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| **From:** | Christine Rowe |
| **To:** | MSFC-SSFL-EIS |
| **Cc:** | Elliott, Allen (MSFC-AS01); ZORBA, PETER D. (HQ-LP040); Fellows, Merrilee (HQ-LD000) |
| **Subject:** | Fwd: NASA DEIS Section 3.7.3 Landslide Potential |
| **Date:** | Sunday, September 08, 2013 12:11:50 AM |
| **Attachments:** | screen shot NASA DEIS Landslides.png<br>The Northridge Earthquake and its Economic and Social Impacts.pdf<br>SCEC001activefaultsLA.pdf |

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Dear Mr. Elliott,

This is the most frightening passage that I have read to date in your draft EIS. That is because the source for locations for an earthquake of a magnitude 6.0 or greater was a book from 1978. ( please see attached)

Your document stated that there has not been an earthquake greater than 6.0 in the region.

It is my understanding that the consultants for this project should have done a literature search regarding earthquake history in the region. Had they done a competent literature search, and an actual review of those documents, they would have discovered both the original sources (their 1978 source), the more recent documents related to the Northridge quake of 1994, and the location of the fault systems related to that Northridge quake.

I believe that the attached statement was not the appropriate statement to quote from the 1978 source considering the earthquake history of California - and the potential for another major quake in California within our lifetimes.

While I did a search for the key word earthquakes in your document, and while your references do mention the Northridge Earthquake, I do not believe that the author of this section realized the regional impact of that earthquake.

This is a link to potential landslide areas:
http://www.quake.ca.gov/gmaps/WH/regulatorymaps.htm

In researching this earthquake - and I was much more familiar with fault zones at the time of the quake - I believe it was on the Oak Ridge Fault Zone. I recall, from my Environmental Geology class at CSUN, learning around 1989, that they did not believe that any of the faults except the San Andreas had the potential for greater than a 6.0. I therefore was very surprised to learn that there was a quake of this magnitude on this fault at the time of the Northridge quake, and that I believe that ridge was along the Santa Susana range all the way to the Moorpark area?

It is called the Pico Thrust or the Northridge Thrust fault I believe which is a part of the Oak Ridge System:
http://www.data.scec.org/significant/oakridge.html
http://www.data.scec.org/significant/losangeles.html

These links state that these faults are blind and cannot be seen on maps.

Would you please have someone with a more geological background than I have look into my comments for accuracy please?

The bottom line - it is scary to quote a 1978 document on earthquakes in Southern California when we have Cal Tech here as a resource.

The links that I just provided said that this fault may never erupt again. But it also said the map is not predictive of the future. Your document really downplayed the risk from earthquakes and landslide potential at the site.

Please see this link and the relationship between Valley Fever in VENTURA COUNTY and the Northridge earthquake.

http://www.ncbi.nlm.nih.gov/pubmed/9062329

- As someone stated at the DEIS meeting, digging up the ground around here is correlated with Valley Fever.

- There is a health risk which could be correlated to the more that you dig up that top soil.
- Appropriate mitigation methods need to be in place.

Respectfully,

***Christine L. Rowe***

# Active Faults in the Los Angeles Metropolitan Region

Southern California Earthquake Center Group C*

*James F. Dolan, Eldon M. Gath, Lisa B. Grant, Mark Legg, Scott Lindvall, Karl Mueller, Michael Oskin, Daniel F. Ponti, Charles M. Rubin, Thomas K. Rockwell, John H, Shaw, Jerome A. Treiman, Chris Walls, and Robert S. Yeats (compiler)

## Introduction

Group C of the Southern California Earthquake Center was charged with an evaluation of earthquake fault sources in the Los Angeles Basin and nearby urbanized areas based on fault geology. The objective was to determine the location of active faults and their slip rates and earthquake recurrence intervals. This includes the location and dip of those faults reaching the surface and blind faults that are expressed at the surface by folding or elevated topography.

Slip rate determinations are based on several timescales. The tectonic regime of the Miocene was generally extensional, and the north-south contractional regime came into being in the early Pliocene with the deposition of the Fernando Formation (Wright, 1991; Yeats and Beall, 1991; Crouch and Suppe, 1993). The longest timescale for slip-rate estimates, then, is the time of imposition of the north-south contractional regime, the past 5 x $10^6$ years. Another timescale is the early and middle Quaternary (~ 2 x $10^6$ years), the time of deposition of the upper Pico member of the Fernando Formation plus the shallow-marine to nonmarine San Pedro Formation. Information for the first two timescales is derived from the subsurface using oil-well and water-well logs, multichannel seismic profiles, and surface geology. A third timescale is the late Quaternary ($10^2$-$10^5$ years), information for which is obtained through trench excavations, boreholes, and high-resolution seismic profiles and ground-penetrating radar augmented by the 232-year-long record of historical seismicity in the Los Angeles area. The shortest timescale (10 yrs) is that afforded by repeated GPS observations.

The late Quaternary rate is the most representative long-term rate in forecasting future behavior because it provides a geologically- and statistically-significant averaging time but is unlikely to be contaminated by Pliocene and early Pleistocene geologic processes no longer active today. Two examples illustrate this problem. (1) The post-Miocene slip rate on the Las Cienegas blind fault was estimated as 2.1-2.3 mm/yr by Schneider et al. (1996) based on Fernando and San Pedro growth strata, but only as 0.09-0.13 mm/yr by Ponti et al. (1996) based on thickness changes of late Quaternary strata between the upthrown and downthrown blocks of the Las Cienegas fault. (2) The late Quaternary displacement on the Whittier fault is almost purely by strike slip (Rockwell et al., 1992), yet the total lateral displacement is too small to be

expressed in offset facies changes of members of the Miocene Puente Formation (Bjorklund and Burke, in review).

The late Quaternary rate may be different from the rate based on GPS observations. For example, the GPS rate across the Eastern California Shear Zone (Sauber et al., 1994; Thatcher et al., 1999; Miller et al., 2001; Dixon et al., 2000) is considerably higher than the late Quaternary geologic estimates. In California, similar differences between GPS and geology may occur on the Garlock fault. In this instances, the GPS rate may not be steady state but may represent a short-term strain transient.

This report summarizes the evidence for slip rates across faults of the Los Angeles metropolitan region and calculates the north-south component of shortening to compare with the convergence rates of about 4.4 mm/yr between downtown Los Angeles and the San Gabriel Mountains based on GPS (Bawden et al., 2001). The references are largely those that summarize recent SCEC-supported work, and they should be consulted for earlier references such as Hoots (1931), Yerkes et al. (1965), Ziony (1985), and Wright (1991) that made important contributions to an understanding of active faulting in Los Angeles.

## Transverse Ranges Southern Boundary Fault System

### Santa Monica fault

The Santa Monica fault is part of the Transverse Ranges Southern Boundary fault system, a west-trending system of reverse, oblique-slip, and strike-slip faults that extends for more than 200 km along the southern edge of the Transverse Ranges (Dolan et al., 1997, 2000a). Other faults in this system, included in this review, are the Hollywood and Raymond faults. The Anacapa-Dume, Malibu Coast, Santa Cruz Island, and Santa Rosa Island faults to the west are also part of this system, but are not included in this report.

The Santa Monica fault extends east from the coastline in Pacific Palisades through Santa Monica and West Los Angeles and merges with the Hollywood fault at the West Beverly Hills Lineament in Beverly Hills, west of the crossing of Santa Monica Boulevard and Wilshire Boulevard, where its strike is northeast. The surface expression of the fault is a series of left-stepping en échelon, south-facing scarps with an overall southward-convex map pattern. Onshore, the fault offsets the surface 2-3.5 km south of the Santa Monica Mountains range front; the range front itself is marked by the inner edge of the Stage 5e marine terrace (Dolan et al., 2000a). Accordingly, the fault traverses alluvium that allows the Quaternary history of the fault to be characterized based on geomorphology, stratigraphy, and seismic reflection characteristics (Dolan and Pratt, 1997; Dolan et al., 2000a).

Uplift of an alluvial-fan surface north of the fault requires a reverse-slip rate of ~0.5 mm/yr (Dolan and Pratt, 1997). The inner-edge altitude of the Stage 5e marine terrace at Potrero

Canyon in Pacific Palisades requires an overall uplift rate of 0.6-0.7 mm/yr and a reverse-slip rate on the fault of about 0.6 mm/yr (McGill, 1989; Dolan et al., 2000a).

A trench excavation on the grounds of the Veteran's Administration hospital at Sawtelle (here called the VA trench), west of I-405, supplemented by a high-resolution seismic profile (Dolan and Pratt, 1997), provided evidence for at least six surface ruptures in the past 50 ky, and at least two and probably three events after the burial of a prominent paleosol dated as 16-17 ka (Dolan et al., 2000a). According to these authors, a well-documented surface rupture occurred between10 and 17 ka, although a more recent earthquake probably occurred in the vicinity of the trench 1-3 ka. This leads to an average earthquake recurrence interval of 7-8 ky, which is much longer than the ~1.9-3.3 ky recurrence interval for earthquakes of $M_w$ 6.9-7.0 that would be expected if the entire Santa Monica fault ruptured at once. The longer recurrence interval may be explained by the Santa Monica fault rupturing along with other faults to the west (Anacapa-Dume fault) or east (Hollywood fault), resulting in greater slip per event.

In the subsurface, the active Santa Monica fault is shown to be the youngest of several faults, the oldest of which sustained major left-lateral strike-slip of basement rocks and Eocene strata prior to the deposition of alluvial strata south of the range front (Yeats, 1968; Tsutsumi, 1996; Tsutsumi et al., 2001). The South strand of the Santa Monica fault underwent normal separation in the late Miocene as documented by a thick sequence of Mohnian strata north of the fault relative to a thinner sequence to the south. The separation changed to south side down in the Delmontian and continued through the deposition of the Fernando Formation. The South strand cuts strata as young as the Middle Pico Member of the Fernando Formation. Thickness differences in the Upper Pico Member indicate that the South strand continued to be active as a blind fault throughout the deposition of the Upper Pico (age 2.5-0.9 Ma, Tsutsumi et al., 2001). The Quaternary San Pedro Formation shows no variation in thickness across the upward projection of the South strand, evidence that it post-dates this strand.

The out-of-sequence North strand of the Santa Monica fault underwent all of its dip separation of 180-200 m during and after deposition of the San Pedro Formation, or in the last ~1 my (D, Ponti in Hummon et al., 1994). If the 0.6 mm/yr dip separation rate characterizes the entire history of the fault, then the North strand of the fault became active at about 300 ka (Dolan et al., 2000a).

The Santa Monica fault has not yielded direct evidence for its strike-slip rate. Evidence for left-lateral strike slip includes the left-stepping pattern of en-échelon faulting, numerous small strike-slip faults in the VA trench (Dolan et al., 2000a), and left-lateral stream offsets on the Malibu Coast fault north of Point Dume (Drumm, 1992; Treiman, 1994). The abrupt changes of dip with depth: steep close to the surface, low-angle at depth (Tsutsumi et al., 2001), suggest a major component of strike slip, possibly a flower structure, with the high-angle strike-slip fault

beneath the range front at depth. Treiman (1994) estimated that the strike-slip rate north of Point Dume is currently < 0.5 mm/yr, diminished from a longer-term Quaternary rate of up to 2 mm/yr.

**Santa Monica Mountains blind thrust**

Davis and Namson (1994) suggested on the basis of a balanced cross section that the Santa Monica Mountains are uplifted along a north-dipping blind thrust with a slip rate of 3.9-5.9 mm/yr over the past 2-3 my. However, Johnson et al. (1996) indicated that this blind fault has a slip rate < 1 mm/yr based on the uplift of marine terraces along the Malibu coast. The 120-ka terrace at Point Dume and Pacific Palisades is being uplifted at a rate of 0.1-0.2 mm/yr (Dolan et al., 2000a). Uplift of the footwall block of the Santa Monica fault at Potrero Canyon (McGill, 1989) is taking place at a rate of < 0.2 mm/yr along the coast (Dolan et al., 2000a). Meigs et al. (1999) show that the south flank of the Santa Monica Mountains has been uplifted over the past several million years at an average rate of 0.5 +/- 0.4 mm/yr, and the north flank has been uplifted at a rate of 0.24 +/- 0.1 mm/yr.

It is unclear if the Santa Monica fault and the blind thrust are the same fault, or if the two faults represent strain partitioning. If the 0.6 mm/yr dip-slip rate is the same as that on the blind thrust, then north-south shortening on the entire structure is 0.4 mm/yr (Dolan et al., 2000a).

**Hollywood fault**

The Hollywood fault extends ENE for a distance of 14 km through Beverly Hills, West Hollywood, and Hollywood to the Los Angeles River and Interstate 5. It is truncated on the west by the NNW-striking West Beverly Hills Lineament (WBHL), which marks a left step of 1.2 km between the Santa Monica fault and Hollywood fault (Dolan et al., 2000a). The lineament, located in Beverly Hills immediately east of the Los Angeles Country Club, is on trend with, and may be the northwest continuation of the Newport-Inglewood fault. The WBHL is a topographic scarp separating highly-dissected older alluvium to the west from young alluvium of the Beverly Hills plain to the east (Dolan et al., 2000a). Subsurface well control shows that the WBHL has normal separation, with its east side down (Tsutsumi et al., 2001).

The Hollywood fault is marked by a steep gravity gradient (Chapman and Chase, 1979) that extends to and beyond the Los Angeles River in the direction of the Raymond fault. However, the Hollywood fault has not been documented as a young fault even as far east as the Los Angeles River, although a south-facing slope in alluvium north of Los Feliz Boulevard may have been produced by a strand of that fault (Dolan et al., 1997; J.F. Dolan, in prep.). A bedrock fault between Mesozoic granitic rocks and Miocene strata south of Los Feliz Boulevard and west

of Interstate 5 is probably the Hollywood fault, but evidence for late Quaternary activity has not been found there (Dolan et al., 1997).

Subsurface evidence for late Quaternary faulting is found in Hollywood, including a borehole transect along Cahuenga Boulevard and trenches and borehole transects at La Brea Avenue, Fuller Avenue, Camino Palmero Avenue, and Vista Street, with the clearest evidence for timing at the Camino Palmero borehole transect (Dolan et al., 1997; 2000b). The most recent faulting at Camino Palmero occurred after deposition of ~9 ka sediments and prior to deposition of sediments dated as ~6 ka (Dolan et al., 1997; 2000b). However, a pronounced ground-water barrier at Highland Ave, between La Brea Avenue and Cahuenga Boulevard, suggests that steeply north-dipping faults extend upward into late Holocene deposits there (Lindvall et al., 2001). The fault dips northward 70°-85° at Camino Palmero based on shear fabric in the fault zone and 60°-70° north dips at the Metrorail subway tunnel between Fuller and La Brea avenues. Quartz diorite is consistently on the north side, faulted against Quaternary alluvium, but at Camino Palmero, separation of soil horizons shows north-side-down separation, suggestive of an unknown component of strike slip (Dolan et al., 1997; 2000b).

Based on sediment accumulation rates determined by radiocarbon dating, the dip separation rate is slow, but is at least 0.075 mm/yr. The narrow Hollywood Basin, filled by Quaternary deposits parallel to and south of the Hollywood fault, contains strata as old as 0.8-1.2 Ma (D. Ponti in Hummon et al., 1994). Dolan et al. (1997) estimate that the strike separation rate on the Hollywood fault is greater than 0.25 mm/yr.

The Hollywood Basin was modeled as the backlimb of a blind thrust generating the Wilshire arch, the axis of which generally follows Wilshire Boulevard (Hummon et al., 1994). However, Tsutsumi et al. (2001) suggest that the Hollywood Basin is a pull-apart basin related to the left step between the Santa Monica and Hollywood faults. Not only is the WBHL characterized by normal separation, but the southern boundary of the basin is the North Salt Lake normal-separation fault of Wright (1991) and Schneider et al. (1996), a fault that is parallel to the Hollywood fault. The thickness of shallow-marine Quaternary San Pedro Formation is greater in the Chevron Laurel Core Hole in the western part of the Hollywood Basin than it is in the central Los Angeles trough (Hummon et al., 1994; Schneider et al., 1996). A pull-apart origin of the Hollywood basin strengthens the case for left-lateral strike slip on the Hollywood fault, although the slip rate is as yet unknown.

In Hollywood, where the fault was studied in detail by Dolan et al. (1997; 2000b), the active fault is close to the Santa Monica Mountains range front. Farther west, however, near the intersection of Sunset and La Cienega boulevards in West Hollywood, the active fault lies near the base of a pronounced south-facing alluvial apron along the mountain front (Dolan et al., 1997; Lindvall et al., 2001). Several south-dipping and north-dipping normal faults displace a

marine abrasion platform overlain by marine sands that are estimated as 400-900 ka in age (Lindvall et al., 2001). Unfaulted soil horizons >100 ka in age provide an upper bound to the age of most of these hangingwall faults. The alignment of bedrock outcrops along a topographic scarp at Sunset Boulevard, previously assumed to be the active trace of the fault, is apparently a Pleistocene beach cliff; the active fault trace must lie farther south (Lindvall et al., 2001). These authors compare the altitudes of the 400-900-ka hangingwall terrace in West Hollywood to the Pleistocene marine terrace identified by Quinn et al. (2000) south of the fault in La Brea Plain, and they conclude that the differential uplift rate across the Hollywood fault is less than 0.14 mm/yr.

**Raymond fault**

The Raymond fault extends 25 km from the Los Angeles River east of Griffith Park east to east-northeast across the San Gabriel Valley through South Pasadena, Pasadena, San Marino, Arcadia, and Monrovia to a junction with the Sierra Madre fault at the foot of the San Gabriel Mountains. A sharp gravity gradient connects the western end of the Raymond fault across the Los Angeles River floodplain with the eastern end of the Hollywood fault, but this connection is not confirmed by geological evidence except for local air-photo lineations. The fault is convex southward, consisting of a western section that strikes east-west and an eastern section that strikes east-northeast. Left-deflected drainages, shutter ridges, sagponds, and pressure ridges in right-stepping restraining bends indicate that the Raymond fault is predominantly a left-slip fault (K. Sieh in Jones et al., 1990), although south-facing scarps along the central reach of the fault indicate a component of dip slip due to motion around a 25° restraining bend (Crook et al., 1987; Weaver and Dolan, 2000). One kilometer west of the change in strike, the Raymond fault has a poorly-defined intersection with the Eagle Rock fault. The Eagle Rock fault is much more poorly defined geomorphically than the Raymond fault, suggesting that it is less active, hence the kinematics of the fault intersection remains obscure. The Raymond fault joins the Sierra Madre fault south of Santa Anita Wash and south of the Clamshell-Sawpit fault in the foothills of the San Gabriel Mountains (Weaver and Dolan, 2000) on which the 1991 Sierra Madre earthquake of $M_W$ 5.8 occurred (Hauksson, 1994). The 1988 Pasadena earthquake of $M_L$ 4.9 probably occurred on the Raymond fault based on the fault-plane solution of the mainshock and the distribution of aftershocks (Jones et al., 1990); this earthquake sequence delineated a fault dipping 80° north.

Trenches excavated by Crook et al. (1987) and Weaver and Dolan (2000) show that the most recent earthquake occurred 1000-2000 years ago (Weaver and Dolan, 2000). Between 5 and 8 earthquakes occurred between 40 and 2 ka, a maximum average recurrence interval of 5.7 to 10 k.y. (Crook et al., 1987; Weaver and Dolan, 2000). Between 3 and 5 of these events

occurred between 41.5 and 31.5 ka, an average recurrence interval equal to or less than 3300 yrs (Weaver and Dolan, 2000). This may indicate a cluster of earthquakes, or it may signify undetected events.

A site in east Pasadena yielded a best-estimate left-lateral strike-slip rate of 4 +1/-0.5 mm/yr based on left offset of a gravel-filled channel of 44 m, with 0.5 m vertical component. This rate is based on sediments within and below the channel dated by radiocarbon and by optically-stimulated luminescence (Marin et al., 2000; Dolan et al., in review). An apparent 3.4-km left-lateral offset of a crystalline basement ridge at the east end of the fault may represent the total slip on the fault (Weaver and Dolan, 2000).

**Santa Susana and Sierra Madre Fault Systems**

The western Transverse Ranges are crossed obliquely by a set of north-dipping reverse faults extending from the Santa Barbara Channel east to an intersection with the San Jacinto fault near Cajon Pass. These faults include, from west to east, the Red Mountain, San Cayetano, Santa Susana, Sierra Madre, and Cucamonga faults. The San Cayetano and Santa Susana faults have the highest documented long-term reverse slip rates in southern California. The Santa Susana and Sierra Madre faults are within the Los Angeles metropolitan area and are described here. The San Gabriel fault is characterized by Quaternary reverse-oblique slip in the east Ventura basin; it traverses the foothills of the San Gabriel Mountains north of the San Fernando Valley and is also described here, even though its long-term history is predominantly that of a strike-slip fault.

**Santa Susana fault**

The Santa Susana fault extends 28 km west-northwest from the northwest edge of the San Fernando Valley into Ventura County and is at the surface high on the south flank of the Santa Susana Mountains. The fault ends near the point where it overrides the south-side-up South strand of the Oak Ridge fault. The fault has a low dip near the surface, locally becoming horizontal. This may in part be due to a distortion of the stress field by the steep topographic gradient on the southern slope of the Santa Susana Mountains (Butler, 1977) as well as to uplift from a blind, south-dipping fault, part of the Oak Ridge fault system (described below).

The fault has two left-stepping lateral ramps (Yeats, 1987). The Gillibrand Canyon ramp on the west is the smaller of the two but is the best documented by subsurface geology. The Pliocene Frew fault (Yeats, 1987) ends or changes strike westward to another fault, also named the Frew fault of the Santa Susana and Tapo Canyon oil fields, and the pre-Saugus Torrey fault also changes strike there, indicating that this ramp influenced Pliocene structures in the Santa Susana footwall (Yeats, 1987). The east Ventura Basin fold belt changes its structural character

across a northeast projection of this lateral ramp (Yeats, 1987), leading Yeats et al. (1994) to call it a segment boundary. The ramp had an effect on the distribution of aftershocks of the Northridge earthquake of 1994. The zone of major moment release in the 1994 earthquake was southeast of the Gillibrand Canyon ramp (Wald et al., 1996). Immediately southeast of the ramp, a zone of 1994 aftershocks "lit up" the Santa Susana fault (Pujol, 1996, cross section A-A' of his fig. 4). Northwest of the ramp, aftershocks in the Santa Susana footwall defined rupture planes that are more steeply dipping than they are southeast of the ramp. (See website of Sara Cavena, geoweb.princeton.edu/students/Cavena/ImageGallery/ImgGallery.html)

The larger ramp at the western edge of the San Fernando Valley is called the San Fernando or Chatsworth ramp (Yeats, 1987; Yeats et al., 1994); this ramp may be influenced by the Miocene Chatsworth set of faults marking the western margin of the San Fernando Valley (Tsutsumi and Yeats, 1999; Yeats, 2001a). The mainshock and a large number of the aftershocks of the 1971 Sylmar (San Fernando) earthquake were located on or close to this ramp; focal mechanisms showed a large component of left slip (Whitcomb et al., 1973). However, the rupture plane of the 1994 earthquake as defined by aftershocks went across this ramp.

The Pico Canyon earthquake of 4 April 1893, of M 5.5-5.9 (Toppozada, 1995), which might have occurred on the Santa Susana fault, caused damage in Newhall, Saugus, Castaic, and the now-vanished oil town of Mentryville (Richter, 1973), in addition to Los Angeles, Pasadena, and Fillmore.

The Santa Susana fault cuts the Quaternary Saugus Formation, and clasts in the Saugus contain evidence for the age of uplift of the Santa Susana Mountains. Most of the Saugus at Horse Flats, south of the Aliso Canyon Oil Field in the Santa Susana Mountains, contains conglomerate clasts largely derived from basement rocks of the San Gabriel Mountains and other crystalline ranges, evidence for deposition prior to uplift of the Santa Susana Mountains (Saul, 1975). In contrast, conglomerate in the uppermost Saugus of Saul (1975) at Horse Flats is dominated by locally-derived Modelo and Towsley clasts, evidence of uplift of the Santa Susana Mountains, presumably by upward movement of the hangingwall of the Santa Susana fault. Similar relations are found on the north side of the range near Magic Mountain amusement park (Treiman and Saul, 1986; Levi and Yeats, 1993, their fig. 3), where the deformed, locally-derived Saugus is called Pacoima Formation, following Oakeshott (1958). Paleomagnetic stratigraphy by Levi and Yeats (1993) permits the estimation of the ages of the base of the Saugus Formation, of the appearance of locally-derived clasts in the Saugus, and of the top of the Saugus as 2.3 Ma, 600-700 ka, and 500 ka, respectively. The age of initiation of the Santa Susana fault is thus constrained to have begun between 2.3 Ma and 600 ka (Huftile and Yeats, 1996).

The total dip-slip displacement on the Santa Susana fault is based on the offset of the base of the Fernando Formation in a balanced cross section (Huftile and Yeats, 1996). The displacement is 4.9 to 5.9 km, giving a dip-slip rate of 2.1 to 9.8 mm/yr. The horizontal component of displacement is 4.1 km, giving a horizontal shortening rate of 5.7 +/- 2.5 mm/yr (Huftile and Yeats, 1996).

An additional constraint on the age of initiation of the Santa Susana fault is based on the age of initiation of clockwise rotation of the Saugus Formation in its hangingwall at Magic Mountain. Most of the Saugus in the Magic Mountain section is rotated clockwise approximately 30°, whereas the Van Norman Dam section in the footwall of the Santa Susana fault is not rotated at all (Levi and Yeats, 1993). The uppermost part of the Magic Mountain section is rotated only about 15°, and the age of initiation of rotation of the Saugus Formation can be estimated at about 1 Ma (Levi and Yeats, 1993; S. Levi and R.S. Yeats, in prep.). If the rotation is evidence that the displacement on the Santa Susana hangingwall is not a translation but a rotation about a pivot point at the Santa Susana fault tip, then the age of initiation of the fault can be estimated as 1 Ma. Using 1 Ma to accumulate 4.9 to 5.9 km of displacement, the long-term slip rate is 4.9-5.9 mm/yr, and the horizontal shortening rate is about 4.1 mm/yr (S. Levi and R.S. Yeats, in prep.).

A trench across the fault at Limekiln Canyon at the northern edge of Horse Flats yielded no evidence of Holocene displacement (Lung and Weick, 1987). However, this trench was across the Older strand of the Santa Susana fault, which has been abandoned for the Younger strand within the Santa Susana Mountains (Yeats, 1987). Lung and Weick (1987) also exposed the fault in a sidehill cut near Tapo Canyon, west of the Gillibrand Canyon lateral ramp; this trench also yielded no evidence for Holocene rupture. As mapped by Ricketts and Whaley (1975) and Yeats (1977; cf. fig. 9.2 of Yeats, 1987), the Santa Susana fault is a single strand bringing Miocene Modelo Formation over Saugus Formation and late Quaternary fan deposits containing debris from the hangingwall. Fan deposits unconformably overlying the fault were undated, but are considered to be Pleistocene because they are extensively dissected by erosion. In a nearby flat-bottomed canyon, older alluvium interpreted by Lung and Weick (1987) as younger than these fan deposits includes peat with an age of 10,010 +/- 580 radiocarbon years. These results appear to be inconsistent with the high long-term slip rate on the Santa Susana fault and with the high north-south shortening rate based on GPS (Argus et al., 1999). Possibly the Holocene displacement is distributed among north-dipping bedding planes in bedrock in the hangingwall, but this cannot be confirmed. Because the Santa Susana fault crops out on the steep southern slopes of the Santa Susana Mountains rather than at the base of the range, age-diagnostic trenching sites are difficult to find, as pointed out by Lung and Weick (1987).

**Sierra Madre fault (west)**

The Santa Susana fault strikes northeast at the Fernando lateral ramp and turns east at the northern margin of the Sylmar Basin to become the Sierra Madre fault. This fault is exposed near the base of the San Gabriel Mountains for 75 km from San Fernando Pass at the Fernando lateral ramp east to its intersection with the San Antonio Canyon fault in the eastern San Gabriel Mountains (Crook et al., 1987), east of which the range front is formed by the Cucamonga fault. Exhumation of the San Gabriel Mountains began about 7 Ma based on fission-track and (U-Th)He geochronology; this may date the time of initiation of the Sierra Madre fault (Blythe et al., 2000). We describe the Sierra Madre fault in two sections, with their boundary the intersection of the Sierra Madre fault with the Raymond and Clamshell-Sawpit faults. A short distance west of this intersection, the Vasquez Creek fault (the Southern strand of the San Gabriel fault of Ehlig, 1975) intersects the Sierra Madre fault at a low angle to strike. East of this intersection, the Sierra Madre fault, like the Cucamonga fault farther east, is a zone of deformation close to the base of the San Gabriel Mountains. To the west, however, the Sierra Madre fault is the northernmost of several north-over-south faults including the Mission Hills, Verdugo, and Northridge Hills faults, all of which appear to be active.

The Sierra Madre fault differs from the Santa Susana fault in that it lies at the base of the range, whereas the Santa Susana fault crops out high on the south slopes of the Santa Susana Mountains. It differs also in its complexity, including a series of boomerang-shaped faults characterized by a west-northwest-striking section of reverse slip and a northeast-striking section of apparent left slip (Oakeshott, 1958). These include the Lopez-Limerock and Sunland faults and possibly the Buck Canyon-Watt faults of Oakeshott (1958). The Saugus Formation in Kagel Canyon and Lopez Canyon is rotated clockwise approximately 34° (Levi and Yeats, 2001), suggesting that these boomerang-shaped blocks are rotating clockwise in a broad system of right-lateral shear related to the San Gabriel fault a short distance to the north (S. Levi and R.S. Yeats, in prep.). It is more difficult to determine the slip and slip rate of a rotating block because these rates would increase from zero at the pivot point to a maximum at the edge of the block. Furthermore, the rotations pertain only to slip rates over the past million years; these faults are not known to have tectonic geomorphic expression or to offset late Quaternary deposits younger than Saugus. Electron-spin resonance plateau dating of fault gouge shows that the most recent movement on the Limerock fault took place at 346 +/- 23 ka (Lee and Schwarcz. 1996).

Crook et al. (1987) concluded that the Sierra Madre fault between the 1971 San Fernando earthquake rupture and the Cucamonga fault is less active than segments to the east and west, based on degree of dissection of fault scarps and the relative age of fan surfaces cut by the fault based on geomorphology and soil development. Following criteria established by Bull (1964), Crook et al. (1987) noted that alluvial fan heads in the vicinity of the 1971 earthquake, such as

the Pacoima and Little Tujunga Canyon fans, are incised to a lesser degree and hence are more active than the Arroyo Seco and Eaton Canyon fans in the Pasadena area farther east. A minimum long-term slip rate on this westernmost part of the fault can be obtained from the intersection of the base of the Saugus, which is 2.3 Ma in age, with the fault at the northern edge of the Sylmar basin. This intersection is at least 5 km below the surface, a minimum slip rate of 2.2 mm/yr. The rate would be larger depending on how much erosion of basement rocks had taken place in the hangingwall after deposition of the Saugus.

In that part of the Sierra Madre fault east of the 1971 earthquake rupture, Crook et al. (1987) were unable to identify any fault scarps or displaced strata involving sediments younger than late Pleistocene, and they concluded that this section of the fault had not produced large earthquakes in several thousand years and possibly not in the Holocene. Rubin et al. (1998) trenched a site in Altadena and found evidence that the most recent earthquake there had occurred in the past 10,000 years. Two earthquakes in the past 18,000 years had resulted in 10.5 m of slip, a minimum slip rate of 0.6 mm/yr. Displacements on these two earthquakes are large enough that Rubin et al. (1998) concluded that they were produced by earthquakes of M 7.2 to 7.6, much larger than the M 6.7 Sylmar earthquake of 1971 involving the western end of the fault.

The north-dipping rupture plane defined by aftershocks of the 1971 earthquake is probably the Sierra Madre fault at depth (Mori et al., 1995; Tsutsumi and Yeats, 1999). But the Sierra Madre range-front fault east of Big Tujunga Canyon did not rupture at the surface (Barrows, 1975; Kahle, 1975; Weber, 1975). The fault plane delineated by 1971 aftershocks passes south of the Sierra Madre fault in the direction of active reverse faults to the south: the Mission Hills and Northridge Hills fault (Mori et al., 1995; Tsutsumi and Yeats, 1999).

**Mission Hills fault**

The Mission Hills fault strikes east-west for about 9 km along the southern edge of the Mission Hills and Granada Hills, which are apparently uplifted by long-term reverse displacement of the hangingwall of this fault. The fault is mapped eastward to the eastern end of the hills near the Golden State Freeway, where it appears to turn southeastward toward the Verdugo fault (Tsutsumi and Yeats, 1999). The fault branches westward into two strands. The northern strand dips 60°-70° north in the Mission Oil Field and juxtaposes Modelo Formation against Fernando Formation. The southern strand extends along the base of the Santa Susana Mountains to Limekiln Canyon, where it brings upper Saugus on the south against lower, marine Saugus on the north. The fault may be linked with the Devonshire fault. Tsutsumi and Yeats (1999) argue that this fault does not join the Simi fault of the Simi Valley, as some maps have

done. The active, north-side-up Simi fault ends where its geomorphic expression ends at the northeastern corner of the Simi Valley (Hanson, 1983).

Dip separation of the base of the Saugus Formation across the Mission Hills fault yields a dip separation rate of 0.6-0.7 mm/yr. The thickness of the Fernando Formation is about the same on both sides of the fault, indicating that slip began after Fernando deposition (Tsutsumi and Yeats, 1999).

Balboa Boulevard follows Bull Canyon, a drainage antecedent to Mission Hills uplift that is now filled with alluvial-fan deposits, some of which developed a large lateral spread during the 1994 earthquake (Holzer et al., 1999). CPT borings show that unfaulted Holocene sediments overlie a fault, considered by R.S. Yeats to be the Mission Hills fault, near Rinaldi Street at the southern edge of the Mission Hills based on a ground-water cascade and stratigraphic changes across the fault (Holzer et al., 1999). A slip rate on the fault could not be determined because the fault was not directly observed in the field.

**Northridge Hills fault**

A series of discontinuous low hills that extend from near the town of Chatsworth east-southeast to the San Diego Freeway marks the crest of a south-vergent fault-propagation fold above the blind, north-dipping, 15-km-long Northridge Hills thrust (Tsutsumi and Yeats, 1999). Well data in the western part of the fault show a dip of 70 degrees, but farther east, growth triangles in a seismic profile along Balboa Boulevard show that the fault is thin-skinned, with a moderate dip. Dip separation across the fault of a sandstone within the Miocene Modelo Formation gives a long-term dip separation rate as high as 0.3 mm/yr.

Baldwin et al. (2000) excavated a trench, several test pits, and several boreholes across a 2-m-high scarp on a probable Holocene terrace adjacent to Aliso Canyon Wash. A gravel bed with a soil age estimate of 6 to 30 ka shows 6 +/- 1 m vertical separation, and an unconformity on the top of the Saugus Formation is warped into a monocline with 13 +/- 2 m of relief. These relations provide a reverse-slip rate of 1.0 +/- 0.7 mm/yr on the blind Northridge Hills thrust (Baldwin et al., 2000).

The fault has no topographic expression east of the San Diego Freeway, where its presence is based on subsurface oil-well data (Tsutsumi and Yeats, 1999) and a steep gradient in the groundwater table (Weber et al., 1980). The fault intersects and either merges with or is truncated by the Verdugo fault at the Pacoima Oil Field (Tsutsumi and Yeats, 1999).

**Verdugo fault**

Both the Mission Hills and Northridge Hills faults appear to merge with the southeast-striking Verdugo fault, which lies on the southwest side of the Pacoima Hills and the Verdugo

Mountains. Vertical separation across this fault is at least 1000 m based on the structural relief between the valley floor and the crest of the Verdugo Mountains and the intersection of the base of the Saugus Formation with the fault in the Pacoima Oil Field (Tsutsumi and Yeats, 1999). The fault at the southwest edge of the Verdugo Mountains is marked by a pronounced gravity gradient (Weber et al., 1980) that is best modeled as a normal-separation fault (Langenheim et al., 2000). Pujol et al. (2001) , using seismic tomography, image the Verdugo fault with a nearly vertical dip. Adjacent to the Pacoima Hills, however, the gravity gradient is more consistent with a thrust-fault geometry (Langenheim et al., 2000), an interpretation supported by subsurface oil-well data around the Pacoima Oil Field (Tsutsumi and Yeats, 1999).

Weber et al. (1980) reported southwest-facing scarps 2-3 m high in alluvial-fan deposits in the Burbank-west Glendale area. In the Sun Valley area, they found minor faults 40 m below the surface in sand and gravel deposits in a gravel pit. Also in Sun Valley, groundwater-bearing alluvial deposits of Big Tujunga Wash are displaced, and in Glendale, there is a groundwater cascade in Verdugo Wash.

The Verdugo fault is on trend to the southeast with the Eagle Rock fault, but Weber et al. (1980) were not able to find evidence of late Quaternary offset. Weaver and Dolan (2000) observed that the Eagle Rock fault, especially its southeastern reach, is much more subdued geomorphically than the Raymond fault farther south.

**San Fernando fault**

The 1971 Sylmar (San Fernando) earthquake produced about 15 km of surface rupture south of the Sierra Madre fault (Sharp, 1975; Barrows, 1975; Weber, 1975); this rupture became known as the San Fernando fault. Slip vectors showed about equal amounts of reverse slip, north side up, and left-lateral strike slip, with the horizontal component of net slip as large as 2.5 m (Sharp, 1975). The Tujunga segment of the San Fernando fault occurred at the range front, evidence of pre-1971 faulting. Trench excavations also showed that the 1971 rupture followed older, prehistoric ruptures (Heath and Leighton, 1973). Bonilla (1973) reported that the most recent prehistoric rupture occurred less than 200 years prior to 1971, although the sample providing the radiocarbon date might be historic. Fumal et al. (1995) excavated trenches on both side of Bonilla's trench and found evidence for only two surface ruptures in the past 3.5-4 ky, including the 1971 break.

Tsutsumi and Yeats (1999, their figs 4f, 4g, and 7) showed that the San Fernando fault did not follow any major fault zone but occurred on the south flank of the Mission Hills syncline and Merrick syncline. Slip vectors measured by Sharp (1975) were parallel to bedding, and Tsutsumi and Yeats (1999) concluded that the San Fernando fault was a flexural-slip fault, formed during folding of the synclines.

Lindvall et al. (1995) described a set of fault scarps, north side up, near Pacoima Wash in the Sylmar Basin west of the Tujunga segment of the 1971 rupture. These faults, which did not rupture in 1971, offset terraces of Pacoima Wash, with an older terrace covered by soils estimated to be 20-30 ka and a younger terrace with a soil age estimated as 8-15 ka. The height of the fault scarps gives a minimum reverse-separation rate of 1 mm/yr across this zone of faulting If these faults are secondary to a master fault dipping 45° north (a non-flexural-slip origin), the master fault would have a reverse-slip rate of 2 mm/yr.

**Sierra Madre fault (east)**

The Sierra Madre fault lies at or south of the range front of the San Gabriel Mountains east of its intersection with the Raymond and Sawpit-Clamshell faults (Crook et al., 1987), passing through the cities of Arcadia, Monrovia, Bradbury, Duarte, Azusa, Glendora, San Dimas, and Claremont. This section of the fault terminates eastward at the northeast-striking San Antonio Canyon left-lateral fault, where the Sierra Madre fault steps left to the Cucamonga fault. This left-lateral fault, together with subsurface left-lateral faults that were the source of the 1988 and 1990 Upland earthquakes (Hauksson and Jones, 1991) lead to the assumption that the Cucamonga fault would have a higher dip-slip rate than the Sierra Madre fault, as suggested by their comparative geomorphic expression (Crook et al., 1987). The Cucamonga fault has a dip-slip rate of 2-5 mm/yr (Dolan et al., 1996), which serves as an upper bound to the slip rate on the eastern Sierra Madre fault. The Sierra Madre fault is expressed as a series of southward-convex lobes, and at several localities, the most active strrand is south of the range front, which is itself marked by less-active or inactive older strands (Crook et al., 1987; Tucker and Dolan, 2001).

Crook et al. (1987) located the fault in several trenches, but they were unable to obtain age control because of the lack of availability of AMS radiocarbon dating. Tucker and Dolan (2001) excavated a trench and several large-diameter boreholes in Horsethief Canyon in San Dimas, near the Glendora Tunnel, where extensive geotechnical observations are available. They found evidence for at least 14 m of slip on the Sierra Madre fault between 24 and 8 ka, and no surface rupture since 8 ka. This leads to a minimum slip rate of 0.6 mm/yr since 24 ka and a minimum of 0.9 mm/yr between 24 and 8 ka. Surface rupture at Horsethief Canyon was the result of earthquakes with M > 7, consistent with the interpretation by Rubin et al. (1998) of large surface displacements during the two most recent surface ruptures in their trench at Altadena along the western part of the fault. The most likely scenario is that the entire Sierra Madre fault ruptures at the same time (Tucker and Dolan, 2001). The Raymond fault could also rupture during Sierra Madre events, but the Raymond fault has undergone at least one and possibly several ruptures since the most recent rupture at Horsethief Canyon. Similarly, trench data suggest that the Cucamonga fault has ruptured at least twice and possibly several times

since the most recent surface rupture on the eastern Sierra Madre fault (Dolan et al., 1996, and in prep.).

**San Gabriel fault**

The San Gabriel fault is the westernmost member of the San Andreas strike-slip fault system to cut across the Transverse Ranges (the others to do so are the San Jacinto fault and the San Andreas fault itself). A precursor fault, the Canton fault, underwent displacement in middle Miocene time and may have crossed the San Fernando Valley to an intersection with the Raymond fault (Powell, 1993; Yeats and Stitt, 2001). This strand was abandoned in the late Miocene, and activity shifted to the present trace of the San Gabriel fault, which crosses the southern foothills of the San Gabriel Mountains to an intersection with the left-lateral San Antonio Canyon fault in the eastern San Gabriel Mountains. The Miocene slip rate on this fault system was 6.6-9.2 mm/yr (Yeats et al., 1994) or even faster (Yeats and Stitt, 2001), but this rate slowed drastically in the Pliocene in the Castaic Lowland and eastward. The fault became inactive in the Ridge Basin, where it is overlain unconformably by the upper part of the Hungry Valley Formation (Crowell, 1982), and the fault is overridden by a south-side-up reverse fault, possibly the eastern extension of the Santa Felicia fault, at the mouth of Violin Canyon (Yeats et al., 1994; Yeats and Stitt, 2001). In both the Ridge Basin and Castaic Lowland, the San Gabriel fault dips moderately to steeply east.

The fault is active east of a segment boundary near the Honor Rancho Oil Field in the Castaic Lowland, an area now largely covered by the city of Santa Clarita. At this segment boundary, the fault changes strike southeastward from southeast to east-southeast and changes separation from normal to the northwest (northeast side down) to reverse to the southeast (northeast side up). The segment boundary is northeast of and on trend with the Gillibrand Canyon lateral ramp on the Santa Susana fault (discussed above). A line connecting these features separates contrasting geologic structures in the east Ventura Basin: the Holser-Del Valle fault system and Newhall-Potrero anticline to the northwest and the Pico anticline and Oat Mountain syncline to the southeast.

The fault has geomorphic expression in Santa Clarita, including linear ridges, trenches, hillside benches, and ponded alluvium along the fault trace (Kahle, 1986). Cotton (1986) showed that the fault cuts Holocene alluvium in trenches near Castaic Junction, and Swanson (2001) found that undated stream terrace material in the fault zone in a railroad cut at Bouquet Junction has a vertical separation of 3 to 5 meters, and an overlying soil zone is offset vertically 1 m. The Pacoima Formation, which overlies the Quaternary Saugus Formation unconformably, has a dip separation of more than 10 m across a secondary reverse fault in this railroad cut

(Swanson, 2001). Distinctive clast assemblages in the Saugus Formation are offset right-laterally about 500 m (Weber, 1982).

If the age of the top of the Saugus Formation is about 500 ka, as estimated from paleomagnetic evidence (Levi and Yeats, 1993), the 500 m of offset would have accumulated at a right-lateral strike-slip rate of 1 mm/yr. Kahle (1986), largely on the basis of geomorphic evidence, estimated the slip rate as less than 1 mm/yr. Yeats et al. (1994) argued for a long-term slip rate of 2.5-3 mm/yr based on reverse separation of the base of the Saugus Formation in the Saugus Oil Field, where dip separation is greatest (Yeats and Stitt, 2001). Estimates of long-term slip rate are larger than those for late Quaternary slip rate, suggesting that the slip rate has slowed with time.

The late Quaternary activity of the San Gabriel fault in the San Gabriel Mountains has not been studied. Electron-spin resonance plateau dating of San Gabriel fault gouge in the Little Tujunga area shows that the most recent movement occurred at 39 +/- 6 ka (Lee and Schwarcz. 1996), although this result is inconsistent with evidence for Holocene displacement farther west in Santa Clarita. The fault splays into a northern and southern branch (Ehlig, 1975), renamed by Powell (1993) the San Gabriel fault *sensu stricto* and the Vasquez Creek fault, respectively. In the eastern San Gabriel Mountains, the San Gabriel fault *sensu stricto* is cut off by the left-lateral San Antonio Canyon fault, suggesting that this is the less active strand. We suggest that the major part of the activity shifts to the Vasquez Creek fault, which merges to the southeast with the Sierra Madre fault. The long-term slip rate on the Vasquez Creek fault, based on offsets of basement rocks, is no more than 5 mm/yr (Powell, 1993), but the Quaternary rate must be much less, based on analogy with the San Gabriel fault farther west (cf. Yeats and Stitt, 2001).

**South-dipping Reverse Faults**

The most damaging earthquake in the history of the United States, the 1994 Northridge earthquake, struck a previously-unknown south-dipping blind reverse fault beneath the eastern Santa Susana Mountains and western San Fernando Valley. Aftershocks of this earthquake terminated updip at the base of the north-dipping 1971 rupture zone (Mori et al., 1995). The Quaternary long-term slip rate on the blind fault was estimated as 1.7 mm/yr (Davis and Namson, 1994; Huftile and Yeats, 1996) based on thickness changes in the Saugus Formation in the Castaic Lowland, a foredeep with respect to the blind fault contributing to uplift of the Santa Susana Mountains and warping of the Santa Susana fault. Only the Saugus Formation appears to have responded to growth of the foredeep (Yeats et al., 1994; Huftile and Yeats, 1996), indicating that faulting began at or after about 2.3 Ma, the age of the base of the Saugus, earlier than the age of initiation of the faster-moving north-dipping Santa Susana fault (Levi and Yeats, 1993; S. Levi and R.S. Yeats, in prep.). The Saugus is even thicker in the Sylmar Basin, which

also acted as a foredeep, but a slip rate based on the Sylmar Basin has not been worked out (Tsutsumi and Yeats, 1999).

Small-scale flexural-slip faulting was recognized by Treiman (1995) in Santa Clarita, where bedding slip in folded Saugus Formation broke the surface of building pads in the Stevenson Ranch housing development during the 1994 Northridge earthquake.

The 1994 earthquake uplifted the footwall of the Santa Susana fault , with the maximum coseismic uplift at Oat Mountain in the hangingwall (Hudnut et al., 1996). The Santa Susana fault occurs high on the south flank of the Santa Susana Mountains rather than at the base of the mountains as the San Cayetano fault does, evidence that uplift of the Santa Susana footwall in 1994 was part of the long-term uplift of the footwall in the late Quaternary accompanying earlier earthquakes on the blind south-dipping fault (Yeats and Huftile, 1995). Other faults with footwalls uplifted by blind faults dipping in the opposite direction are the western San Cayetano fault, underlain by the Sisar fault, and the Red Mountain fault, underlain by the Padre Juan fault (Yeats and Huftile, 1995). The correlation between footwall uplift and blind south-dipping reverse fault is not perfect, however. The fault as illuminated by 1994 aftershocks continues east of the Santa Susana Mountains beneath the San Fernando Valley, and the only uplift is that of the Mission Hills, which could also be explained by uplift on the north-dipping Mission Hills reverse fault. Pujol et al. (2001), using seismic tomography, imaged a south-dipping thrust beneath the north-dipping Northridge Hills thrust.

Yeats and Huftile (1995) interpreted the 1994 south-dipping earthquake fault as the eastern blind continuation of the Oak Ridge fault, which reaches the surface in the Ventura Basin. They proposed that the Oak Ridge fault curves from an east-west strike to east-southeast, following changes in strike in the pre-Saugus Frew and Torrey faults. The long-term slip rate on the Oak Ridge fault is 3.7-4.5 mm/yr near the point where the fault is overridden by the Santa Susana fault (Huftile and Yeats, 1996), a rate at least twice as fast as that of the 1994 blind thrust. The cause of the eastward decrease in slip rate is unclear, unless part is taken up by the south-side-up Holser and Del Valle faults in the east Ventura Basin (Yeats et al., 1994; Yeats, 2001). Long-term slip rate on each of these faults is estimated as not more than 1 mm/yr, but this is poorly constrained because the Saugus is eroded away where fault displacements are largest.

Farther east, in the southeastern San Fernando Valley east of Universal Studios, Weber et al. (1980) mapped a sharp photo lineament south of the Los Angeles River close to a sharp gravity gradient. They correlated this structure to the Benedict Canyon bedrock fault of Hoots (1931), which has left separation where it crosses the Santa Monica Mountains and has its north side down farther east along the northern base of the range. At the eastern end of the Santa Monica Mountains, where the Los Angeles River turns to the south, the bottom of the alluvial

basin appears to be displaced relatively downward 170 m on the north side, near where faceted spurs have been identified on the flanks of the range. However, Weber et al. (1980) were unable to find evidence that this fault displaces Quaternary deposits; the faceted spurs could be caused by fluvial erosion and not fault displacement.

**Los Angeles fold-and-thrust belt**

**Introduction**

The M 5.9 Whittier Narrows earthquake of October 1, 1987, occurred on a previously-unrecognized blind thrust fault in the eastern part of the Los Angeles Basin, leading to a paradigm shift in geological understanding of the active tectonics of the basin. This earthquake provided evidence that anticlines housing the great oil fields of the Los Angeles Basin overlie seismogenic source faults. The previous belief had been that Los Angeles is primarily a strike-slip province. The appearance of an earthquake in the Los Angeles Basin with a reverse-fault signature similar to those in the Transverse Ranges led to a reappraisal of the anticlines of the Los Angeles Basin for their earthquake potential. This reappraisal used the tools of the petroleum geologist: oil-well data and seismic profiles, as well as ground-water data (Dept. of Water Resources, 1961) and tectonic geomorphology.

The folds extend from the Newport-Inglewood fault eastward to the Elysian Park, Montebello, Santa Fe Springs, West Coyote, East Coyote, Richfield, and Kraemer anticlines, all housing oil fields except the Elysian Park anticline. Davis et al. (1989) constructed balanced (retrodeformable) cross sections across the Los Angeles Basin and concluded that the blind fault generating the Whittier Narrows earthquake is part of a thrust ramp they called the Elysian Park thrust. The anticlinal feature overlying the thrust ramp was referred to by them as the Santa Monica Mountains anticlinorium, uplift of which produced the Santa Monica Mountains, the Elysian, Repetto, and Montebello Hills, and the Puente Hills. (An anticlinorium is a major anticlinal structure that consists of several smaller anticlines.) The folds were drawn as fault-propagation folds, that is, slip on faults is consumed updip by folding, following Suppe and Medwedeff (1990). The long-term slip rate on the Elysian Park thrust was estimated by Davis et al. (1989) as 2.5-5.2 mm/yr.

Shaw and Suppe (1996) also constructed balanced cross sections across the Los Angeles Basin using a relatively high-quality 2D seismic data set, but in contrast to Davis et al. (1989), they interpreted their folds to be generated by fault-bend folding, following Suppe (1983). The blind thrust consists of thrust flats and thrust ramps, and the folds are generated as a result of the non-planar geometry of the thrust surface. In the Shaw and Suppe model, the thrust ramps generate dip panels that they called trends, and the thrust flats make up the lowlands, principally the central Los Angeles Basin lowland. These make up one very large fault called the Compton-

Los Alamitos thrust. They decoupled their northwest-trending Elysian Park trend from the east-west-trending Santa Monica Mountains anticlinorium of Davis et al. (1989). The slip rate on the thrust ramp beneath the Elysian Park trend was estimated as 1.7 +/- 0.4 mm/yr. Here we discuss the Elysian Park trend within the Los Angeles Basin as limited by Shaw and Suppe (1996). In this summary, we discuss the individual structures making up the Elysian Park trend separately, although the possibility exists that several of these structures might rupture together in a cascade, an implication of the models of both Davis et al. (1989) and Shaw and Suppe (1996).

**Las Cienegas fault**

The last oil-exploration and development campaign in Los Angeles took place in the downtown area in the 1960s, largely on the Las Cienegas structural shelf between the deep central trough and the Santa Monica Mountains. Hummon et al. (1994) showed that the base of shallow-marine Pleistocene gravels, 0.8-1.0 Ma in age (D. Ponti in Hummon et al., 1994) is upwarped along a broad arch in Hollywood and West Hollywood called by them the Wilshire arch because its axis approximately follows Wilshire Boulevard. The south side of the arch leads into the central trough, and the north side into an elongate low called the Hollywood Basin.

Hummon et al. (1994) proposed that the arch is formed by the blind, north-dipping Wilshire thrust dipping 10°-15° north. If the Hollywood Basin is the backlimb of this arch, a fault-bend fold model yields a dip-slip rate of 1.5-1.9 mm/yr over the past 0.8-1.0 m.y. They also located the fault using an elastic-dislocation model of the wavelength (10 km) and amplitude (400 m) of the Wilshire arch, following King et al. (1988), who showed that the wavelength of a fold associated with an active fault can be compared to the wavelength of coseismic folding. This model locates a fault dippng 30°-35° north, with the fault tip 2.0 to 2.8 km below the surface, consistent with a diffuse zone of seismicity. This yields a right-oblique slip rate of 2.6-3.2 mm/yr.

These models depend on the Hollywood Basin being the backlimb of the fault generating the Wilshire arch. However, Tsutsumi (1996) and Tsutsumi et al. (2001) showed that the Hollywood Basin is a pull-apart basin related to the left step between the Santa Monica and Hollywood faults, hence a strike-slip feature in contrast to the dip-slip backlimb of the Wilshire arch. Schneider et al. (1996) used Pliocene and younger growth strata between the Las Cienegas structural shelf and the central trough to model the blind fault generating the boundary between the central trough and the structural shelf. The vertical component of displacement is the difference in thickness of coeval strata between the shelf and the trough, backstripped to obtain pre-compaction thicknesses. The horizontal component is the difference in shortening by line-length balancing of horizons of different ages. Analysis of growth strata show that the folds grew through progressive limb rotation, with fault dip of 61° at East Beverly Hills Oil Field and

62° at Las Cienegas Oil Field. The slip rates on the fault over the past 5 m.y. were1.1-1.3 mm/yr at East Beverly Hills and 1.3-1.5 mm/yr at Las Cienegas, with horizontal convergence rates 0.5-0.6 mm/yr at East Beverly Hills and 0.6-0.7 mm/yr at Las Cienegas.

Ponti et al. (1996) and Quinn et al. (2000) compared relative vertical displacement between the structural shelf and the central trough for the past 330 ky and found a vertical uplift rate no more than 0.09-0.13 mm/yr, about an order of magnitude lower than the slip rate of Schneider et al. (1996). Although the uplifted side of the Las Cienegas blind fault is still active based on topographic expression (Dolan and Sieh, 1992; M. Oskin, pers. commun., 2000), it is clear that the long-term rate is much higher than the late Quaternary rate. Analysis of additional cross sections eastward in the Boyle Heights and East Los Angeles districts near the Pomona Freeway between Las Cienegas and Bandini oil fields (R.S. Yeats and G.J. Huftile, see R.S. Yeats website) shows that the vertical changes of the Pleistocene San Pedro Formation across the Las Cienegas blind fault are considerably less eastward and essentially non-existent south of Bandini Oil Field (Yeats et al., 1999).

This eastern edge of the Los Angeles trough was depicted in a cross section by Shaw and Suppe (1996, their cross section Y-Y') as the Las Cienegas trend, a fault-bend fold generated by a thrust ramp of their Las Cienegas thrust. Growth triangles imaged on their seismic profiles showed that displacement on the blind thrust took place during deposition of the upper Pico (latest Pliocene) and continued into the Quaternary. Shaw and Shearer (1999) named this structure the Los Angeles segment of their Puente Hills thrust.

**Elysian Park anticlinorium**

The Elysian Park anticlinorium *sensu stricto* is a southward-verging anticline 20 km long with a curved, southward-convex axis, lying between the left-lateral(?) Hollywood fault on the northwest through the Silver Lake district and the cities of South Pasadena and Alhambra to the right-lateral East Montebello fault on the east in the city of San Gabriel. Uplift of the structure has produced the Elysian, Repetto, and Monterey Park Hills. From the Los Angeles River eastward, the southern range front of the hills is formed by the active axial surface between the south limb of the anticlinorium and the nearly-flat dips of the Las Cienegas structural shelf (R.S. Yeats and G.J. Huftile, work in progress).

Oskin et al. (2000) studied parasitic minor folds in the vicinity of the axial surface, the largest being the Coyote Pass escarpment and monocline close to the range front. Bullard and Lettis (1993) concluded that these folds provide evidence for a southward migration of deformation. Deformed late Quaternary deposits across the Coyote Pass escarpment and related structures allowed Oskin et al. (2000) to estimate a contraction rate across the structure of 0.6-1.1 mm/yr and a late Quaternary slip rate on the blind Elysian Park reverse fault of 0.8-2.2 mm/yr.

The dip of the blind fault was determined by analysis of growth strata, similar to the method of Schneider et al. (1996).

The late Quaternary slip rate on the Elysian Park fault is similar to the long-term slip rate on the Las Cienegas fault, suggesting that convergence is shifting northeastward from the Las Cienegas fault to the Elysian Park fault (Yeats et al., 1999). Unlike the Las Cienegas fault, with structural growth taking place throughout the Pliocene and early Pleistocene, the Elysian Park anticlinorium shows no significant decrease in thickness of the Repetto and early Pico members of the Fernando Formation between the structural shelf and the south limb of the anticlinorium, based on oil-well data. However, Soper and Grant (1932), based on surface geology, concluded that this structure was active in the Pliocene based on an unconformity between the Pico and Repetto members of the Fernando Formation. A possible western continuation of the Elysian Park fault in downtown Los Angeles, the San Vicente fault of Schneider et al. (1996) has relatively small reverse separation superposed on a much larger normal separation during the Miocene. However, the San Vicente fault north of East Beverly Hills Oil Field shows evidence of Pliocene growth, earlier than that at the Elysian Park axial surface (Schneider et al., 1996, their fig. 4) and consistent with observations of Soper and Grant (1932).

An unresolved problem is the origin of the MacArthur Park escarpment southwest of the Hollywood Freeway and several minor folds in alluvium on the crest of the Wilshire arch mapped by Dolan et al. (1997) along Wilshire Boulevard and La Brea Avenue to the north. The MacArthur Park lineament is the northwest-trending range front between southwest-dipping strata of the Elysian Park anticlinorium and Quaternary deposits atop the Wilshire arch, which are cut off at the range front. Oskin et al. (2000) show the MacArthur Park escarpment as the continuation of the Coyote Pass escarpment, based on uplifted fluvial terraces. However, the MacArthur Park escarpment does not correspond to the same axial surface between low-dipping strata of the Las Cienegas structural shelf and southwest-dipping strata of the anticlinorium. Cross sections constructed by R.S. Yeats and G.J. Huftile across the Los Angeles Downtown Oil Field and the Jefferson pool of the Las Cienegas Oil Field (see R.S. Yeats website) show that the range front is northeast of the active axial surface.

**Whittier Narrows earthquake source fault**

The fault-plane solution for the 1987 Whittier Narrows earthquake showed a moderately-dipping fault plane with an east-west strike (Hauksson and Jones, 1989). Releveling after the earthquake showed an uplifted area extending from the Santa Fe Springs anticline northward across the intervening La Habra syncline to the Montebello anticline (Lin and Stein, 1989). Shaw and Shearer (1999) relocated the mainshock and aftershocks of the earthquake, illuminating a fault plane dipping about 25° north, a dip consistent with fault-plane reflections on

a seismic profile west of the crest of the Santa Fe Springs anticline between -3 and -7 km below sea level. The fault tip is located beneath the south side of the Santa Fe Springs anticline based on a trishear kinematic model (Allmendinger and Shaw, 2000). The long-term slip rate was estimated as 0.5 to 2.0 mm/yr, with the faster limit based on GPS evidence (Argus et al., 1999); a minimum long-term slip rate is 0.5-0.9 mm/yr (Shaw et al., 2000).

High-resolution seismic profiles across the updip projection of the active axial surface between the Santa Fe Springs anticline and low-dipping strata to the south provide structural data within 15 m of the surface, with south dips of 20° to 25° north of the axial surface and horizontal dips to the south (Williams et al., 2000; Christofferson et al., 2000 and in prep.). If these dipping sediments can be dated through borehole traverses and trench excavations, a short-term slip rate could be calculated.

The fault is part of the Puente Hills thrust of Shaw and Shearer (1999), with the Santa Fe Springs segment stepped to the right from their Los Angeles segment farther west. The cloud of aftershocks of the 1987 earthquake is limited to the Santa Fe Springs segment (Hauksson and Jones, 1989).

The Montebello anticline to the north is a separate structure from the Las Cienegas, Elysian Park, or Santa Fe Springs structure. It is described below as part of the Whittier fault system.

**Coyote folds**

The Puente Hills thrust steps right east of the Santa Fe Springs anticline to a north-dipping reverse fault beneath the Coyote Hills (Shaw and Shearer, 1999). The Whittier earthquake of July 8, 1929, with intensities as high as VII, had its epicenter close to this stepover, with meizoseismals oriented north-south (Richter, 1958).

The Coyote Hills in the cities of La Mirada, La Habra, Fullerton, and Placentia are uplifted along a string of doubly-plunging anticlines. From west to east, these are the West Coyote anticline, housing the West Coyote Oil Field, and the Hualde and Anaheim domes of the East Coyote Oil Field. Farther to the southeast in the cities of Yorba Linda and Orange, the Richfield and Kraemer anticlines converge with the Whittier fault north of the Santa Ana River in the foothills of the Puente Hills. The south-verging Coyote folds each include an axial reverse fault, the South Flank fault of West Coyote and the Stern fault of East Coyote (Wright, 1991). Myers (2001) showed that the Stern fault underwent 1200 m of left-lateral strike slip, when the fault was nearly vertical, and became inactive prior to folding in the Quaternary. This strike-slip fault was traced westward across the Leffingwell Oil Field and must extend eastward south of the Anaheim dome of the East Coyote Oil Field. Folding began during deposition of the Pico member of the Fernando Formation.

Myers (2001) and D. Myers, J. Nabelek, and R. Yeats (in prep.) used dislocation modeling to locate the blind fault generating the Coyote folds, yielding dips consistent with those observed using aftershocks and fault-plane reflections beneath the Santa Fe Springs anticline (Shaw and Shearer, 1999), although there is large uncertainty in fault dip. Several dated horizons were projected into the East Coyote fold: the Brunhes-Matuyama boundary from a water well in Pico Rivera south of the Montebello anticline (D. Ponti, pers. commun., 2000), an age estimate of 1.4 +/- 0.4 Ma of a mollusc in the San Pedro Formation in the West Coyote Hills (Powell and Stevens, 2000), and the dated Nomlaki Tuff (3.4 +/- 0.3 Ma, Sarna-Wojcicki et al., 1991) near the Meyer shale in the Santa Fe Springs Oil Field (A. Sarna-Wojcicki and T.H. McCulloh, pers. comm., 2000). This leads to a slip rate on the blind thrust of 1.2 +1.4/-0.5 mm/yr.

Dislocation modeling was also applied to the Santa Fe Springs anticline, resulting in a slip rate slightly higher than that at East Coyote and a fault dip consistent with that obtained by fault-plane reflections and distribution of 1987 mainshock and aftershocks (D. Myers, J. Nabelek, and R. Yeats, in prep.).

### Peralta Hills thrust

South of the Coyote folds, Burruel Ridge and the Peralta Hills project westward into the Los Angeles Basin from the Santa Ana Mountains, possibly deflecting the course of the Santa Ana River westward. This feature is a southward-vergent anticline with the thrust on the south side; west of the Santa Ana River, the anticline projects into the Olive Oil Field. Bryant and Fife (1982) suggested that bedrock structures are thrust southward against Pleistocene terrace deposits, although subsequent geotechnical work by others suggests that they may have mapped a landslide. West of the Costa Mesa Freeway in Orange, immediately south of the Olive anticline, a scarp in alluvial deposits of the Santa Ana River adjacent to Lincoln Avenue appears to be active. A contractional structure, if extended eastward across the northern Santa Ana Mountains, could explain the difference in slip rate between the Elsinore fault at Glen Ivy and the Whittier fault at Santa Ana Canyon.

## Northwest-striking faults in the northernmost Peninsular Ranges

### Introduction

The southern part of the Los Angeles metropolitan area is tectonically a part of the Peninsular Ranges, with northwest-striking right-lateral faults that are part of the southern San Andreas fault system. Slip rates on these faults are highest on the San Andreas fault itself, lower on the San Jacinto fault, and still lower on the Whittier-Elsinore and the Newport-Inglewood faults (Yeats, 2001b). Davis et al. (1989) and Shaw and Suppe (1996) pointed out that these are

not simple strike-slip faults; reverse slip is also important and locally may be dominant. Davis et al. (1989) even suggested that the Whittier fault may be relatively unimportant compared to the regional blind thrust that underlies the Puente Hills. It seems likely that strain partitioning is an important element in the earthquake evaluation of these faults, just as it is in the central Coast Ranges, affected by reverse-fault earthquakes in 1983 (Coalinga) and 1985 (Kettleman Hills) as well as the great Fort Tejon strike-slip earthquake of 1857 and several Parkfield earthquakes from then until 1966.

Here we discuss those northwest-striking local faults that strongly impact the Los Angeles metropolitan region: the Whittier-Elsinore, Newport-Inglewood, and Palos Verdes faults. The San Jacinto fault is important to the San Bernardino-Riverside metropolitan area, and the San Andreas fault is important to the entire Los Angeles metropolitan region, but these faults are not discussed here. Offshore faults in the California Continental Borderland, in particular the San Diego Trough-San Pedro fault and the San Clemente fault, have an impact on the Los Angeles region, but too little is known about their slip rates to include them in this discussion.

Also included in this section are the east-northeast-striking San Jose fault and the north-northwest-striking Chino fault and a consideration of the active-tectonic significance of the Santa Ana Mountains and San Joaquin Hills.

**Whittier-Elsinore fault**

The Whittier and Elsinore fault is marked by a band of diffuse seismicity, although this is much less pronounced than the seismicity marking the San Jacinto fault to the east.

The late Pleistocene to Holocene strike-slip rate on the Elsinore fault at Glen Ivy Marsh south of Corona is 5.3-5.9 mm/yr (Millman and Rockwell, 1986), with evidence for 4 to 5 earthquakes of M 6-7 since about 1060 AD (Rockwell et al., 1986). The most recent event was probably the Temescal Valley earthquake of M 6 on May 15, 1910, with about 15 km of surface rupture (Rockwell, 1989). Northwest of Glen Ivy, the fault divides into two subpararallel strands, with the northeastern strand becoming the Chino fault and the southwestern strand, following the northeastern range front of the Santa Ana Mountains, becoming the Whittier fault. East of Santa Ana Canyon, the Whittier fault turns west-northwest into the northern end of the Santa Ana Mountains, where digital terrain images suggest right-lateral stream offsets. At Santa Ana Canyon, the Whittier fault has a right-lateral strike-slip rate of 2-3 mm/yr based on a 400-m offset of terraces of the Santa Ana River that are 140 ka in age (Gath, 1997; Gath et al., 1998; Rockwell et al., 1988). Farther west, at Olinda Creek, one strand of the Whittier fault has a right-lateral strike-slip rate of about one mm/yr. The stream offset by this strand is offset the same amount by another strand, and Gath et al. (1992) assigned a strike-slip rate on both strands of at least 2 mm/yr. The two strands are part of a positive flower structure, with Miocene Puente

Formation thrust over alluvial deposits; however, the displacement is mainly by strike slip (Gath et al., 1992). In addition, the tectonic geomorphic expression of the fault is characteristically strike slip, including right-deflected streams and shutter ridges (Rockwell et al., 1988).

The slip rate difference led Rockwell et al. (1992) to conclude that about 2.6 mm/yr of strike slip escapes along the Chino fault. However, some of this difference can be accounted for by the Coyote folds that intersect the Whittier fault at Santa Ana Canyon. The slip rate on the blind thrust generating the East Coyote folds (Myers, 2001) is enough to account for part of the difference between the strike-slip rate at Glen Ivy Marsh and that at Olinda Creek. Additional displacement could take place on the Peralta Hills thrust and on a footwall anticline beneath the Whittier fault between Turnbull Canyon (Herzog, 1998) and Yorba Linda (see fig. 17 in Myers, 2001, and R.S. Yeats website), including the 304 and 184 anticlines of the Whittier Oil Field (Herzog, 1998) and the Brea anticline of the Brea-Olinda Oil Field. This anticline (locally an anticlinorium) is considered to be active due to footwall uplift east of Turnbull Canyon; west of Turnbull Canyon, the Whittier fault lies at the Puente Hills range front (Herzog, 1998).

At the Whittier Narrows of the San Gabriel River, the Whittier fault turns more northerly to become the East Montebello fault. At Alhambra Wash in Rosemead, Gath et al. (1994) and Gath and Gonzalez (1995) trenched a strand of the East Montebello fault and found a slip rate of only 0.2 +/- 0.1 mm/yr; a second, larger scarp to the west was not investigated. This suggests a lower slip rate than that measured at Olinda Creek, which could be accounted for by growth of the Montebello anticline, which is truncated on the east by the East Montebello fault. The Montebello anticline was not uplifted separately from the Santa Fe Springs anticline during the 1987 Whittier Narrows earthquake (Lin and Stein, 1989), suggesting that its uplift history is controlled by strike slip on the Whittier fault instead of (or in addition to) reverse slip on the blind Santa Fe Springs segment of the Puente Hills thrust.

Despite the evidence for late Quaternary strike slip, the total right slip on the Whittier fault is relatively small. Part of the difficulty in establishing piercing-point offsets is that the modern Whittier fault reactivated a Miocene normal fault with the north side down (Yeats and Beall, 1991; Bjorklund and Burke, in review). McCulloh et al. (2000) estimate the right separation as 8-9 km based on offset facies and isopachs of Paleogene strata. This estimate faces the difficulty that north of the fault, Paleogene facies boundaries turn abruptly westward in the southeastern Puente Hills. The Santa Rosa basalt dated at 10.6 Ma is offset across the Elsinore fault no more than 15 km (Hull and Nicholson, 1992). Bjorklund and Burke (in review) are able to construct isopachs of the late Miocene Sycamore Canyon member of the Puente Formation without any offset, although the isopachs south of the fault are parallel to it, and an undetermined amount of strike slip is permitted by the isopach data.

Throughout most of its length on the south side of the Puente Hills, the fault has reverse separation, north side up, with maximum vertical separation of 4267 m in the northwest Puente Hills (McCulloh et al., 2000). This separation is less to the southeast, and near the Horseshoe Bend of the Santa Ana River, the sense of separation in bedrock (although probably not in late Quaternary deposits) changes to south side up, and the dip is vertical (Bjorklund and Burke, in review; McCulloh et al., 2000). Nonetheless, northwest of Horseshoe Bend of the Santa Ana River, the dominant expression is reverse slip, with a dip of 60° to 75° north. At Rideout Heights at the northwestern end of the Whittier fault, the late Pleistocene-Quaternary uplift rate is 0.6 +/- 0.1 mm/yr, and the dip separation rate is 0.97 +/- 0.1 mm/yr (Herzog, 1998), about the same as the strike-slip rate.

**Puente Hills, San Jose Hills, and the San Jose fault**

Davis et al. (1989) implied that the uplift of the Puente Hills is dominated by the Elysian Park blind thrust. Shaw and Shearer (1999) named the regional blind thrust generating the 1987 Whittier Narrows earthquake the Puente Hills thrust, although the topographic expression of the Puente Hills thrust is the Santa Fe Springs anticline and the Coyote Hills, not the Puente Hills. Herzog (1998) observed that the Puente Hills are restricted to the region between the Santa Ana and San Gabriel rivers, where the west-northwest-striking Whittier fault is a restraining bend between the northwest-striking Elsinore fault and north-northwest-striking East Montebello fault. Bjorklund and Burke (in review, based on structure contours of the La Vida member of the Puente Formation, map the structure of the Whittier fault hangingwall as a south-vergent anticline with its culmination west of Brea Canyon, next to the Brea-Olinda Oil Field. The uplifted footwall of the fault between Turnbull Canyon and Yorba Linda, related to a footwall anticline, attests to dip-slip on part of the Whittier fault system, evidence of partitioning between strike slip, as seen in the geomorphology and trench excavations, and dip slip, as seen in anticlines in both the footwall and hangingwall.

In contrast to the southern Puente Hills, the northern Puente Hills and San Jose Hills appear to be structurally more complex, and folding dominates (Olmstead, 1950). The San Jose Hills trend east-northeast and are uplifted along a west-southwest-plunging anticline underlain by the La Vida member of the Puente Formation, the Glendora Volcanics, and Cretaceous granitic rocks. The San Jose fault lies at the southern range front, steps left where the anticlinal axis steps left (Tan, in press a, b), and dies out at the surface farther west in the south limb of the anticline. Farther south, the Amar syncline is in an alluviated lowland, and still farther south, the Puente Hills anticline, housing the Walnut Oil Field, is also expressed as tectonic topography in the Little Puente Hills (Tan, in press a, b). This leads to the suggestion by R.S. Yeats that these

folds, along with the Glendora South Hills farther north (Shelton, 1955), may be previously-unrecognized reverse-fault earthquake sources with a Transverse Ranges trend.

This implies that the Upland strike-slip earthquakes of 1988 and 1990 (Hauksson and Jones, 1991) may not have originated on the northeastern continuation of the San Jose fault. However, their source could have been the continuation of a strike-slip fault farther northwest, such as the Walnut Creek fault mapped by Tan (in press a, b) along the southwestern margin of the San Gabriel Valley or the Indian Hill fault mapped in the San Gabriel Valley farther northwest (Dept. of Water Resources, 1966; 1970; located on maps by Hauksson and Jones, 1991). A difficulty in evaluating these sources is that the youngest bedrock is Puente Formation; the thick Pliocene of the western San Gabriel Valley is absent. The Indian Hill fault appears to offset the base of water-bearing sediments, with the north side up (Dept. of Water Resources, 1970).

**Chino fault**

The Chino fault has been regarded as a strike-slip member of the Elsinore fault system (Rockwell et al., 1992). An earthquake of M 4.3 in February, 1989, with its epicenter southwest of the surface trace of the fault, had a fault-plane solution consistent with right-lateral strike slip on the Chino fault (Hauksson and Jones, 1991). A strike-slip fault with a more northerly strike than that of the Elsinore fault should be transtensional; indeed, small depressions are found at right stepovers along the fault (E.M. Gath, in prep.). On the other hand, the Chino fault has reverse separation throughout its length, with the southwest side up (Gray, 1961; Durham and Yerkes, 1964; Castro, 1975; Schoellhamer et al., 1981). In the Chino Hills, the Mahala anticline in the hangingwall of the Chino fault has topographic expression, following the Chino Hills drainage divide. McCulloh et al. (2000) suggested that the total right slip on the Chino fault can be no greater than a few kilometers, based on isopachs of Paleogene strata. R.S. Yeats (in prep.) suggests that the Mahala-Chino structure might comprise an active fold-reverse fault pair that is propagating north-northwestward toward the San Jose Hills, although the 1989 earthquake provided evidence that this fault can generate strike-slip earthquakes. Alternatively, the Chino fault could bend to a more northerly strike, cutting off the San Jose Hills on the east.

Heath et al. (1982) estimated a slip rate of 0.06 mm/yr horizontal and the same rate vertical near Prado Dam. Their slip rate was based on the 8-m vertical separation of a paleosol, the age of which was estimated as 125 ka. This separation was both by faulting and downwarping. They had no independent evidence for horizontal offset of this paleosol or of younger deposits; they simply assumed that the horizontal offset would be no larger than the vertical. Chris Walls and Eldon Gath suggest that the fault is active and is predominantly right lateral, based on northeast-facing fault scarps, deflected drainage, and beheaded drainage in the

Chino Hills and northeast-facing fault scarps and vegetated lineaments in the alluvium near and southeast of Prado Dam (see also Weber, 1977). Walls and Gath salvage-logged a trench excavation in the Chino Hills in which an organic colluvial layer overlying Puente Formation is offset 4.2-5.6 m right laterally with 10-15 cm apparent vertical separation. Charcoal from this colluvium was dated by Chris Walls as 11,219 +/- 331 and 9543 +/- 55 radiocarbon years.

To the east, the Central Avenue fault may be a right stepover from the Chino fault, based on photo lineations and geomorphic features being studied by J.A. Treiman (in prep.).

**Newport-Inglewood fault and the Compton-Los Alamitos trend**

Like the Whittier-Elsinore fault, the Newport-Inglewood fault, 70 km long onshore, is marked by a band of diffuse seismicity. Several earthquakes have struck the fault zone, including the March 10, 1933 "Long Beach" earthquake of M 6.4, with its epicenter off Newport Beach, and smaller earthquakes at Inglewood on June 20, 1920 (M 4.9), Gardena on October 22, 1941 (M 4.9), and Torrance-Gardena on November 14,1941 (M 5.4; Hauksson, 1990). Many microearthquakes are characterized by right-lateral strike-slip focal mechanisms, as was the 1933 earthquake (Hauksson, 1987; 1990). No historical earthquake is known to have been accompanied by surface rupture (Barrows, 1974).

The Newport-Inglewood fault continues offshore to the southeast (Fischer and Mills, 1991) and makes landfall in La Jolla as the Rose Canyon fault, which has evidence of Holocene right-lateral strike slip and a slip rate of 1.5 mm/yr (Lindvall and Rockwell, 1995). It is not a continuous surface fault like the Whittier fault, but instead is marked by a series of uplifts and anticlines including Newport Mesa, Huntington Beach Mesa, Bolsa Chica Mesa, Alamitos Heights and Landing Hill, Signal Hill and Reservoir Hill, Dominguez Hills, Rosecrans Hills, and the Baldwin Hills (Barrows, 1974). Farther northwest, it is on trend with the Cheviot Hills and the West Beverly Hills Lineament, the latter marking the left stepover between the presumably left-lateral Santa Monica and Hollywood faults (Dolan et al., 1997; 2000b). The right-lateral stress field is evident from the predominance of reverse faults in the west-trending Dominguez anticline, the coincidence of Signal Hill with a short, northeast step (Pickler fault) in the Long Beach segment of the fault, and normal separation on north-striking faults in Sunset Beach and Huntington Beach oil fields (Yeats, 1973; Harding, 1973).

Freeman et al. (1992) worked out long-term strike-slip rates on the fault by correlating electric-log facies of strata of 6 to 2.3 Ma on one side of the fault to a best match on the opposite side. At Seal Beach and Huntington Beach oil fields, this gave a slip rate of 0.49-0.52 mm/yr. At Long Beach Oil Field, the slip rate is 0.5 mm/yr, and at Inglewood Oil Field, at the northwest end of the zone, the slip rate is 0.31 mm/yr. With error bars, the approximate slip rate can be estimated as about 0.5 mm/yr. Slip rates can also be determined from offset anticlines at Seal

Beach and Inglewood oil fields, and offset isopachs (Freeman et al. (1992). Maximum displacement measured is about 4 km for strata about 7 Ma at Huntington Beach Oil Field. The maximum displacement at Inglewood Oil Field is 1.4 km for strata of 4 Ma (Wright et al., 1973), indicating that strike slip at Inglewood did not start until the Pliocene, later than it started at Huntington Beach. Freeman et al. (1992) estimated the ratio of vertical to horizontal slip to be 1:20. Grant et al. (1997) estimated a minimum Holocene right-lateral strike-slip rate of 0.30-0.55 mm/yr for the southern Newport-Inglewood fault zone in the Huntington Beach Oil Field.

Yet a purely strike-slip history, even taking into account restraining bends such as the one at Dominguez Hills and a transfer of strike slip to folds west of the fault at Sawtelle Oil Field (Tsutsumi et al., 2001), cannot explain the Central Uplift, the name applied by the petroleum industry to the elevated structure of the Newport-Inglewood trend with respect to the central trough to the northeast and the Wilmington structural shelf to the southwest. Davis et al. (1989) accounted for the Central Uplift by a blind thrust. Shaw and Suppe (1996) described the northeast-dipping flank of the Central Uplift as the Compton-Los Alamitos trend, a fault-bend fold that overlies a thrust ramp with 4 km of slip, based on upward-narrowing growth triangles of sedimentary strata above the ramp. The base of the growth triangle, marking the age of initiation of thrusting, was estimated as 2.5 Ma, near the top of the Repetto Member of the Fernando Formation. With this information, the long-term dip-slip rate was calculated as 1.4 +/- 0.4 mm/yr.

T.K. Rockwell and K.J. Mueller excavated a trench, and K.J. Mueller acquired CPT borings across the surface projection of the Compton-Los Alamitos axial surface (Mueller, 1997), showing that this surface does not deform peat deposits dated as 1.9 ka or the Gaspur aquifer (cf. Dept. of Water Resources, 1961) dated as 15-20 ka. Additional work (K.J. Mueller and T.K. Rockwell, in prep.), including structure contours on five aquifers ranging in age from 15-20 ka to 730 ka tied into the global eustatic sea level curve (D.J. Ponti, in prep.), additional trenching and CPT profiles on the Los Alamitos air base, and analysis of a digital elevation model shows no folding of the Gaspur aquifer on the air base. But the Sunnyside (720 ka), Lynnwood (650 ka), and Gage (330 ka) aquifers are folded consistent with the Shaw and Suppe (1996) model but at a slower rate, about 0.5 mm/yr.

Grant et al. (1997) showed that a splay of the North branch of the Newport-Inglewood fault at Huntington Beach has a vertical separation rate of 0.2 mm/yr. They found evidence of five earthquakes, with the oldest shortly after 11.0-12.3 ka. Events younger than 4.4-5.0 ka may be present but are unresolvable with their data.

**San Joaquin Hills**

Adjacent to the Newport-Inglewood fault where it crosses the shoreline, the San Joaquin Hills are uplifted at a rate of 0.21-0.27 mm/yr, based on mapping and dating late Quaternary shorelines (Grant et al., 1999; in press). The relations are best explained by a southwest-dipping blind thrust with a slip rate of 0.42-0.79 mm/yr. Rivero et al. (2000) consider this southwest-dipping thrust to be part of a larger structure extending offshore to the south and dipping 23°. In their view, the southwest-dipping thrust is a hangingwall structure in their east-dipping Oceanside thrust, a Miocene low-angle normal fault reactivated in the Quaternary. They described a similar thrust farther west, the Thirtymile Bank fault, which is too far offshore to be included in this summary.

Coseismic coastal uplift of the San Joaquin Hills may have generated the largest historical earthquake in the Los Angeles region, an earthquake experienced by the Portolá expedition on July 28, 1769. Late Holocene marsh deposits and shorelines are elevated 1 m to 3.6 m above the active shoreline in a pattern that is best explained by tectonic uplift accompanying an earthquake of M>7. Radiocarbon dating and pollen analysis constrain the date of the earthquake as between 1635 and 1855 A.D., with the strong possibility that this was the earthquake reported by Portolá (Grant et al., in revision).

**Palos Verdes fault**

The Palos Verdes fault follows the northeastern range front of the Palos Verdes Hills between Redondo Beach and San Pedro, extending across Los Angeles Harbor onto the continental shelf to the southeast. The Palos Verdes Hills are etched by a flight of marine terraces with their ages estimated as 0.45 to 1.5 Ma, leading to an uplift-rate determination of 0.7 +/- 0.2 mm/yr (Ward and Valensise, 1994). The uplift pattern of the Palos Verdes terraces enabled Ward and Valensise (1994) to model the uplift of the Palos Verdes anticlinorium, 15 km long and 8 km wide, as due to a restraining bend on an oblique reverse-right slip fault dipping to the southwest with a long-term slip rate of 3.0-3.7 mm/yr. The uplift rate of Ward and Valensise (1994), and therefore the slip rate on the fault, is controlled by the correlation of the marine terraces; more recent work by D.J. Ponti suggests a slower uplift rate, 0.3-0.5 mm/yr.

Northwest of San Pedro, high-resolution seismic profiles show that the channel of the ancestral Los Angeles River, dated as 120-80 ka, is deflected 300 m, leading to an intermediate-term slip rate of 2.5-3.8 mm/yr, with strike slip predominating (Stephenson et al., 1995). To the southeast, in Los Angeles Harbor, McNeilan et al. (1996) showed that an early Holocene paleochannel has been deflected 21-24 m, indicating a slip rate of 2.7 mm/yr for the past 7.8-8 ka, with the ratio of horizontal to vertical slip 7:1 to 8:1.

In contrast, Davis et al. (1989) interpreted the Palos Verdes anticlinorium and fault along with the Torrance-Wilmington-Belmont (TWB) anticlinorium to the northeast, as overlying a

décollement. Shaw and Suppe (1996) considered the Palos Verdes anticlinorium as the hangingwall of a backthrust related to a fault-bend fold, with uplift of the anticlinorium the same as that calculated by Ward and Valensise (1994). The slip rate of the fault underlying the TWB anticlinorium was calculated as 1.2 +/- 0.4 mm/yr. 3D seismic data suggest that the TWB anticlinorium is a tip-line fold developed above a northeast-dipping thrust ramp that offsets and folds basement; the forelimb of this fold contains deformed Pliocene strata (J. Shaw, in prep.).

Well data show that the TWB anticlinorium stopped growing in middle Pico time and is overlain unconformably by undeformed strata (Wright, 1991). This argues against the TWB being linked to the Palos Verdes fold, dated by younger uplifted marine terraces. However, J. Shaw (in prep.) has found that the unconformity and overlying strata in the TWB anticlinorium are, indeed, folded gently about the axial surface bounding the southern edge of the forelimb, consistent with reverse-fault seismicity described by Hauksson (1990), although the slip rate on this structure has slowed down in the Quaternary. The two models linking the Palos Verdes and Compton-Los Alamitos structures (Shaw and Suppe, 1996) are (1) the Compton structure refolds part of the Palos Verdes fault (favored by J. Shaw, in prep.) and (2) the Palos Verdes fault is offset by the Compton ramp, or is a backthrust above the Compton ramp (Davis et al., 1989).

The Palos Verdes fault extends offshore to the southeast, where it is clearly mapped by sidescan sonar (M.V. Gardner, in prep., C. Goldfinger et al., in prep.) and high-resolution seismic-reflection profiles (Francis et al., 1999 and in prep.). At a point about 10 km southeast of the breakwater, the fault bends southward (releasing bend) and breaks up into several youthful traces that cut through the Beta Oil Field (Fischer et al., 1977; Kelsch et al., 1998). The fault appears to bend into a more northerly trend (transtensional) that controls the location of San Gabriel submarine canyon, as shown by multibeam bathymetry of Gardner et al. (2000). The fault splits into two major faults around Lasuen Knoll, a restraining-bend pop-up structure. The principal trace of the Palos Verdes fault lies along the southwest flank of Lasuen Knoll, where it is clearly expressed in seismic profiles (Bohannon et al., 1998; Mallory et al., 2000). The Palos Verdes fault zone continues southeast as the Coronado Bank fault zone with alternating regions of transpressional pop-up structures and broad transtensional sags (Legg, 1985; Legg and Kennedy, 1991; M. Legg and C. Goldfinger, in prep.) Overall, the Palos Verdes-Coronado Bank fault zone is complex and segmented, commonly with two sub-parallel faults. Uplift at left bends and sags at right bends show the right-slip character. The eastern fault zone from Lasuen Knoll to La Jolla submarine canyon is poorly known and may be tied to the Oceanside detachment/thrust fault system (M. Legg, C. Sorlien, and C. Nicholson, in prep).

To the northwest, off Redondo Beach, the fault is not as easy to trace on sidescan sonar (C. Goldfinger, M. Legg, R.S. Yeats, and G.J. Huftile, in prep.). The shelf is cut by the Redondo and Santa Monica submarine canyons (Nardin and Henyey, 1978); uplifted areas on the shelf

bring Miocene strata to the surface (Junger and Wagner, 1977). Some authors extend the Palos Verdes fault northwest as a strike-slip fault to an intersection with the Dume fault. An alternative is for various "horsetail" strands to splay westward, including the Redondo Canyon fault. These western splays should have reverse separation and consume slip in Santa Monica Bay on the north side of the Shelf Projection anticline of Nardin and Henyey (1978). Hauksson (1990; see also Davis et al., 1989) showed this region as the northwestern continuation of their Torrance-Wilmington fold and thrust belt. A north-trending graben near the head of Redondo submarine canyon suggests a pull-apart origin at a right stepover on the Palos Verdes fault where it extends offshore. Numerous fault traces have been mapped on the shelf in Santa Monica Bay (Vedder, 1986) although possible nearshore fault traces are presently unknown due to lack of data in the immediate coastal area. The coast-parallel trend of ancient Ballona Creek (Los Angeles River channel) immediately offshore Playa del Rey to Manhattan Beach may be fault-controlled (M. Legg and D. Francis, in prep.).

Earthquakes in Santa Monica Bay with reverse-fault focal mechanisms, with the largest the Malibu earthquakes of January 1, 1979 and January 19, 1989, each with magnitude 5.0 (Hauksson and Saldivar, 1989; Hauksson, 1990), are too far south to be attributed to the Dume fault. These earthquakes may be related to the western splays of the Palos Verdes fault. However, there are also many strike-slip earthquakes in this region, so the northern end of the Palos Verdes fault still remains poorly located.

The overall pattern of a segmented Palos Verdes fault, with alternating areas of extension and contraction, continues in Santa Monica Bay. The predominance of west to west-northwest trending anticlinoria along the southwest flank of the Palos Verdes fault is consistent with a reduction of strike slip northwestward toward the Transverse Ranges, with slip taken up by shortening on folds and horsetail splays.

## Discussion: Problems for SCEC II

### Introduction

The main purpose of this report is to synthesize what we know about the earthquake geology of the Los Angeles metropolitan area rather than analyze the data with respect to conflicting tectonic hypotheses. However, it is possible to see where we stand at the end of SCEC I and point out the major unsolved problems for SCEC II. The questions that we raise today could not have been posed at the time SCEC I began.

### Convergence rate discrepancy between late Quaternary geology and GPS

Walls et al. (1998) compared the convergence rates across the Los Angeles metropolitan area with convergence rates based on geologically-determined slip rates on individual faults.

These rates appeared to be in agreement when the higher rates of Davis et al. (1989) and Davis and Namson (1994) were used (Argus et al., 1999), but recent studies of late Quaternary slip rates, summarized above, suggest that the geological rates in the Los Angeles and San Gabriel basins are slower than the GPS rates would predict. Bawden et al. (2001), after removing GPS sites contaminated by groundwater- and oil-pumping effects, determined an average southward shortening across the Los Angeles Basin of 4.4 +/- 0.8 mm/yr in a direction N35° +/- 5° E. The GPS rates could be a temporary velocity transient, as has been suggested for parts of the Great Basin, but this is less likely in Los Angeles because the GPS and geological rates appear to be in agreement in the Ventura Basin (Huftile and Yeats, 1995; 1996) and opposite the Cucamonga fault east of the San Jose Hills. In fact, the geologically-determined rates are higher than GPS rates in the western Ventura basin.

The principal problem is the unexplained lower slip rate on the Sierra Madre fault between the 1971 rupture zone and the Cucamonga fault (Crook et al., 1987, reinforced by more recently-determined late Quaternary slip rates, discussed above). The shortening across the Sierra Madre, Elysian Park, and Puente Hills faults, together with a contractional component across the Raymond and Whittier strike-slip faults, sums to 3-3.5 mm/yr. The discrepancy could be accounted for by the San Jose fault and a blind reverse fault beneath the northern Puente Hills anticline at Walnut, but this is not yet known. West of the San Fernando Valley, the Santa Susana, San Cayetano, and Oak Ridge faults have slip rates that are high enough to be consistent with GPS results (Huftile and Yeats, 1995; 1996), and this may be the case also for the Cucamonga fault. The Verdugo fault in the eastern San Fernando Valley could take up some of the strain, but the Eagle Rock fault between the Verdugo and Raymond faults has poor geomorphic expression and probably hase a low slip rate.

Some of the shortening could be taken up by folding. The blind Santa Monica Mountains thrust was thought to have a high slip rate by Namson and Davis (1994), but studies of the marine terraces along the Malibu coast show that the slip rate of that thrust is much lower, possibly an order of magnitude lower.

This is a major problem for SCEC II because of the possibility of other faults, as yet unidentified, that take up the missing horizontal convergence indicated by GPS. We don't want to be surprised by another Northridge blind thrust.

**Short-term vs long-term slip rates**

In the western Ventura Basin, the short-term rates are somewhat faster than the long-term rates but are in a general way consistent in that they involve the same faults. In the Los Angeles Basin, the long-term slip rates (2-5 x $10^6$ yrs) on the Las Cienegas and Compton-Los Alamitos faults are much higher than the short-term rates measured in $10^4$-$10^5$ yrs. Strike slip on the

Newport-Inglewood fault appears to have started earlier in the southeastern Los Angeles Basin than farther northwest. High slip rates on both the Raymond and Whittier faults must be considered in light of low total displacement on these faults, evidence that the presently-operating strike-slip phase is relatively young. The northwest-striking right-slip faults of the Peninsular Ranges may have propagated into the Los Angeles metropolitan area only in the Quaternary, implying that slip rates on these faults might approach zero as the Transverse Ranges boundary is approached.

If confirmed by additional work, this leads to a higher weighting of slip rates based on late Quaternary offsets than longer-term rates in probabilistic hazard analyses.

**Offshore faults**

The Newport-Inglewood, Palos Verdes, Santa Monica, and Malibu Coast faults extend offshore, where their geology is poorly understood compared to onshore faults. Newly-emerging technology of side-scan sonar, high-resolution swath bathymetry, high-resolution seismic profiling, and remotely-operated submersibles is expensive, but these techniques, together with piston cores, are necessary to characterize the offshore portions of onshore faults. For example, high-resolution multibeam bathymetry offshore from metropolitan Los Angeles (Gardner et al., 2000; Marlow et al., 2000) has provided a new understanding of the geometry and recency of movement on major offshore faults, including the San Pedro Basin and Avalon Knoll fault zones, both of which have prominent seafloor expression and likely Holocene activity. In addition, some faults are completely offshore, but close enough to metropolitan areas that they will impact the Los Angeles and San Diego metropolitan areas, just as a modern repetition of the December 21, 1812 earthquake would impact coastal cities around the Santa Barbara Channel.

Offshore paleoseismology is possible based on the analysis of turbidites in submarine channels, as has already been shown by work by C. Goldfinger, H. Nelson, and Gorsline et al. (2000). Turbidites at the mouth of Noyo Canyon off the northern California coast have been age-calibrated by AMS dating of foraminiferal tests, giving a paleoseismological record of the northern San Andreas fault for the past 13,000 years, a record consistent with the shorter record available from trench excavations (C. Goldfinger and H. Nelson, in prep.). Gorsline et al. (2000) concluded that the larger, more areally extensive turbidites in Santa Monica Basin were generated by earthquakes. These turbidites were dated using $^{210}$Pb and AMS $^{14}$C and by counting varves. The most recent turbidite might have recorded the 1812 earthquake in the western Transverse Ranges. Recurrence frequency of these large turbidites is 470 years. Submarine fans and turbidite-filled channels in the Borderland can be surveyed with high-resolution seismic imagery combined with piston cores to provide information on fault displacements during individual earthquakes and strong shaking generating turbidites.

The present Group C team comprises terrestrial geologists, with a few notable exceptions, and terrestrial geology has dominated most of the funding. A major problem is the expense of gathering data, but this can be alleviated by forming partnerships with other agencies, including NOAA, NSF, and USGS Marine Geology Branch.

**Strain partitioning**

The early days of SCEC were characterized by lively debate between those advocating a dominance of dip-slip faulting, especially blind thrusting, vs those suggesting that strike-slip faulting is important also. In part, the two camps were using two different time scales. Slip rates based on blind thrusting are based on growth strata deposited over several million years whereas slip rates on strike-slip faults are based on trench excavations and late Quaternary tectonic geomorphology, including stream deflections and shutter ridges.

It appears that both camps are partly correct. Strike slip on the Newport-Inglewood fault does not explain the Central Uplift, atop which the Newport-Inglewood oil fields are located, and strike slip on the Whittier fault does not explain footwall uplift between the Whittier and Brea-Olinda oil fields, nor does it explain uplift of the Coyote Hills. A clue may be seen in examining focal-mechanism solutions in Santa Monica Bay (Hauksson and Saldivar, 1989), which show both strike-slip and reverse-slip solutions. The mainshock of the 1987 Whittier Narrows earthquake was a reverse fault, but the largest aftershock was strike slip, probably on the East Montebello fault. The 1986 Oceanside earthquake (Hauksson and Jones, 1991) had a northwest-trending thrust mechanism although it took place on a restraining bend of the San Diego Trough fault (Legg, 1985). Alternatively, this earthquake may have been related to the blind, low-angle Thirtymile Bank fault (Rivero et al., 2000).

A problem for SCEC II is the question of how dip-slip earthquakes relate to strike-slip earthquakes. Would a Los Angeles cascade include both dip-slip and strike-slip events? Does the fast-moving Raymond strike-slip fault sometimes rupture alone and at other times rupture with the Sierra Madre or Hollywood fault, or with the San Andreas fault? Would a dip-slip event on the Sierra Madre fault reduce strain buildup on the Raymond fault across strike from it, or would a dip-slip event on the Puente Hills blind thrust reduce or add to strain buildup on the Whittier fault?

A corollary to this problem is the accommodation of north-south convergence. Is convergence accompanied by east-west escape-block tectonics, as proposed by Walls et al. (1998) or by crustal thickening, as favored by Argus et al. (1999). Part of the debate in these two papers is influenced by how the right-lateral shear strain on the San Andreas fault is factored out to get at the convergence signal, but the late Quaternary geology is important, too.

Most of the useful late Quaternary slip rate data in Los Angeles have been published in the past five years, as AMS radiocarbon dating has become more widely available. SCEC II has the opportunity of following up on this breakthrough in a focused late Quaternary dating project, including attempts to do paleoseismology on blind thrusts, as has already been accomplished in the San Joaquin Hills (Grant et al., in revision) and is currently being attempted for the Puente Hills blind thrust. A key to the success of this endeavor is a better age-calibrated stratigraphy for the late Quaternary, already begun by the USGS on the Las Cienegas structural shelf and in the Los Angeles Basin west of the Newport-Inglewood fault (Ponti et al., 2001). East of the Newport-Inglewood fault, late Quaternary marine deposits have been dated in the San Joaquin Hills (Grant et al., 1999) and are currently being correlated with marine faunas (Powell et al., submitted). In addition, with the availability of higher-quality imaging and digital elevation models, including TOPSAR, there is a need to quantify tectonic geomorphology to the point that it can contribute to an estimate of slip rates.

**Paleoseismology of blind thrusts**

Study of multichannel seismic profiles and petroleum-industry well data has resulted in the delineation of blind thrusts in the Los Angeles Basin, including the source fault for the 1987 Whittier Narrows earthquake (Dolan et al., 1995; Shaw and Suppe, 1996, Schneider et al., 1996; Shaw and Shearer, 1999; Tsutsumi et al., 2001), but little progress has been made in determining slip rates and recurrence intervals on these faults. High-resolution seismic profiles (Williams et al., 2000; Christofferson et al., 2000), trenching, and analysis of water-well logs (Mueller, 1997; K.J. Mueller and T.K. Rockwell, in prep.) and high-resolution late Quaternary stratigraphy (Ponti et al., 1996; D.J. Ponti, in prep.) are necessary to obtain a paleoseismic history of blind thrusts comparable to that obtained by trenching of surface faults.

**Dates of most recent large earthquakes**

Research by SCEC geologists has demonstrated that many active faults are potentially very hazardous to the Los Angeles metropolitan region because of their proximity to densely-populated areas. The slip rates of many metropolitan faults are difficult to measure because the faults are blind, the slip rates are low, or the data have been destroyed by urbanization. Therefore, it may be difficult to reconcile geologically-derived slip rates with geodetically-measured deformation. However, it would be useful to learn where Los Angeles is in the seismic cycle of potentially-hazardous urban faults. Two historical earthquakes have been correlated to local faults: the 1769 earthquake reported by the Portolá expedition (Grant et al., in revision) and the May 10, 1910 Temescal Valley earthquake on the Elsinore fault (Rockwell, 1989). More

paleoseismic data are needed for time-dependent hazard calculations, analysis of deformation rates, and studies of triggered earthquakes and strain partitioning.

The Los Angeles metropolitan area needs a focused study comparable to BAPEX in the San Francisco Bay area. This would include study of the late Quaternary history of the San Jose, Walnut Creek-Indian Hill, Chino, Peralta Hills, and Newport-Inglewood faults, and the Palos Verdes fault northwest of Los Angeles Harbor.

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# The
# NORTHRIDGE EARTHQUAKE, USA
## and its
## ECONOMIC AND SOCIAL IMPACTS

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# 1. INTRODUCTION AND GENERAL DESCRIPTION

## 1.1 General Description

The Northridge earthquake that struck at 4.31 a.m. on Monday, January 17, 1994 affected an area of 2,192 square miles in the San Fernando Valley, a densely populated residential area of northern Los Angeles, California.[1] Three counties, Los Angeles, Ventura and Orange were affected by the earthquake. The area has been repeatedly struck by moderate to large earthquakes, and Los Angeles County is one of the best-prepared regions of the United States. Yet in terms of financial losses, Northridge is one of the worst disasters in US history.

The earthquake was of moderate size, measuring 6.7 moment magnitude, on an unknown 'blind thrust' fault 20 miles northwest of Los Angeles. The depth of the earthquake was 11 miles (18 km), and near-record ground shaking was recorded. Peak horizontal ground accelerations approached or exceeded 1g in the region of the epicentre, and 11 of 100 monitoring instruments measured in excess of 0.25g. The peak vertical acceleration measured 0.48g. There were 14,000 reported aftershocks, many in the magnitude of 4.0-5.0 range. The duration of the earthquake was 15 seconds.

Human Impacts:
57 people were killed, and 72 deaths have been attributed to the earthquake.[2] 11,800 people received hospital treatment for injuries. 22,000 people were left homeless. The earthquake occurred in the early morning on a national holiday.[3] Had it occurred at another time of day or date, building occupancies would have led to more extreme human losses. A number of bridges and multi-storey car parks collapsed, yet only one person died as a result.

Economic Impacts:
Preliminary total damage estimate were USD 15-17 billion,[4] but these total direct loss estimates have been revised upwards over time.[5] The Average Reported Estimated Direct Loss (AREDL) has been calculated to be USD 41.8 billion, using the estimates set out in section 2.1. The scale of the losses was unprecedented and indirect losses were high, exceeding all previous predictions. The earthquake alerted federal and state governments, as well as private insurers to the magnitude of potential losses from earthquakes in urban areas.

## 1.2 Detailed Description of Earthquake

The Northridge earthquake occurred on an unknown 'blind thrust', meaning that the rupture never spread to the earth's surface, but stopped some way below it. Several hidden fault zones have subsequently been identified which have changed the perception of earthquake risk in the greater Los Angeles area.[6] The earthquake occurred in the densely populated San Fernando Valley, which has been repeatedly struck by moderate to large earthquakes. This is a predominantly residential area in one of the most well prepared regions of the United States.

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[1] See http://www fema.gov/NR/nr_0106 htm
[2] ibid
[3] EQE (1994)
[4] ibid
[5] Scawthorn et al (1997), Eguchi et al (1998), Bolin and Stanford (1998), FEMA (2000)
[6] Smolka (1995)

The size of the earthquake was moderate, yet some affected areas had ground motions more than twice those allowed for in the building code. Most of the structures in the affected area had been built within the last three decades and the relevant building standards had been considered to be reasonably earthquake resistant. As a result, the percentage of buildings destroyed by the ground motions was small, and the greatest damage occurred within about 16 km of the epicentre. Approximately 114,000 residential and commercial structures were damaged, including some 450 public buildings, sections of six freeways and 27 bridges, as well as power, water and sewer utilities.[7] Liquefaction and landslides were not a major cause of structural damage.

Lifelines:
Lifelines[8] were badly affected by the earthquake, particularly power, water and sewer utilities. Utility lifelines were restored within days, in most cases. The longest restoration period was 12 days for the gas supply.[9] Damage to transportation lifelines was more severe. Traffic disruptions were a major problem after the earthquake, as the area is almost entirely dependent on automobiles. Portions of 11 major arteries into Los Angeles had to close and 9 bridges on major interchanges collapsed.[10] Months afterwards there were still major traffic disruptions and sections of the Interstate (I) 5 and the Santa Monica Freeway were closed. These highways returned to normal service at varying rates, and transport-related effects included freight problems with raw materials and manufactured goods, as well as employee and consumer commuting problems.[11]

### 1.3 Emergency Response

The California Governor's Office of Emergency Services (OES) co-ordinates overall state agency response. 104 emergency service stations were operational and traffic congestion was minor, in part due to the timing of the earthquake. Emergency operations appear to have been well co-ordinated. Immediately after the earthquake, local building and safety departments organised teams of inspectors to identify the extent of the damage. Buildings were inspected and tagged according to their structural safety. These coloured tags did not include damage to contents and damage that was not easily visible, and the full extent of earthquake damage was often unknown until wall surfaces had been exposed and the structure examined. 105,000 inspections were carried out in the building safety process.[12]

There were 110 fires. The Los Angeles County Fire Department lost its computer aided dispatch capability for a critical 7 hours, and subsequent fire fighting was hampered by the lack of water.[13] Fortunately, there was little wind and the Northridge earthquake was 'linear', unlike Kobe, so the increased demand for manpower and material resources during and after the earthquake did not exceed the available supply.[14]

Prior to the earthquake, the OES had commissioned an Early Post Earthquake Damage Assessment Tool (EPEDAT)[15] to serve both the emergency response and planning needs of the agency. Immediately after the earthquake, an estimated shaking-intensity map for the Los Angeles area with likely damage levels was compiled, reducing uncertainty and enabling emergency managers to locate and focus on the hardest hit areas. This Geographical Information Systems (GIS) system

[7] EQE (1994)
[8] A common definition for utility and transportation systems. See Eguchi (1997)
[9] Eguchi (1997)
[10] ibid
[11] Gordon et al (1996)
[12] Eguchi et al (1998). Refer to section 4.2 for a discussion on the social impacts
[13] EQE (1994)
[14] Eguchi (1997), p 117.
[15] Goltz (1996).

improved the amount and timing of information available for the emergency response. The initial damage assessment was prepared for the California Office of Emergency Services (OES) immediately after the earthquake using GIS for the first time. This data were collated, analysed and distributed through a field office set up by the Federal Emergency Management Agency (FEMA) to co-ordinate activities. The United States Geological Survey (USGS) was entrusted with the communication of information. FEMA also introduced a teleregistration scheme to speed the federal disaster response.[16]

# 2. ESTIMATED LOSSES

## 2.1 Direct losses

The preliminary total damage estimate ranged between USD 15-17 billion,[17] and was prepared for the California Office of Emergency Services (OES) the day after the earthquake. This was required for the disaster aid application to the President and Congress, and Governor Wilson, the Governor of California warned that the disaster could cost as much as USD 30 billion. A refined loss estimate of USD 13-22 billion was prepared for the OES by 25th January, eight days after the event.[18] Later estimates of total direct losses totalled USD 25 billion,[19] then upwards to figures of USD 39.6 billion[20] and USD 44 billion.[21] The Average Reported Estimated Direct Loss (AREDL) has been calculated to be USD 41.8 billion,[22] using the estimates set out in the table below.

**TABLE 1:**

| **ESTIMATES OF LOSSES in billion USD** | | | | |
|---|---|---|---|---|
| **Source** | **Time after disaster** | **Direct or total** | **Primary or Secondary** | **Amount of Estimate (USD)** |
| OES (EQE, 1994) | 1 day | direct | secondary | USD 15-17 billion |
| OES (in Goltz, 1996) | 8 days | direct | secondary | USD 13-22 billion |
| RMS. (1999) | 15 months | total | secondary | USD 25-30 billion |
| Smolka (1995) | 18 months | total | secondary | USD 40 billion |
| ***Scawthorne et al (1997)**** | ***20 months*** | ***direct*** | ***Primary*** | ***USD 39.6 billion*** |
| Collins (1998) | | total | secondary | USD 30-40 billion |
| ***OES* (in Eguchi et al, 1998)**** | ***3+ years*** | ***direct*** | ***Primary*** | ***USD 44 billion*** |
| Bolin and Stanford (1998)* | 4 years | direct | secondary | USD 44 billion |
| ***AREDL*** | | | | ***USD 41.8 billion*** |

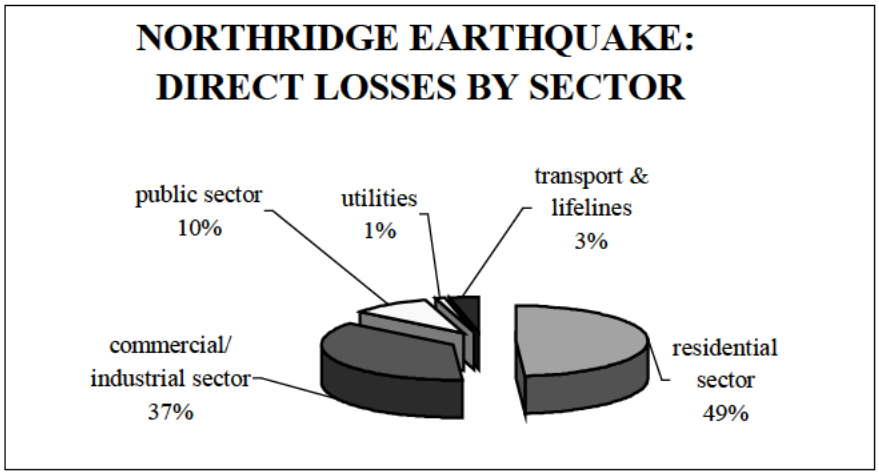
***(Estimates used for calculation of AREDL)***

The increase in the losses over time was due to the initial damage estimates being prepared by building inspectors checking for safety, rather than losses. 105,000 initial safety checks were made. 333,000 insurance claim inspections were made later by loss adjusters, with increased estimates.[23] Many buildings did not pose an immediate safety concern, but required repair. Structural damage was found in many modern structures, hidden by finishes and fireproofing. Damage to contents,

[16] See http://www.fema.gov/rt/10442-e2 html
[17] EQE (1994). See http://www.eqe.com/publications northridge/execside htm
[18] Goltz (1996)
[19] RMS (1999)
[20] Scawthorn et al (1997)
[21] Eguchi et al (1998), Bolin and Stanford (1998)
[22] There is always a wide range of reported loss estimates. The Average Reported Estimated Direct Loss (AREDL) meets the following criteria: only estimates of direct losses, only estimates made at least four months after the disaster, only primary estimates or those based on original data.
[23] Refer to Eguchi et al (1998) for a detailed discussion

water damage due to broken pipework, the exposure of asbestos-related materials, as well as retroactive building code requirements for replacement work all increased the direct economic losses even further.

**FIGURE 1**: Direct losses by sector




Most damage was incurred in the residential and commercial sectors, as shown in figure 1 and table 2. Although the Northridge earthquake occurred in a residential area, commercial and industrial losses were proportionately very high. Damage to agriculture was comparatively minimal. Public sector losses were relatively small, but Los Angeles is a car-bound society dependent on motor vehicles for urban transportation, and damage to infrastructure affected indirect losses. These indirect losses have been estimated to be over USD 7.5 billion,[24] of which more than 80% were from business interruptions. Most of these losses were uninsured and have had major social and economic impact on the affected area. Tax revenue losses are estimated to be USD 0.86 billion. Almost 1% of the USD 4.1 billion Small Business Administration loans has currently defaulted. The San Fernando Valley had been subjected to a recession for three years prior to the earthquake, and this exacerbated the effects of the earthquake.[25]

**TABLE 2: ESTIMATED DIRECT ECONOMIC LOSSES IN USD BILLIONS**

| Sector | Estimated direct losses in USD billions | Percentage share of direct losses | Amount insured, in USD billions | Amount uninsured, in USD billions |
|---|---|---|---|---|
| Residential | 20.6 | 49.3% | 9.88 | 10.72 |
| Commercial/Industrial | 15.2 | 36.4% | 4.02 | 11.18 |
| Public infrastructure | 6.0 | 14.3% | No mention | 6.0 |
| Agricultural | No mention | na | 0.004 | na |
| **DIRECT LOSSES** | **41.8** | **100%** | **13.9** | **27.9** |

[24] Refer to table 3
[25] Alesch & Holly (1996), Bolin & Stanford (1999)

## Public Sector Losses

Losses resulting from damage to infrastructure (power, gas, water) and direct damage to production centres were initially estimated at USD 6 billion, equivalent to 15 -30% of actual property losses. Lifeline damage was estimated at USD 2 billion.[26] Some 450 public buildings, sections of six freeways and 27 bridges, as well as power, water and sewer utilities were damaged.[27]

Transportation: Traffic disruptions were a major problem after the earthquake, as the area is almost entirely dependent on automobiles for urban transportation. Portions of 11 major arteries into Los Angeles had to close and 9 bridges on major interchanges collapsed. All of these structures had already been scheduled for retrofitting after the 1989 Loma Prieta earthquake, when 860 structures were identified in need of retrofit. None of the 122 structures, which had already been strengthened, failed in the Northridge earthquake.[28] A report prepared for the California Department of Transportation concluded that had the bridges been retrofitted, they would have survived the earthquake with little damage.[29] There was no significant damage to any of the airports in the vicinity.

Lifelines: Various lifelines were affected by the earthquake, and losses varied considerably as set out: LADWP (Power) - USD 136m, SoCal Edison - USD 0.5m, LADWP (Water) - USD 44m, MWD - USD 5m, LA City (Sewer) USD 36m, SoCal Gas - USD 60m, PacBell - USD 26m, GTE USD 3.5m, Caltrans - USD 1450m. Almost 95% of the damage to lifelines were eligible for federal assistance. Under the terms of the Stafford Act, FEMA was liable for 90% of these costs, while the utilities had to cover the 10% shortfall, USD 0.3 billion.[30]

Schools: Almost half of Los Angeles schools were damaged and costs exceeded USD 100 million.[31]

Hospitals: 31 Los Angeles area hospitals were damaged, and 9 were forced to evacuate.

## Corporate/Business Losses

Corporate damage has been estimated at approximately USD 15.2 billion.[32] The area's largest shopping centre, the Northridge Fashion Centre, was virtually destroyed and did not open for more than a year and a half. Several multi-storey reinforced concrete parking structures collapsed, and many were severely damaged, causing indirect retail losses.[33] 57% of Los Angeles businesses in the affected area reported experiencing some type of direct physical damage due to the earthquake, of which the most common type was non-structural (68% of those with reported damage) damage to furnishings (56%) damage to equipment (52%) damage to inventory or stock (50%) structural damage to building (39%) and buildings declared unsafe (15%).[34]

In some buildings the structural damage exposed asbestos (insulation and fireproofing), which delayed reconstruction due to the specialist removal requirements. In addition, the structural damage caused large-scale failure of sprinkler and utility pipes in inadequately braced ceilings and equipment. These failures of air conditioning units, ducting and sprinkler systems caused serious interior damage to many business premises, flooding the contents below. This in turn affected the ability of some stores to reopen, exacerbating the indirect business interruption losses. [35]

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[26] Eguchi (1997)
[27] EQE (1994)
[28] EQE (1994) Scawthorn et al (1997)
[29] Eguchi (1997), p 121.
[30] Eguchi (1997), Eguchi et al (1998)
[31] EQE (1994)
[32] Updated from Scawthorn et al (1997). The original figure was based on total losses of USD 39.6 billion, and has been amended by the same percentage.
[33] EQE (1994)
[34] Tierney (1997)
[35] EQE (1994), Smolka (1995)

### Residential Losses

Total damage from residential exposure has been estimated as USD 20.6 billion, 49% of the total losses.[36] Building inspectors with the task of estimating initial damage estimated that 82% of all structures rendered uninhabitable by the earthquake were residential.[37] This percentage totalled 14,600 dwelling units, of which 77% were apartments and 23% were single family dwellings. Soil conditions played a major role in damages.[38] Many structures failed due to inadequate bracing or lack of connection to foundations. Mobile homes were found to be more vulnerable to fires, and 100-150 mobile homes were destroyed by conflagrations from gas and propane lines.[39]

### Agriculture Losses

There is no data readily available, although some insured losses have been reported.

## 2.2 Indirect Losses

A number of studies assessing the indirect losses have been undertaken, usually with a focus on the restoration of lifelines. Indirect impacts associated with the failure of lifeline systems may far outweigh the direct costs of repairing the system.[40] Several studies have surveyed businesses in the impacted area,[41] and one such study modelled the economic impacts using their Southern California Planning Model, estimating business interruption losses to total USD 6.5 billion in terms of lost output.[42]

**TABLE 3:**

| **ESTIMATED INDIRECT LOSSES in billion USD** | | |
|---|---|---|
| **Commercial** | Business interruption | **6.402** |
| **Unemployment** | 69,014 person-years of employment | |
| **Residential** | Vacated housing | **0.098** |
| **Other federal agencies** | Default on SBA loans | **0.376** |
| **Federal and state losses** | Tax revenue losses | **0.86** |
| **TOTAL** | | **7.736** |

Source: Gordon et al (1996), FEMA (1999), SBA (1999)

[36] Updated from Scawthorn et al (1997). The original figure of USD 19.5 was based on total losses of USD 39.6 billion, and has been amended by the same percentage.
[37] EQE (1994)
[38] ISO (1994)
[39] EQE (1994) This vulnerability is due to the likelihood of detachment of the structure from its foundation and the effect of this failure on utility lines such as gas and propane.
[40] Eguchi (1997)
[41] Alesch & Holly (1996), Tierney (1997)
[42] Gordon et al (1996)

## Public Sector Losses

Lifelines have been shown to be extremely vulnerable to earthquakes, and their failure can result in substantial direct and indirect losses.[43] Transportation lifelines proved to be problematical, and months after the earthquake there were still major traffic disruptions and sections of the Interstate (I) 5 and the Santa Monica Freeway were closed. These highways returned to normal service at varying rates, and transport-related effects included freight problems with raw materials and manufactured goods, as well as employee and consumer commuting problems.[44]

## Corporate/Business Losses

Aggregate business losses have been estimated at USD 6.4 billion, of which 48% were direct business interruptions.[45] Losses of $1 billion were suffered outside the region. Studies indicate that 15-30% of businesses damaged closed down permanently.[46] Some business losses were alleviated by the quick restoration of utilities, but damage to transportation routes, car-parking garages and retail areas affected losses. Residents who remained in Northridge changed their shopping habits. Businesses were also hampered by the slow response of public agencies, and their inability to obtain Small Business Administration loans.

Only about 20% of businesses carried earthquake insurance for damage or business interruption and only slightly more than 25% of those filed claims.[47] The highest job losses were in the retail (24%) and health service (18%) sectors. Half of the Northridge job losses, equivalent to 69,014 person-years of employment, occurred in the fault zone. Tax revenue losses associated with business interruption amounted to a total of USD 0.86 billion, of which USD 530 million was at federal level, USD 163 million at State level, and USD 164.4 million at local level.[48]

Indirect losses have major economic and social impacts on society. Many individuals change their spending patterns and draw on savings, current earnings and credit for essential rebuilding after a major disaster. Discretionary income is drastically reduced, which in turn affects many small businesses. Damage was not found to be a reliable predictor of business failure, while entrepreneurial skills were a critical factor in the ability of a business to survive. Some small businesses were failing as a result of the Northridge earthquake two years after the event.[49]

## Residential

There were 9 billion unit-days of vacated housing. 25% of damaged multi-dwellings and 80% of damaged single dwellings were vacated for more than 3 months. This amounted to USD 98 million, approximately 1.5% of the total cost of business interruption.[50]

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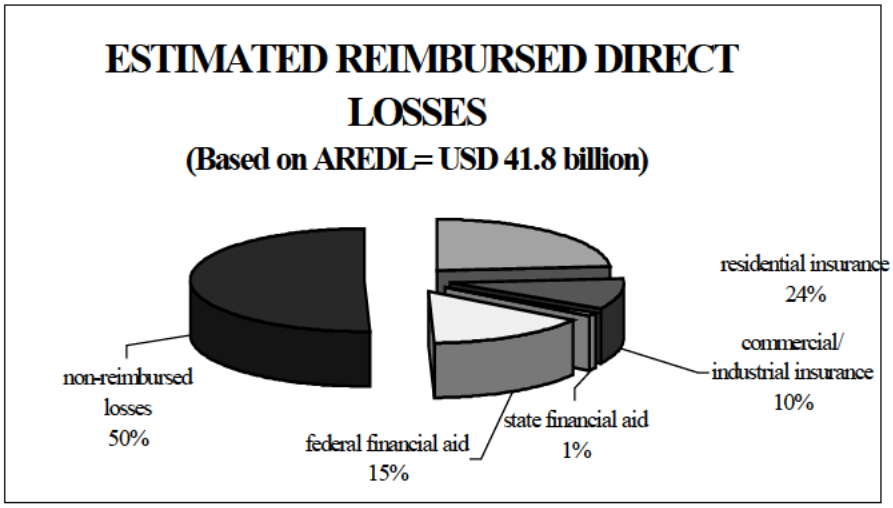
[43] Eguchi (1997)
[44] Gordon et al (1996))
[45] Gordon et al (1996)
[46] ibid.
[47] Tierney (1997)
[48] Gordon et al (1996)
[49] Alesch & Holly (1996)
[50] Gordon et al (1996)

## 3. REIMBURSED LOSSES

**FIGURE 2:**




Source: FEMA (2000) HUD (2000), Eguchi et al (1998) Scawthorne (1997), IBHS (1999)

**TABLE 4:**

| REIMBURSED LOSSES in USD billions | | | | | |
|---|---|---|---|---|---|
| | | **Insured** | **Uninsured** | **TOTAL** | ***Direct reimbursed losses*** |
| **FEMA** | Public Assistance program | | 4.578 | **6.197** | *4.0** |
| | Individual Assistance program | | 1.424 | | *1.193* |
| | Administrative costs | | 0.195 | | |
| **Other federal agencies** | HUD | | 0.837 | **1.962** | *0.837* |
| | Dept of Interior | | 0.005 | | *0.005* |
| | Department of Education | | 0.256 | | *0.256* |
| | Federal costs unaccounted for (this includes mission assignments to other agencies) | | 0.864 | | |
| **California State*** | Public Assistance program | | 0.45 | **0.606** | *0.45* |
| | Individual Assistance program | | 0.06 | | *0.06* |
| | State Employment Dept | | 0.041 | | |
| | State Board of Control | | 0.055 | | |
| **Voluntary aid** | Red Cross, Salvation Army | | 0.037 | **0.037** | |
| **Insurance payments** | Residential insurance | 9.88 | | **13.9** | *9.88* |
| | Commercial insurance | 4.02 | | | *4.02* |
| **TOTAL REIMBURSED LOSSES** | | **13.9** | **8.8** | **22.7** | ***20.7*** |

Source: FEMA (2000) HUD (2000), Eguchi et al (1998) Scawthorne (1997), IBHS (1999)

* *Estimated portion of direct loss reimbursements for public assistance programme.*
Estimates of total losses include structural damage, individual and family grants, as well as *rental assistance, relocation costs, debris removal, mission assignments, medical and funeral costs.* (*Items italicised have not been included in the direct loss estimate.*)

## 3.1 Government

**Federal aid**

A Major Disaster Declaration must be requested by the governor, and declared by the president. It includes an agreement to commit state funds and resources to the long-term recovery.[51] On February 12th 1994, President Clinton signed the bill for the President's Disaster Relief Fund that authorised USD 8.6 billion in aid for the earthquake victims.[52] The Federal Emergency Management Agency (FEMA) co-ordinates federal assistance when disasters and emergencies are declared and so administers this fund. The proportions for Northridge were 90% federal and 10% state.

Total federal expenditure amounted to USD 13 billion,[53] of which USD 8.16 billion were reimbursed federal losses by the Federal Emergency Management Agency (FEMA) and other federal agencies. Federal assistance was generous, perhaps due to the political importance of California. The earthquake occurred in a congressional election year.[54] Although FEMA plays a key role in disaster assistance, other agencies such as the Small Business Administration (SBA) U.S. Department of Agriculture (USDA), Department of Housing and Urban Development (HUD), U.S. Department of Transportation (DOT) U.S. Department of Interior (DOI) are also involved.

**TABLE 5:**

| **FEMA FUNDING in USD billions** | | |
|---|---|---|
| **Individual Assistance**: | | |
| Temporary housing, emergency home repairs, mortgage assistance | **1.193** | **1.424** |
| *Personal property replacement, permanent repairs, transportation, medical and funeral expenses* | ***0.167*** | |
| *Disaster unemployment assistance* | ***0.009*** | |
| *Housing inspection services* | ***0.023*** | |
| *Crisis counselling* | ***0.032*** | |
| **Public Assistance** | | |
| Payments to state and local governments for repair and replacement of damaged infrastructure, emergency services and debris removal | | **4.578*** |
| *Mission assignments to other federal agencies* | | ***0.020*** |
| *Administrative costs* | | ***0.194*** |
| *Hazard mitigation measures* | | ***0.741*** |
| **Total FEMA relief costs** | | **6.957** |

Source: FEMA (2000)

Note that items italicised have not been included in the direct loss estimate.

**Estimated portion of direct loss reimbursements for public assistance programme = USD 4 billion. This excludes indirect loss reimbursements, such as debris removal and emergency services.*

Table 5 sets out the current details of reimbursements from FEMA, dated January 31, 2000, totalling USD 6.957 billion. Other federal expenditure amounted to USD 6.043 billion, of which some costs relate to the Small Business Administration loans and hazard mitigation projects. Direct reimbursements from FEMA have been estimated at USD 5.193 billion and those from other

[51] See http://www.fema.gov/about/4-sect1 htm
[52] ISO (1994)
[53] FEMA (2000)
[54] Bolin & Stanford (1998)

agencies USD 1.098 billion, totalling 6.291 billion for direct federal reimbursements.[55] By the close of 1994, FEMA reported that some 667,801 Southern Californians had applied for federal aid, three times as many as following Hurricane Andrew in 1992.[56]

**Other federal agencies disaster aid**

Although FEMA plays a key role in disaster assistance, other agencies such as the Small Business Administration (SBA) U.S. Department of Agriculture (USDA), Department of Housing and Urban Development (HUD), U.S. Department of Transportation (DOT) U.S. Department of Interior (DOI) are among those that also play a role. The details available of aid from these agencies are set out below.

| | |
|---|---|
| Department of Housing and Urban Development (HUD) | USD 0.837 billion[57] |
| Department of Interior - historic preservation work | USD 0.005 billion[58] |
| Department of Education | USD 255.6 million[59] |
| Federal costs unaccounted for | USD 0.864 billion[60]. |
| **TOTAL** | **USD 1.098 billion** |

**Federal Disaster Loans**

The federal government provides assistance to victims in the private sector through the Small Business Administration (SBA), who make low-interest long-term loans (generally 4%, up to 30 years). SBA loans are available to restore structures to their pre-disaster condition, and may be increased up to 20% to include mitigation measures. Loans to a limit of USD 200,000 are available to residential homeowners, renters and non-farm businesses. Similar loans, to a maximum of USD 1.5 million, are available to businesses and private, non-profit organisations. In some cases, the SBA will refinance existing mortgages on homes and business properties.

39,129 commercial and 193,867 residential SBA applications were made (as of 24.3.1995), an unprecedented number.[61] Of a sample population, 11% had applied for SBA loan assistance for their business losses. Of this number, half had received loan amounts requested, 30% had their applications turned down and 10% of the loans were still pending. For the businesses that had received SBA loan assistance, the median percentage of business losses covered was about 50%.[62] 124,245 SBA loans, amounting to USD 4.1 billion[63] were approved. The SBA announced that 9,144 loans totalling USD 286 million were in default, and have estimated that a further USD 90 million of Northridge borrowers are likely to default on their loans.[64]

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[55] Refer to table 5 for details. Direct reimbursements exclude rental assistance, relocation costs, debris removal, medical and funeral costs, mission assignments and administration costs.
[56] See http://www.fema.gov/NW294/94_015 htm
[57] HUD (2000)
[58] See http://www.fema.gov/NW295/95_129.txt
[59] See : http://nces.ed.gov/pubs/d96/D96T356 html, item 96.
[60] This figure is the unknown element of the federal disaster relief programme, and includes the FEMA USD 0.20 billion assigned to other federal agencies.
[61] Gordon et al (1996)
[62] Tierney (1997)
[63] See http://www.fema.gov/library/df_4htm
[64] See http://www.sba.gov/IG/sar3-99.pdf

## 3.2 State Sector

The Governor's Office of Emergency Services (OES) co-ordinates overall state agency response to major disasters. Under the Stafford Act, the state was liable for 10% of the costs of the federal assistance programme and contributed USD 0.6 billion in reimbursements. California voters rejected a proposed USD 2-billion bond issue earmarked for earthquake relief, and so only some of the repair and rebuilding needs could be met. A plea was made to President Clinton, who agreed to redistribute USD 225 million from infrastructure budgets to enable the affected cities to make 30-year no-interest deferred loans to owners of damaged buildings.[65]

| | |
|---|---|
| State Board of control | USD 0.055 billion |
| California Employment Development Department | USD 0.041 billion |
| Individual/Family Grant programmes | USD 0.06 billion |
| Public Assistance | USD 0.45 billion |
| **Total California State share** | **USD 0.6 billion[66]** |

## 3.3 Private Insurance Sector

There are two estimates of insured losses. The Property Claim Services (PCS) estimated the final losses to be USD 12.5 billion, after adjusting them upwards eight times from an initial USD 2.5 billion to a final figure of USD 12.5 billion, 20 months later. The Institute of Building and Home Safety (IBHS) reached a final estimate of USD 15.3 billion. The National Research Council (NRC) recommends the use of both the PCS and IBHS figures, the advantage of the IBHS figures being that they provide disaggregated catastrophe claims information.[67] The average has been calculated to be USD 13.9 billion, as set out in table 6 below.

**TABLE 6:**

| **ESTIMATES OF INSURED LOSSES** | | | |
|---|---|---|---|
| | **PCS estimate[68]** | **IBHS estimate[69]** | **Average** |
| **Residential** | USD 8.4 billion | USD 11.35 billion | **USD 9.88 billion** |
| **Commercial** | USD 4.1 billion | USD 3.95 billion | **USD 4.02 billion** |
| **TOTAL** | USD 12.5 billion | USD 15.3 billion | **USD 13.9 billion** |

Source: IBHS (1999), Kerney (2000), Scawthorne et al (1997), Eguchi et al (1998)

Both the PCS and the IBHS adjusted their estimates of insured losses upward over time. Several factors have contributed to the large increases. The seismological data on which initial estimates were based was incorrect, and estimates were prepared assuming a smaller earthquake with an epicentre further from central Los Angeles.[70] Adjustment (such as replacement of new for old) and retroactive building codes contributed to the underestimation of these losses.[71] Reopened claims with additional discovered damage, higher living expenses resulting from longer repair periods, and a large number of claims initially thought to be below the level of the deductible all increased estimates. Underinsurance was a major issue that was not reflected in most of the settlements, due

[65] See http://www.huduser.org/publications/destech/bigone/sect1 html
[66] Eguchi et al (1998)
[67] NRC (1999)
[68] Kerney (2000), Scawthorne et al (1997), Eguchi et al (1998)
[69] IBHS (1999)
[70] Scawthorne (1995)
[71] Eguchi et al (1998), Scawthorne (1995)

to its political sensitivity.[72] It has also been suggested that insurers were generous in their claims settlement to influence moves to repeal the mandatory offer requirement.[73]

Legal issues regarding Northridge claims have centred on the interpretation of the statute of limitations in residential property claims, delayed discovery of loss, waiver and estoppel, and the obligations of the insurer. The California Department of Insurance (CDI) instigated a mediation program to resolve disputes over earthquake claims without costly litigation. This program has investigated more than 3,300 complaints about insurance-related claims and recovered over USD 71 million from insurers.[74] Allstate opened 9,000 of its 46,000 homeowner's claims for reevaluation, as part of a settlement of two civil suits that charged Allstate with deliberately underreporting estimates by loss adjusters during inspections. Allstate put aside USD 60 million to deal with these claims, and have earmarked USD 5 million to set up a charitable foundation.[75]

### 3.4 Aid from other sources

Volunteer assistance was received from volunteer organisations including the American Red Cross (ARC) and Salvation Army. The ARC sheltered 22,000 people, served 1.7 million meals and operated various other programmes. The ARC spent USD 36 million on their programme. The Salvation Army spent more than $1 million for displaced persons' housing and mass feeding.[76]

## 4. ECONOMIC AND SOCIAL IMPACTS

### 4.1 Economic Impacts

Almost 67% of all estimated direct losses were uninsured. Federal financial aid met over 15% of these losses, while 1% were covered by state financial aid.[77] Over 56% of the federal aid programme went to meet the public losses through the Public Assistance programme, while approximately 28% of private losses were met by the FEMA and other federal aid programmes. Despite generous federal, state and insurance reimbursements half of the direct losses were borne by the disaster victims.[78] "*Many homeowners, renters and businesses paid thousands of dollars out of their own pockets to rebuild their own lives*",[79] said James Witt, director of FEMA.

Northridge earthquake demonstrated the success of a modern building code in reducing deaths and injuries to a very small fraction of the affected population. Most of the buildings were built within the last three decades, and were considered to be reasonably earthquake resistant.[80] However, there was considerable economic loss and social disruption, raising the issue of how much protection should be provided economically. This debate should not be the sole responsibility of the engineers and code developers; society must participate in the process of weighing the costs and benefits of more protection.

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[72] Collins (1998)
[73] Eguchi et al (1998)
[74] See http://www.insurance.ca.gov/PRS/PRS1997/Pr032-97.htm
[75] See http://www.claimsmag.com/Issues/November/feature_allstate.asp
[76] See http://www.fema.gov/NR/nr_0106.htm
[77] Refer to figure 2, and table 4 for details
[78] Based on AREDL=USD 41.8 billion. Refer to section 2.1 for details
[79] See http://www.fema.gov/library/wittspch5.htm
[80] EQE (1994)

The scale of losses inflicted by the Northridge earthquake has forced both federal and state governments to reassess the levels of disaster aid, particularly in the current climate of shrinking budgets and federal cutbacks. The focus of government has increasingly shifted from post-disaster relief operations to pre-disaster mitigation measures,[81] and the stated mitigation goal of FEMA is to reduce natural disaster losses by half by the year 2010. Northridge earthquake illustrated graphically the value of the seismic strengthening and risk reduction programmes, which can avoid substantial losses. None of the failed transportation structures had been strengthened, yet all 122 strengthened structures were undamaged.[82] Examples of other retrofitting successes, such as department stores, hospitals etc. have been highlighted and used by FEMA as justification for their shift of policy to mitigation.[83]

Small businesses are often hardest hit by natural disasters, as they seldom carry insurance or possess the resources to make a meaningful recovery. Small businesses are also rarely diversified in terms of products or services, and their customers are often victims of the same disaster. They have less mobility than other members of the community, and generally suffer both personal and business losses. Damage is not a reliable predictor of business failure. Small businesses were still failing as a result of the Northridge earthquake two years after the event. Entrepreneurial skills were a critical factor in the ability of a business to survive. When these businesses fail, there are costs to the individual and to the community. A significant effect can be the downward spiral of a neighbourhood. In contrast, large businesses are able to relocate their operations temporarily, and offset losses against other locations. [84]

Business interruption effects have been estimated to be USD 6.5 billion, of which USD 5.5 billion were in the Northridge region. [85] Most businesses had earthquake insurance for their homes, but only 13% of small businesses were insured. This led to large uninsured losses, and many business failures. The rate of business failure varied among sectors. Manufacturing was the least affected, due to customers outside the region, while retail and service firms were most badly affected.[86] Tax revenue losses associated with business interruption amounted to a total of USD 0.86 billion, of which USD 530 million was at federal level, USD 163 million at State level, and USD 164.4 million at local level.[87]

Northridge earthquake was a direct hit on an urban area and the scale of losses caused by the earthquake far exceeded expectations. The threat of the 'Big One' has occupied much forethought and research at local and national level.[88] The US has a large concentration of localised industries, such as the entertainment and aerospace industries in southern California, the electronics industry in San Francisco, the aerospace industry in the Pacific Northwest and the financial sector in New York. These industries could be seriously affected in the case of a major earthquake.[89]

### 4.2 Social Impacts

Disasters are often accompanied by a desire for a recovery to reproduce a return to normalcy, and achieve the status quo of the socio-economic and built environment prior to the earthquake. This is

[81] See http://www.fema.gov/library/wittspch5.htm
[82] EQE (1994), Eguchi (1997)
[83] See http://www.fema.gov/library/wittspch5.htm and http://www.fema.gov/impact/impact00.htm
[84] Alesch & Holly (1996)
[85] Gordon et al (1996)
[86] Alesch & Holly (1996)
[87] Gordon et al (1996)
[88] See http://www.huduser.org/publications/destech/bigone/sect1 html
[89] Scawthorne et al (1997). The risks are greater in areas where earthquake preparedness is less established, rather than California.

almost impossible to achieve. There are many federal, state and local participants each with their own political, economic, social or environmental agenda, and at best recovery takes the form of restructuring, rather than the desired reversion to the previous status quo.

There are certain groups less likely to achieve any semblance of their prior socio-economic level, and these groups are often the most vulnerable members of society - the low income, immigrant, unemployed and elderly groups. They also have the least access to resources to manage their losses.[90] Social, economic and political processes structure the lives of different groups of people in different ways and affect their ability to react to a natural hazard. Their level of vulnerability only becomes apparent in the face of disaster.[91]

The earthquake affected a large area of the San Fernando Valley, which supports half of the city of Los Angeles' population. Approximately 48% of the population were homeowners - middle class and therefore not obviously insecure- yet many proved to be vulnerable to the hazard. This vulnerability had been increased by the declining market value of housing in the area (which followed a boom of the 80s), job redundancies due to corporate restructuring, defence spending cuts, increasing liabilities due to underemployment, as well as the high insurance deductibles, which are based on the value of the property rather than the level of damage.[92]

Northridge earthquake provided a generous system of federal social protection by international standards, yet victims received at most partial compensation for their losses and had to find means to cover their losses. Many individuals changed their spending patterns and drew on savings, current earnings and credit for essential rebuilding after the disaster. Discretionary income is drastically reduced, which in turn impacts many small businesses.[93]

Despite substantial financial aid, people and businesses moved out of damaged downtown areas and did not return. An estimated 60,000 people migrated and only 20,000 moved into the area. Many of these newcomers were Hispanic and Korean, and were younger and poorer than their predecessors. These migrants had different retail habits, which changed the social structure of the area.[94] The downtown areas of Whittier, Santa Cruz and Northridge were slow to recover.[95]

Disasters also offer an opportunity to improve safety measures. The moves initiated by Northridge earthquake were an increase in the level of geological hazard mapping, the development of new building code standards, seismic retrofitting of older structures to meet revised seismic codes, as well as improved emergency preparedness. This preparedness involved emergency training for households and residents and the creation of Disaster Assistance Response Teams, (DART). A non-profit corporation, the Emergency Network Los Angeles (ENLA) was established to act as an umbrella organisation for the NGOs (non-governmental organisations) and approximately 300 CBOs (community based organisations) that provided a second tier protection for the vulnerable members of society, whose needs were not met through conventional channels. The other aim of the ENLA is to provide a network for future disasters.[96] Both government and non-governmental organisations have benefited from a history of collaboration over a number of Californian earthquakes.

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[90] Bolin & Stanford (1998)
[91] Blaikie et al (1994)
[92] Bolin & Stanford (1998)
[93] Alesch & Holly (1996)
[94] Alesch & Holly (1996)
[95] CDI (1997/8)
[96] Bolin & Stanford (1998)

Due to the localised impact of the earthquake, damage was concentrated in particular areas. 15 of such areas (later increased to 17) with red-tagged[97] damage levels averaging 60% of the housing stock, were designated 'ghost towns' by the Los Angeles Housing Department (LAHD). All but 4 of these areas were heterogeneous, middle-income neighbourhoods. The high number of abandoned structures soon made these areas a target for looters, and they were rapidly blighted by squatters and street gangs. This degeneration had serious social effects on the remaining housing, businesses and neighbourhoods. The federal Department of Housing and Urban Development (HUD) and its state counterpart, the LAHD targeted assistance towards these areas, but it was not always economically viable to reconstruct this housing stock in a weak housing market. As a consequence, there is less available low-income housing provision in Los Angeles. In many cases non-structural damage, damage to parking facilities and outbuildings was not repaired. This has led to neighbourhood decline and a negative spiral of property values.[98]

# 5. INSTITUTIONAL ASPECTS

## 5.1 Regulatory/legal framework

The Robert T. Stafford Disaster Relief and Emergency Assistance Act of 1988 is the core legislation under which federal emergency relief is managed. In order to qualify as a major disaster the event must be clearly more than state or local governments can handle alone. A Major Disaster Declaration must be requested by the governor, and declared by the president. This declaration is based on the damage assessment, and an agreement to commit state funds and resources to the long-term recovery.[99] There are two main categories of disaster aid, namely:

- Individual Assistance (IA), for damage to residences, businesses and personal property losses. This aid includes Disaster Housing, Disaster Grants and other Disaster Aid Programmes, such as legal aid, unemployment assistance, crisis counselling. Applications are made through a Disaster Application Centre or by tele-registration, normally to a 60-day deadline. Low-Interest Disaster Loans are also available through the Small Business Association.
- Public Assistance (PA), is aid to the state or local government to pay part of the costs of rebuilding the community's damaged infrastructure and public facilities. This may include debris removal, emergency protective measures, loans for essential government functions and grants for public schools.

Under the Stafford Act the financial burden of emergency assistance is placed on the taxpayers, and the federal government provides funds to state, local governments and private non-profit organisations to cover at least 75% of the costs of the repair, restoration or replacement of public facilities. At the time of Northridge, the percentage (the Volkmer percentage) provided by the federal government met 90%[100] of the replacement costs. Generally, public assistance programs pay 75% of the approved project costs, but this can be increased at the discretion of the President.

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[97] Tagging of buildings is set out in the California State Post-Disaster Safety Assessment Plan. Inspectors affix tags to inspected buildings. Green tags indicate that no hazards have been discovered, yellow tags allow only limited entry, and presuppose a potential danger, while red tags indicate immediate danger and non-admittance. (Eguchi et al, 1998)

[98] Comerio (1996), in Bolin & Stanford (1999)

[99] See http://www.fema.gov/about/4-sect1 htm

[100] According to the Insurance Services Office, the federal government has reduced its share of disaster assistance programmes from 100% for Hurricane Andrew, 90% for the Midwest floods, to 75% for the Northridge earthquake. ISO (1994) Other authors, such as Kunreuther (1998), Bolin & Stanford (1998) maintain that the percentage for Northridge was 90%.

## 5.2 Mitigation measures

Current policy, as set out in the Stafford Disaster Relief and Emergency Assistance Act of 1988, places the financial burden of emergency assistance on the taxpayer. This policy has meant that local communities have had little interest in investing in mitigation measures.[101] FEMA breakdown of costs indicate that USD 0.741 billion was spent on hazard mitigation directly as a result of Northridge.[102] As a result of the increasing losses from natural hazards, FEMA adopted a National Mitigation Strategy, aimed at reducing loss of life and property damage by increasing mitigation. There are five main elements:

- Public Awareness and Training for architects, engineers, building and local officials.
- Leadership and Co-ordination: all twenty nine affected federal agencies have issued regulations to incorporate seismic safety measures in all new buildings owned or leased by the Federal Government and to reduce the earthquake risk to existing federally owned or leased buildings.
- Hazard Identification and Risk Assessment: FEMA has commissioned the National Institute of Building Sciences to develop a nationally applicable standardised method for estimating potential earthquake losses.
- Applied Research and Technology Transfer: Reports, recommending the NEHRP provisions for new buildings and a comprehensive set of nationally applicable consensus-backed guidelines has been distributed.
- Incentives and Resources: The 1993 Volkmer Amendment to the Stafford Act following the Midwest floods incorporated a new formula for post-disaster mitigation funding. This increased the Northridge mitigation funds to nearly USD 1billion instead of the USD 200 million under the old formula.[103]

Under the terms of the Stafford Act the state must prepare a disaster mitigation plan for future events. For each major disaster declared by the President, FEMA will fund up to 75% of the eligible costs of each mitigation project, provided the additional 25% is raised by the state or local sources, in cash, in-kind services or donated materials. Small Business Administration (SBA) applicants can request up to 20% increase in their loan for appropriate hazard mitigation.[104] The Hazard Mitigation Grant Program (HMGP) can provide up to 15% of the federal share of Public and Individual Assistance programmes, minus administrative expenses.

FEMA also created a Seismic Hazard Mitigation Program for Hospitals (SHMPH), which provided grants totalling USD 1.7 billion to participating hospitals, almost 25% of the costs incurred. The program was initiated after disagreement with the California OES about the state requirements, under PIN3, that hospitals meet the 1992 California Building Code.[105] FEMA has established a community based disaster mitigation programme, 'Project Impact', which has absorbed USD 80 million of funding.[106] Other mitigation measures have been undertaken, which include:

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| Research into design criteria for steel moment-resisting construction | USD 8.7 million[107] |
| FEMA Preparedness, Training and Exercises Directorate | USD 144 million[108] |
| US Fire Administration | USD 29 million |
| Risk Assessment of natural hazards | USD 128 million |

[101] See Kunreuther & Roth (1998) introduction.
[102] FEMA (2000)
[103] Moore (1997)
[104] See http://www.huduser.org/publications/destech/bigone/sect1.html
[105] See http://www.fema.gov/IG/shmp_bk.htm
[106] See http://www.fema.gov/nwz98/98017 htm and http://www fema.gov/impact/impact00 htm
[107] See http://www.fema.gov/NWZ95/95_129.txt This was done as a direct result of the poor performance of the steel construction method, which is widely used, and was believed to be seismically resistant.
[108] See http://www.fema.gov/nwz98/98017 htm

| | |
|---|---|
| Emergency Food and Shelter Program | USD 100 million |
| LA Unified School District (securing of overhead lights in schools) | USD 120 million[109] |

The pressures of the immediate needs of constituents ensure that mitigation measures are often short-term recovery plans rather than long-term mitigation measures. California State offered USD 250 million for financing of seismic retrofitting and another USD 50 million to match funds to help localities retrofit public buildings[110]. The California Department of Insurance (CDI) initiated two earthquake retrofit programmes in 1997, providing grants or low interest loans for low- to moderate-income households so reducing the risk of earthquake damage. The CDI also organised home inspections and mitigation measures using CDI approved seismic retrofit contractors.[111] The California Earthquake Authority launched a retrofit programme, SAFER, in October 1999.[112]

Mitigation measures could include better structural design, tougher enforcement of building codes or improved land-use planning. In view of the low frequency of catastrophic events, individual homeowners and small businesses are often unwilling to commit their funds to mitigation measures.[113] Such measures could reduce some of the potential losses from an earthquake, but there appears to be reluctance by the insurance industry to provide incentives such as premium reductions to encourage their adoption. Regulatory restrictions constrain realistic setting of rates and incentives would encourage residents in high-risk areas to purchase coverage, thus increasing insurers risks.[114] Suggestion has been made for a seal of approval for structures complying with building codes, similar to current termite and radon inspections, as a mandatory condition for use when financing a property.[115]

**Building Codes:**

Building Design Codes:

Los Angeles building codes specify buildings to resist a horizontal acceleration of 0.4g. The model codes only require consideration of vertical acceleration in special design cases such as the design of cantilevered elements, and in areas of high seismicity. Los Angeles City adopted an Unreinforced Masonry Retrofit code in 1981, but this was not adopted in other areas affected by the earthquake such as Fillmore, Whittier, Santa Cruz and Coalinga, due to the high costs associated with the strengthening procedures.[116]

When designed to conform to the lateral force requirements of the code the structure should:

- Resist minor earthquake motions without damage
- Resist moderate earthquake ground motions without structural damage, but may experience some non-structural damage
- Resist major earthquake ground motion having an intensity equal to the strongest forecast for the building site, without collapse, but with possible structural damage.

Current building codes focus on saving lives, and not property loss. "*The purpose of the Uniform Building Code is to provide minimum standards to safeguard life or limb, property and public welfare by regulating and controlling the design, construction, quality of materials, use and occupancy, location and maintenance of all buildings and structures.*" Prescriptive building codes,

[109] See http://www.fema.gov/library/wittspch5 htm
[110] See http://www.huduser.org/publications/destech/bigone/sect1.html
[111] See http://www.insurance.ca.gov/EXECUTIVE/CatSeries/Earthquake/Earthquake.3.htm and http://www.insurance.ca.gov/PRSarchive/PRS1999/Pr149-99 htm
[112] See http://www.earthquakeauthority.com/data/about/about html
[113] Petak (1998). The CEA provides an incentive of 5% premium discount for retrofitted houses.
[114] Roth (1997)
[115] Kunreuther (1996)
[116] Bolin & Stanford (1999)

based on proven performance standards, are perceived to be a way of addressing the economic consequences of earthquakes.[117]

Building codes form the primary form of protection against losses from earthquakes, but adoption of a code will not necessarily ensure that building practice meets the standards set out in the code without competent enforcement. Building codes are often not enforced in hazard-prone areas, and varying levels of enforcement lead to different standards.[118]

The state of California requires all cities to adopt the most current version of the Uniform Building Code (UBC) as the minimum code for the city/county. [119] A city/county may choose to adopt a more restrictive code; so the requirements and regulations could differ between San Francisco and Los Angeles. The City of Los Angeles introduced retroactive building codes to improve the seismic standards of buildings, and replacement work had to comply with these codes in order to obtain building permits.

The UBC code contains seismic design provisions and it existed long before the National Earthquake Hazards Reduction Program (NEHRP) provisions were developed. The NEHRP standards were drafted by the Building Seismic Safety Council (BSSC), a council under the National Institute of Building Sciences (NIBS). The NEHRP provisions have enabled the Federal Emergency Management Agency (FEMA) to provide a uniform guide for seismic risks, but states are not obliged to adopt these measures.

FEMA has issued a set of guideline provisions that all three code bodies in the US have adopted, which set out design criteria based on the seismic risk of the area. Federal policies have encouraged a uniform set of codes. The advantages are that of legal liability (the uniform code would be widely accepted as up to date practice) as well as the increased efficiency of a uniform standard for compliance and enforcement.[120]

The International Code Council[121] (ICC) is a non-profit organisation created in order to develop a single set of national codes, and the final draft of the International Building Code[122] for the United States has been completed. This code provides a comprehensive set of construction codes without regional limitations, but it will require adoption and enforcement by state, county and municipal authorities. FEMA has signed an agreement with the ICC to work together on Project Impact, a series of mitigation measures, and has committed funding to encourage adoption and enforcement of the new International Code.[123] There is a competitive effort led by the National Fire Protection Association, but it does not look likely to succeed.[124]

**Land-Use Planning:**

The Alquist-Priolo Act of 1972 is the principal form of land use planning for earthquakes in California, and is designed to prevent development along active fault lines. The legislation requires evaluation of the site by an engineering geologist who can make recommendations for 'safe' construction, and it also requires real estate agents or sellers to disclose risks if the property lies

[117] Moore, FEMA representative (1997); Petak (1998)
[118] Kunreuther (1996)
[119] Petak (2000)
[120] Wright (2000)
[121] The ICC was founded in 1994 as an umbrella organisation by the Building Officials and Code Administrators (BOCA), the International Conference of Building Officials (ICBO), and the Southern Building Code Congress International (SBCCI).
[122] See http://www.intlcode.org
[123] See http://www.intlcode.org/newsrel/nr100899.html
[124] See http://www.nfpa.org.

within 1/8 mile of a trace of an active earthquake fault. Studies indicate that this legislation has not been implemented.[125]

# 6. EARTHQUAKE INSURANCE

## 6.1 Earthquake insurance in the US

The insured losses of Northridge cost more than three times the total earthquake premiums California insurers collected in the 25-year period prior to the disaster. Prior to Hurricane Hugo in 1989, with insured losses of $4 billion, the insurance industry had never suffered losses in excess of $1 billion. Since then, over 10 disasters have exceeded that amount.[126]

These recent losses have made it more difficult and expensive to find insurance for natural disasters. The increased risks posed by natural disasters are also due to the increasing number of Americans living in high risk areas, increasing capital investment - sometimes in new technologies, a large number of unsafe buildings, vulnerable lifelines, as well as the increasing interdependence of people. Some insurers and reinsurers consider the earthquake premiums inadequate at present and believe that the potential losses far exceed their capacity, encouraging them to withdraw from the market completely.[127]

Earthquakes pose a significant risk in at least 39 states. Unlike California, these states are not well prepared for these events, and as a consequence are potentially likely to face higher human and physical losses than a comparable earthquake in California. Although the potential for US earthquake insurance appears great, each state has a different regulatory body and system, which makes the potential risk difficult and expensive for the insurer to determine. The eastern United States has experienced a number of damaging earthquakes, such as the 1755 Boston, 1811 New Madrid, and 1884 New York earthquakes. There are longer recurrence periods, and therefore less information and greater uncertainty about these risks. There is a credible risk of a magnitude 5-6 earthquake affecting cities such as Philadelphia, Boston or New York, yet no planning has been made for this risk.[128] Although there are some current moves to make lifelines more resilient to earthquakes, and for new construction to meet seismic building codes, the overall lack of preparedness, ageing buildings and infrastructure leave society exposed.

Earthquake insurance can be purchased as a supplement to standard coverage, but the take-up is low except in high-risk areas. California, and subsequently Washington, the Midwest and Oregon have all seen increased pricing plans, based on more detailed information of the seismic risks. Insurers are now departing from their past practice of basing earthquake premiums on historical data and using scientific research and computer simulation models to predict earthquake risks.[129] Earthquake insurance policies are usually for replacement coverage, replacing old for new, which increases the liability of the insurance company.[130]

## 6.2 Earthquake insurance in California

[125] Palm (1998)
[126] Kunreuther (1998)
[127] CDI (1997/8), Roth (1997)
[128] Jacob (1995)
[129] Risk Management Solutions, in New York Times (1999)
[130] Roth (1997)

Demand for both residential and commercial earthquake insurance has increased over the past 15 years, due to earthquakes, media publicity and rising property values. At the time of the Northridge earthquake, 40% of homes in Los Angeles County had earthquake insurance. This earthquake insurance tends to be purchased by higher-value homeowners, and similarly larger commercial businesses. Mortgage lenders do not normally require earthquake insurance. The reasons given for this are that most loans are on post-1940 properties (built according to some earthquake code) therefore the probability of default is unlikely if there is still positive net equity in the property. Lenders also spread their risks geographically and often pass the risks on to others, and may not discriminate on mortgage loans, because of state and federal anti-redlining legislation.[131]

In general, it is large multistate companies with multiple lines of insurance business that have the financial resources to provide insurance against natural catastrophes. The Northridge earthquake demonstrated that the losses were subsidised by other lines of business and business written in other states.[132] Over the last decade, the number of insurers writing homeowners policies in California has dropped by 23%, resulting in a higher concentration of policies, an increased market share and therefore, a disproportionately larger exposure for the three largest homeowners insurers.[133] Seismologists from the United States Geological Survey (USGS) have predicted an increase in seismic tremors and major magnitude 8 earthquakes, and the occurrence of earthquakes of a magnitude of 6.0+ is expected every 1.6 years for the next 30 years, which has increased insurers concerns about their exposure.[134]

**Residential earthquake insurance.**

In 1985 California State introduced the 'mandatory offer law', which required insurers selling homeowners policies on one- to four-family units to offer earthquake coverage for these structures.[135] This law requires any insurer writing residential property insurance to offer its prospective and existing clients coverage for loss due to earthquake. The offer must be in writing, subject to minimum coverages. The client has 30 days to accept the offer, but if it is not accepted, the insurer must renew the offer every 2 years.[136]

The mandatory earthquake offer requirement took away from insurers the ability to manage their total risk exposure as they were required to insure old structures in poor condition as well as newer structures, leading to adverse selection problems. After the Northridge earthquake, homeowners decided to avail themselves of this insurance policy, but the high level of losses and seismologists' predictions of further earthquakes caused most insurers to stop writing residential policies, the only legal recourse open to them due to the mandatory offer law. This caused an insurance availability crisis.

The California Earthquake Authority (CEA) was created by the Legislature in 1996 to address the crisis in insurance availability. It is a state-run company funded by the private sector offering earthquake insurance as an endorsement of homeowners' insurance policies. The funds to pay insured loss claims come from premiums, participating insurance companies and reinsurance purchased by the CEA. No public money, including the State General Fund, is pledged to cover losses. The CEA has a total claims-paying capacity of $7.2 billion.

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[131] Palm (1998)
[132] Roth (1998)
[133] ISO (1996)
[134] This information stems from "Seismic Hazards in Southern California: Probable Earthquakes 1994-2024", and is discussed in CDI (1997/8), Macilwain (1994), NYT (1999).
[135] Roth (1997), CDI (1997/8)
[136] CDI (1999)

The CEA commissioned earthquake risk analyses for the entire state, dividing the state into 19 separate rate territories. Rates are dependent on earthquake risk, as well as the age and construction of the home, soil type and proximity to faults. These rates subsequently doubled to actuarially based premiums, but due to political pressure the rates in northern California were reduced despite the results of the risk modelling.[137] The rating structure of the CEA has been controversial since its inception.[138] The average cost for a basic policy is now $2.79 per $1,000 coverage, but can be as high as $8 per $1000.[139]

Deductibles were increased from 5-10% to a standard 15%, the value of contents was lowered to $5000 and additional living costs was limited to $1500. The standard coverage offered by the CEA does not cover out buildings and structures, for example detached garages, garden walls, swimming pools, patios, fences or driveways. Some participating companies have introduced a reduced 10% deductible, and higher coverage limits for personal property and additional living expenses. Depending on its date and type of construction, a retrofitted house may be eligible for a 5% premium discount.

It is important to note that the deductible is 15% of the replacement cost of the structure itself. This ensures that the CEA will not pay any claims for structure damage or contents damage unless the damage to the structure exceeds 15%. Should any residents be forced out of their home, the policy will, however, still pay the additional living expenses allowance, up to its $1500 limit, even if there is minimal structural damage. Many homeowners have chosen not to insure due to the increased premium rates, reduction in coverage offered by the CEA and the low chance that the loss will exceed the 15% deductible. These factors have caused the average level of residential earthquake coverage in California to drop by half to 17%.

**Commercial earthquake insurance**

There is no mandatory offer requirement for commercial earthquake insurance. Commercial rates are low and appear to be readily available. Approximately 80% of earthquake exposure are on commercial property, yet it is the owners of commercial properties, rather than the small businesses renting the space that purchase this earthquake insurance. Most commercial buildings are only partially insured for earthquake damage, and many older buildings are not covered at all. Small businesses do not buy insurance due to the high cost of cover, their short time horizon, the low number of assets at risk, and the perceived availability of loans and grants. There is generally little coverage for loss of use or business interruption losses.[140]

# 7. CONCLUSIONS

Northridge earthquake was relatively small in terms of seismic intensity, yet its financial impact made it one of the worst disasters in US history. The economic losses were extreme, exceeding all previous predictions. The earthquake provided a graphic illustration of the magnitude of potential losses, alerting federal and state governments, as well as private insurers, to the large risk exposure from earthquakes and the need for greater loss control to reverse the trend. Research has shown that potential direct losses from natural disasters are only likely to increase over time as more Americans live in 'high risk' areas, yet often fail to take the commensurate structural steps to safeguard their property. Indirect losses have also escalated due to the increased interdependence of people and businesses on all forms of communication and other infrastructure.

[137] Petak (2000)
[138] Consumer Watchdog (1999)
[139] III (2000)
[140] CDI, 1997/98

Although the earthquake occurred in one of the best-prepared regions of the world, the extent of the financial losses was extreme. The levels of reimbursement were high; yet non-reimbursed losses still amounted to 50% of the total losses. These losses of approximately USD 21 billion were met by the victims of the disaster and have had major social impacts on the communities affected.

The federal and state governments provided the primary source of relief and economic recovery. FEMA estimates of total federal expenditure on Northridge are more than USD 13 billion, making it the most expensive natural disaster in US history for the federal government. However, federal disaster relief programmes have been reduced over time from 100% assistance for Hurricane Hugo, 90% for Northridge to a current lower level of 75%. This level could be reduced further, particularly in the light of federal cutbacks. This is likely to mean that future disasters will not be covered by government aid to the same extent.

The future role of private insurance in the protection of financial losses from catastrophic events is uncertain, and will depend on the extent of future federal relief programmes for natural disasters. Should these federal programmes be reduced, the demand for private insurance will increase. However, the increasing scale of these losses has made it more difficult and expensive to find insurance for natural disasters. The insured losses inflicted by the Northridge earthquake were so extreme they amounted to three times the total earthquake premiums collected by California insurers in the 25-year period prior to the disaster. As more research becomes available regarding the risk of potential losses posed by earthquakes, insurers increase their premiums, increase the levels of the deductible or reduce the level of coverage. This in turn lowers the level of insurance penetration and leaves more of society vulnerable should a disaster occur.

Northridge earthquake highlighted the value of two preventive measures. First, it showed that good data collection and the use of Geographical Information Systems (GIS) could reduce delay and minimise losses. The proactive steps taken by the California Office of Emergency Services (OES) in the commission of a GIS system appeared to serve the emergency response and planning needs of the agency admirably. It enabled data to be collated, analysed and distributed which in turn improved the ability of the authorities to co-ordinate the response and to focus on the hardest hit areas.

In addition, the earthquake proved the value of seismic strengthening and mitigation measures in reducing deaths and injuries to a very small fraction of the affected population. Current building codes focus on saving lives, but this does not reduce the economic and social costs to a community. The economic costs of better seismic protection are high, and the issue of how much building codes should address the economic consequences of earthquakes has led to considerable debate. The public is not always willing to invest in costly mitigation measures that are essentially long-term, when the likelihood of residential occupation is short-term. This risk debate cannot be restricted to the engineers and code developers, and society at large must participate in assessing the costs and benefits of better seismic protection. In addition, the earthquake demonstrated the vulnerability of some of these building types. Most of the structures affected by the earthquake were constructed in the last three decades and were considered to be earthquake resistant, but not all buildings proved resistant. This has led to improved seismic building codes and highlighted the need for a modern standardised building code.

The probability of another Northridge earthquake, with a similar or greater scale of losses, appears to be high. Yet federal and state governments are keen to shift the responsibility for disaster relief, and funding is unlikely to be equally generous next time. Insurers have grown wary - as the increased premium rates and reduced coverage offered by the California Earthquake Authority indicate - and earthquake insurance is no longer as widely carried by the public as before. Who will

bear the costs of the next Northridge earthquake? Will it be the federal government? The state government? The private insurers? Or the disaster victims? The likelihood is that it will be the latter, but this will result in clear political, economic and social costs. The situation becomes more complex as the percentage of society vulnerable to natural disaster increases. There is no simple solution to this problem, and the result will probably be a trade-off between political, economic and social factors. The issue this trade-off raises is one that only society at large can make.

*"With few exceptions, the country's catastrophe strategy has been to stay lucky. It has worked, in an era of infrequent catastrophes, smaller populations and exposures. But it cannot work forever and, will not work where increased populations and exposures are a fact of life."* [141]

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