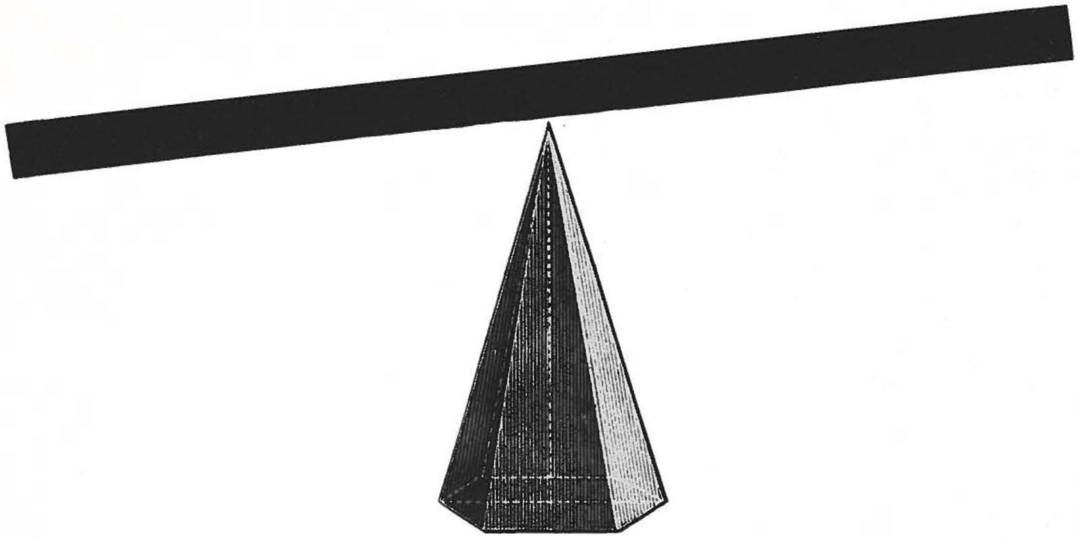


THE SAN ANDREAS FAULT

Its significance in California's past and future

By CLARENCE R. ALLEN

EVERY earthquake on, or close to, the San Andreas fault, no matter how small, seems to renew interest in this intriguing geologic feature. Is it true, as the newspapers usually say, that these earthquakes represent the San Andreas's "periodic shrug"? What *is* the San Andreas fault, and what do geologists and seismologists expect in the way of future activity?

The San Andreas fault is literally a gigantic fracture of the earth's crust—the principal member of a great fracture system that cuts obliquely across the state of California from Point Arena to the Imperial Valley. Although other fractures of this type are known at scattered localities throughout the world, perhaps none is so long, so well exposed, and so thoroughly studied as the San Andreas. That the San Andreas is truly a fracture is indicated not only by geologic evidence of rock bodies that have been offset by it, but also by systematic ground fractures that develop along the fault during our largest earthquakes.

Seismologists believe that the fracturing that causes most California earthquakes commences at a depth of about 10 miles, but only during the large earthquakes does this fracturing actually reach and displace the surface of the ground. At such times the fracturing probably extends a comparable distance below the point of origin—perhaps to the base of the earth's crust at 20 to 30 miles. This is about as much as can be said in response to the often-asked question: "How deep is the San Andreas fault?"

It is, of course, the largest earthquakes that are of primary concern to the geologist, not only because they are the most disastrous, but also because the associated displacements of the ground surface tend to form much of the landscape around us. Most mountains in southern California owe their existence to repeated vertical displacements along bounding faults.

A significant difference between the San Andreas and many other active faults is that the displacements along it have been predominantly horizontal rather than vertical. During every large historical earthquake on the San Andreas fault that has been studied in detail, ground offsets indicate that the west or coastal part of California has moved northward relative to points across the fault to the east. Displacements of 15 to 16 feet were common along the part of the fault north of San Francisco during the 1906 earthquake. In the 1940 Imperial Valley earthquake the banks of the All-American Canal were horizontally offset nearly 15 feet, and the nearby International Border was presumably displaced a like amount. The sparse historical records of the 1857 Fort Tejon earthquake suggest similar displacements at that time along the segment of the San Andreas fault north of Los Angeles.

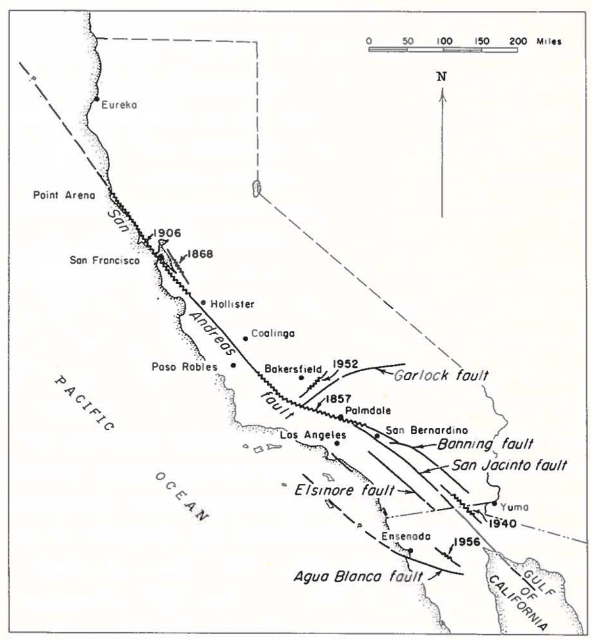
The geological evidence suggests that this same type of movement has characterized the fault throughout its history, which probably goes back at least 100 million years. Indeed, Hill and Dibblee recently have suggested that the *total* displacement along the fault caused by repeated movements during this time may be as much as 350 miles!

Although isolated segments of the San Andreas fault had been recognized by geologists prior to the turn of the century, its continuity and geologic importance were not fully appreciated until after the San Francisco earthquake of 1906. As shown on the map at the right, the slippage that caused this earthquake broke the ground along the fault from Point Arena almost to Hollister—a distance of 190 miles. Investigations following the earthquake showed that the same physiographic and geologic features that characterized the fault in this segment also continued several hundred miles southeast, at least as far as San Bernardino, thus suggesting for the first time the continuity of the fault across most of the state.

What are some of these characteristic features? Most obvious is the tendency of the fault to occupy a broad trench and to be marked by exceptionally linear stream valleys. This pattern is caused not only by actual ground displacements, but perhaps even more by preferential stream erosion in the soft crushed rocks of the fault zone, which attains widths of several miles in places.

Such "rift topography," as it is called by geologists, is far more apparent from the air than on the ground. Thousands of people unknowingly cross the fault on highways every day, but few people escape noticing the anomalous topography when flying across the fault at high altitude. It is even more spectacular in oblique photographs taken from rockets over White Sands, New Mexico.

The problem of what happens at the ends of the San Andreas fault is a jackpot question that geologists wish they could answer—and the question is especially perplexing if horizontal



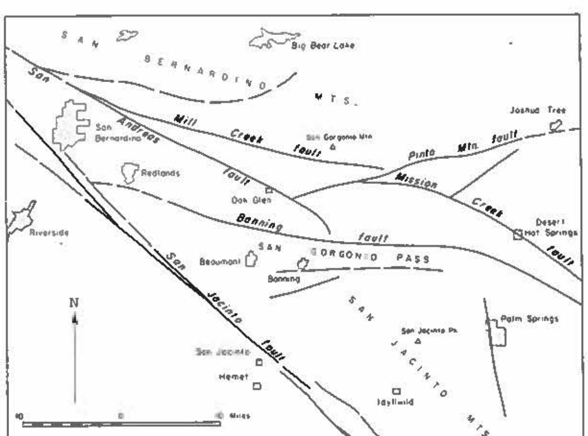
San Andreas and associated fault zones in California and northern Mexico. Zigzag lines show where surface of ground was broken during historic earthquakes.

Aerial photograph of one of the many branches of the San Andreas fault. This very noticeable earthquake line, located just north of Indio, was caused by earthquakes in prehistoric times.

Oblique aerial view of the San Andreas fault in the Carrizo Plain area, 45 miles west of Bakersfield, California.

displacements have amounted to hundreds of miles. About 100 miles north of Point Arena, the seaward prolongation of the fault intersects the great Gorda submarine escarpment, and some investigators have suggested that the fault veers sharply westward to follow this escarpment and its extension, the Mendocino escarpment. A broad zone of earthquake epicenters continues northwestward, however, and it seems more likely that the fault zone continues along this trend to a point off the Oregon coast where the epicenters finally die out.

On the southern end of the San Andreas fault, complications arise even before the fault trace disappears into the Gulf of California. Epicentral locations of earthquakes leave no doubt that the zone as a whole extends into the Gulf, but the fault frays out into a number of great branches southeast of San Bernardino, and it is not clear which, if any, of the branches truly deserves the parent name.



The fault pattern in the San Andreas fault zone near San Gorgonio Pass, 70 miles east of Los Angeles.

In southern California, the northwestward-trending San Andreas fault comes into conflict with a great system of east-west structures exemplified by the mountain ranges from Santa Barbara to San Bernardino—the so-called Transverse Ranges. It is on the north side of this zone that the San Andreas fault makes its abrupt eastward bend, and even more severe complications take place within the Transverse Ranges themselves. It appears that faults associated with the Transverse Range and San Antonio systems have alternately offset one another, so that the modern breaks do not necessarily represent the trend or position of former breaks.

A good example of this literal "butchery" is given by the fault pattern in San Gorgonio Pass, 70 miles east of Los Angeles. As is shown on the map below, the San Andreas is not a continuous surface break through this area; many of the branches evidently represent former through-going lines of faulting that subsequently have been deformed and disrupted.

At the present time, the San Jacinto fault appears to be the most active member of the San Andreas system in southern California, and the southeastward prolongation of its trend is marked by features of recent displacement across the delta of the Colorado River and into the Gulf of California. The fault pattern of this area, as well as that of the Gulf floor itself, suggests that the San Andreas fault dies out southeastward as a great series of parallel *en echelon* fractures.

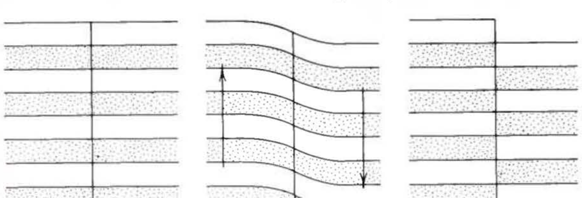
What caused the 1906 earthquake? Following study of the 1906 displacements, H. F. Reid postulated that the fracturing had been the result of a slow build-up of regional shear-strain in the years prior to the earthquake. The coastal part of California west of the fault was envisaged as drifting uniformly northward with respect to the continental part of the state farther east, and the resulting distortion within the fault zone presumably had become so great in 1906 that the rocks broke and caused the earthquake. Thus the observed displacements at the time of the earthquake were thought to be the result of elastic rebound of rocks within the fault zone, caused by slowly accumulating regional strain.

An obvious test of Reid's elastic rebound theory was to measure, at intervals of several years, the precise relative positions of survey stations

Displacement of this Imperial Valley orange grove occurred in the 1940 earthquakes. At the International Border, about 1 mile south, the horizontal slip was almost 15 feet.

located at some distance from the fault, and on both sides of it. Any continuous drift of the two blocks should show up as progressive displacements within the triangulation network.

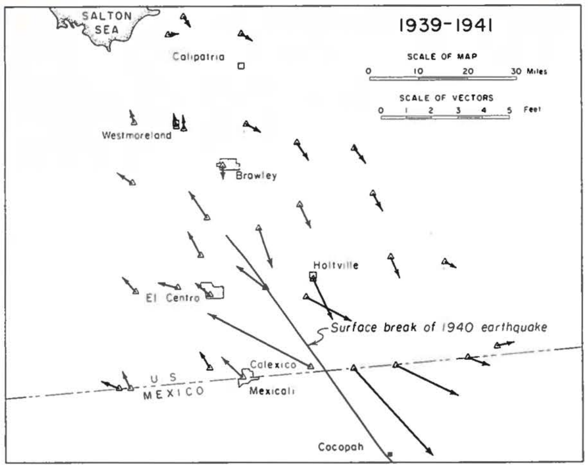
A vigorous surveying program therefore was initiated by the U.S. Coast and Geodetic Survey following the 1906 earthquake, utilizing networks first surveyed as early as 1851. Despite some early difficulty in adjustment of the survey data—a real mathematical problem in itself—it has now been firmly established that a drift such as Reid postulated is indeed taking place. Across the northern part of the fault zone, for which the most complete data exist, the coastal part of California is drifting uniformly northward at about two inches per year relative to parts of the state farther east; the resulting strain must be accumulating in the fault zone.



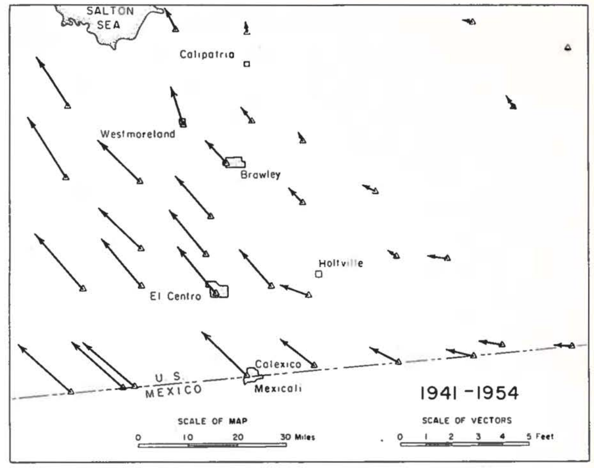
A schematic representation of the elastic rebound theory. Unstrained rocks (A) are distorted by relative drift between the two blocks (B), causing strains within the fault zone that finally become so great that the rocks break along the fault and rebound to a new unstrained configuration (C).

Although the basic principles of the elastic rebound theory have thus been pretty well demonstrated, the fundamental question of what *causes* the drift remains virtually as unanswered as it was in 1906. Certainly some sort of deep-seated rock flowage is necessary, but there is still spirited debate among geologists and geophysicists as to whether this is caused by crustal contraction, convection currents in the deeper layers, forces resulting from the earth's rotation, or still other causes.

A diagrammatic substantiation of the elastic rebound theory is given by U.S. Coast and Geodetic Survey measurements in the Imperial Valley, which is one of the most seismically active areas along the fault zone. The maps on the following page show, by means of vectors, the relative displacements of triangulation stations in this area during two periods: the relatively short interval from 1939 to 1941, and the longer subsequent interval from 1941 to 1954. Note that the 1939-1941 period includes the 1940 earthquake, and the vectors shown on the map are largely the result of ground displacements at that time. These geodetic measurements support the field observations in showing maximum displacement near the International Border. As



Displacements of triangulation stations (note vector scale) in the Imperial Valley from 1939 to 1941. (1939 data includes surveys started in 1935). Displacements are caused primarily by elastic rebound during the 1940 earthquake.



Displacement of triangulation stations in the Imperial Valley from 1941 to 1954—assuming the stations on the east side of the valley to have remained stationary. Data for these maps are from the U.S. Coast and Geodetic Survey.

predicted by the theory, displacements decrease rapidly away from the fault trace, corresponding roughly to the limits of the zone that was most strained prior to the 1940 earthquake. The 1941-54 map shows the continued slow build-up of strain since that time, and it is interesting to note that the great width of the distorted area (at least as wide as the map) supports the geological evidence of a wide fault zone with many branching and parallel fractures. The relative rate of drift of the two sides of the Imperial Valley may be even slightly greater than the two inches per year measured over a longer period in the northern part of the state.

It is dangerously tempting to use the measured drift rate together with the 1906 field observations to extrapolate fault activity into the future. One might argue that, at the rate of two inches per year, it would have taken about 100 years to accumulate sufficient strain to cause the elastic rebound of 16 feet that was commonly observed along the fault in 1906; and inasmuch as the strains are still accumulating, the hasty conclusion might be reached that San Francisco would experience another great earthquake in 2006. This hypothetical 100-year period would be even more disconcerting to those of us living in the southern part of the state, where the last great earthquake on the main San Andreas fault occurred in 1857! Some of the factors that make such predictions unwarranted at the present time are:

1. There is no assurance that the ground displacements during the next great earthquake will be the same as those measured in 1906, although the historical evidence does suggest that most of the San Andreas fault is characterized by infrequent major shocks rather than by many small ones.

2. Some part of the accumulating strain presumably is non-elastic; that is, the drift must be causing some permanent deformation of the rocks that will not be recovered as elastic rebound.

3. Strain must be relieved to some extent by faults subsidiary to the San Andreas. For instance, the 1952 Kern County earthquake—though not on the San Andreas fault—must have relieved some of the regional strain.

4. The rate of strain has not been firmly established for the part of California near Los Angeles, although there is every geologic reason to expect the distortions here to be of the same order of magnitude as those measured farther north and south. Even in these better-studied areas, more needs to be known about the regional extent of distortion before firm quantitative conclusions can be drawn.

But in spite of our inability to make a firm prediction of the next major movement on the San Andreas fault, the general expectations based on knowledge of the accumulating strains and earthquake history seem valid. Most geologists would not be surprised at a great earthquake along the fault's central or southern portion within the next 25 years. Certainly the segment of the fault between Hollister and San Bernardino now appears far more dangerous than the segment of the fault near San Francisco which broke in 1906.

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About the authors

Lee A. DuBridge, who writes on "The Shape of the Future" on page 2, has been president of the California Institute of Technology since 1946. His article has been adapted from an address delivered at the inaugura tion of Dr. Henry David as president of the New School for Social Research in New York City on October 23, 1961.

Clarence R. Allen, associate professor of geology at Caltech, discusses "The San Andreas Fault—Its Significance in California's Past and Future" on page 16. Dr. Allen's interest in earth surfaces began when he entered Reed College in Portland, Oregon, but found that he couldn't take a geology course there, so he ended up with a BA in physics instead, in 1949. This led naturally to the study of geophysics when he came to Caltech to get his MS in 1951, and his PhD in 1954. After a year of teaching at the University of Minnesota, he returned to Caltech in 1955 as assistant professor of geology. He has been associate professor since 1957. His background in geophysics, physics, and geology—plus a good working knowledge of seismology—comes in handy for his current research on the San Andreas fault.

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