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Prospects for Larger or More Frequent Earthquakes in the Los Angeles Metropolitan Region

James F. Dolan,* Kerry Sieh, Thomas K. Rockwell, Robert S. Yeats, John Shaw, John Suppe, Gary J. Huftile, Eldon M. Gath

Far too few moderate earthquakes have occurred within the Los Angeles, California, metropolitan region during the 200-year-long historic period to account for observed strain accumulation, indicating that the historic era represents either a lull between clusters of moderate earthquakes or part of a centuries-long interseismic period between much larger (moment magnitude, M_w, 7.2 to 7.6) events. Geologic slip rates and relations between moment magnitude, average coseismic slip, and rupture area show that either of these hypotheses is possible, but that the latter is the more plausible of the two. The average time between M_w 7.2 to 7.6 earthquakes from a combination of six fault systems within the metropolitan area was estimated to be about 140 years.

Californians have long anticipated the recurrence of the "Big One," a great earthquake (M ~ 8) emanating from a long section of the San Andreas fault (SAF), such as occurred in 1857 and 1906. Consequently, earthquake hazard assessment and preparedness in southern California has historically focused primarily on the SAF and its various strike-slip branches (Fig. 1) (*1*, *2*). In the past decade, however, several moderate earthquakes have occurred on faults beneath the Los Angeles metropolitan area. Moderate to large earthquakes (M_w 6.5 to 7.5) on these faults could potentially cause even more damage than a much larger earthquake on the more distant SAF. This was dramatically demonstrated by the 1994 M_w 6.7 Northridge earthquake, the second most expensive natural disaster in U.S. history (after Hurricane Andrew) (*3*).

The Los Angeles region is geologically complex, and almost 100 active faults have been identified in the area (*4–8*). Because of their size and proximity to major population centers, six major fault systems are of particular concern (*9–12*).

1) The Sierra Madre–Cucamonga system extends for 100 km along the northern edge of the densely populated San Fernando and San Gabriel valleys (*13*, *14*). The westernmost 19 km of the north-dipping Sierra Madre fault zone (including the San Fernando fault) ruptured during the 1971 M_w 6.7 Sylmar earthquake, which claimed 64 lives and caused $558 million in damage (1971 dollars; ~$2 billion in 1994 dollars) (*15*).

2) The Los Angeles basin fault system comprises two major blind thrust fault ramps (Elysian Park and Compton ramps) that are connected by a mid-basin flat fault segment (*7*, *16*). The Whittier fault (*17*) and the northern Newport-Inglewood fault zone (*4*, *7*) may represent partitioned strike-slip faults above the blind thrust faults. This system underlies the most densely urbanized part of the region, including downtown Los Angeles.

3) The Santa Monica Mountains fault system, which extends for 90 km from near downtown Los Angeles westward along the Malibu Coast, consists of a large blind thrust ramp and the surficial Hollywood–Santa Monica–Malibu Coast subsystem, which we interpret as a set of predominantly left-lateral strike-slip faults (*4*, *5*, *16*, *18–20*).

4) The Oak Ridge fault system is a major south-dipping thrust system that extends for more than 70 km from just east of Ventura to at least the eastern end of the Santa Clarita River Valley (*21*, *22*). A previously unrecognized, blind eastern extension of this system appears to have been responsible for the 17 January 1994 M_w 6.7 Northridge earthquake (*8*).

5) The San Cayetano fault, which dips moderately northward, extends for 40 km along the northern boundary of the oil-rich Ventura basin (*23*). The eastern part of this fault exhibits one of the highest slip rates in the region (7.5 to 10.4 mm $year^{-1}$) (*23*).

6) The Palos Verdes fault, which is best known from its onshore extent along the northeastern edge of the Palos Verdes Peninsula in the southwestern part of the Los Angeles basin, also extends as a submarine feature for more than 50 km to the south of the peninsula (*24*). Recent studies indicate that the Palos Verdes fault is slipping at a rate of approximately 3 mm $year^{-1}$ (*25*).

The large number of damaging, moderate ($4.8 \leq M_w \leq 6.7$) earthquakes that have occurred in the Los Angeles region

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since 1971 has given rise to the perception that this earthquake frequency is typical of the area. In reality, however, few large earthquakes have occurred on faults within the metropolitan region during the two centuries of historic record, the two largest being the M_w 6.7 Northridge and San Fernando events of 1994 and 1971, respectively (*26–30*).

Geodetic studies indicate a shortening rate across the Transverse Ranges in the greater metropolitan region of approximately 8.5 mm $year^{-1}$(*31*). These data suggest that far too few moderate earthquakes have occurred within the region to account for observed strain accumulation, indicating that a deficit of seismic energy release exists in metropolitan southern California (*32*).

In this article we use reasonable geologic slip rates for the known active faults within the metropolitan area, together with newly determined local relations between moment magnitude (M_w), average coseismic slip, and rupture area, to attempt a quantitative assessment of the potential for future destructive earthquakes from faults within the Los Angeles metropolitan region (*12*). We compare the rate of historical seismic moment release with longer term rates derived from geologic data to quantify the historical earthquake deficit. We then propose two end-member scenarios: In the first scenario, strain is released in numerous, moderate, Northridge-like earthquakes; in the second, strain is released in less frequent but much larger (M_w 7.2 to 7.6) earthquakes. Geological slip rates allow us to estimate repeat times for earthquakes in each of these scenarios.

Source Parameters

Moment magnitude can be empirically related to known geological parameters, such as rupture area (A) and average co-

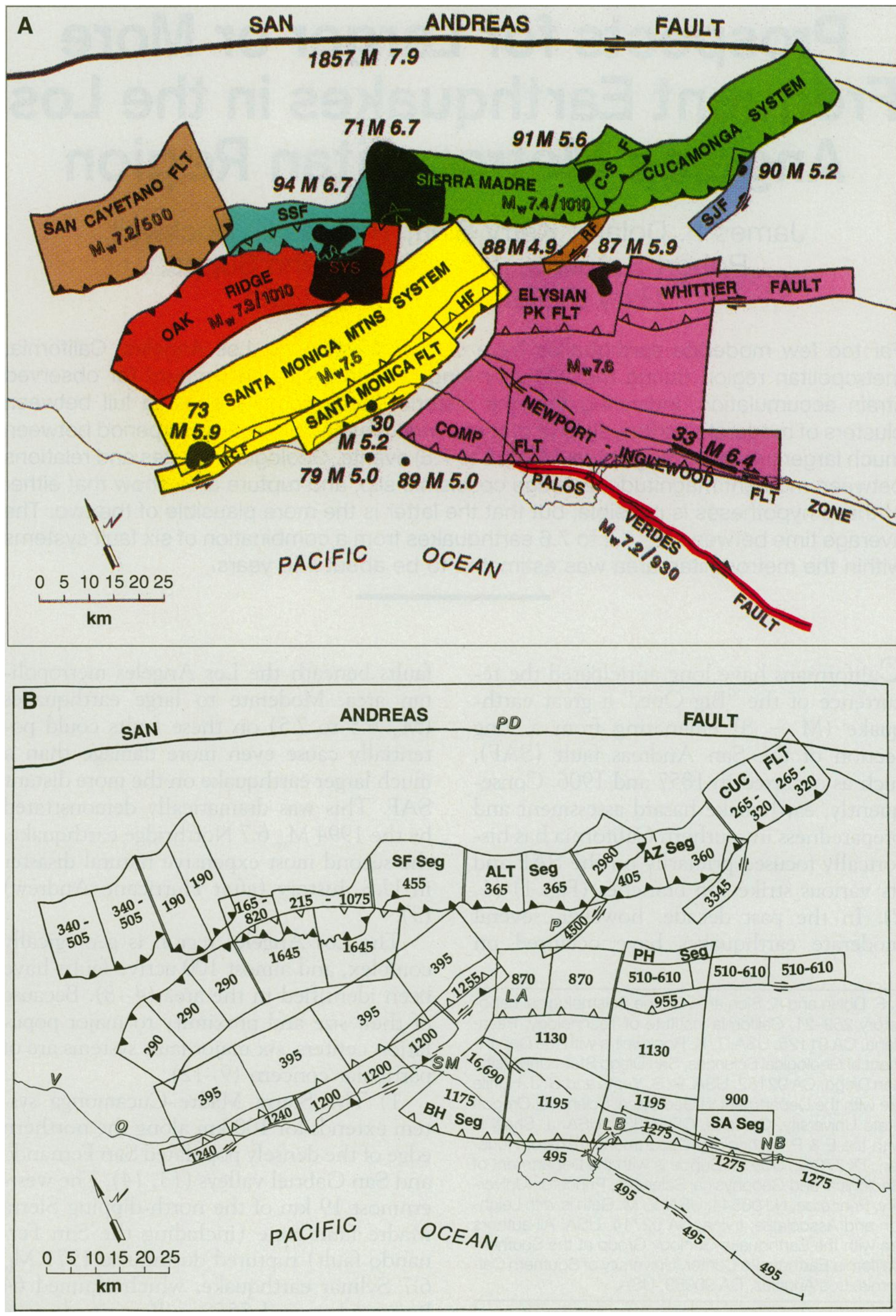

Fig. 1. (**A**) Historical earthquake ruptures and proposed large earthquake sources within the greater Los Angeles metropolitan area. Black areas denote surface projections of rupture planes of selected moderate historic earthquakes (*6, 35–40, 65–67*). Date and magnitude (M_w) of each earthquake are also shown. Historic ruptures on vertical strike-slip faults (1857 and 1933 earthquakes) are shown as heavy black lines. Polygons represent map projections of nonvertical fault planes. Thin lines denote near-vertical faults. Intermediate-width lines outline major fault systems that we consider could cause large earthquakes (M_w 7.2 to 7.6). Solid barbs denote thrust faults that break the surface; barbs point downdip. Open barbs represent the upper edge of blind thrust fault ramps; barbs point downdip. Predominantly strike-slip faults are shown by double arrows along the surficial trace of each fault. Maximum credible earthquakes and their average recurrence intervals are shown for each fault system (for example, M_w 7.4/1010 on the Sierra Madre system indicates a recurrence interval of approximately 1010 years for a M_w 7.4 earthquake rupturing the entire system). Comp FLT, Compton fault; C-SF, Clamshell-Sawpit fault; HF, Hollywood fault; MCF, Malibu Coast fault; RF, Raymond fault; SJF, San José fault; SSF, Santa Susana fault. (**B**) Map showing the 51 potential, moderate (M_w 6.5 to 6.8; average M_w 6.7) earthquake sources within the metropolitan region that we used in our moderate-earthquake scenario. The number within each earthquake source area denotes the approximate average recurrence interval (in years) for a moderate earthquake from each source region. In this scenario, for example, the source of the Northridge earthquake produces a M_w 6.7 event every 1645 years. Double lines denote geologically reasonable segment boundaries. ALT Seg, Altadena segment; AZ Seg, Azusa segment; BH Seg, Baldwin Hills segment; CUC FLT, Cucamonga fault; LA, downtown Los Angeles; LB, Long Beach; NB, Newport Beach; O, Oxnard; P, Pasadena; PD, Palmdale; PH Seg, Puente Hills segment; SA Seg, Santa Ana segment; SF Seg, San Fernando segment; SM, Santa Monica; V, Ventura.

seismic displacement over the rupture plane (D). Several compilations of parameters have been published, most of them for a worldwide earthquake data set [for example, (*2, 33, 34*)]; however, these relations can depend on geographic location and tectonic setting. Therefore, we have constructed new regressions of M_w versus rupture area and average coseismic slip using data from eight well-studied, off–San Andreas southern California earthquakes that have occurred since 1932 (Fig. 2 and Table 1) (*35–41*). We converted seismic moments (M_o) for the eight earthquakes to M_w using the equation $M_w = (\log M_o - 16.1)/1.5$ (*42*).

The regression (Fig. 2A) shows that for a given rupture area, M_w for a southern California earthquake will be larger than would be expected from the regressions on worldwide data. The discrepancy is larger for smaller events, ranging from about 0.3 units for $M_w = 5.0$ to about 0.1 units for $M_w = 7.5$.

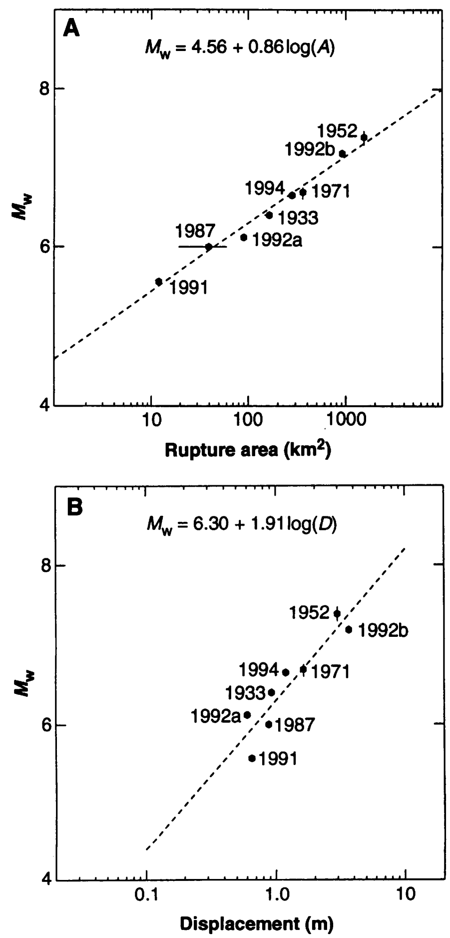

Fig. 2. New regressions for southern California earthquake parameters. (**A**) Rupture area (square kilometers) plotted as a function of moment magnitude (M_w) for southern California earthquakes (Table 1). Data sources as in (*35–40*). (**B**) Moment magnitude versus average slip over the rupture plane for southern California events was determined by solving the equation $M_o = \mu AD$.

From the equation above and the definition of seismic moment, $M_o = \mu AD$, where μ = shear rigidity, we can determine the relation between M_w and D (Fig. 2B) (*43*). The relation for southern California contrasts markedly with that of the global data (*34*). Displacements for small southern California earthquakes are larger than would be expected, whereas displacements for large events ($M_w > 7.4$) are smaller than expected.

Geologically Reasonable Scenarios

Recent advances in understanding the active tectonics and structure of the Los Angeles region, particularly the identification of large thrust fault systems beneath the metropolitan area, have led to a more complete understanding of potentially seismogenic faults of the region (*5–7*). To construct geologically realistic earthquake scenarios based on these data, we used the location, extent, and dip of seismogenic faults, together with the depth of the base of the seismogenic zone as determined from the base of deepest seismicity (*44*), to determine fault plane area. We then used the new regression equations for southern California earthquakes to determine the moment magnitude and average displacement of postulated earthquakes on each fault (Table 2). The recurrence interval for a particular earthquake is then the average slip estimate for each fault or fault segment divided by the geologically determined slip rate of the fault (*45*).

Moderate-Earthquake Scenario

One means of quantifying the historical earthquake deficit is to assume that all strain across the region is released uniformly during moderate ($M_w \sim 6.7$) earthquakes (*46*). For this scenario we determined geologically reasonable segment boundaries for all structures (Fig. 1B) (*47*). We then arbitrarily divided the segments defined by these boundaries into M_w 6.7–sized subsegments (Fig. 1B). Because subsegment size is ultimately controlled by the geologically defined segments, which are not identical in size, the resulting moderate earthquake sources range from 175 km^2 (M_w 6.5) to 397 km^2 (M_w 6.8). This process results in 51 moderate (average M_w 6.7) earthquake sources within the greater Los Angeles metropolitan area (Fig. 1B).

We converted the recurrence interval (RI) for each source into an expected earthquake frequency (f), such that $f = 1/RI$. Taking the inverse of the sum of the frequencies for all 51 sources yields an average expected repeat time for M_w 6.7 earthquakes of about 11 years, assuming that all strain across the region is accommodated in such events. Uniform release of strain in M_w 6.7 earthquakes thus requires that between 13 and 17 moderate earthquakes should have occurred during the historic period. Only two such events have been recorded (*26, 27*), indicating that there is a historical deficit of 11 to 15 M_w 6.7 earthquakes. Fifteen M_w 6.7 earthquakes correspond to a cumulative stored seismic moment of 2.12×10^{27} dyne cm, which is equivalent to a M_w 7.5 earthquake.

Large-Earthquake Scenario

In this scenario, we asummed that all strain across the Los Angeles region is released during large (M_w 7.2 to 7.6) earthquakes and that each of the six major fault systems described in the introduction fails in its own characteristic earthquake (*48*). For the four single-fault systems (Sierra Madre–Cucamonga, Oak Ridge, San Cayetano, and Palos Verdes), we used the total area of each fault to calculate a moment magnitude, which we then used to calculate the average coseismic slip for each earthquake (Table 2).

The two remaining large fault systems (Santa Monica Mountains and Los Angeles basin) involve multiple faults with varying slip rates and slip directions (*49*). Unlike the four single-fault systems, strain is partitioned on the Santa Monica Mountains and Los Angeles basin systems such that dip-slip

Table 1. Parameters for historical southern California earthquakes (*35–40*).

Earthquake	M_o	M_w	Rupture area (km^2) min–max (avg)	Average slip (cm)
1933 Long Beach	5×10^{25}	6.40	150–180 (165)	84–101
1952 Kern County	1×10^{27}	7.29	1450–1625 (1540)	196–400
	1.9×10^{27}	7.45		
	2.0×10^{27}	7.47		
1971 San Fernando	1.0×10^{26}	6.60	360	87–143
	1.7×10^{26}	6.75		
1987 Whittier Narrows	1.0×10^{25}	6.00	20–60 (40)	34–142
1991 Sierra Madre	2.8×10^{24}	5.57	12	65
1992a Joshua Tree	1.9×10^{25}	6.12	90	60
1992b Landers	7.5×10^{26}	7.18	910	330–404
1994 Northridge	1.2×10^{26}	6.65	280	119

motion is accommodated along the blind thrust faults, and strike-slip motion is accommodated along the surficial strike-slip faults. Therefore, we treated these different subsystems independently and calculated sizes and recurrence intervals for earthquakes occurring on each of these individual structures. Adding the moments of these individual subevents yields the overall size of the maximum credible earthquake on each system (50).

Our calculations indicate (Fig. 1A) the following: (i) The Sierra Madre–Cucamonga system is capable of producing a M_w 7.4 earthquake approximately every 980 to 1040 years. (ii) Rupture of the Santa Monica Mountains blind thrust fault would produce a M_w 7.2 earthquake about every 740 years, whereas the Hollywood–Santa Monica–Malibu Coast fault system could independently produce a M_w 7.3 earthquake approximately every 2195 to 3290 years. If these subsystems were to rupture together, they would generate a M_w 7.5 earthquake. (iii) If only the blind thrust faults of the Los Angeles basin system were to rupture, they would produce a M_w 7.5 earthquake about every 2845 years. The Whittier fault is capable of independently producing a M_w 7.1 earthquake about every 840 to 1005 years. If the Whittier fault and the blind thrust faults were to rupture together, they could produce a M_w 7.6 earthquake. Although it is possible that the northern Newport-Inglewood (N-I) fault could rupture together with both the blind thrust faults and the Whittier fault, the extremely long recurrence interval that we calculate for the N-I fault indicates that this would be a very rare event. (iv) The Oak Ridge system is capable of generating a M_w 7.3 earthquake approximately every 1010 years. (v) Rupture of the entire San Cayetano fault would produce a M_w 7.2 earthquake every 455 to 545 years. (vi) The Palos Verdes fault could generate a M_w 7.2 earthquake approximately every 925 years.

The collective average recurrence interval for the seven large (M_w 7.2 to 7.5) earthquakes that we propose on these six systems is about 140 years (*51*), a return time comparable with that of M ~ 7.8 to 7.9 earthquakes on the San Andreas fault (*52, 53*). Within the Los Angeles region the historic record, which for M_w 7.2 to 7.6 earthquakes is probably complete as far back as the early 1780s (*26, 27*), is devoid of such large earthquakes. Thus, it has been at least 210 years since the most recent large earthquake in the Los Angeles region, a time interval that is longer than the average recurrence interval that we calculated for large earthquakes.

The two scenarios discussed above represent reasonable end-member possibilities for strain release. However, the actual means of strain release within the Los Angeles region is undoubtedly more complex, with some combination of moderate and large earthquakes (Table 2). Hough (*54*), for example, suggests a fractal distribution of earthquakes in which most seismic moment release is concentrated in infrequent large events.

Table 2. Parameters for large scenario earthquakes rupturing entire fault systems and for intermediate-sized earthquakes rupturing parts of fault systems. N/D, not determined.

Fault	Rupture area (km^2)	M_o (10^{26})	M_w	Average slip (m)	Slip rate (mm year^{-1})	Recurrence interval (years)	Depth (km)	Dip
Sierra Madre–Cucamonga	2220	18.0	7.4	3.94	3.8–4.0	980–1040		
Sierra Madre	1500	10.9	7.3	3.30	4.1	805		
Asuza segment	615	3.4	7.0	2.21	4.25	520	0–16	55°N
Altadena segment	490	2.6	6.9	1.99	4.0	500	0–16	55°N
San Fernando segment	400	2.0	6.8	1.82	4.0	455	0–16	50°N
Cucamonga	480	2.5	6.9	1.98	4.5–5.5	360–440	0–16	50°N
Clamshell-Sawpit	240	1.0	6.6	1.45	0.5	2890	0–16	57°NW
Oak Ridge	1370	9.7	7.3	3.17	3.1	1010		
East segment	635	3.6	7.0	2.25	1.0	2245	8–19 (E) to 0–20 (W)	45°S
West segment	730	4.3	7.0	2.39	5.0	480	0–20	55°S
Santa Monica Mountains (blind thrust+HF-SMF-MCF)	2655	22.8	7.5	N/D	N/D	N/D		
Santa Monica Mtns. thrust	1170	7.9	7.2	2.95	4.0	740	14.3–19.5	20°N
HF-SMF-MCF	1485	10.8	7.3	3.29	1.0–1.5	2190–3290		
Hollywood	260	1.1	6.6	1.50	1.0–1.5	1005–1505	0–17	70°N
Santa Monica	715	4.2	7.0	2.36	1.0–1.5	1575–2365	0–17	65°N
Malibu Coast	510	2.7	6.9	2.03	1.0–1.5	1355–2035	0–17	75°N
San Cayetano	1095	7.2	7.2	2.87	5.3–6.3	455–545		
East segment	470	2.4	6.9	1.96	7.5	260	0–20	40°N
West segment	625	3.5	7.0	2.23	3.6–5.4	415–620	0–20	50°N
Los Angeles basin (blind thrusts + Whittier flt)	3110	30.7	7.6	N/D	N/D	N/D		
Blind thrust system only	2220	21.4	7.5	3.94	1.5	2605		
Elysian Park thrust	815	5.0	7.1	2.51	1.7	1475	10.5–16	22°NE
Los Angeles segment	505	2.7	6.9	2.02	1.7	1190		
Puente Hills segment	310	1.4	6.7	1.62	1.7	955		
Mid-basin flat	610	3.4	7.0	2.20	1.4	1575	10.5	0°
Compton thrust	1105	7.3	7.2	2.88	1.4	2055	5.5–10.5	23°NE
Baldwin Hills segment	320	1.5	6.7	1.54	1.4	1180		
central segment	660	3.8	7.0	2.29	1.4	1635		
Santa Ana segment	175	0.68	6.5	1.26	1.4			
Whittier	815	5.0	7.1	2.51	2.5–3.0	840–1005	0–16	70°NE
Newport-Inglewood (north)	330	1.5	6.7	1.67	<0.1	>16,690	0–9	74°NE
Palos Verdes	1030	6.7	7.2	2.78	3.0	930	0–16	90°
Santa Susana	545	3.0	6.9	2.09	1.6–8.0	260–1310	0–16	60°N
Raymond	325	1.5	6.7	1.66	0.4	4500	0–16	80°NE
San Jose	330	1.6	6.7	1.67	0.5	3345	0–16	75°NE
Newport-Inglewood (south)	815	5.0	7.1	2.51	1.2	2095	0–16	90°

Implications for Seismic Hazards

These scenarios indicate that there is a marked deficit in moment release in the greater Los Angeles metropolitan area during the 200-year historic period; geologic fault slip rates and geodetic shortening rates show that we have had far too few earthquakes to account for strain accumulation. There are three possible explanations for this observation. (i) A significant portion of strain is released aseismically. (ii) Most of the strain is released in moderate earthquakes. (iii) Much, or most, of the strain is released in much larger earthquakes (M_w 7.2 to 7.6) with longer recurrence intervals.

There is no evidence that any significant aseismic fault creep occurs within the brittle, upper crust of the Los Angeles metropolitan region. If aseismic creep were occurring, we would expect to see abundant microseismicity on major thrust fault ramps as well as extensive disruption of built structures where they lie atop surficial faults or the traces of active folding above blind thrust faults (*55*). Neither phenomenon has been observed in the metropolitan area. If no significant fault creep occurs in the region, then fault slip must be accommodated during earthquakes.

If all strain release occurs during moderate, M_w 6.7 earthquakes, then the historic period must represent a lull between clusters of such earthquakes. The average 11-year recurrence interval for M_w 6.7 earthquakes on the 51 sources we have defined predicts that 17 such events should have occurred during the past 195 years, but we have experienced only two such events. Elsewhere in the world, temporal and spatial clusters of destructive earthquakes have been observed at decade-long time scales along both thrust faults (for example, Coalinga–Kettleman Hills, California, 1982–85) and strike-slip faults (for example, North Anatolian fault, Turkey, 1939–44) (*56*). Therefore, we cannot rule out the possibility that much of the accumulated strain in the Los Angeles metropolitan region could be released by a cluster of moderate earthquakes. Given the level of damage from the Northridge earthquake, such a sequence would certainly strain the ability of the region (and the nation) to absorb the resultant losses.

Paleoseismologic data are too sparse and incomplete to tell us when the most recent large earthquake occurred in the Los Angeles area. However, data from several faults suggest that large earthquakes may indeed have occurred in the region. For example, recurrence interval data from excavations across the Santa Monica, Hollywood, and Malibu Coast faults indicate that these faults have ruptured during Holocene time, but that the most recent surface-rupturing earthquakes occurred several thousand years ago (*19, 20*). Furthermore, average recurrence intervals for the Santa Monica and Malibu Coast faults determined during trench studies (*19*) are approximately 3000 to 5000 years, far longer than would be expected if these faults ruptured individually (Table 2). Similarly, occurrence of the most recent surface-rupturing earthquake on the Hollywood fault more than 2000 to 4000 years ago (*20*) indicates a much longer period than would be expected if the Hollywood fault ruptured by itself during moderate earthquakes (Table 2). These data, although not definitive, suggest that the surficial faults of the Hollywood–Santa Monica–Malibu Coast system rupture in conjunction either with each other or with other faults. The Santa Monica Mountains blind thrust fault, which may be mechanically linked to the surficial faults at depth, may well rupture with these surficial faults during large earthquakes.

Similarly, paleoseismologic data from the Whittier fault suggest that this fault has ruptured in combination with other faults in the past. These data reveal a recurrence interval of approximately 1700 years for surface-rupturing earthquakes (*17*), considerably longer than the repeat time of 875 to 1050 years that we calculate for a M_w 7.1 earthquake generated by rupture of only the Whittier fault (Table 2). The Whittier fault may rupture together with either the northern Elsinore fault (*57*) or the Elysian Park blind thrust (*7*).

These data indicate that events such as those proposed in our large-earthquake scenario (M_w 7.2 to 7.6) may have occurred in the Los Angeles metropolitan region in the past and may recur in the future. Similar tectonic regimes elsewhere in the world have produced thrust- and reverse-fault earthquakes of this size [for example, 1944 San Juan, Argentina, surface wave magnitude (M_s) 7.4; 1952 Kern County, California, M_w 7.4; 1964 Niigata, Japan, M_s 7.5; 1977 Caucete, Argentina, M_s 7.4; 1978 Tabas-e-Golshan, Iran, M_s 7.4; 1980 El Asnam, Algeria, M 7.3; 1988 Spitak, Armenia, M_s 6.9; and 1992 Suusamyr, Kyrgyzstan, M_s 7.4] (*58*).

We conclude that faults within the Los Angeles region are capable of generating earthquakes in the range of M_w 7.2 to 7.6. Documented examples of long-term earthquake clustering (*52, 59*) indicate that we could well be in the middle of a centuries-long quiescent period. However, it has been at least 210 years since such an event has occurred in the region, indicating that we are within the expected average recurrence time for an earthquake of this size, as determined by our model. The effects of such a large earthquake would be substantially different from the recent, moderate Northridge earthquake in several important respects. Specifically, a large earthquake would cause strong ground shaking over a much larger area and would have a much longer duration. Given the potentially devastating effects such a large earthquake would have on life and property in the region, we believe that Los Angeles must consider the potential for such an event in future planning scenarios.

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9. We define a fault system as a set of faults that are closely linked both geographically and kinematically and which therefore might plausibly rupture together. In the Los Angeles region, partitioning of oblique slip into parallel strike-slip and thrust faults occurs on several of the large fault systems in metropolitan southern California. For example, at depth the steeply dipping Whittier fault probably interacts with the Puente Hills segment of the Elysian Park thrust system, and the moderately to steeply dipping Hollywood–Santa Monica–Malibu Coast fault (HF-SMF-MCF) system must interact with the Santa Monica Mountains blind thrust fault. We hypothesize that the surficial faults accommodate the strike-slip component along these two oblique-slip systems—right-lateral in the case of the Whittier fault, left-lateral in the case of the HF-SMF-MCF system—whereas the contractional component of motion along the system is accommodated by folding and movement along the blind thrust ramps.
10. Some active fault systems have been generalized. (For example, the Elysian Park thrust system in East Los Angeles is shown as a single fault rather than as an imbricate thrust stack; known east-trending faults in this system are not used. The Verdugo Hills fault system is assumed to be part of the Sierra Madre fault zone.) Furthermore, some active faults have been intentionally omitted, either because they are (i) too poorly known [for example, (*60*)], (ii) too small to produce moderate earthquakes by themselves [for example, (*61*)], or (iii) characterized by complex slip behavior [for example, (*62*)]. At our present level of understanding, such generalizations and omissions are appropriate. Finally, it is possible that we have not yet identified all active faults in the region. Given the uncertainties, we tried to be conservative. The overall effect of our source and slip rate characterization is to produce a probable underestimate of the rate of strain accumulation across the Los Angeles metropolitan region.
11. The southern Newport-Inglewood (N-I) fault system, as modeled in this study, is capable of producing a M_w 7.1 earthquake. However, we arbitrarily truncated the fault at the southeastern boundary of our study area. The fault system probably continues all the way to San Diego and thus may be capable of an earthquake considerably larger than M_w 7.1. Within the metropolitan region, we distinguished the northern and southern N-I fault zones on the basis of a marked northward decrease in slip rate (*7*) and a pronounced change in structural style (*4*) at the north end of the 1933 earthquake rupture zone. We hy-

pothesize that this structural transition is caused by a northward transfer of slip westward off the N-I fault zone onto northwest-trending contractional structures and, possibly, the northern part of the Palos Verdes fault.
12. We do not consider the San Andreas and San Jacinto faults in this study.
13. R. Crook *et al.*, *U.S. Geol. Surv. Prof. Pap.* **1339**, 27 (1987).
14. D. Morton and J. Matti, *ibid.*, p. 179.
15. B. Kamb *et al.*, *ibid.* **733**, 41 (1971); R. Kachadoorian, *ibid.*, p. 5.
16. The Elysian Park thrust system was originally defined as a northeast- to north-dipping blind thrust fault extending from Orange County in the southeast, through downtown Los Angeles, and westward beneath the Santa Monica Mountains along the Malibu coast to Point Mugu (*5*). However, our geomorphologic analysis indicates that this zone of contractional deformation actually comprises two distinct thrust fault systems, an east-west–trending thrust ramp beneath the Santa Monica Mountains that we refer to as the Santa Monica Mountains thrust fault, and a west-northwest–trending system that extends from the Elysian Park Hills northwest of Los Angeles through downtown and East Los Angeles (Los Angeles segment) and southeastward beneath the Puente Hills (Puente Hills segment) (*7*). Specifically, the N85E-trending eastern Santa Monica Mountains, which have developed above the Santa Monica Mountains blind thrust fault, form a well-defined, distinct topographic entity that extends for more than 5 km to the east of southwest-dipping, N65W-striking Miocene-Pliocene strata [T. Dibblee, *Geologic Map of Hollywood-Burbank (South 1/2) Quadrangle DF-30* (Dibblee Geological Foundation, Santa Barbara, CA, 1991)] that have been deformed above the northwest-striking Elysian Park thrust ramp in the Elysian Park Hills. Because of their geographic association with the Elysian Park Hills, we retain the name Elysian Park thrust fault for the Los Angeles and Puente Hills segments of the blind thrust ramp.
17. T. Rockwell *et al.*, *Geol. Soc. Am. Abstr. Programs* **20**, 224 (1988); E. Gath *et al.*, *Geol. Soc. Am. Abstr. Programs Cordilleran Sect.* **24**, 26 (1992).
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24. J. Vedder *et al.*, *Geologic Map of Mid-Southern California Continental Margin (Map 2A), California Continental Margin Geologic Map Series (area 2 of 7; map sheet 1 of 4)*, H. Greene and M. Kennedy, Eds. (U.S. Geological Survey, Menlo Park, CA, and California Division of Mines and Geology, Sacramento, CA, 1986), 1:250,000.
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28. Large, historic earthquakes on the San Andreas fault (for example, 8 December 1812 and 9 January 1857) are not included in our analysis.
29. A large earthquake (*M* 7?) on 21 December 1812 damaged mission buildings in Santa Barbara and the western Transverse Ranges and produced a small tsunami. This event is not included in our scenario because all researchers place its position in the Santa Barbara Channel, well to the west of the western limit of our study area (*26*). We have also excluded the moderate earthquake of 11 July 1855 (*M* 6?), which damaged structures at Los Angeles and Mission San Gabriel (13 km east-northeast of Los Angeles). Although this event almost certainly occurred beneath what is now metropolitan Los Angeles, it was probably smaller than our M_w 6.7–scenario earthquakes (*26*).
30. Record keeping in southern California began with the establishment of Spanish missions during the late 1770s to early 1780s (*26, 27*). The early part of the record is of variable quality, particularly from 1832 to 1848 (*27*), but is certainly complete for Northridge-sized events since 1850, and is probably complete at that level since 1800 (*27*). The record for larger events ($M_w \geq 7.2$) is probably complete for the region since the earliest mission records (*27*).
31. For simplicity we divided the 155-km-wide metropolitan region into western, central, and eastern segments. We then used a weighted average of these rates to determine an average shortening rate across the region of 8.5 mm year^{-1}. In the west, geodetic data across the Ventura basin reveal extremely rapid north-south shortening of approximately 8.5 ± 1 mm year^{-1} (*63*). This rate does not include the Santa Monica Mountains fault system. A. Donnellan *et al.* [*J. Geophys. Res.* **98**, 21727 (1993)] reported a 1 ± 2 mm year^{-1} shortening rate between Oat Mountain along the southern edge of the Ventura basin and Castro Peak in the western Santa Monica Mountains. Although this rate does not account for all shortening across the Santa Monica Mountains system, the geographic position of Castro Peak above the upper part of the Santa Monica Mountains blind thrust ramp indicates that the rate probably includes part of the motion. Measurements from Mount Pinos just south of the San Andreas fault to Castro Peak yield an overall shortening rate across the region of 11 ± 2 mm year^{-1} (*63*). On the basis of these data we used an average shortening rate for the western region of 10 mm year^{-1}. The shortening rate across the central Los Angeles region is provided by geodetic measurements across the Los Angeles basin from the Jet Propulsion Laboratory (JPL) in Pasadena to the Palos Verdes Peninsula (PV). There is some debate about the shortening rate, with estimates ranging from 5 mm year^{-1} (*64*) to 7.9 mm year^{-1} [K. Hudnut *et al.*, *Seismol. Res. Lett.* **65**, 59 (abstr.) (1994)]. These rates probably slightly underestimate shortening within the metropolitan region because the measurements only include part of the region of elastic strain accumulation associated with the faults we used in our scenarios; JPL is located in the middle of the Sierra Madre fault zone and the PV site is adjacent to the Palos Verdes fault. An overall Transverse Ranges shortening rate of 13 ± 2 mm year^{-1} (calculated with the San Andreas fault component removed) determined from north of the San Andreas fault near Bakersfield to Santa Catalina Island south of PV (*64*) indicates significant shortening on faults outside the metropolitan area. For the central part of the region we used a shortening rate of 10 mm year^{-1}. In the east the only fault included in our study area is the Sierra Madre–Cucamonga system, for which we used a geologically defined slip rate of 4.5 to 5.5 mm year^{-1} on the Cucamonga fault, which dips approximately 50° (*14*). Converting this slip rate into a shortening rate yields 2.9 to 3.5 mm year^{-1}. The Cucamonga fault is 35 km long (*14*). A shortening rate of 10 mm year^{-1} for the remaining 120-km length of the area results in an overall shortening rate across the metropolitan region of approximately 8.5 mm year^{-1}.
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41. Our regression is specific to southern California and uses recent estimates of rupture area and average coseismic slip derived from modeling strong motion, teleseismic, and geodetic data. Because we attempted to model earthquakes within the Los Angeles metropolitan region, we used only earthquakes where the seismogenic crust is likely to be similar. Therefore, we did not use earthquakes from the southern San Jacinto and Salton Trough areas (for example, the 1968 Borrego Mountains, 1987 Elmore Ranch, and 1987 Superstition Hills earthquakes) because heat flow in this region is considerably higher than in the Los Angeles metropolitan area. Consequently, crustal rheology (and presumably earthquake behavior) is probably significantly different than in the Los Angeles metropolitan region, where heat flow is relatively low.
42. T. Hanks and H. Kanamori, *J. Geophys. Res.* **84**, 2348 (1979).
43. Crustal shear rigidity increases markedly downward in the uppermost 5 km of the Earth's crust [see, for example, (*37*)], leading to different values for earthquakes that rupture to the surface versus earthquakes that rupture only the lower part of the seismogenic zone (that is, >5 km depth). We have taken this into account in using the seismic moment equation to calculate average slip per event for the eight earthquakes that we used for our southern California regressions. For earthquakes that only ruptured below 5 km depth (1987 Whittier Narrows, 1991 Sierra Madre, and 1994 Northridge), we used a value of 3.6×10^{11} dyne cm^{-2}, whereas for the 1992 Landers earthquake, which ruptured to the surface, we used an overall rigidity of 3.0×10^{11} dyne cm^{-2}. For the 1933 Long Beach and 1952 Kern County earthquakes, which ruptured to within a few kilometers of the Earth's surface, we used intermediate values of 3.3×10^{11} dyne cm^{-2} and 3.45×10^{11} dyne cm^{-2}, respectively. Although one of the two faults that ruptured during the 1971 San Fernando earthquake did rupture the surface, the other fault only ruptured to within about 4 km of the surface (*36*). We therefore used an intermediate value of 3.3×10^{11} dyne cm^{-2} for this earthquake.
44. The base of recent seismicity over much of the metropolitan region is approximately 15 to 16 km (*6*). However, the 1994 Northridge mainshock originated at 19 km (*3*), and earthquakes in the northwestern part of the metropolitan area in the Ventura basin extend as deep as 20 to 24 km [A. Bryant and L. Jones, *J. Geophys. Res.* **97**, 437 (1992)], where the base of the brittle upper crust has been bowed down by rapid convergence and sediment loading (*22*).
45. Slip rates used in this study vary widely in quality. Extensive geologic studies constrain the slip rates for the surficial Whittier, Palos Verdes, Cucamonga, San Cayetano, western Oak Ridge faults, and the Elysian Park and Compton blind thrust faults (*7, 14, 17,*

21–23, 25). Slip rates on the Santa Monica Mountains thrust fault and the eastern Oak Ridge system are based on balanced section modeling assuming late Pliocene fault initiation (*5, 18*). Slip rates for some other faults (Sierra Madre fault and southern Newport-Inglewood fault zone) have been extrapolated along the strike from well-determined slip rates determined elsewhere on those fault systems [(*14*); T. Rockwell *et al*., in *Environmental Perils, San Diego Region,* P. Abbott and W. Elliott, Eds. (San Diego Association of Geologists, San Diego, CA, 1991), pp. 37–46; S. Lindvall and T. Rockwell, in preparation]. We used the range of geological maximum and minimum slip rates for the Santa Susana fault [G. Huftile and R. Yeats, unpublished data]. The Raymond fault slip rate was calculated by assuming that the known recurrence interval (4500 years) (*13*) records M_w 6.7 events that rupture the entire fault with 1.7 m of slip in each event (Table 2). Forty-seven meters of uplift of the 125,000 oxygen isotope stage 5e marine terrace along the Santa Monica fault (SMF) [J. McGill, *U.S. Geol. Surv. Misc. Invest. Ser. Map I-1828* (1989)] indicates a dip-slip rate of approximately 0.5 mm $year^{-1}$. The SMF, however, exhibits a significant, if not predominant, component of strike-slip motion [J. Dolan *et al*., *Eos* **73**, 589 (abstr.) (1992)]. Therefore, we assumed a conservative overall slip rate of 1 to 1.5 mm $year^{-1}$. We extrapolated this rate to the adjacent Hollywood and Malibu Coast faults, for which slip rates are not available. Slip rates for the Clamshell-Sawpit and San Jose faults are unknown. We assumed 0.5 mm $year^{-1}$ to be a reasonable slip rate for these faults on the basis of their geomorphic expression and the recent occurrence of moderate earthquakes on these faults (1988 and 1990 Upland and 1991 Sierra Madre) (*38, 39, 65*).

46. We used M_w 6.7 earthquakes as a convenient size for an average moderate earthquake because the Los Angeles area has recently experienced two such earthquakes, the 1971 San Fernando and 1994 Northridge earthquakes, which were nearly identical in size (Table 1) (*36, 40*). There are several additional reasons for using earthquakes of this size. The level of damage caused by these earthquakes is well understood, making M_w 6.7 a useful size for planning purposes. Furthermore, residents of the Los Angeles region know what these earthquakes felt like and will readily be able to understand such a scenario. Finally, M_w 6.7 is approximately the smallest sized earthquake that we can reasonably propose to accommodate all seismically released strain; a scenario based on smaller events (for example, M_w 6.0) would result in implausibly short repeat times.
47. The role of "geologically reasonable" segment boundaries in controlling the ultimate size of an earthquake rupture is very poorly understood, but these boundaries represent a useful starting point for our model. For surficial faults we defined segment boundaries on the basis of pronounced breaks in surficial fault traces, intersections with other active faults, and edges of historical earthquake ruptures. For blind thrust faults we used lateral ramps defined by discontinuities in overlying fold trends (*9*) and major along-strike changes in geomorphology above blind thrust fault ramps.
48. We cannot rule out the possibility that even larger earthquakes could occur within the metropolitan region. For example, if the Sierra Madre–Cucamonga fault system ruptured together with the Santa Susana and San Cayetano faults, they would produce a M_w 7.64 earthquake. Similarly, the Sierra Madre–Cucamonga system could conceivably rupture coseismically with the San Andreas fault in a *M* 8 earthquake. However, these scenarios require rupture of multiple large fault systems, which, though possible, we consider unlikely.
49. The variability of slip directions on different faults within these strain-partitioned systems precludes simply adding the areas of the faults to calculate the overall moment magnitude of a systemwide earthquake. Rather, we calculated the moment magnitude of subevents occurring on faults that exhibit similar slip directions. For example, we calculated moment magnitudes for two different subevents on the Santa Monica Mountains system: one on the blind thrust ramp and one on the HF-SMF-MCF strike-slip fault system. We then added these to obtain the overall moment magnitude of the systemwide earthquake (M_w 7.5). The variability in coseismic slip direction on the different faults also prevents us from calculating the overall average coseismic slip. Furthermore, because the multiple faults exhibit differing slip rates, we cannot calculate a simple overall average slip rate across the entire system. Consequently, we cannot calculate a recurrence interval for systemwide earthquakes on the Santa Monica Mountains and Los Angeles basin systems.
50. Coseismic rupture of both strike-slip and thrust faults has been observed in a number of large earthquakes worldwide (for example, 1932 Chang Ma, China, *M* 7.6; 1957 Gobi-Altai, Mongolia, M_s 8.0; 1967 Mogod, Mongolia, *M* 7.8; and 1988 Spitak, Armenia, *M* 6.9).
51. We used seven large earthquakes on the six sources because both the blind thrust and strike-slip subsystems of the Santa Monica Mountains system are capable of producing earthquakes of $M_w \geq 7.2$. For the Los Angeles basin system we used an earthquake that ruptures only the blind thrust faults.
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55. Two lines of reasoning indicate to us that no aseismic fault creep is occurring along blind thrusts in the region. (i) Because slip on surficial faults is generally concentrated along discrete zones only a few centimeters to a few meters wide, evidence for fault creep in the form of broken roads, sidewalks, pipelines, and oil wells would be obvious, even with relatively slow slip rates. Recent research of growth strata has shown that near-surface deformation above blind thrust faults is similarly discrete, generally encompassing zones less than 10 to 20 m wide (*7*). Thus, as with surficial faults, fault creep along blind thrust faults would leave obvious traces in any structures built atop an active fold axial surface. No such deformation has been observed. (ii) Blind thrust ramps in the metropolitan region are not slipping aseismically. The term aseismic fault slip is somewhat of a misnomer, as the fault is not actually slipping without causing earthquakes. Rather, slip along such faults is accommodated by minute motions during many thousands of microearthquakes. Creeping faults are only aseismic with respect to moderate and large earthquakes. The creeping segment of the San Andreas fault in central California is a good example. During historic time this section of the fault has not produced any large earthquakes, but it is characterized by the occurrence of thousands of small earthquakes [D. Hill *et al*., *U.S. Geol. Surv. Prof. Pap.* **1515**, 115 (1990)]. The greater Los Angeles metropolitan area is one of the most densely instrumented regions in the world, and microearthquakes $M < 2.0$ are routinely recorded and located by the Southern California Seismographic Network. If any of the blind thrust faults were creeping aseismically, then we would expect them to be highlighted by clouds of thousands of microearthquakes. In fact, Los Angeles area blind thrust ramps are characterized by an almost total absence of microearthquakes, below even the background level in the area. This absence of microseismicity suggests to us that thrust ramps are locked and accumulating strain. Furthermore, all evidence that we have about the relation between maximum faulting depth and the base of seismicity determined from microearthquake studies indicates that earthquakes in the Los Angeles region either rupture down to the base of microseismicity, or extend even deeper than the maximum depth of microseismicity. For example, before the Northridge earthquake, most researchers in the region would have predicted the expected maximum depth of earthquake rupture at the base of microseismicity, or about 15 to 16 km (*44*). The Northridge earthquake, however, ruptured to 20 km depth (*3*).
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60. Some of the more prominent faults that have been omitted are the blind thrust fault system beneath Santa Monica Bay, source of the 1930, 1979, and 1989 earthquakes (Fig. 1A) (*6, 66*); the probable southeastern continuation of the Elysian Park blind thrust fault beneath the Santa Ana mountains (*7*); known east-west–trending blind thrust faults in East Los Angeles, including the fault responsible for the 1987 Whittier Narrows earthquake; and the possible northern extension of the Palos Verdes fault in Santa Monica Bay (*24*).
61. One of the more prominent faults that has been omitted is the Wilshire fault [C. Hummon *et al*., *Geology* **22**, 291 (1994)].
62. One of the faults that has been omitted is the San Gabriel fault, which apparently exhibits oblique right-lateral–reverse motion in the northwest [W. Cotton *et al*., *U.S. Geol. Surv. Final Tech. Rep.* (1988); R. Yeats *et al*., *Am. Assoc. Pet. Geol. Bull.* **78**, 1040 (1994)], but may exhibit oblique left-lateral–reverse motion in the southeast [F. Weber, "Geologic and Geomorphic Investigation of the San Gabriel Fault Zone, Los Angeles and Ventura Counties, California," Calif. Div. Mines Geol. Annu. Tech. Rep. 1977–78 (1979)].
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