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Forecasting Southern California Earthquakes

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Summary. Since 1978 and 1979, California has had a significantly higher frequency of moderate to large earthquakes than in the preceding 25 years. In the past such periods have also been associated with major destructive earthquakes, of magnitude 7 or greater, and the annual probability of occurrence of such an event is now 13 percent in California. The increase in seismicity is associated with a marked deviation in the pattern of strain accumulation, a correlation that is physically plausible. Although great earthquakes (magnitude greater than 7.5) are too infrequent to have clear associations with any pattern of seismicity that is now observed, the San Andreas fault in southern California has accumulated sufficient potential displacement since the last rupture in 1857 to generate a great earthquake along part or all of its length.

When asked when the next great earthquake might be expected, seismologists often say, "The longer it's been since the last big one, the sooner the next one will be." Underlying this idea is the hypothesis that earthquakes occur as a result of the accumulation of elastic strain in the brittle lithosphere and that the strain is due ultimately to motion of lithospheric plates at a nearly steady rate. Rapid progress is being made in understanding the factors that control the timing of release of the accumulated strain. Great plate-boundary earthquakes recur at intervals that may vary as much as 50 percent from an average value (*1*). However, there is some evidence that the interval may be proportional to the displacement generated by faulting in the previous earthquake at the same site (*2, 3*). If strictly true, this result would permit a more precise estimate of the time of occurrence of the next great earthquake, provided the long-term displacement rate is both constant and well-known.

The average recurrence interval of about 150 years for the San Andreas fault in southern California is almost equal to the elapsed time since the last great earthquake that ruptured the fault from Cholame Valley to Cajon Pass in 1857 (Fig. 1). Moreover, the displacement rate of about 3 centimeters per year for much of this segment, when divided into the displacements north of Los Angeles near Palmdale in 1857, also leads to an estimate of 100 to 150 years for the interval preceding the next event. Both observations mark the San Andreas fault north and east of Los Angeles as a mature seismic gap and the prime candidate for producing southern California's next great earthquake.

Moreover, California has recently emerged from a 25-year period of quiescence for large earthquakes. Because of the potential for severe losses of life and property from such a great earthquake so near Los Angeles, southern California is the area most intensively under study in current U.S. efforts to predict earthquakes.

Great earthquakes—those of magnitude (M) > 7.5—are infrequent; they have occurred in California only four times in the last 125 years. Major earthquakes ($7.5 > M > 6.5$) are several times more frequent and are capable of inflicting severe damage if located in densely populated areas. The 1971 Sylmar earthquake of $M = 6.5$ resulted in 61 deaths and more than $500 million in property damage. Large earthquakes ($6.5 > M > 5.5$) occur more than twice yearly in California and have effects varying from minor damage at the low end of the scale to potentially heavy damage at the upper end. The losses suffered in the 1933 Long Beach earthquake of $M = 6.3$ were 115 lives and $40 million in 1933 dollars. Moderate earthquakes ($5.5 > M > 4.5$) are of statistical interest because of their frequency of occurrence but only rarely cause damage.

Although construction practices have improved in the 50 years since the Long Beach earthquake, a major or large event in California's urban areas could, depending on the exact location and time of day, lead to very severe damage and loss of life. A report (*4*) issued by the National Security Council through the Federal Emergency Management Administration lists the effects to be expected from several plausible events. The consequences are appalling. A repeat of the 1857 earthquake could be expected to lead to 10,000 to 15,000 deaths, 50,000 persons hospitalized, and $17 billion in property losses, with an uncertainty of a factor of 2 to 3. The worst case cited, an earthquake of $M = 7.5$ on the Newport-Inglewood fault near Long Beach, could cause 20,000 lives to be lost and $69 billion in property damage with the same factor of uncertainty. Even if losses of life and property are half those estimated, a reduction of the risk by even a

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small amount would be of immense value.

The observations we describe here indicate not only that great, plate-boundary earthquakes occur with some approximate predictability but that large and major intraplate earthquakes have a nonrandom distribution in space and time. Moreover, the strains that ultimately lead to earthquakes accumulate nonlinearly, with the period in which strains are most favorable for California's most typical earthquakes corresponding to a period in which moderate to large earthquakes have increased in frequency. In the past, such periods of high seismic activity have been associated with large or major earthquakes, even though the San Andreas fault itself has remained relatively inactive.

Slip Rate and Earthquake Recurrence on the San Andreas Fault

In historical times only two of the four major seismically distinct sections of the San Andreas fault (Fig. 1B) have produced great earthquakes—the northern segment, in 1906 (*5*), and the south-central segment, in 1857 (*6*). Both of these segments have been characterized by low levels of seismic activity since their respective great earthquakes and are considered to be slowly maturing seismic gaps (*7*).

The 170-kilometer-long central segment of the fault is principally characterized by relatively continuous fault creep (*8*). The rate of creep locally exceeds 30 millimeters per year and appears to account for most but perhaps not all of the 33 to 45 mm/year of annual shear that has accumulated during the past century across a 70-km-wide geodetic network spanning the fault at that latitude (*9*).

The southernmost segment of the San Andreas fault has not produced a great earthquake during the 213 years of historical record, and creep, although recognized locally (*10*), is very minor relative to modern geodetically determined rates of deformation (*11*) and the probable long-term (millennial) slip rate (*12*). Recently, arguments by Allen (*13*) have been marshaled in favor of the generation of a future great earthquake by slip along this segment of the fault.

In lieu of a long and well-documented history, geological studies of prehistoric earthquakes and the poorly known great earthquake of 1857 have been the principal avenues to understanding the long-term behavior of the San Andreas fault system. Geomorphic and stratigraphic studies at several localities along the San Andreas fault system have provided a partial understanding of the behavior of that major plate boundary.

In 1857, slip varied markedly along the south-central reach of the San Andreas fault (*14*). Along much of the northwestern half of the 1857 break, right-lateral slip was 8 to 10 meters. Along most of the southern half of the rupture, slip amounted to 3 to 4½ m. A time-predictable model (*2, 3*) would thus predict that the southeastern half of the 1857 break would be the next to rupture. Other geological data, however, caution against making such a simple analysis.

At the Wallace Creek locality (Fig. 1B), slip in 1857 amounted to 9 to 10 m, and analysis of old stream channels shows that at least the previous two slip events were of similar size (*1*). Study of the geomorphology and stratigraphy of Wallace Creek itself reveals that the average Holocene rate of fault slip has been somewhere between 33 and 64 mm/year (*1*). Therefore the average time between slip events of 9 to 10 m, if such displacements can be expected for future earthquakes, must be between 140 and 300 years.

Pallett Creek, 205 km southeast of Wallace Creek, is situated along the segment of the fault that experienced only 3 to 4½ m of slip in 1857. Here, the times

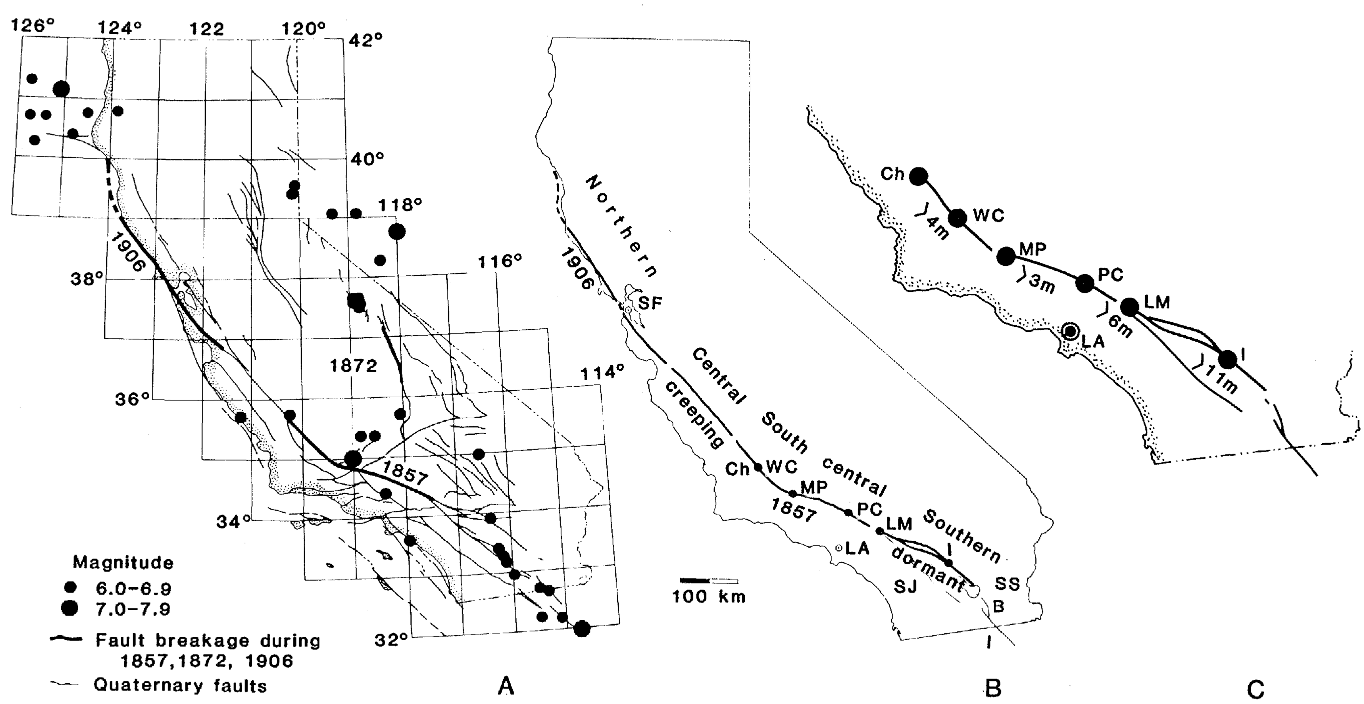

Fig. 1. (A) Earthquakes of magnitude 6 or larger for the 50-year period 1932 to 1981 in California and adjacent areas. Surface faulting shown for three historic earthquakes of magnitude 8 or greater. Faults active during Quaternary are also shown. (B) The San Andreas fault can be broken down into four segments in terms of its historic activity—northern, central, south-central, and southern. Studies at Wallace Creek (*WC*), Mill Potrero (*MP*), Pallett Creek (*PC*), Lost Marsh (*LM*), and at a site near Indio (*I*) are revealing much of the record of its prehistoric behavior. Three other major southern California fault zones are also shown—the San Jacinto (*SJ*), the Imperial (*I*), and the Brawley (*B*) faults. *SS*, Salton Sea; *Ch*, Cholame; *LA*, Los Angeles; *SF*, San Francisco. (C) Present knowledge of the displacement rates and occurrence times of great earthquakes on the San Andreas fault in southern California leads to the identification of accumulated minimum deficit in fault slip since the last great earthquake. Segments might fail independently, or in conjunction with an adjacent segment or segments.

of individual large earthquakes have been determined by radiocarbon dating (*15*). Because of uncertainties in the analysis, the average interval for the past 2000 years may lie anywhere between 123 and 225 years.

The latest three large events at Pallett Creek probably correlate with three large events recognized and dated in an excavation at Mill Potrero about midway between Wallace Creek and Pallett Creek (*16*).

The recent history of faulting at Lost Swamp, just beyond the southeastern limit of the 1857 rupture (*6*), is comparable to the Pallett Creek and Mill Potrero evidence. Here, at least two and probably several large events postdate A.D. 1300 (*17*). It is quite likely that these correlate with the latest three prehistoric events recognized at Pallett Creek. The average Holocene rate of fault slip is well constrained to about 25 mm/year at Lost Swamp, a value substantially lower than that derived from Wallace Creek.

Little is known about the prehistoric behavior of the southern segment of the San Andreas fault, except that near its center, at Indio, no slip associated with a great earthquake appears to have occurred for at least the past 560 years (*18*).

Discussion

The evidence above leads us to several tentative conclusions regarding the timing and magnitudes of future great San Andreas fault events in central and southern California. In order of stored potential displacement, based on the interval since the last major or great event multiplied by the average displacement rate, the southern segment of the fault is ranked highest. Youthful scarps and lateral offsets along most of this segment indicate appreciable Holocene displacement, and yet no great earthquakes seem to have occurred for at least 560 years. Based on geologic evidence, Quaternary slip rates may be a few centimeters per year (*12*). Currently, geodetic observations (*11*) suggest right-lateral shear strain rate of about 2 cm/year across the San Andreas fault near Indio (Anza and Salton net in Fig. 7). Using this slip rate and a minimum period of dormancy of 560 years, we conclude that 11 m or more of potential displacement has accumulated.

Lost Swamp, near Cajon Pass, ranks second among the sites in terms of minimum stored displacement. The 1857 earthquake rupture did not reach the site, although the A.D. 1720 event recorded at Mill Potrero and Pallett Creek

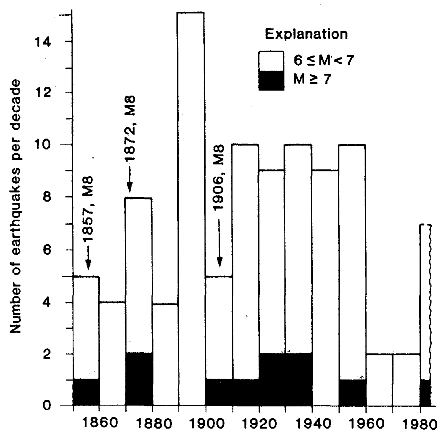

Fig. 2. Number of earthquakes in California of magnitude 6 or greater per decade since 1850, after (*20*). Note marked variations in activity, especially decades of very low release in the 1960's and 1970's, increase in activity since 1980, and maximum from 1890 to 1900 prior to the great earthquake of 1906. Earthquakes of magnitude 8 or greater are indicated by arrows.

most probably did. The displacement rate at Lost Marsh is well established at 25 mm/year, so that about 6 m of potential displacement has accumulated since about 1720.

The displacement rate at Wallace Creek in the Carrizo plain is less well known. If the unlikely but possible high value of 64 mm/year were correct, 8 m would be stored. However, a more conservative estimate of 33 mm/year would account for an accumulation of 4.1 m of potential displacement.

At Pallett Creek, the displacement rate has not been determined, but it is reasonable to assume that 25 mm/year is a minimum value, so that more than 3.1 m of slip has accumulated.

These minimum estimates of the potential slip accumulated since the last great earthquakes are shown in Fig. 1C. They indicate the minimum displacement values we would expect at each site if the fault broke there during a great earthquake today.

Much controversy surrounds the issue of which segment of the fault will be the next to rupture. Considering the recurrence interval data from the various sites, it is conceivable that the entire fault in southern California could rupture at once. A more likely scenario would be rupture of the segment including the Indio, Lost Swamp, and Pallett Creek sites, or a segment including only the Lost Swamp and Pallett Creek sites. Other reasonable scenarios include rupture of the short segment between Cholame and Wallace Creek or a repeat of the 1857 rupture, with faulting continuing from Cholame almost to Lost Swamp. Forecasting more accurately the timing of such future possible events must await the collection of more precise and abundant data on the dating and displacements of past great earthquakes. We seek in the pattern of their occurrence, rupture lengths, and displacement a model that can lead to more accurate long-term forecasts.

In any case, the present period of dormancy for the south-central segment (125 years) is between 55 and 100 percent of the average recurrence interval for great earthquakes known from the Pallett Creek record. Intervals between great earthquakes in areas of long historical record are known to vary from the average recurrence interval by as much as 45 percent (*1*). Thus we should consider all or part of the south-central segment to be capable of generating a great earthquake now. It should be understood, however, that the next great event would not be breaking millennial tradition there if it waited another 75 years before occurring.

The dormancy of the southern segment of the San Andreas fault for at least the better part of the past millennium is certainly surprising, in view of its location between the Imperial-Brawley fault system (Fig. 1B) and the south-central reach of the San Andreas fault. At least three great earthquakes have resulted from slippage along all or part of the south-central reach during the period of dormancy of the southern reach. The Imperial and Brawley faults have been extraordinarily active during the period of historical record, but their activity terminates abruptly at the southern end of the Salton Sea (*19*). Thus we conclude that dislocations have been gradually piling up at both ends of the dormant southern segment, and it must be regarded as a potentially dangerous gap.

Long-Term Changes in Rate of Occurrence of Earthquakes

The rate of occurrence of moderate to large earthquakes in California has varied appreciably in both time and location. For example, the number of shocks of $M \geq 6$ per decade (Fig. 2) shows more than a sevenfold variation during the period 1850 and 1981. The largest number of events in Fig. 2 occurred in the decade 1890 to 1900, just before the great San Francisco earthquake of 1906. The five decades from 1910 to 1960 are marked by a relatively high and nearly uniform release of shocks of $M > 6$. Bufe and Toppozada (*20*) note that the number of shocks of $M \geq 6$ in the two

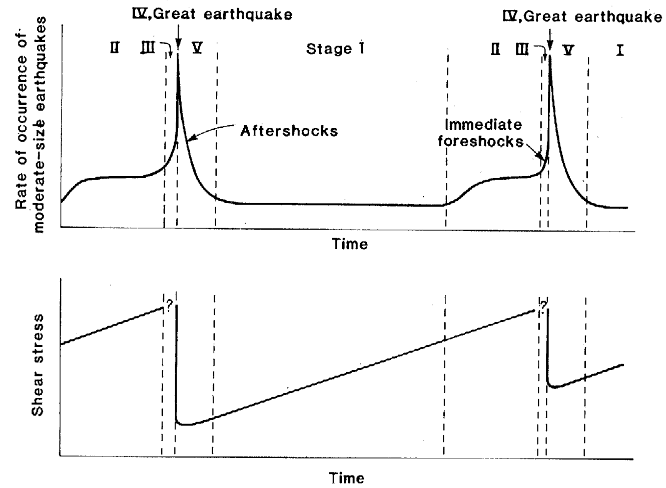

Fig. 3. Idealized model of cycle involving repeat of great earthquakes along a given segment of a plate boundary. Shear stress is gradually built up near plate boundary by movement of plates and is released suddenly at times of great earthquakes.

decades from 1960 to 1980 is anomalously low and is less than that associated with any of the other decades since 1850. In the two years 1980 and 1981 the level of activity was at least 3½ times that of either of the two previous decades. Hence, it is clear that California has recently emerged from a period of seismic quiescence that began in the 1950's.

Figure 1A shows the locations of earthquakes of $M > 6$ during the 50-year period 1932 to 1981 in California and adjacent parts of Nevada, Mexico, and offshore. During that period, activity was concentrated along the San Jacinto, Imperial, and Cerro Prieto faults between 32° and 33.5°N, in a broad region near the Kern County earthquake ($M = 7.7$) of 1952 (35°N,119°W), near the Nevada-California border, and in the area off the coast of northern California. None of the shocks in Fig. 1A occurred along the fault segments that ruptured in the events of $M \geq 8$ of 1857, 1872, and 1906.

Great events are usually followed for several years by aftershocks (stage V of Fig. 3). Much of the 50- to 500-year interval between great earthquakes is characterized by slow buildup of strain and by low levels of small to moderate-size shocks (stage I). Activity often increases in the general vicinity of the coming rupture zone years to decades before great shocks (stage II), but usually not along the coming rupture zone itself. The low level of activity for the last 50 years (Fig. 1A) along the rupture zones of the great shocks of 1872 and 1906 is probably associated with stage I of the earthquake cycle.

No shocks of $M > 6$ have occurred in the vicinity of the 1906 fault break since 1926 (*7*). The area surrounding the 1906 rupture zone was very active, however, for events of $M > 5$ and $M > 6$ during at least the 25-year period preceding the 1906 earthquake (Figs. 4 and 5). Nevertheless, very little of that activity was situated on the 300- to 400-km segment of the San Andreas fault that broke in 1906. The distribution of activity prior to 1906 suggests that the entire coastal fault system in the San Franciso Bay area is maintained in a delicate equilibrium with respect to tectonic stresses (*7*). Note that the rate of production of shocks of $M > 5$ and that of $M > 6$ in Fig. 5 decreased to zero for a decade shortly after the occurrence of the shock of magnitude 6.7 on the Hayward fault in 1868. In addition to the high rates for the period

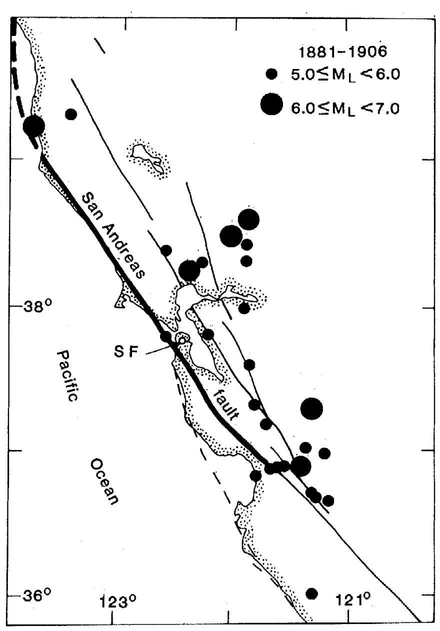

Fig. 4. Earthquakes of $M \geq 5$ during the 25-year period before the great San Francisco earthquake of 1906. Data and Quaternary faults are from Ellsworth *et al.* (*7*). Note concentration of earthquakes in region surrounding fault break (heavy line) of coming great shock of 1906 and near quiescence along 1906 rupture zone itself. *SF*, San Francisco; M_L, local magnitude scale.

1881 to 1906, high rates for $M > 5$ are also associated with 10-year or longer intervals preceding the four events of $6.5 < M < 6.8$, whose magnitudes are exceeded only by that of the shock of 1906.

Although no shocks of $M > 6$ have occurred in the area of Fig. 4 since 1926, the rate of occurrence of $M > 5$ shocks has increased (Fig. 5) since 1945 by about a factor of 2 compared with the low level for the period 1906 to 1945. Nevertheless, the rate for the past 35 years is still lower than that for the intervals 1855 to 1870 and 1881 to 1906. The record of shocks in the area of Fig. 4 is complete for the entire period 1855 to 1981 for $M > 5.5$ (*7*). Since some events of $5.0 < M < 5.5$ may have been missed in the last century, the actual levels of activity prior to 1906 probably were even greater than Figs. 4 and 5 indicate.

Ellsworth *et al.* (*7*) conclude that the next great ($M > 8$) earthquake in the San Francisco Bay area is still decades away but that the increase in activity for $M > 5$ during the last few decades indicates that the region is entering stage II of the earthquake cycle, in which events of $M \sim 6$ and perhaps as large as $M = 7$ can be expected. The pattern of events of $M > 5$ is similar to that for the period 1855 to 1906 but at a lower level. These patterns of seismicity and very rough estimates of about 150 to 220 years for repeat times of great shocks along the 1906 segment (*20*) suggest to us that the San Francisco Bay area is now in a state comparable to that which existed a few years to a few decades before 1865. During the next few decades shocks of $M > 6$ are more likely to occur than has been the case for the past few decades. Nevertheless, we have no evidence that would suggest a more specific timing or imminence for events of $M > 6$.

Cumulative numbers of earthquakes in southern and northern California, as taken from the Caltech and University of California, Berkeley, catalogs for the 50-year period 1932 to 1982, are shown in Fig. 6 for events of $M > 5$ and $M > 6$. The times of occurrence of the four largest events ($M > 7$) are indicated by arrows. The rates of occurrence of moderate to large shocks tend to be nearly constant for time scales of a few years to a few decades. For example, the rate of release in southern California is remarkably uniform for both traces from 1932 until just after the 1952 earthquake of $M = 7.7$. Likewise, the rates in southern California are nearly uniform from about 1954 to 1978. The latter rates, however, are lower by a factor of 2 to 4 than the rates for the interval 1932 to 1954. Likewise, both curves for northern California indicate high rates of release from 1932 to 1962, low rates from 1962 through 1978, and high rates in 1980 and 1981. Both curves for southern California also indicate an increased rate of activity starting in 1978 or 1979.

For both areas the changes in activity with time are more pronounced for $M > 6$ than for $M > 5$. For southern California the rate of release is less marked for $M > 4$ than it is for $M > 5$ (*21*). Hence, we might expect that events of $M > 7$, although few in number, would cluster even more preferentially in time than smaller shocks. The four events of $M > 7.0$ in Fig. 6 and the 1906 shock (Fig. 5) are all associated with time intervals in which the rate of seismic release was high for either $M > 5$ or $M > 6$. The probability of all five events occurring in such intervals by chance is only about 4 percent. Since intervals of nearly constant release in Figs. 5 and 6 typically last for years to decades, it seems reasonable to conclude that the period of renewed activity of the past few years will extend for at least several years and may last for one or more decades. There is now an increased probability that a shock of $M \geq 7$ will occur. The probability of such an event appears to be similar to that for the interval 1910 to 1955, about 13 percent per year for all of California.

It is clear that large parts of California, but not all the seismically active parts of the state, have participated in the recent increased rates shown in Fig. 6. Areas near the 1906 fault break did not contribute at all to the counts of $M > 6$ of the last 50 years in Fig. 6. Of the seven earthquakes of $M > 6$ in California since 1978, two occurred in southernmost California and northern Baja California, the largest event ($M = 7.0$) was located off the coast of northern California near the Mendocino fracture zone, and four were part of a swarm of large shocks along the east side of the Sierra Nevada. The increases in activity in Fig. 6 since 1978 are mainly attributable to the area south of 34.3°N, to the region near the California-Nevada border, and to the offshore area of northern California. The region between 34.3° and 37.1°N, including the rupture zones of the great earthquakes of 1857 and 1872, did not contribute any shocks of $M > 5$ from 1978 through October 1981. Estimates of the rate of activity of the past few years for each of the four curves in Fig. 6 are subject to a fairly large uncertainty, since they are of necessity based on a short-time sample and since they depend on the way in which the large events in the swarm of

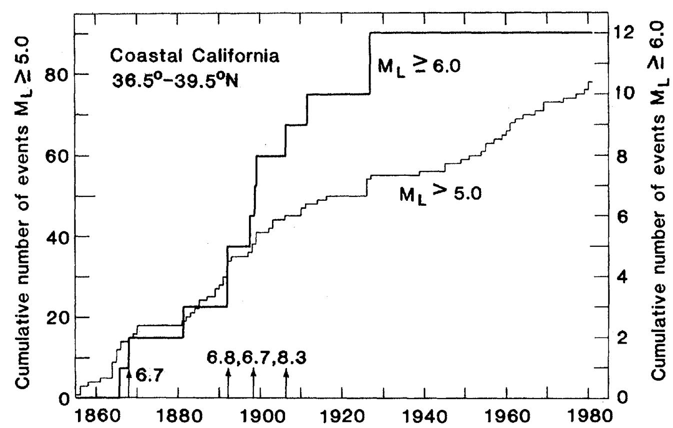

Fig. 5. Cumulative number of earthquakes of $M \geq 5$ and 6 in coastal area of California near San Francisco from 1855 to 1981 (*7*). Times of occurrence of events of $M > 6.5$ are indicated by arrows.

1980 and 1981 are counted. We can conclude, nonetheless, that the rates of the past few years are comparable to the fairly high rates of the period 1932 to 1954.

Such variations in the rate of seismicity are not unusual. For example, the period 1952 to 1957 had at least five destructive events in California and the period 1898 to 1906 had 14 destructive events in northern California, southern California, western Nevada, and northern Mexico. This period, probably coincidentally, was also one of high seismic activity along the Aleutian arc and the middle American trench. A remarkable sequence of 14 great earthquakes, $M \geq 7.4$, occurred in the Aleutian-Alaskan arc in 1898 to 1907, breaking the arc over more than 2000 km. The most comparable previous period in the Aleutians was 1844 to 1858, coincident in time with the 1857 Fort Tejon event in southern California.

High activity also occurred in California in the period 1868 to 1872, which included the great Inyo County earthquake. More recently, there were clusters of damaging earthquakes in 1915 to 1922, 1931 to 1934, 1939 to 1943, and 1952 to 1956. The intervals between these periods of activity are 13 to 16 years, and their durations are about 3 to 6 years. Based on the previous record of seismicity, 1979 to 1985 might be expected to be a period of high seismic activity, at least in California and western Nevada.

The increase of seismic activity since 1978 is mainly due to events in the Imperial Valley, Southern Mojave Desert, Mammoth area of the eastern Sierras, Santa Barbara, and offshore northern California. These are all in different tectonic provinces and well removed from the San Andreas fault, particularly the regions affected by the 1857 and 1906 events. Apparently sympathetic behavior between the Mammoth area, the Nevada–Santa Barbara–San Jacinto–Imperial Valley area, and the northern Baja area also occurred in 1915 to 1918 and 1940 to 1942. A large earthquake on the San Jacinto fault is the principal missing element in the current episode.

Causes of Long-Term Variations in Seismic Activity

In the last section we showed that the rate of occurrence of moderate to large earthquakes varies by a factor of up to 7 for time scales of years to decades. Here

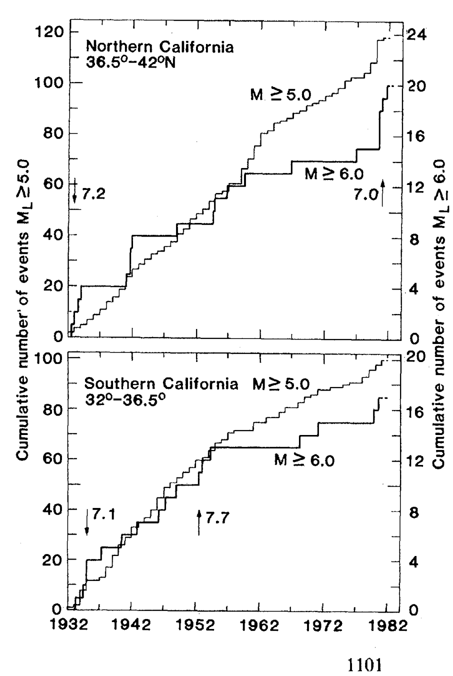

Fig. 6. Cumulative number of earthquakes of $M_L > 5$ and 6 in northern and southern California and adjacent areas from 1932 to 1981. Note high rates of activity from 1932 to the early 1950's, low rates of release from about 1960 to 1978, and increased activity since about 1978. Times of occurrence of four events of $M_L > 7.0$ are indicated by arrows. Obvious aftershocks were omitted from counts.

we examine the hypotheses that these variations either (i) are the result of random variations, (ii) are related to changes in the rate of strain accumulation on time scales of years to decades, or (iii) are related in a deterministic manner to the stages of the cycle of great earthquakes.

Ellsworth *et al.* (*7*) showed that the hypothesis that earthquakes from 1855 to 1980 near the 1906 fault break have a Poisson distribution can be rejected at the 95 percent level of confidence. In fact, the event rate precipitously declined after the 1906 earthquake (*7*). Activity in southern California also declined markedly shortly after the 1952 shock, the next largest earthquake in California of the last 100 years. Relatively low levels of activity can be seen in Fig. 2 in each decade following the 1857 and the 1872 earthquakes. Unfortunately, the record for $M > 5$ is not complete for the decades preceding and following those two shocks. Thus inferences about changes in the seismic regime before and after shocks in California of $M > 7.5$ must be drawn almost exclusively from the earthquakes of 1906 and 1952.

Mogi (*22*) found that moderate to large earthquakes became more numerous in a broad region surrounding the coming rupture zones of great Japanese earthquakes within a few decades of those great events. It is not clear whether such a pattern precedes large shocks along plate boundaries of the transform type, of which California is a typical example. The pattern of high activity in Fig. 4 that surrounds the 1906 rupture zone from 1881 to 1906 and low activity along that coming rupture zone itself is nearly identical to that described by Mogi. Although it can be inferred (*20*) that the 1906 rupture zone is returning to the seismic regime that characterized the 50 years prior to the great San Francisco earthquake—that is, the Mogi doughnut pattern—we have only that case on which to rest forecasts of future activity on the San Andreas fault. The long period of quiescence along the Carrizo-Palmdale-Coachella segments of the San Andreas fault certainly can be taken as the hole of a doughnut ringed by more active regions, but the pattern here is even less fertile ground for making forecasts. More specific statements concerning the proximity of great or major earthquakes in California require additional information, such as observations of strain accumulation rates.

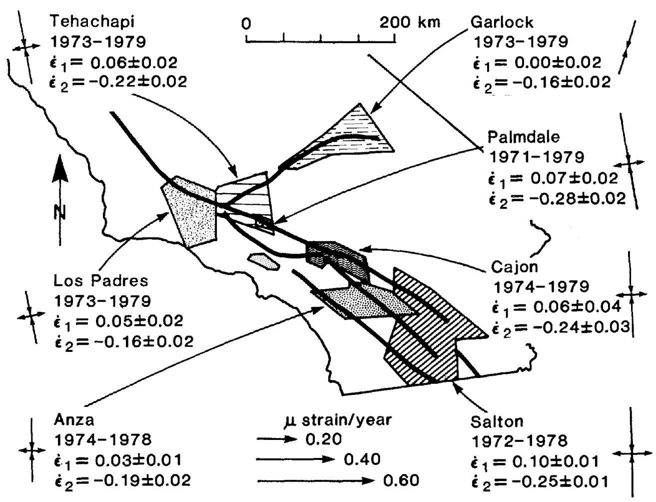

Fig. 7. Geodimeter trilateration networks in southern California and average annual horizontal principal strains ($\dot\epsilon$) for the period 1972 to early 1979. [From Prescott *et al.* (*23*)]

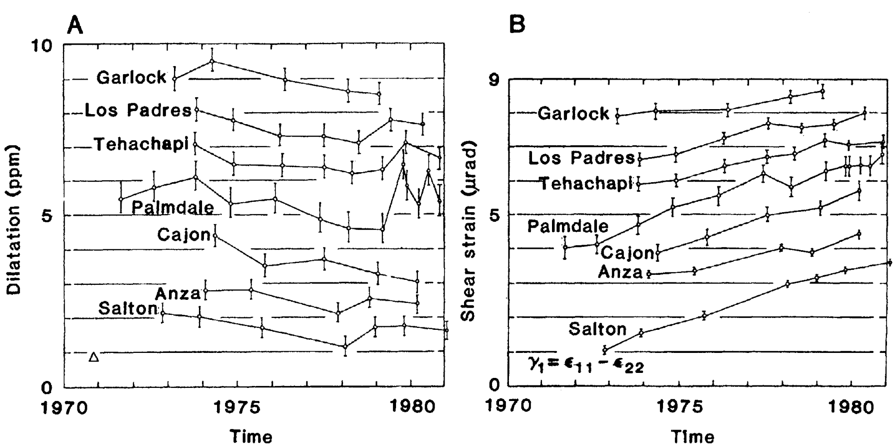

Fig. 8. (A) Dilatational and (B) shear strains in southern California Geodimeter networks, 1972 to 1980. The dilatational strain is $\epsilon_{11} + \epsilon_{22}$, the east-west and north-south strains; the shear is $\epsilon_{11} - \epsilon_{22}$ and represents the horizontal right-lateral shear on a N45°W vertical plane. [Figures 5 and 6 of Savage *et al.* (*11*)]

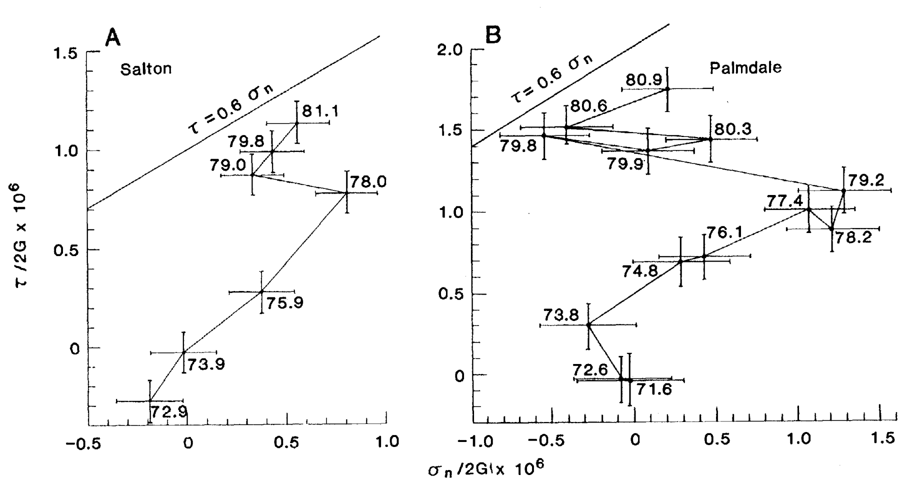

Fig. 9. Shear and normal components of stress, τ and σ_n, divided by the shear modulus, G, on the San Andreas fault (A) at the Salton Sea and (B) at Palmdale; σ_n and G are in bars. The number associated with each point is the decimal year.

Strain Accumulation in Southern California

Savage and co-workers (*11*) recently described the pattern of strain accumulation in southern California between 1973 and 1980. They measured distances between monuments with a precise laser ranging system, a Geodolite, about once each year. More than 200 such lines were measured, about 30 in each of the networks shown in Fig. 7. The distances measured are between 10 and 35 km. The changes in length of the lines between surveys are used to compute the average strain within each network on the assumption that the strain is uniform over each net. Random errors, after refractive index corrections along the air path of the laser beam, permit determinations of the average strain over the networks within 1 standard deviation of less than 2×10^{-7}. Systematic errors are more difficult to account for, but apparently are unimportant.

From 1973 to 1978, the strain field in southern California was uniform in orientation and annual rate with all networks showing nearly north-south compression at 2×10^{-7} to 3×10^{-7} per year and no east-west change (Fig. 7) (*23*). Between the beginning of 1978 and 1979 the pattern changed: the Salton, Anza, and Los Padres nets showed positive dilatational strain and both north-south and east-west components became extensional (Fig. 8). This extensional strain episode appeared in the Tehachapi and Palmdale nets between early and late 1979. The positive dilatation at Palmdale in the 6 months between March and October 1979 was a remarkable 2×10^{-6}, for a strain rate of 4×10^{-6} per year. Throughout the period of observation the shear strain on a N45°W vertical plane, in the right-lateral sense consistent with the long-term motion on the San Andreas fault, increased at an approximately constant rate (Fig. 8B) (*11*).

Discussion

These measurements were begun with the intention of determining the long-term pattern of accumulation of strain near the San Andreas fault prior to the next great earthquake. To achieve rupture along 300-km-long sections of the fault, as in 1857 and 1906, requires that the ratio of the shear to the normal stresses along the entire section be close to the coefficient of friction of the fault surface. If the stresses increased linearly with time to the point of failure, predicting the next great earthquake would depend primarily on our discerning in the patterns of seismicity some repeatable and well-defined character that heralded large-scale failure and our detecting premonitory aseismic slip just before the seismic failure. Although both seismicity patterns and premonitory slip have been observed, the data are not yet sufficient to indicate just how consistently these phenomena precede large earthquakes. Foreshocks, for example, have occurred before only about half the major earthquakes of the past 20 years. On the other hand, if strains accumulate nonlinearly, then at least certain periods can be identified as ones of high seismic risk. More significantly, various physical models of the manner in which the fault zone is brought to the point of failure can be tested against the temporal and spatial patterns of strain and seismicity.

The episode of positive dilatation from 1978 to 1980 was considered for a variety of reasons by Savage *et al.* (*11*) to be real, not due to some unknown source of systematic error in the measurements. There is as yet no satisfactory physical model that explains the episode. Nevertheless, it is important that the pattern of strain accumulation appears to be episodic, not linear. Moreover, the strains accumulated during the episode can be shown to reduce the normal stress acting across the strike-slip faults of the San Andreas system (and the normal faults of the Basin and Range system) and thus reduce their frictional strength (*24*).

To calculate the changes in shear and normal stress across the San Andreas fault in each of the networks, we transform the coordinates of the horizontal strain field for each measurement interval into the shear and normal strains on the fault, converting strain to stress through the appropriate equations of elasticity (*24*). The results are shown in Fig. 9, where, for reference, a slope of 0.6 for the Coulomb static frictional failure envelope is shown. The intercept of the failure envelope is unknown, of course, as the absolute state of stress at the usual focal depths for San Andreas earthquakes is unknown. Provided, as laboratory and field experiments have shown, faulting is triggered when the static friction is overcome—that is, $\tau/\sigma_n \geq 0.6$—then a slope of less than 0.6 on the curves of shear versus normal stress in Fig. 9 implies that strike-slip failure should be inhibited. Conversely, a slope exceeding 0.6 indicates a period in which strike-slip failure should be enhanced.

Of the five networks showing a significant reduction in the normal stress on the San Andreas fault system, only the Salton network area showed markedly increased seismicity, the $M = 6.8$ El Centro earthquake of 15 October 1979. The absence of an increase in seismicity near Palmdale, where the frictional strength due to the normal stress accumulated between 1973 and 1978 disappeared within 6 months in 1979 (Fig. 9), indicates that the San Andreas fault is not yet in a critical state for right-lateral strike-slip in that area. If in subsequent such episodes there begin to be associated higher levels of seismicity, then the fault might be assumed to be approaching the point of failure.

The general increase in the numbers of moderate to large earthquakes beginning in 1978 and 1979 correlates well with the onset of the strain episode, as Savage *et al.* (*11*) pointed out. Although the areas showing the greatest increase in seismicity are not closely monitored for strain accumulation, except for the Salton Sea area, the large areal extent of the strain episode makes it plausible that the strain and seismicity are causally related.

Conclusions

In southern California, the San Andreas fault constitutes a mature seismic gap. From the San Bernardino vicinity north to the Carrizo Plain, the long-term displacement rate is between 25 and perhaps 45 mm/year, and great earthquakes yielding 4 m or more in displacement are now possible given the 125 years since the last great earthquake in 1857. From Cajon Pass near San Bernardino south to Salton Sea there have been no historic major earthquakes, and provided most of the potential displacement is associated with earthquakes, this segment is a prime candidate for a great earthquake.

The displacements associated with each event, the long-term rates of displacement, and the timing of the prehistoric events, if more precisely known, could be used to establish a model for the behavior of each segment of the fault. If, for example, the time-predictable model adequately characterized its behavior, the next event on any segment might be much more accurately forecast. There is thus an imperative need for more extensive studies of the past behavior of the San Andreas fault. Seismicity throughout California has risen dramatically over the past 2 years, returning to levels that in the past have been associated with earthquakes of $M \geq 7$. A 28-year hiatus in occurrence of such major events has already been concluded with the occurrence of an $M > 7$ event near Eureka in November 1980. If the rate of occurrence of such major events has returned to previous levels along with the resurgence of moderate earthquake seismicity, then the annual probability for such an earthquake somewhere in California has risen to about 13 percent per year.

There is no strong evidence to indicate where the next $M \sim 7$ event might occur. Based on past patterns of seismicity, the San Jacinto fault south of San Bernardino is a candidate, but there are other possibilities.

The seismicity increased approximately concurrently with a change in the pattern of strain accumulation in southern California. The change is one that would favor strain release on the right-lateral strike-slip or normal faults having a northwesterly to northerly trend which characterize the San Andreas fault system and the Basin and Range faults. The geodetic observations are not extensive or frequent enough to establish the correlation in every locale in which the increase in seismicity has been observed. It appears, nevertheless, that the strain buildup is nonlinear and that there may be periods in which an increased susceptibility to damaging earthquakes may be identified.

We conclude that California is likely to experience one or more $M > 7$ earthquake in the next decade. However, without extensive real-time observations of strain and seismicity in the areas of principal concern, more precise and reliable predictions of such events are unlikely in that time. There is not yet an adequate observational base against which to test physical models of the failure process that leads to great earthquakes. Reliance on empirically established precursory phenomena will still be necessary until a better formulation of a theoretical model is possible. Both as a means of developing the observational basis for better models and collecting data which will have value as precursory signals, an extensive network for closely monitoring and for analyzing strain and seismicity data in real time is imperative.

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Regulation of Circadian Rhythmicity

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It's been a hard day's night.
I should be sleeping like a log.
—The Beatles, 1964

Daily rhythms in behavior, such as rest and activity, are so familiar and so clearly coupled to the cycle of night and day that they did not elicit systematic scientific investigation until the present century. It was, naturally, believed that they merely reflected responses to the alternation of light and darkness in the environment. This interpretation was first questioned in 1729 when the French astronomer de Mairan observed that the daily leaf movements of a plant persisted in constant darkness (*1*). Two hundred years later, the persistence of periodicity in the activity of wild mice housed in constant light led Johnson to postulate the presence of a "self-winding and self-regulating physiological clock" (*2*). The existence of endogenous clocks did not become widely accepted, however, until the 1950's (*3*). The fact that the periods of free-running rhythms (that is, those observed under constant conditions) differ from those of all known environmental cycles and differ among individuals excludes the possibility that cryptic environmental cues drive or time these rhythms. By now, daily rhythms in a variety of organisms and in many functions within an individual have been shown to free run in nonperiodic environments (*4*–*6*). Such self-sustained oscillations with periods close to 24 hours are called circadian rhythms.

Although circadian rhythms are generated endogenously they are regulated by exogenous cycles, especially those of light and darkness. The effects of environmental cycles on two circadian rhythms in humans are illustrated in Fig. 1. During the first 6 days, while the subject was living under natural conditions, his sleep-wake cycle and body-temperature rhythms expressed period lengths of 24 hours and maintained stable phase relationships to the day-night cycle. On the seventh day, the subject was isolated underground without access to any time cues (*7*). During the subsequent 17 days of isolation, his sleep-wake cycle and body-temperature rhythms drifted toward later times each day and expressed a free-running period of 25.4 hours. After returning to natural conditions on the 24th day, his rhythms again became synchronized to the 24-hour day. If the subject subsequently made a transcontinental flight from Europe to America, his rhythms would shift (while he experienced "jet lag") to match the phase of the local environmental cycle. The imposition of period and phase con-

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