Paleomagnetism-based limits on earthquake magnitudes in northwestern metropolitan Los Angeles, California, USA

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ABSTRACT

We have used paleomagnetism to estimate the maximum moment magnitude (M_w) of earthquakes in the east Ventura Basin and San Fernando Valley, in metropolitan Los Angeles. Magnetic declinations show differential rotation between crustal blocks with linear dimensions of 10–20 km, similar to the thickness of the seismogenic layer. The maximum magnitude of an earthquake based on blocks of this size is $M_w = 6.8$, comparable to the 1971 San Fernando and 1994 Northridge earthquakes and consistent with paleoseismic trenching and surface ruptures of the 1971 earthquake. The paleomagnetic results suggest that the blocks have retained their configuration while moving relative to each other for the past ~0.8 m.y. Therefore, it is unlikely that in this area multiple blocks combined to trigger much larger shocks during this period, in contrast to adjacent regions where events with $M_w > 7$ have been postulated on the basis of paleoseismic excavations.

Keywords: paleomagnetism, block rotations, earthquake magnitude, seismic moment.

INTRODUCTION

The western Transverse Ranges of southern California were struck by the 1971 San Fernando (Sylmar) and the 1994 Northridge earthquakes, both with magnitude $M_w = 6.7$. These were the largest shocks recorded in metropolitan Los Angeles, and they were accompanied by loss of life and property. In assessing the potential for earthquake damage in this area, we ask, what is the largest earthquake that can be sustained in this geologic setting? We conducted a high-resolution paleomagnetic study of four sections of the late Cenozoic Saugus Formation in the area of the 1971 and 1994 earthquakes (Levi and Yeats, 1993, 2003). For each section we determined a distinct and well-defined paleodeclination, which shows that the crust in this area is fragmented into blocks 10–20 km in linear dimension. Together with the thickness of the seismogenic layer and estimates for the static stress drop, we calculated the maximum seismic moment. The corresponding moment-magnitude, $M_w = 6.8$, is similar to the 1971 and 1994 earthquakes. We do not expect earthquake magnitudes with $M_w > 7$ in this part of the Los Angeles metropolitan area. To our knowledge, this is the first time paleomagnetism has been used to forecast earthquake magnitudes.

TECTONIC SETTING

The tectonic stresses in southern and central California west of the San Andreas fault arise primarily from dextral shear between the North America and Pacific plates. This is considered the main reason for clockwise rotations of many formations west of the San Andreas fault, from the Gulf of California to San Francisco (see references in Levi and Yeats, 2003). The study area is west of the San Andreas fault in the Big Bend region between latitudes 34° and 35°N (Fig. 1), where the San Andreas fault strikes west-northwest (~295°), in contrast to its northwest trend north and south of this region. Along the Big Bend segment, the relative plate motions, ~323 ° (Atwater and Stock, 1998), are more oblique to the San Andreas fault, resulting in greater compressive strain than to the north and south, as indicated by enhanced crustal shortening, folding, thrusting, and uplift in the Transverse Ranges.

The average slip azimuth of four $M_w > 5.5$ earthquakes in this area is 30° ± 6° (Jackson and Molnar, 1990), and data from global positioning system (GPS) networks suggest that uniaxial contraction across the Los Angeles basin is oriented N36° ± 5°E (Bawden et al., 2001). These results suggest that the average azimuth of the slip vectors is somewhat clockwise from normal incidence to the Big Bend segment of the San Andreas fault. Many prominent active faults in the western Transverse Ranges strike generally east-west; therefore, if the plate interaction zone west of the San Andreas fault is segmented into smaller blocks, dextral shearing will produce rotational torques and clockwise block rotations in addition to net translation. Paleomagnetic measurements are best suited for documenting the sense and magnitude of block rotations over geological time scales (e.g., Kamerling and Luyendyk, 1979). Geodetic studies over the past two decades suggest that the rotations are continuing (Donnellan et al., 1993; Molnar and Gipson, 1994).

GEOLOGY OF THE SAUGUS FORMATION

The Saugus Formation (Winterer and Durham, 1962) comprises deformed continental and brackish-water strata. In the center of the east Ventura Basin, these strata conformably overlie Pliocene deposits and are traversed by the San Gabriel fault (Fig. 2). The Saugus is overlain by generally flat lying terrace deposits similar to, but somewhat more consolidated than, modern alluvium of the Santa Clara River. Farther east, the Saugus occurs as discontinuous patches that unconformably overlie faulted strata as old as Eocene and are overridden by the Santa Susana fault (Yeats, 1987). In the northern San Fernando Valley, the Saugus occurs in the hanging wall of the San Fernando fault, which underwent surface rupture in the 1971 earthquake. The predominant lithologies of the Saugus Formation are brown, reddish-brown, and tan coarse-grained sandstone and conglomerate. Paleomagnetic sites were selected at finer-grained interbeds of brown and reddish-brown mudstone and greenish-gray siltstone, typically 0.5–5 m thick and interbedded with coarse-grained strata.

SUMMARY OF PALEOMAGNETIC RESULTS

The four Saugus locations are shown in Figures 1 and 2. We initially undertook this as a magnetostratigraphic study to better date the Saugus Formation, which was previously designated only as Pliocene–Pleistocene. Near Magic Mountain, we calibrated the paleomagnetic results by using the 0.76 Ma Bishop ash (Levi and Yeats, 1993). The ash bed and pattern of paleomagnetic reversals indicate that in the Magic Mountain area, the Saugus Formation was deposited between 2.3 and 0.5 Ma. The Saugus Formation spans a similar time interval in the Van Norman Lake section. The more accurate and precise ages of the Saugus Formation are crucial for constraining rates of sedimentation, tectonic convergence, and uplift. The Saugus sites at Soledad Canyon and the Merrick syncline have predominantly reverse polarity, and each section contains several normal intervals. By analogy with the Magic Mountain and Van Norman Lake sections, Levi and Yeats (2003) concluded that the Saugus Formation in Soledad Canyon and the Merrick syncline was deposited during the Matuyama chron, sometime between 2.6 and 0.78 Ma. In addition to normal and reverse polarity, most of the sites of the Saugus Formation retained stable magnetic remanence with accurate paleomagnetic direc-

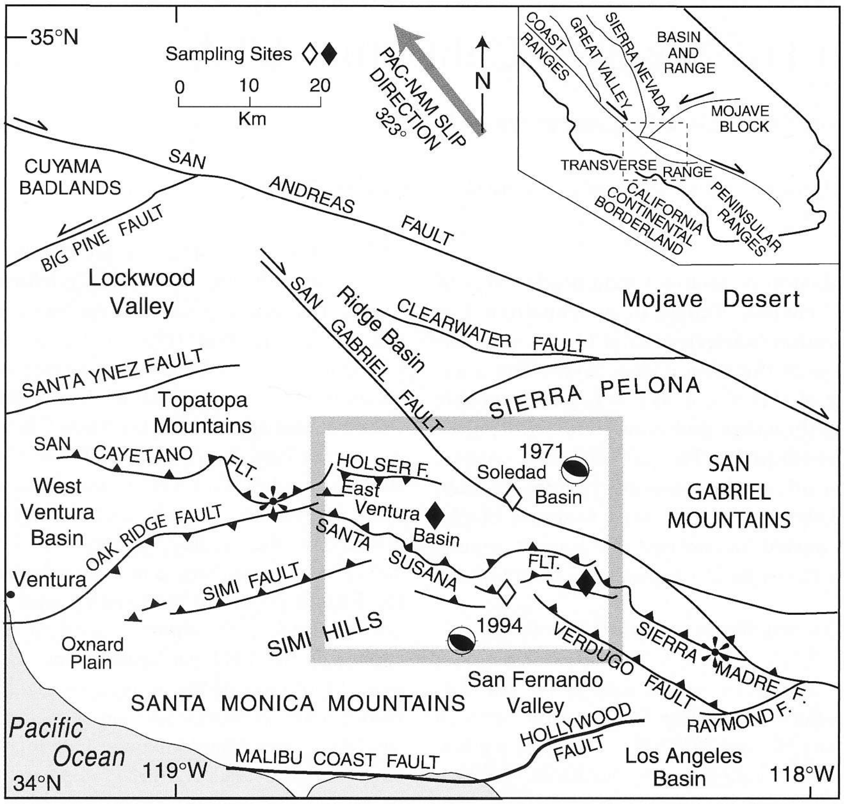

Figure 1. Structural map of part of California Transverse Ranges. Rectangle encloses study area (Figure 2). Diamonds identify Saugus Formation paleomagnetic sections. Filled diamonds are rotated, open diamonds are nonrotated sections. Asterisks identify two paleoseismic trenches (Rubin et al., 1998; Dolan and Rockwell, 2001). Circles are locations and focal mechanisms of 1971 San Fernando and 1994 Northridge earthquakes (Hauksson et al., 1995; Mori et al., 1995). Abbreviations: PAC-NAM,—Pacific–North America plates; F., Flt.—fault.

tions (declination and inclination) (Levi and Yeats, 1993, 2003). Data relevant to this study are summarized in Table 1.

The average geomagnetic field during Saugus deposition can be represented as a geocentric axial dipole, intersecting Earth's surface at the north and south geographic poles, with the average declinations at Earth's surface directed north-south, along lines of longitude. During this period, deviations from the north-south direction of average, structurally corrected formation declinations are interpreted as tectonic rotations about vertical axes.

BLOCK DELINEATION

Four sections of the Saugus Formation are in an area ~35 × 25 km, areas, making it possible to document small-scale crustal fragmentation. The paleomagnetic data show that two sections are rotated clockwise, while the other two are unrotated (Figs. 2 and 3). Our results are consistent with other studies that show predominance of clockwise rotations of Neogene crustal blocks west of the San Andreas fault (e.g., Greenhaus and Cox, 1979; Luyendyk et al., 1985; Liddicoat, 1992). Given the spatial distribution of the sites in each of the four sections, sampled over areas 3–16 km^2, and the location of the bounding faults and lateral ramps, the blocks are estimated to have linear dimensions of 10–20 km. The Van Norman Lake and Soledad Canyon areas might be considered a single nonrotated domain, flanked by the rotated Magic Mountain domain on the west and the Merrick syncline domain to the east. However, the presence of the Santa Susana and San Gabriel faults between these nonrotated areas (Fig. 2) indicates that they are distinct, and the four sections belong to different blocks.

On the basis of the paleomagnetic data and structural geologic analyses (Levi and Yeats, 1993, 2003), we suggest tentative partial boundaries for the blocks (Fig. 2). The Magic Mountain domain is bounded on the south by the Santa Susana fault from its fault tip on the west to the northeast-trending segment boundary at the Gillibrand Canyon lateral ramp on the east. The Gillibrand Canyon segment boundary (Yeats, 1987) is delineated by structure contours on the Santa Susana fault and a contrast in structures in the hanging wall of the of the Santa Susana fault (Fig. 2). The northern boundary of the Magic Mountain domain is assumed to include the Holser fault and part of the San Gabriel fault. The unrotated Van Norman Lake block is bounded by the Santa Susana fault to the north and west; on the south, it is bounded by the Mission Hills fault or Northridge Hills fault between the northeast-trending San Fernando lateral ramp on the Santa Susana fault on the west and the northeast-trending Pacoima segment boundary to the east, where it intersects the ~30° bend between the Mission Hills and Verdugo faults (Tsutsumi and Yeats, 1999). The Merrick syncline domain boundaries are interpreted to include the San Fernando or Verdugo faults on the south, between the Pacoima and Sunland segment boundaries, and the San Gabriel fault to the northeast. The unrotated Soledad Canyon domain, in the San Gabriel block, is bounded on the southwest by the San Gabriel fault.

REGIONAL EARTHQUAKE PARAMETERS

Regional earthquake parameters were obtained by analyzing the two largest historical earthquakes in the study area. The 1971 San Fernando earthquake beneath the San Gabriel Mountains was modeled as "a double event that occurred on two separate, subparallel thrust faults" (Heaton, 1982, p. 2037). The hypocentral depth of the first event was ~13 km, rupturing a fault dipping ~54° to the northeast. The second shock was about 4 s later from a hypocentral depth of 8 km, on an ~45° northeast-dipping fault. The aftershocks outlined a zone dipping ~40° to the northeast, reaching maximum depths of 18–20 km (Hanks, 1974; Mori et al., 1995). The 1994 Northridge earthquake nucleated at a depth of ~18 km, and the aftershocks extended upward to depths of 5–8 km, along a previously unrecognized fault dipping ~40° to the southwest (Hauksson et al., 1995; Mori et al., 1995). The seismicity of the 1971 and 1994 earthquakes suggests that the seismogenic layer in the study area extends to depths approaching 20 km. Together with the paleomagnetically determined horizontal dimensions, the horizontal and vertical lengths of the blocks are roughly the same, and the data suggest that the crust in the study area is fragmented into subequidimensional blocks with dimensions of 10–20 km. If earthquakes in this region are modeled as circular ruptures, the seismic moment is given by:

$$M_0 = (16/7)a^3\Delta\sigma, \qquad (1)$$

where a is the radius of an assumed circular rupture, and $\Delta\sigma$ is the static stress drop (Scholz, 2002, p. 204). For many intermediate and large earthquakes, $\Delta\sigma$ values are between 1 and 100 bar (Hanks, 1977). For the study area, representative $\Delta\sigma$ values were estimated from the 1971 San Fernando and 1994 Northridge earthquakes. The 1971 event has a composite seismic moment of 1.7×10^{26} dyne-cm (Heaton, 1982). For a rupture length of 16

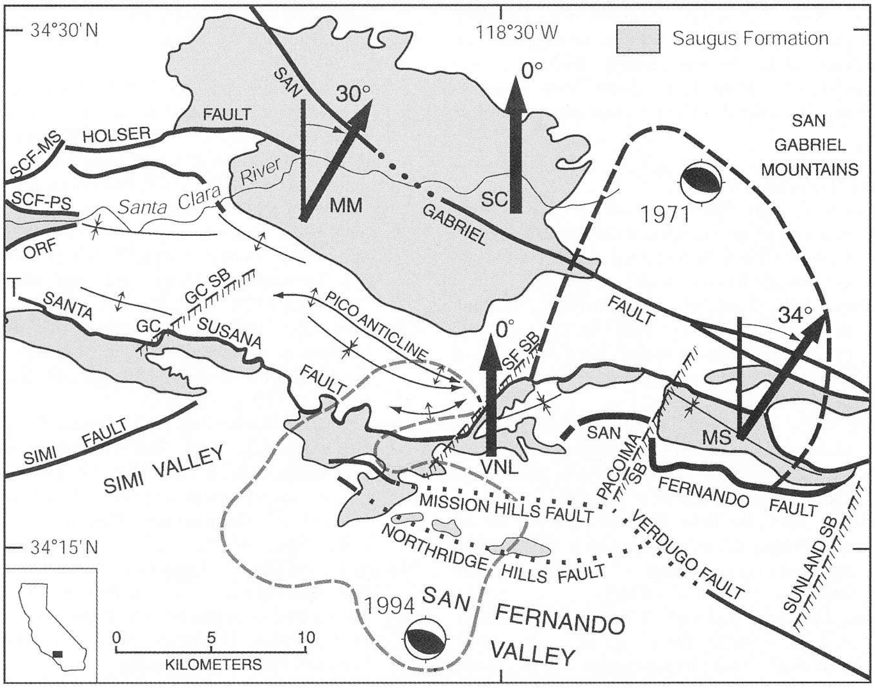

Figure 2. Tectonic map of study area. Merrick syncline (MS) domain: Kagel Ridge, Little Tujunga Canyon, and Marek Canyon sites; Soledad Canyon (SC) block; Magic Mountain (MM) area: Transmission Line and Santa Clara River sections; VNL block: Van Norman Lake section and Horse Flats sites in San Fernando Valley. Bold arrows indicate average declination of each area with magnitude of clockwise rotation (in degrees). Faults are shown in heavy lines, dotted where covered. Heavier lines indicate surface ruptures of San Fernando fault during 1971 earthquake. Circles identify epicenters and focal mechanisms of 1971 and 1994 earthquakes; dashed curves are surface projections of 0.5 m contours of slip distribution (Mori et al., 1995). Northeast-trending dashed lines show Gillibrand Canyon (GC), San Fernando (SF), Pacoima, and Sunland segment boundaries (SB). T:—Santa Susana fault tip; ORF:—Oak Ridge fault; SCF-MS:—San Cayetano fault, main strand; SCF-PS:—San Cayetano fault, Piru strand.

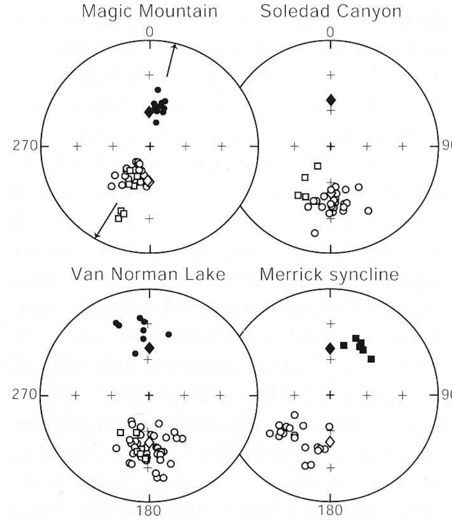

Figure 3. Site-mean, structurally corrected paleomagnetic directions of four sections in east Ventura Basin and San Fernando Valley. Each datum (circle and squares) represents average direction of typically six specimens. Diamonds represent normal (solid) and reverse (open) directions of Pliocene–Pleistocene geocentric axial dipole. Open circles are reverse, upper hemisphere, directions of Matuyama sites; solid circles (Magic Mountain domain) are normal, lower hemisphere Brunhes sites. At Merrick syncline, solid squares represent normal-polarity Matuyama sites; open squares at other three domains represent normal polarity Matuyama sites inverted through origin to reverse polarity. Deviations of the mean direction of the Magic Mountain and Merrick syncline domains from north-south axis (0°–180°) indicate clockwise rotation of these blocks. Perimeter circles indicate horizontal directions (zero inclination); interior + symbols designate 30° increments of inclination.

km and width of 25 km (Heaton, 1982), the radius of a circular rupture with equivalent area is 11.3 km. Using equation 1, we obtain $\Delta\sigma = 52$ bar. For the 1994 event, Wald et al. (1996) obtained $\Delta\sigma = 74$ bar on the basis of mean slip of 140 cm. For consistency with our treatment of the 1971 earthquake, we used the Wald et al. (1996) combined inversion seismic moment of 1.4×10^{26} dyne-cm. For a rupture width of 24 km and rupture length of 18 km, the radius, a, of the equivalent rupture area is 11.7 km, and $\Delta\sigma = 38$ bar. The average of these three values is 55 bar, which we take as the representative static stress drop for the study area. From the paleomagnetic results and the depth of the deepest observed aftershocks, we estimate the maximum rupture radius $a = 12$ km. This leads to a seismic moment $M_0 = 2.17 \times 10^{26}$ dyne-cm, which might be uncertain by as much as a factor of two. The corresponding moment-magnitude is $\mathbf{M_w} = 6.8$, which we consider near maximum for earthquakes in the study area. For comparison, using $a = 12$ km and $\Delta\sigma = 100$ bar, we obtain $\mathbf{M_w} = 7.0$.

DISCUSSION

The relation between the seismic moment, M_0, and mean slip, Δu, is $M_0 = \mu \Delta u A$, where A is the rupture area and μ is the rigidity. For the study area, we use a crustal model (Wald et al., 1996) with $\mu = 36.0 \times 10^9$ N/m^2 (36.0 GPa). Taking $a = 12$ km, the estimated mean slip $\Delta u = 1.3$ m. The parameters for calculating Δu have significant uncertainties: $\mu \pm 20\%$, $\Delta\sigma \pm 50\%$, $a \pm 20\%$; hence, the uncertainty in Δu may approach a factor of 2.

GPS data augmented by interferometric synthetic aperture radar imagery, which account for fluctuations due to fluid pumping, indicate that the residual tectonic signal across the Los Angeles basin is ~4.4 mm/yr uniaxial contraction (Bawden et al., 2001). A balanced cross section in the study area obtains a similar value for the Quaternary, 5.7 ± 2.5 mm/yr (Huftile and Yeats, 1996). Using a mean slip rate of 5 mm/yr, the recurrence interval for an earthquake $\mathbf{M_w} = 6.8$ within a given block is 270 yr. This is a minimum estimate of the recurrence interval, because it assumes that shortening occurs entirely at a single fault.

After the 1971 San Fernando (Sylmar) earthquake, as much as 2.5 m of total slip was measured along the ruptured San Fernando fault (Sharp, 1975), consistent with the measured $\mathbf{M_w} = 6.7$. Subsequent paleoseismic trenching (Fumal et al., 1995) detected evidence for two earthquakes in the past 3.5 k.y. In contrast, offsets on excavated faults in

TABLE 1. SUMMARY OF PALEOMAGNETIC RESULTS

Domain/block	$K \times L$ (km^2)	Chron	N (n)	$R = D \pm \Delta D$
Magic Mountain	4 × 4	Brunhes	10 (16)	14° ± 6°
		Matuyama	29 (51)	30° ± 5°
Van Norman Lake	3 × 3	Matuyama	57 (83)	0° ± 4°
Merrick syncline	3 × 3	Matuyama	25 (52)	34° ± 6°
Soledad Canyon	4 × 1	Matuyama	28 (34)	0° ± 6°

Note: K, L = approximate linear dimensions of sampling areas; N = number of sites used for calculating paleomagnetic directions; n = number of sites measured; R = rotation; D = mean paleodeclination; ΔD = angular radius of 95% cone of confidence (Demarest, 1983).

neighboring regions in the Los Angeles metropolitan area (Fig. 1, asterisks) have been interpreted to represent paleoearthquakes with $\mathbf{M_w}$ = 7.2–7.6, i.e., the Sierra Madre fault (Rubin et al., 1998; Tucker and Dolan, 2001) and the San Cayetano fault (Dolan and Rockwell, 2001). Are faults for which paleoseismic excavations suggest $\mathbf{M_w} > 7$ associated with larger blocks? To answer this question, paleomagnetic studies should be done in areas where fault offsets leading to earthquake magnitudes are available. Similarly, it would be valuable to conduct additional paleoseismic trenching in our study area for direct comparison and calibration of earthquake magnitudes.

For the clockwise-rotated Magic Mountain and Kagel Ridge blocks, there is no stratigraphic, time-dependent pattern of the Matuyama declinations (Fig. 3), indicating that the rotations did not commence until the youngest Matuyama strata were deposited, and the rotation of the Magic Mountain domain probably did not begin until the Brunhes chron, ca. 0.8 Ma (Levi and Yeats, 1993). From this result, we infer that the mapped blocks have retained their structural configuration during the Brunhes chron, moving quasi-independently in response to distributed dextral shear in the Pacific–North America plate boundary zone. We consider it unlikely that, in the study area, several domains might have combined to trigger a much larger earthquake during the past 0.8 m.y.

This paper describes the use of paleomagnetism to identify discrete blocks and establish the time interval over which they have moved independently. When a suitable paleomagnetic study can be conducted, this method allows a deterministic estimate of the maximum considered earthquake for a specific block or a region characterized by such blocks. This method is not earthquake specific; rather, it estimates maximum potential earthquake magnitudes for particular geographical areas. The maximum considered earthquake calculated from geometrical considerations in this study is $\mathbf{M_w}$ = 6.8, similar to the 1971 San Fernando and 1994 Northridge earthquakes. Our analysis applies only to this study area, where we documented segmentation of the local crust into relatively small blocks. Paleoseismic trenching suggests that earthquakes with moment magnitudes $\mathbf{M_w} > 7$ have occurred in adjacent areas, where the crustal blocks are presumably larger. However, for the east Ventura Basin and San Fernando Valley, we conclude that expected earthquake magnitudes are $\mathbf{M_w} < 7$, somewhat reducing the estimated seismic hazard for this part of the Los Angeles metropolitan area.

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