quake research. For conventional fixed-base buildings, design practice has advanced incrementally as earthquakes occur and lessons are learned. The weakness in this approach is that we have yet to learn the lessons from a very large ($M_w > 7$) earthquake directly beneath an urban area. This is particularly true for tall buildings that are vulnerable to large ground displacements, both for damage and possible collapse.

Designs of base-isolated buildings are based on site-specific ground motions that should account for near-source effects. However, the ground motions presented here are large compared to those currently used for design at sites close to major California faults, and the strongest of our ground motions require exceptional measures for the isolation system to maintain functionality of the building. The practicality of such a goal in the near-source region of a $M_w \geq 7.0$ earthquake is uncertain. Although the focus of this paper is modern buildings, an even greater hazard lies in structures built before modern codes, especially unreinforced or nominally retrofitted brick buildings and nonductile concrete buildings.

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Earthquakes in the Los Angeles Metropolitan Region: A Possible Fractal Distribution of Rupture Size

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Although there is debate on the maximum size of earthquake that is possible on any of several known fault systems in the greater Los Angeles metropolitan region, it is reasonable to assume that the distribution of earthquakes will follow a fractal distribution of rupture areas. For this assumption and an overall slip-rate for the region of approximately 1 centimeter per year, roughly one magnitude 7.4 to 7.5 event is expected to occur every 245 to 325 years. A model in which the earthquake distribution is fractal predicts that, additionally, there should be approximately six events in the range of magnitude 6.6 in this same span of time, a higher rate than has occurred in the historic record.

In recent years, geologic and geodetic investigations have made possible the evaluation of the earthquake potential for the greater Los Angeles metropolitan region, an area of about 160 km by 100 km (*1*, *2*). By evaluating available geologic and geodetic data for the total region, Dolan *et al.* (*1*) argue that 0.9 to 1.2 cm/year of slip will occur over the distribution of known and unknown faults in the region.

A report by the scientists of the Southern California Earthquake Center (SCEC) has shown that the long-term geodetic deformation rate cannot be accounted for by a continuation of the historic seismic record and has proposed three alternatives: (i) that significant aseismic slip occurs; (ii) that moderate earthquakes [that is, around magnitude (M) 6] must occur significantly more frequently than they did during the historic record; or (iii) that infrequent very large events will occur (*3*).

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In general, it is difficult to determine a priori whether a given fault system will rupture all at once, as occurred during the M 7.3 Landers earthquake in 1992 (*4*), or in isolated segments, as in 1994 during the M 6.7 Northridge earthquake (*5*). In the evaluation of seismic hazard, the distribution of expected earthquakes is critical. It is reasonable to conjecture that the long-term distribution of earthquake rupture areas will be fractal. Studies have shown that the distribution of segmentation of known fault lengths is fractal (*6*) and that the well-known log-normal distribution of earthquake magnitudes is also essentially consistent with this hypothesis (*7*). Although it has been proposed that individual fault segments will not produce a fractal distribution of events (*8*), it is commonly assumed that earthquake release in a region with numerous faults will occur by events with a log-normal distribution of magnitudes, with a maximum event size imposed for each region (*9*).

Dolan *et al.* (1) have focused on interpretation of an earthquake budget derived from a synthesis of geologic slip rate data estimated in recent years for Los Angeles area faults. They show that the geologic and geodetic results are generally consistent and contrast two "end-member" scenarios to make up their established earthquake budget: one in which all strain is released by moderate (~M 6.7) events, and one in which all moment release occurs during large earthquakes (roughly M 7.2 to 7.6). In this paper, we present a hybrid model similar to that used in the SCEC studies (8), allowing a fractal distribution of rupture sizes. We focus on determining the expected rate of moderate and large earthquakes in the greater Los Angeles metropolitan region given the known activity over the historical period, the best available compilation of geologic data, and the most plausible model for the distribution of earthquake rupture.

We first consider the expected rate of seismic moment accrual across the Southern California region, starting with the equation for seismic moment

$$M_o = \mu A d \qquad (1)$$

where μ is the rigidity, A is the rupture area, and d is the slip. For a rectangular fault, $A = WL$, where W is the fault width and L is the fault length. If slip of 0.9 to 1.2 cm/year occurs over a region 160 km wide down to an average seismogenic depth of 17.5 km, the total moment accrual rate dM_o/dt is 7.6×10^{24} to 10.1×10^{24} dyne·cm/year, for a nominal crustal rigidity.

Dolan *et al.* (1) showed that recent moderate to large earthquakes located off of the San Andreas fault are well fit by the relation

$$M_w = 4.56 + 0.86\log(A) \qquad (2)$$

where A is in square kilometers and M_w is the moment magnitude, related to seismic moment (10) by

$$\log M_o = 1.5M_w + 16.1 \qquad (3)$$

Equation 2 can be combined with the log-normal distribution of seismicity

$$\log N_c = a - bM \qquad (4)$$

to constrain the fractal distribution of rupture areas; N_c is the cumulative number of events with magnitude above M, and a and b are constants (b is the seismic "b-value"). Using M_w as the magnitude in Eq. 4 and assuming a b-value of 1, we find

$$\log N_a = c - 0.86\log(A) \qquad (5)$$

where N_a is the cumulative number of events above area A and c is a constant.

To illustrate how a fractal distribution will fill out a given earthquake budget, we consider a discrete distribution of events. For every occurrence of an earthquake with the maximum rupture area, the coefficient of

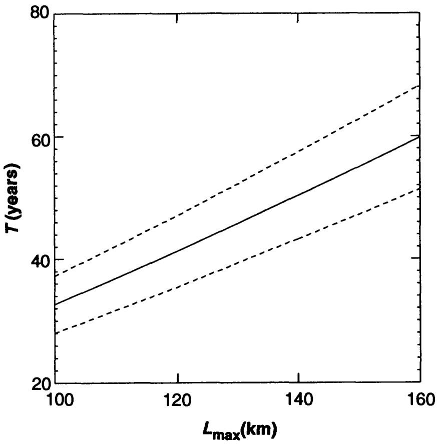

Fig. 1. Average repeat time for moderate events as a function of maximum rupture length L_{max}. Dashed lines indicate results corresponding to an overall slip rate range of 0.9 to 1.2 cm/year; solid line corresponds to the average value. The sizes of the moderate events range from M 6.49 for L_{max} = 100 km to M 6.67 for L_{max} = 160 km.

0.86 in Eq. 5 predicts that there will be 6.2 events with 1/10 the maximum area [that is, $(10^{0.86} - 1)$], 46 events with 1/100 the area, and so forth.

If we define $M_{o,1}$ to be the moment of the largest event expected in the region, $M_{o,2}$ to be the moment of the event with a rupture length 1/10 that of $M_{o,1}$, and so forth, the total seismic moment is

$$M_{o,total} = M_{o,1} + 6.2M_{o,2} + 46M_{o,3} + \ldots \qquad (6)$$

To evaluate the relative contributions of the terms of Eq. 6, we must determine how M_o scales with rupture area. For a model with constant stress drop and circular rupture, moment is predicted to scale as radius cubed. For earthquakes that rupture the width of the seismogenic zone, previously determined scaling relations predict that M_o depends on L^2 (11).

Combining Eqs. 2 and 3, we obtain a direct empirical relation between moment and area for Southern California earthquakes: $\log M_o = 1.29\log(A) + 22.94$. We thus predict that moment will decrease by a factor of about 20, corresponding to a factor of 10 decrease in rupture area. Because Eq. 2 is generally appropriate for $M_w > 6.0$ and because progressively smaller moments will decrease significantly faster with decreasing rupture size, we consider only the first two terms in Eq. 6. Estimating $M_{o,2}/M_{o,1}$ from Eqs. 2 and 3, we find

$$M_{o,total} = 1.32M_{o,1} \qquad (7)$$

That is, a fractal distribution of rupture lengths implies that most of the total moment release will have to occur in the largest events.

If we define time T_m to be the repeat time of $M_{o,1}$

$$T_m = \frac{1.32M_{o,1}}{(dM_o/dt)} \qquad (8)$$

where dM_o/dt is the moment accrual rate determined above and $M_{o,1}$ is controlled primarily by L_{max}. From Eq. 8 and a given $M_{o,1}$, we can estimate a range of T_m values corresponding to the estimated range of dM_o/dt. We can thus estimate a long-term average estimate of T_m, although it is important to note that periodicity of large events is neither implied nor required by our model.

If L_{max} is assumed to be 100 km, Eqs. 1 to 7 indicate that the maximum moment magnitude $M_{w,1}$ is 7.35, occurring on average every 174 to 231 years (the range in values reflects the overall slip rate range of 0.9 to 1.2 cm/year). The average T_m is 203 years. Unless the historic record for the region is significantly nonrepresentative of the long-term rate, this range of repeat times (and the corresponding rate of moderate-sized events, discussed below) is implausibly low. With our model, one of the few ways that T_m can increase is to allow a longer L_{max}. Assuming a value of 130 km (12), we obtain a maximum $M_{w,1}$ of 7.45, with T_m = 245 to 325 years and an average of 284 years.

For the assumed fractal distribution, we predict that for every occurrence of $M_{w,1}$, there will be 6.2 events with rupture areas 1/10 as big. By Eq. 2, and for L_{max} of 130 km, this corresponds to about six events with M 6.6 in the time T_m, yielding an average repeat time of 46 years. For L_{max} = 100 km, we find an average repeat time of 33 years for M 6.5 events, again somewhat implausible considering the historic record. In Fig. 1, we present the average repeat time for moderate events (M 6.5 to 6.7) as a function of L_{max}. An additional consideration, however, is that aftershock distributions are also characterized by log-normal distributions; perhaps 10 to 15% of the smaller events could thus be taken up by aftershocks of the largest events.

If L_{max} is 160 km, $M_{w,1}$ is 7.53 and the average repeat time is 372 years. The average repeat time of M_w = 6.7 events is then 60 years. This is a plausible but not our preferred model because it requires a rupture length comparable to the entire dimension of the Los Angeles region.

The analysis presented here is very simple; in reality, a continuous range of earthquake magnitudes is expected in a fractal distribution. However, our calculations illustrate the fundamental results of combining the total earthquake budget for the greater Los Angeles region with a physically plausible earthquake distribution. Most of the moment release is expected to be taken up by infrequent but extremely large events. Moderate events, with magnitudes similar to that of the recent (17 January 1994)

Northridge earthquake, are also expected, with an average repeat time of 40 to 52 years. The historic record of M 6.5 to 6.7 events in the Los Angeles Basin is still under the long-term predicted rate, even allowing for occasional large events.

Uncertainty in our results stems from three primary factors: the overall slip rate for the region, the maximum rupture size, and the effective fractal dimension implied by our choice of *b*-value and scaling coefficient in Eq. 2. (We do not consider the prima facie assumption of a fractal distribution to be at issue.) The first source of uncertainty is accounted for directly: Our results correspond to the range of slip rates determined from geologic and geodetic compilations (*1*, *2*). The second factor is also addressed: Maximum rupture lengths shorter than 100 km are discounted because of the unrealistically frequent rate of moderate events that is implied. We do not consider the third factor to be significant because of the nature of fractal distributions and earthquake scaling relations: A scaling constant of 1 instead of 0.86 (that is, a strictly self-similar distribution of rupture areas) in Eq. 2 would change Eq. 6 to $M_{o,total} = 1.45M_{o,1}$. This change would increase T_m by about 9% and increase the number of moderate events (M_w 6.6) from about six to nine.

Our calculations are independent of the known details of faulting and slip rates on individual faults in the region, as summarized by Dolan *et al.* (*1*). Their results can be compared to ours: The six multiple–fault-segment scenarios yield events with M_w 7.20 to 7.58, produced, on average, every 140 years. This value is about half of our preferred estimate but is not inconsistent with our results because 70 to 80% of the geologically determined scenario earthquakes have M_w = 7.2 to 7.3 (*14*). Also, the fractal analysis permits a fraction of the moment rate, approximately 30%, to be accounted for by moderate events.

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Rapid Accretion and Early Differentiation of Mars Indicated by $^{142}Nd/^{144}Nd$ in SNC Meteorites

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Small differences in the ratio of neodymium-142 to neodymium-144 in early formed mantle reservoirs in planetary bodies are the result of in situ decay of the extinct radionuclide samarium-146 and can be used to constrain early planetary differentiation and therefore the time scale of planetary accretion. The martian meteorite Nakhla (~1.3 billion years old), the type sample of the nakhlite subgroup of the Shergottite-Nakhlite-Chassigny (SNC) meteorites, exhibits a 59 ± 13 parts per million excess in the ratio of neodymium-142 to neodymium-144 relative to normal neodymium. This anomaly records differentiation in the martian mantle before 4539 million years ago and implies that Mars experienced no giant impacts at any time later than 27 million years after the origin of the solar system.

Planets in the inner solar system are widely believed to have accreted from an initial swarm of planetesimals by hierarchical coagulation, which involves the merging of objects of increasing size until only a small number of large objects remain in each radial zone (*1*). According to this view, the late stages of planetary accretion are dominated by a few giant impacts. The spins of both Earth and Mars are consistent with one or more of these events during accretion (*2*). Giant impacts generate transient, mantle-wide magma oceans, and therefore the histories of the terrestrial planets are expected to have begun with an epoch of giant impacts and magma oceans. However, the durations for these accretionary epochs are unknown. Estimates from planetesimal coagulation models are generically uncertain at late times and fundamental issues remain unresolved, so isotopic age determinations are needed to constrain accretion and giant impact time scales directly.

The presence of a small but significant abundance of ^{146}Sm (which decays by α emission to ^{142}Nd with a half-life of 103 million years) in the early solar system provides a means for dating early episodes of differentiation in planetary bodies based on the preservation of isotopic signatures at depth in mantle reservoirs (*3*). The ^{146}Sm-^{142}Nd system is ideal for dating differentiation episodes in the silicate portions of planets because other large-scale cosmochemical processes such as volatile depletion or core formation do not fractionate Sm/Nd and because this system can be linked to the long-lived ^{147}Sm-^{143}Nd system. Because the initial solar system abundance of ^{146}Sm was small [$^{146}Sm/^{144}Sm$ = 0.0080 ± 0.0010 at 4566 million years ago (Ma) (*4*)] and the range of Sm/Nd fractionation in large-scale reservoirs is limited, $^{142}Nd/^{144}Nd$ shifts resulting from ^{146}Sm decay are generally expected to be less than one part in 10^4 (= 1 ϵ-unit). Use of the ^{146}Sm-^{142}Nd systematics therefore requires accurate determination of $^{142}Nd/^{144}Nd$ shifts at a resolution of better than 20 ppm (±0.2 ϵ-unit) relative to a reference standard. We report well-resolved ^{142}Nd shifts in SNC meteorites and outline their significance for the early history of Mars (*5*), which is where these meteorites are thought to have been derived (*6*).

Identification of a ^{142}Nd anomaly in a

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