was passed.

In 1961, the Los Angeles Regional Water Pollution Control Board initiated the first documented hazardous waste remedial investigation of groundwater in the nearby San Gabriel Basin. The California Water Company had reported poor taste and odor from groundwater extracted from a well (Hatheway, 1992).

The basin was contaminated with synthetic organic compounds commonly used as industrial solvents. Large portions of the basin were placed on the federal Superfund clean-up list in 1984, and in 1988 the EPA recommended treatment of the extracted groundwater by air stripping. Clean-up of the San Gabriel Basin aquifer began in earnest in 1993, when the state established the San Gabriel Basin Water Quality Authority.

Following these studies, the California Department of Health Services requested that all major purveyors of groundwater in the Los Angeles region conduct tests to determine if potentially harmful levels of contaminants were present. The testing revealed the presence of volatile organic compounds, chromium, and nitrates in much of the eastern San Fernando Valley. The primary contaminants are trichloroethene and perchloroethene (PCE). These are common industrial solvents used in a variety of applications, including dry cleaning, metal plating, and machinery degreasing (Environmental Protection Agency, 1993). The clean-up of the basin is unusual in that one cannot point to a single industrial source responsible for the contamination. For studying and remediating the problem, the EPA in 1986 divided the San Fernando Valley into four areas: North Hollywood, Crystal Springs, Verdugo, and Pollock (Figure 26). These areas were added to the National Priorities List (NPL) as individual Superfund sites. In 2004 the EPA deleted the Verdugo Basin site from the NPL as a result of consistently decreasing levels of PCE contamination over time, to below maximum contaminant levels.

The San Fernando groundwater basin was affected between the 1940s and 1960s, especially by the manufacture of thousands of World War II aircraft, when the disposal of large quantities of chemical wastes was not regulated (Environmental Protection Agency, 1991). Also, illegal dumping and underground storage tank leaks may have contributed to the basin-wide contamination. Groundwater monitoring conducted between 1981 and 1987 indicated that approximately 50 percent of the more than 100 public water-supply wells in the region were affected. Many wells have now been taken out of service. The San Fernando groundwater basin provides drinking water to approximately 600,000 residents.

Active clean-up of the San Fernando groundwater basin included soil and sludge excavation, treatment, and disposal. Several groundwater extraction wells have been installed in the more highly contaminated areas of the plume. The groundwater is treated through aeration, and the air is then passed through activated granular carbon to trap the volatile organic compounds before discharge into the atmosphere. The treated water is added to the water distribution system after testing or is reinjected back into the aquifer.

Refinery Spills and Cleanup

The Los Angeles coastal plain is ideal for petroleum-handling facilities, being close to the source product and the Port of Los Angeles. Fifteen refineries and 33 above-ground bulk-liquid tank farms are located in and around the city. However, pools of light, non–aqueous-phase liquid (LNAPL) hydrocarbon product, including gasoline, are widespread in the subsurface beneath many of these facilities, typically perched on the water table. Some LNAPL pools are hundreds of acres (hectares) in size, and the total estimated volume is 7.5 million barrels (Testa, 1992). Remediation of LNAPL contamination began in the 1970s at some sites and was accelerated by regulatory order in the mid-1980s. Most major petroleum-handling facilities have implemented aquifer restoration programs. In the western and southern basin, the Silverado Aquifer is the primary source of potable water for municipal supplies, and its protection from contamination is a high priority. Recovered LNAPL is routinely recycled at the refineries (Testa and Winegardner, 1990; Testa, 1992).

Solid Waste

On February 24, 1873, Los Angeles established what could loosely be termed its first "regulated" landfill. The city created a garbage and dead animal plot and directed the town marshal to ensure that material was buried at least 3 ft (1 m) below ground surface. This was the start of the formal waste management process that continues today. In 1955, the Los Angeles County Sanitation District developed its first Master Plan for County Solid Waste Management. This plan, one of the first such plans in the country, called for the development of six new landfills. Open burning of solid waste at home, at landfills, or in incinerators was banned in Los Angeles County in 1957. Before the ban, nearly every household had its own incinerator for burning trash, and there were an estimated 150 garbage/refuse dumps (Hatheway, 1992).

In 1972 the state legislature passed the California Solid Waste Management and Resource Recovery Act. This legislation established the 10-member Solid Waste Management Board and required each county and city to have an official solid waste management plan. For the first time, California had specific criteria for siting and operating landfills. Major revisions and updating of regulations culminated in

1989 with the passage of the California Integrated Waste Management Act (CIWMA), establishing the six-member California Integrated Waste Management Board (CIWMB). The CIWMA included mandates to require each city and county to prepare integrated waste management plans that include diversion of 50 percent of all solid waste from landfills through source reduction, recycling, and composting activities by January 1, 2000 (California Public Resources Code, 2006). The City of Los Angeles met and surpassed the CIWMA goals by achieving a solid waste diversion of 58 percent in the year 2000 (Los Angeles Bureau of Sanitation, 2001). The city has now adopted the new goal of 70 percent solid waste diversion by the year 2020.

The solid waste reduction and recycling goals mandated by the CIWMA of 1989 are mainly addressed by curbside sorting of recyclable metals, paper, and glass; diverting and reusing construction and demolition debris; and diverting and composting green waste. Asphalt paving is commonly recycled in California, primarily from road and highway construction. Waste concrete is often crushed and reused as well. Green waste is segregated and composted for reuse as fertilizer or soil augmentation. Green waste requires special handling to avoid build-up of heat and potential smoldering (Burgoyne, 2003).

California waste is classified into four categories: hazardous waste, designated waste, nonhazardous solid waste, and inert waste (California Code of Regulations, 2006a, 2006b). In general, hazardous waste is material that, because of its origin, quantity, concentration, or other characteristics, may harm human health or the environment. Designated waste is nonhazardous waste that contains pollutants that potentially could be released into the environment at concentrations that would degrade surface water or groundwater. Designated waste can also be hazardous waste that has been granted a variance from being handled as a hazardous waste. Nonhazardous solid waste is typically residential or commercial refuse or garbage. Inert waste is concrete or building demolition waste that contains no putrescible or soluble materials.

Jurisdiction over the disposal of nonhazardous solid waste is shared by state, regional, and local governmental agencies. The principal agencies with authority over sites in the Los Angeles area are 1) the Regional Water Quality Control Board, Los Angeles Region, which has primary jurisdiction over waste containment and protection of water quality; 2) the California Integrated Waste Management Board, which has responsibility for landfill design, operation, and closure; and 3) the County of Los Angeles Department of Health Services, which serves as a local enforcement agency for the CIWMB and for the South Coast Air Quality Management District, which regulates air emissions from landfills.

In California, landfill classification is based upon siting criteria and the types of waste that a landfill can accept (California Code of Regulations, 2006a, 2006b). No landfill site is allowed within a specified distance of a Holocene fault, airports, 100-year flood plains, wetlands, or areas of rapid geologic change. The California landfill classification designates three disposal site types: Classes I, II, and III.

Class I disposal sites accept hazardous waste so long as it is fully characterized, is not in liquid form, and meets all land disposal restrictions, such as pretreatment to reduce the concentration of pollutants. These sites have the most restrictive siting criteria in order to protect groundwater and surface water from being contaminated by landfill wastes for the foreseeable future. Class I disposal sites must not be underlain by usable groundwater and must have double liners and sophisticated monitoring systems to verify that waste is not escaping from the unit. The natural substrate and any artificial liner must have a hydraulic conductivity of 10^{-7} cm/s or less to prevent lateral or vertical migration of fluids from the landfill.

Class II disposal sites accept designated waste and are located where site characteristics and containment structures isolate waste and are required to have composite liners.

Class III disposal sites accept inert and nonhazardous wastes such as earth, rock, and concrete. These sites can only accept inert solid wastes that are neither water-soluble nor decomposable. There is low probability that these wastes will contaminate any surface water or groundwater.

The city owns and conducts monitoring and maintenance on five inactive landfills: Bishop Canyon, Branford, Lopez Canyon, Sheldon/Arleta, and Toyon Canyon landfills. All city solid waste is now transported to private landfills and facilities in Los Angeles County and a number of surrounding counties, with the majority going to Bradley, Chiquita Canyon, and Sunshine Canyon landfills (Figure 26). In 2000 the city disposed of approximately 3,750,000 tons of waste in landfills and two permitted transformation facilities (Los Angeles Bureau of Sanitation, 2001).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the guidance, encouragement, and helpful review provided by Series Editor and fellow Angeleno Dr. Allen W. Hatheway. His patience and enthusiasm formed an integral part in the completion of this article. Key contributions were provided by Joseph W. Cobarrubias, William F. Cole, Tim Latiolait, Wolfgang Roth, Anthony F. Stirbys, and Stephen M. Testa. We would like to thank Nicole Pagano, Kristine Uhlman, Judy Ehlen, Terry Stransky, and David Perry for their thorough review and comments on this article. We would like to extend a special note of thanks to Steve Lipshie and Roy Shlemon for their exhaustive review and knowledgeable insights about Los Angeles area geology. Drafting was provided by Miriam Roque of the City of Los Angeles and Mark Scop of ENSR AECOM. The collaborative effort represented by the authors' affiliations is a testimony to the open communication shared by individuals, corporations, and public agencies within the environmental and geotechnical field. Finally, we wish to thank the Star Publishing Company for allowing use of their copyrighted material, previously published in *Engineering Geology Practice in Southern California* (Pipkin and Proctor, 1992).

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