THE TECTONIC ENVIRONMENTS OF SEISMICALLY ACTIVE AND INACTIVE AREAS ALONG THE SAN ANDREAS FAULT SYSTEM*

By

Clarence R. Allen

California Institute of Technology
Pasadena, California

On several recent occasions the author has made the statement that in California the geologist is in a somewhat better position than is the seismologist to delineate areas of high seismic hazard from great earthquakes, simply because of the inadequacy of the statistical sample based on the relatively short seismic history as compared to the much greater time span that the geologist is able to interpret from the Quaternary geologic history. A number of recent studies have pointed out the lack of correlation between areas of current seismic activity and areas of great earthquakes in the historic past (Niazi, 1964; Allen and others, 1965; Ryall and others, 1966; Brune and Allen, 1967a). The purpose of this paper is to go one step further and ask if the geologist can say anything about the maximum size of earthquakes that might be generated in any area on the basis of its distinctive geologic features. More specifically, are different segments of the San Andreas fault--which currently show markedly varying mechanisms of strain release ranging from continuous creep to infrequent great earthquakes--characterized by contrasting geologic features that might suggest that these differences in current behavior are permanent rather than temporary characteristics of these individual fault segments? That is, are there geologic features that might somehow allow us to predict that some segments of the fault will be the repeated sites of great earthquakes, whereas other segments might never experience great earthquakes but instead be characterized by continuous creep or by numerous smaller shocks? If those same segments of the fault that show distinctive strain-release characteristics also show distinctive geologic characteristics, then one must suspect that the answer to this question is indeed "yes," although such an affirmative answer must be contingent on a demonstration that this is mechanically reasonable and possible.

Most geologists had assumed until recent years that fault scarps and other physiographic features of Quaternary displacement along the San Andreas fault had resulted solely from large earthquakes, inasmuch as ground displacements were not usually thought to have been associated with earthquakes of less than about magnitude 6.5 (Tocher, 1958; Allen and others, 1965). Numerous field studies within the past few years, however, have indicated that both continuous fault creep and surficial

*California Institute of Technology, Division of the Geological Sciences Contribution No. 1496 displacements during small earthquakes are much more prevalent than had been suspected. Creep has now been documented along most of the San Andreas fault between the Hollister area and Parkfield (Tocher, 1960; Brown and Wallace, this publication), along the Calaveras-Hayward fault system (Radbruch and others, 1966; Rogers and Nason, this publication), and along the Imperial fault in the Imperial Valley (Brune and Allen, 1967b). Appreciable and unexpected displacement during a relatively small earthquake was dramatically illustrated by rupture of some 40 kilometers of the San Andreas fault during the magnitude 5.5 Parkfield earthquake of 1966 (Brown and others, 1967), as well as by rupture along 10 km of the Imperial fault during a shock of only magnitude 3.6, also in 1966 (Brune and Allen, 1967b). Indeed, these carefully studied very recent occurrences suggest that many previous similar events have probably gone undetected, and that possibly fault topography can develop along "active" faults just as well by this mechanism as by large earthquakes alone. Thus it seems that the necessity for postulating intermittent great earthquakes along all segments of the San Andreas fault has been removed, at least from the point of view of geologic evidence. The only geologic tool for distinguishing between creep and intermittent sudden displacements in the past seems to be the study of offset stream patterns, but Wallace's (this publication) careful study of offset drainages in the Carrizo Plain--the most ideal of all areas--indicates that the drainage history cannot be followed far enough back in time to give diagnostic evidence on this point prior to the last great earthquake here in 1857.

If one looks at the over-all seismic activity along the San Andreas fault zone within recent years, he finds that the activity is concentrated in three general areas, designated on figure 1 as the northern California active area, the central California active area, and the southern California active area. These three regions have included the great bulk of the small and moderate earthquake activity along the San Andreas fault since the establishment of seismograph networks throughout the state, and probably since the time of the great 1906 earthquake (Byerly, 1937; Niazi, 1964; Allen and others, 1965; Ryall and others, 1966). It is significant, moreover, that it is only in these areas that creep along the fault has been recognized. In contrast, the two intervening areas of the fault have been almost completely quiescent during this same period, and this remarkable inactivity--comparable to that of stable continental areas--extends well down into the micro-earthquake range, at least in the southern segment (Brune and Allen, 1967a). But the most striking fact is that these two segments of the fault that are currently quiet are the very two segments that ruptured during the only two truly great earthquakes on the fault within the historic record--those of 1857 and 1906. Furthermore, several lines of evidence suggest that these two segments of the fault are geologically distinct from the remaining parts.

Although the trace of the 1857 break is not completely known, available evidence suggests that the fault was ruptured for at least 350 km from Cholame, 20 km south of Parkfield (fig. 1), to near San Bernardino

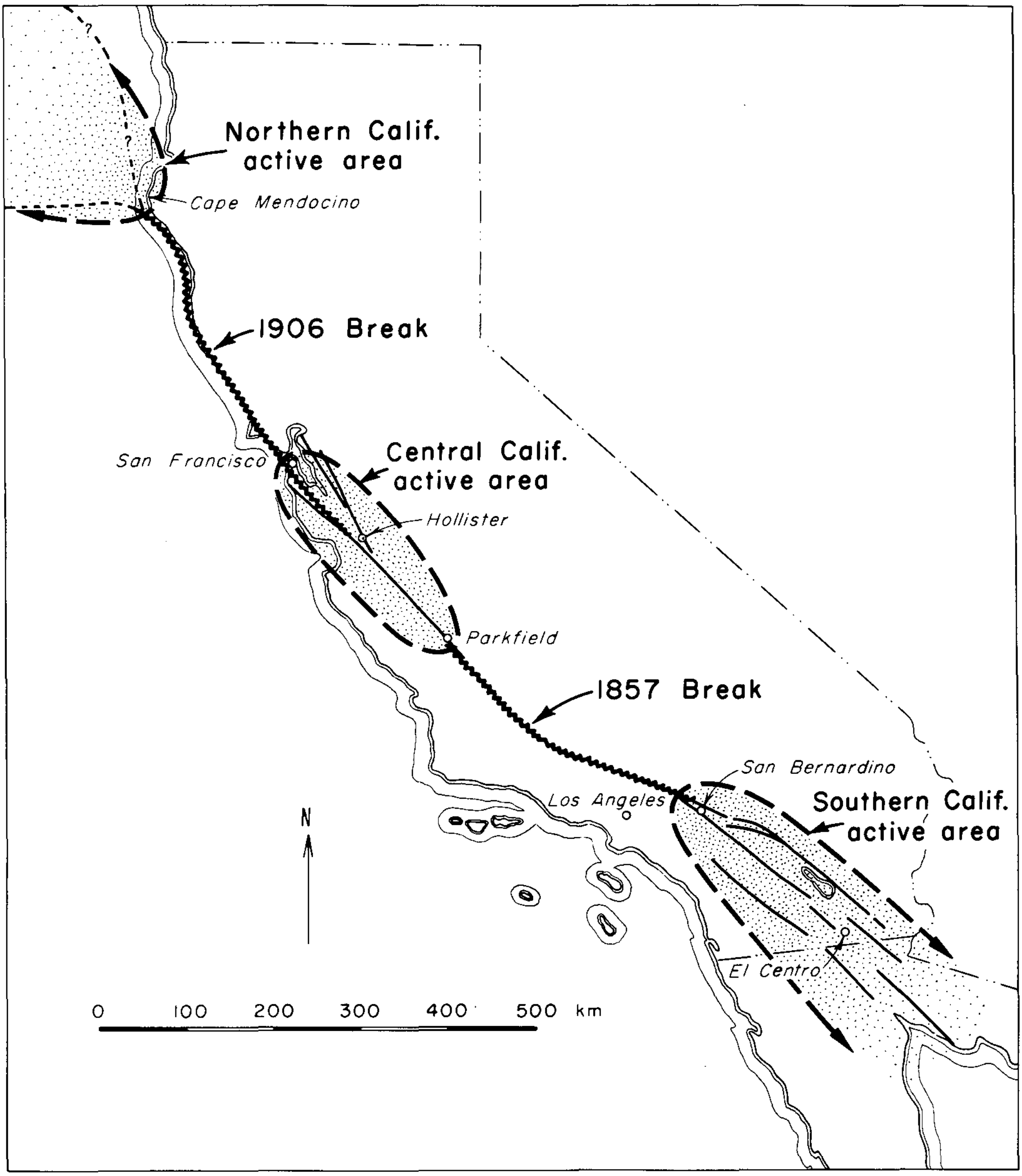

Figure 1.--Areas of contrasting seismic behavior along the San Andreas fault zone in California.

(Lawson and others, 1908; Wood, 1955; Allen and others, 1965). The San Andreas fault is a relatively simple and easily followed break throughout most of this segment, but southeast from San Bernardino it splits into a number of branches, and there is increasing evidence of tectonic extension as the Gulf of California is approached. En echelon faults represent the typical tectonic pattern of this southeastern region (Biehler and others, 1964), perhaps reflecting transform faulting along the crest of the East-Pacific rise, and the crustal structure becomes progressively more oceanic toward the southeast. Even in the Salton Sea area, at the northernmost end of the Gulf of California structural province, an anomalous crust of either greatly reduced thickness or increased density is indicated by gravity data (Biehler, 1965), and the fact that earthquakes in this region have typical swarm characteristics (Richter, 1958) further substantiates the unique geological character of this province. Northwest from San Bernardino the fault can be followed as a single, relatively simple break, at least as reflected in Quaternary faulting, as far as Cholame, where a distinct en echelon offset of about 1 km takes place in the fault trace--the first major interruption northwest of San Bernardino. This is apparently the reason for the existence of Cholame Valley at this location, an unusual feature in the otherwise rugged topography along the fault trace (Dickinson, 1966). Similarly, a major change in basement rock types adjacent to the fault takes place near Cholame, where Franciscan basement on the east side of the fault contrasts markedly with the Sierran basement that occurs on both sides of the fault for several hundred kilometers to the southeast. Inasmuch as the Franciscan rocks were probably laid down directly on oceanic crust (Bailey and others, 1964; Ernst, 1965), this difference in basement rock types may have much more profound significance to fault mechanics than the surface exposures themselves might imply. An additional distinct characteristic of the 1857 segment of the fault is the abrupt bend of about 30° that takes place midway along its length, in contrast to the relatively straight sectors both to the northwest and southeast.

The segment of the fault that broke in 1906 (fig. 1) possesses many of the same characteristics as the 1857 segment, although the fact that much of this northern part of the fault is under water permits greater speculation. This segment of the fault is similarly a relatively simple and single break, bounded at both ends by areas of splaying and complication. The 1906 break ended on the south near Hollister, where major branching of the fault takes place in its junction with the Calaveras-Hayward fault system. Assuming that the break on the north continued into the Cape Mendocino area, which seems reasonable in view of the faulting at Shelter Cove in 1906 (Lawson and others, 1908), the fault is again approaching an area of very complicated branching, at least as suggested by the submarine topography and magnetic anomalies (Shepard and Emery, 1941; Menard and Dietz, 1952; Raff and Mason, 1961; Wilson, 1965). Similarly, in a manner analogous to that of the 1857 segment, a major and abrupt bend takes place midway in this northern segment, as recently documented by Curray and Nason (1967). Sierran basement apparently lies against Franciscan basement throughout most of this segment, but it is clear that the underlying crust must become completely oceanic in nature at about the point where the 1906 break ended northward, in a manner somewhat analogous to the transition to oceanic crust in approaching the Gulf of California at the opposite extremity of the fault. Most of the segment of the fault that broke in 1906 has since been remarkably quiescent in its seismicity (Niazi, 1964; Ryall and others, 1966).

Thus it is herein suggested that infrequent great earthquakes are the typical mechanism of strain release along the two segments of the fault that broke in 1857 and 1906, both of which are relatively simple and free of splaying branches, both of which have abrupt curves near their midpoints which might serve as temporary "locking" devices, both of which lack small earthquakes and creep, and both of which are probably characterized by high normal stresses across the fault. On the other hand, it is suggested that the geologic nature of the three remaining areas is such that they perhaps never experience truly great earthquakes, but that accumulating strain in these areas is relieved by moderate and small earthquakes, together with creep. Tectonic extension is more evident in these areas, and it seems likely that normal stresses across the fault zone are reduced, thus permitting this type of strain release. This viewpoint is supported by the relatively low stress-drops measured from recent earthquakes in these areas (Aki, this publication; Brune and Allen, 1967b). Inasmuch as these geologic contrasts are relatively permanent, it is further argued that the present behavior is characteristic of the entire Recent geologic epoch.

There is, of course, a complete continuum of earthquakes from the "moderate" to the "great" range, so that one should not expect completely distinct and mutually exclusive environments associated with the two categories. That there is some overlap is exemplified by the great variety of types of earthquakes on the San Andreas fault that have hit the San Francisco Peninsula within the historic record (for example, 1838, 1906, 1957). Nevertheless, for the fault as a whole, the contrasts in seismic behavior appear more impressive than the similarities, as was emphasized many years ago by Byerly (1937) in his statement that "it appears that the regions of greatest fault displacement at the time of great shocks are distinct from those of more or less continuous activity of a minor sort."

Whether or not the absence of seismic activity along the 1857 and 1906 sectors of the fault will continue up to the very day of the next great earthquake is unknown but it seems unlikely. Foreshocks may commence several months or years before the main event, as demonstrated by Fedotov (1967) for parts of the Kurile Islands active zone. Nevertheless, according to the point of view presented herein, the total time involved in the foreshock and aftershock sequences should be small as compared to the much longer period during which the fault remains essentially quiescent.

An additional factor aiding high creep rates along the segment of the San Andreas fault between Hollister and Parkfield, as well as along the Calaveras-Hayward system, may be the great abundance of Franciscan serpentine within the fault zone in these sectors. Anyone who has seen the striking evidence of shearing and mobility demonstrated by these chaotic outcrops cannot help but be impressed by the possible mechanical significance of this particular rock type. Brown and Wallace (this publication) indicate that although a relatively constant creep rate of about 2 centimeters per year characterizes the fault between Hollister and Parkfield, this creep rate drops off abruptly to zero between Parkfield and Cholame; and it is very near Cholame that the last outcrops of serpentine occur within the fault zone as it is traced southward. That these serpentine bodies are relatively massive and of significant size is indicated by the recent magnetic studies of Hanna (this publication), and the increasing evidence of the shallowness of earthquake activity along the fault makes it a reasonable hypothesis that basement rock types such as serpentine might indeed affect the nature of surficial strain release along the fault. Likewise, parts of the Calaveras-Hayward fault system along which creep has been documented are areas in which serpentine is relatively abundant, whereas the main San Andreas fault north of Hollister (the 1906 segment) lacks both abundant serpentine and evidence of creep. At the moment, this possible correlation between creep rates and the presence of significant amounts of serpentine within the fault zone must be regarded as pure speculation, but it represents an interesting hypothesis to test in future work along the San Andreas fault and other similar features.

One might question whether, if strain is taking place uniformly throughout the length of the San Andreas fault system, infrequent great earthquakes that are generated on some segments of the fault are mechanically compatible with creep and smaller earthquakes on other segments. Several authors have pointed out that small shocks alone cannot serve as a "safety valve" for the prevention of large shocks, inasmuch as an inordinate number of such small shocks would be required--far more than is indicated by measured relationships between earthquake frequency and magnitude (Allen and others, 1965). But, if together with small shocks, we include creep and moderate earthquakes--those up to a magnitude of about 7-1/2--then it appears that a mechanical balance is indeed possible. Brune (in press) has recently calculated that small and moderate earthquakes that have occurred in the Imperial Valley during a 34-year period (including the 1940 shock of magnitude 7.1) may be sufficient to have relieved the 8 centimeters per year of shear strain across the region measured by Whitten (1956), provided that primarily plastic flow occurs below about 7 km. A modest amount of creep would make this balance even more reasonable and permit a somewhat greater thickness of the elastic layer, and there are several suggestions of creep along faults within the valley.

It should be noted that in lumping "moderate" earthquakes in the magnitude 7 range with the smaller events, a number of damaging and very significant shocks are included. Thus not only the 1940 Imperial Valley earthquake is included, but also shocks such as the 1836 and 1868 earthquakes on the Hayward fault. Although the magnitudes of these shocks are not known, the lengths of fault rupture associated with them make it unlikely that they were in any sense great earthquakes such as the 1857 and 1906 events. The 1838 earthquake on the San Andreas fault is a more questionable event, inasmuch as it possibly could have been a very large earthquake with faulting comparable to that in 1906 (Louderback, 1947). From an engineering point of view, however, these shocks were probably similar to the larger events in terms of local shaking and damage, so that the argument presented in this paper may have little bearing on the relative seismic hazards of different parts of the fault zone.

An obvious conclusion from the line of reasoning presented herein is that, if strain is accumulating relatively uniformly along the entire length of the San Andreas fault, the most likely locus for the next great earthquake is the same segment that broke in 1857, and the second most likely is the 1906 segment. This is in agreement with Richter's (1964) conclusion. If, on the other hand, the 1838 earthquake in the northern part of the state was as similar to the 1906 event as Louderback (1947) suggested it might have been, then the rate of occurrence of great earthquakes in the two segments is different, and possibly the 1906 segment is by now again the most dangerous. Lacking positive evidence of a great extent of faulting in 1838, the author prefers the former viewpoint.

There is some suggestion that similar relationships between geology and strain-release mechanisms exist along other major strike-slip fault systems of the world. Most of the moderate and smaller earthquake activity along the Alpine fault system of New Zealand takes place north of the area where it splays out northward into a complex series of branching faults, a number of which have been characterized by damaging but not great earthquakes within the historic record (Richter, 1958). South of this area, however, in the central part of the South Island, the Alpine fault is a relatively simple, single, continuous break that has abundant evidence of Recent displacement but almost totally lacks even small earthquakes at the present time (Hayes, 1953; Suggate, 1963). Still farther south, as the fault approaches the continental margin in Fiordland, regional seismic activity again increases. This quiet segment of the fault has not recorded a great earthquake within the historic record, but analogy with the California situation suggests that this segment should be among the most suspect for a great earthquake in the future, assuming that strain is taking place uniformly across New Zealand as it appears to be in California.

In a situation somewhat similar to those in California and New Zealand, but apparently being viewed at a different stage in its cycle of activity, is the relatively continuous 900-km segment of the North Anatolian fault zone in Turkey, between Abant and Karlıova (Allen, 1966). This segment has been the locus of several large earthquakes since 1939, all of which have been associated with right-lateral faulting that has sequentially extended over virtually the entire fault length. This sort of thing had evidently not happened prior to 1939 for perhaps several hundred years, judging from the fact that of the many farmers living along the fault trace who were interviewed by the author, none could remember ever having experienced or having heard from their families of previous faulting similar to that which occurred in 1939 and the succeeding years, despite the abundance of Quaternary scarps and other physiographic evidence of "activity" along the fault. West of Abant, however, where the fault system splays out into many subparallel branches as it approaches the Aegean Sea, smaller activity has been common for many years going well back into the historic record. It is also noteworthy for comparison with the California situation that surficial faulting during the great 1939 earthquake along the eastern segment of the North Anatolian fault ended on the west at the en echelon offset in the fault near Niksar and on the east at the en echelon offset near Erzincan (Paréjas and others, 1942; Allen, 1966). Between these two localities, the fault trace is simple and continuous.

In summary, the author suggests that those two segments of the San Andreas fault that have been characterized by great earthquakes within the historic record, in 1857 and 1906, have likewise generated infrequent great shocks throughout the recent geologic past, and that the present absence of small earthquakes and creep is typical of the past and probable future behavior between large shocks. The three remaining segments of the fault, on the other hand, are currently the sites of abundant small and moderate earthquakes, together with fault creep, and it is suggested that this behavior stays relatively constant with time; truly great earthquakes are unlikely in these areas. The reasoning behind these suggestions is that the two types of fault segments have distinct geologic characteristics: The 1857 and 1906 zones are both characterized by (1) a single, relatively simple fault trace as reflected by Quaternary displacements, (2) an absence of splaying branch faults, and (3) a marked bend midway in each segment that might well form a "locking" device that temporarily resists accumulating strain. The three active areas, on the other hand, show considerable evidence of complexities in the fault trace such as branching, splaying, and en echelon breaks. Although several authors have argued that the maximum size of an earthquake to be expected along a fault is roughly a function of its total length (Albee and Smith, 1966), it is argued herein that a further critical factor is the relative simplicity of the fault trace; complexly branching fault systems, regardless of their total lengths, are likely to be characterized by smaller and more frequent earthquakes than single continuous breaks, at least for strike-slip faults. It is further suggested that basement rock types may have an effect on the type of seismic strain release observed at the surface, and specifically that high creep rates along parts of the San Andreas fault may be related to the local abundance of serpentine within the fault zone.

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DISCUSSION

T. M. Atwater (Scripps Institute of Oceanography, La Jolla):
Several people have mentioned the extreme shallowness of foci on the San Andreas fault. Just how shallow are these?

C. R. Allen:
I would guess at a figure of about 8 km as being a good average, although no really large earthquakes have taken place on the fault during the time in which good depth determinations have been obtainable, and the large shocks may be deeper. In probably the most precise measurements to date, I believe that Jerry Eaton has obtained depths ranging from 0 to about 15 km for aftershocks of the Parkfield earthquake.

E. M. Buckingham (City of Oakland):
I would like to emphasize the correlation between great earthquakes and curvature of the rift, and also that the splaying out may be an attempt of the rift to straighten itself out.

C. R. Allen:
I agree.