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RELATIONSHIP BETWEEN SEISMICITY AND GEOLOGIC STRUCTURE IN THE SOUTHERN CALIFORNIA REGION

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ABSTRACT

Data from 10,126 earthquakes that occurred in the southern California region between 1934 and 1963 have been synthesized in the attempt to understand better their relationship to regional geologic structure, which is here dominated by a system of faults related mainly to the San Andreas system. Most of these faults have been considered "active" from physiographic evidence, but both geologic and short-term seismic criteria for "active" versus "inactive" faults are generally inadequate.

Of the large historic earthquakes that have been associated with surficial fault displacements, most and perhaps all were on major throughgoing faults having a previous history of extensive Quaternary displacements. The same relationship holds for most earthquakes down to magnitude 6.0, but smaller shocks are much more randomly spread throughout the region, and most are not clearly associated with any mappable surficial faults.

Virtually all areas of high seismicity in this region fall within areas having numerous Quaternary fault scarps, but not all intensely faulted areas have been active during this particular 29-year period. Strain-release maps show high activity in the Salton trough, the Agua Blanca-San Miguel fault region of Baja California, most of the Transverse Ranges, the central Mojave Desert, and the Owens Valley-southern Sierra Nevada region. Areas of low activity include the San Diego region, the western and easternmost Mojave Desert, and the southern San Joaquin Valley. Because these areas also generally lack Quaternary faults, they probably represent truly stable blocks. In contrast, regions of low seismicity during this period that show widespread Quaternary faulting include the San Andreas fault within and north of the Transverse Ranges, the Garlock fault, and several quiescent zones along major faults within otherwise very active regions. We suspect that seismic quiescence in large areas may be temporary and that they represent likely candidates for future large earthquakes. Without more adequate geodetic control, however, it is not known that strain is necessarily accumulating in all of these areas. Even in areas of demonstrated regional shearing, the relative importance of elastic strain accumulation versus fault slippage is unknown, although slippage is clearly not taking place everywhere along major "active" faults of the region.

Recurrence curves of earthquake magnitude versus frequency are presented for six tectonically distinct 8500-km^2 areas within the region. They suggest either that an area of this small size or that a sample period of only 29 years is insufficient for establishing valid recurrence expectancies; on this basis the San Andreas fault would be the least hazardous zone of the region, because only a few small earthquakes have occurred here during this particular period. Although

recurrence expectancies apparently break down for these smaller areas, historic records suggest that the calculated recurrence rate of 52 years for M = 8.0 earthquakes for the entire region may well be valid. Neither a fault map nor the 29-year seismic record provides sufficient information for detailed seismic zoning maps; not only are many other geologic factors important in determining seismic risk, but the strain-release or epicenter map by itself may give a partially reversed picture of future seismic expectance.

Seismic and structural relationships suggest that the fault theory still provides the most satisfactory explanation of earthquakes in this region.

Introduction

The problem. The purpose of this study has been to gain a better understanding of current tectonic processes in an area of present-day mountain building. Southern California offers particular opportunity for this type of study because of the presence of one of the world's most closely spaced seismograph networks with a relatively long history of recording, together with the fact that the geologic structure of the region is reasonably well mapped and understood. The basic attack in this study has been to attempt to compare seismic activity, as represented by areally averaged strain-release sums and by frequency-magnitude relationships, with the geologic structure, which in this region is dominated by a complex system of faults that in large part would be considered "active" from geologic evidence alone.

At first glance, a relationship between seismicity and geologic structure is obvious because most earthquakes do occur in regions where active faults are recognized. In a gross sense, as was pointed out by Montessus de Ballore (1924), regions of high seismicity are also regions containing young mountains. But in detail the correlation between faults and earthquakes may break down for a number of possible reasons that will be examined in this study:

1. Seismic events at depth may not be directly and simply reflected in surface geology.
2. The recorded seismic history of a region may not encompass a long enough time period to represent true secular seismicity.
3. Earthquakes may not recur on pre-existing breaks.
4. From geologic evidence alone, it is difficult to determine the recency of displacement on a fault, and thus its degree of "activity."
5. Earthquake focal mechanisms in some regions may be more complex than is usually visualized in the simple elastic rebound theory. Honda (1957) and others have suggested this for Japan, where in places there appears to be no obvious correlation between epicenters and surficial faults (Tsuboi, 1958).
6. Gradual slippage along faults, without accompanying earthquakes, may be a more important tectonic process than has heretofore been recognized. Such slippage has recently been documented along a part of the San Andreas fault in California (Steinbrugge *et al*, 1960).
7. Evison (1963) has recently argued that earthquakes are not caused by faulting, in which case there need be no direct correlation.

The attempt to understand the relationship between seismicity and geologic structure in southern California is not new, but this study differs from previous

studies in scope and mode of presentation. The most ambitious of these earlier studies is that of Wood (1947), although the number of epicenters used by him was about one-eighth of that used in this study, and his geologic information was inadequate and is now out of date. Other significant studies bearing on the geological

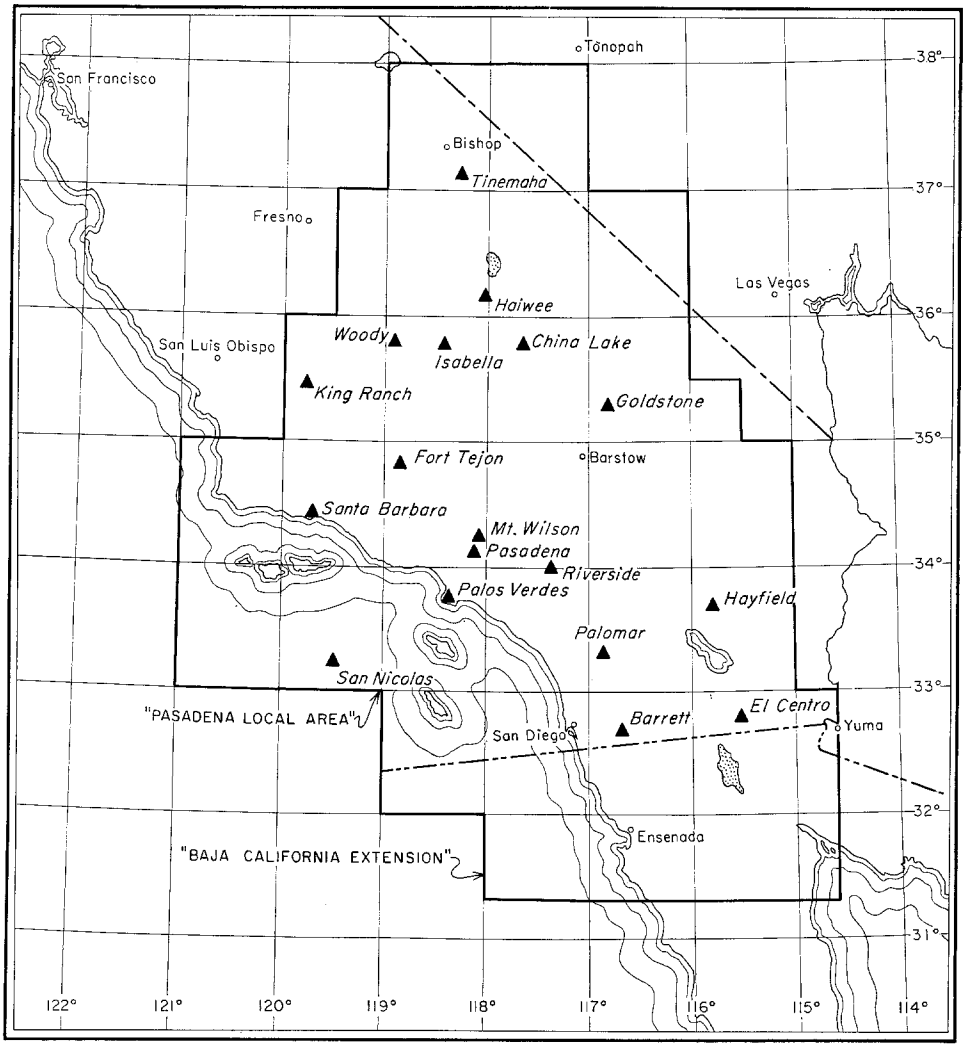

FIG. 1. Map of area covered by the Pasadena seismological network, showing locations of stations operating January 1, 1963.

relations of seismicity in this region have been those of Gutenberg (1941, 1943), Clements and Emery (1947), Gutenberg and Richter (1954), and Richter (1958). A more recent related study is that on seismic regionalization by Richter (1959), which differs from the present investigation in its emphasis on local ground conditions and maximum earthquake intensities which may be expected. Another significant related study is that by Woollard (1958), which considers tectonic-seismic

relationships for the entire United States, but on a scale very different from that of this study. Recently, St. Amand *et al* (1963) have discussed in a primarily historical paper many aspects of the seismicity and tectonics of this region as part of a larger summary of earthquakes of the western United States. Most recently, fault and epicenter maps of earthquakes greater than magnitude 4.0 throughout California have been published by the California Department of Water Resources (1964), the data for the southern part of the state having been summarized from the IBM cards that were prepared as part of the present study. Investigations of seismicity in other regions of the world have, of course, been numerous; particular mention should be made of the recent vigorous attempts in the Soviet Union to establish geologic criteria for predicting seismicity (e.g., Gzovsky, 1957).

Materials used. The data used in this study are predominantly those reported in the Quarterly Bulletin of Local Shocks of the Seismological Laboratory of the California Institute of Technology. The Bulletin has been issued regularly since January 1, 1934, and includes the reports of 18 stations of the southern California network as of January 1, 1963 (Figure 1). In 1934 there were only seven such stations, and the number has increased gradually through the years. Changing techniques in procedures of location for local earthquakes, which since 1961 have been located primarily by computer programs, have been summarized by Nordquist (1964). The aim of the Laboratory has been to report and locate all shocks of Magnitude 3.0 and greater within the "Pasadena local area" as shown in Figure 1. This area is likewise the subject of the present investigation, except that we have also considered shocks from the "Baja California extension," while recognizing that only the larger shocks from this area have been reported in the Bulletin. The total area outlined by the heavy line in Figure 1 is herein termed the "southern California region"; it includes about one-half of the area of California, small parts of Nevada and Arizona, and parts of nothernmost Baja California and Sonora, Mexico. Pertinent data from each of the 10,126 earthquakes that have been reported from this region in the Local Bulletin between January 1, 1934 and January 1, 1963 have been entered on IBM cards (Nordquist, 1964), and the results that follow are primarily from analysis of these data using the IBM 7090 Computer at the California Institute of Technology.

In the course of this investigation, the determination of the epicenters through the years has been the responsibility of Richter; St. Amand and Nordquist have been mainly concerned with statistical treatment of the data; and Allen has had primary responsibility for preparation of the strain-release and geologic maps, as well as the frequency-magnitude diagrams. All of the authors share responsibility for the conclusions.

Geologic Structure

General statement. The geologic structure of the southern California region has been synthesized and summarized in many papers, and it is our present purpose only to discuss those aspects of the structural framework that pertain directly to this study. These include (1) the tectonic history of southern California as it relates to current seismicity and comparison with other circum-Pacific regions, (2) basic differences between major geologic provinces within the region as might be reflected in current seismicity, (3) centers of Quaternary volcanism and their relationship to

other structural features, and (4) the problem of field distinction between "active" and "inactive" faults. Most of the major faults of the region are shown on Plate 1, but these faults will not be discussed in detail except in relation to specific earthquakes. [Plate 1 is located in cover pocket—Ed.]

Tectonic history. Virtually the entire region here under discussion was at one time a part of the great Cordilleran geosyncline that underwent major orogenic deformation and intrusion in late Mesozoic time, in common with the entire west coast of both Americas. Although crystalline rocks as old as Precambrian crop out locally in the Transverse Ranges north of Los Angeles (Silver *et al*, 1963), most of the basement rocks of the region are either batholithic intrusive rocks of the late Mesozoic orogeny or earlier sedimentary and volcanic rocks that were severely deformed and metamorphosed at that time. In contrast to the widespread pre-Cenozoic geosynclinal and orogenic events, the Cenozoic history has been characterized by the development of local fault-controlled basins and fragmentation of the continental border. The chief agent of this fragmentation has been the San Andreas fault system, which probably came into existence in early Cenozoic time (Crowell, 1962) and has dominated the tectonic framework of coastal California ever since. The eastern limit of the region affected by the San Andreas fault is difficult to determine, but even earlier right-lateral shear perhaps existed along a parallel zone centered on the California-Nevada border (Albers, 1964), and right-lateral movements have continued on some of these faults into Quaternary time. Thus structural features related to the San Andreas system apparently dominate the entire region being considered herein, although important local differences are caused by special situations that will be considered in discussing the individual geologic provinces.

Although coastal California is clearly part of the circum-Pacific belt of mountain-building activity, it is atypical of much of the rest of the belt in that it lacks the deep offshore trench, abundant active volcanism, and earthquakes of intermediate and deep focal depth. California is certainly not a true volcanic island arc now, although the Cordilleran geosyncline may once have represented such a tectonic environment. The San Andreas fault, on the other hand, is by no means the unique feature of the circum-Pacific rim that it was once thought to be, and there is good reason to believe that seismic patterns related to this fault system may have close analogies in other circum-Pacific areas of regional strike-slip faulting such as Chile, New Zealand, the Philippines, and Taiwan (Allen, 1962).

Geologic provinces. The southern California region is readily divisible into eight regions that have distinctive geologic and tectonic characteristics. These natural provinces are shown in Figure 2 after Jahns (1954), who has summarized their distinguishing features. With one principal exception, these regions are characterized more by differences in geologic history, rock make-up, and present physiography than by fundamental differences in underlying fault patterns.

North- or northwest-trending faults characterize all of the eight provinces with the exception of the Transverse Ranges, which represent the only east-trending mountain system of the Pacific coast—and indeed one of the few in either North or South America. The Transverse Ranges are apparently the continental manifestation of the much more extensive Murray fracture zone of the Pacific sea floor, which extends westward from the California coast for at least 4000 km (Menard,

1955). East-trending structural features of the province extend inland almost to the Colorado River, but speculation that the "Texas lineament" or other alleged lineaments carry through still farther to the east has never been documented. Although displacement on the Murray fracture zone has apparently been right-handed in the Pacific basin, amounting to perhaps 640 km (Raff, 1962), the continental slope is not obviously offset one way or the other, and most faults of the Transverse Ranges

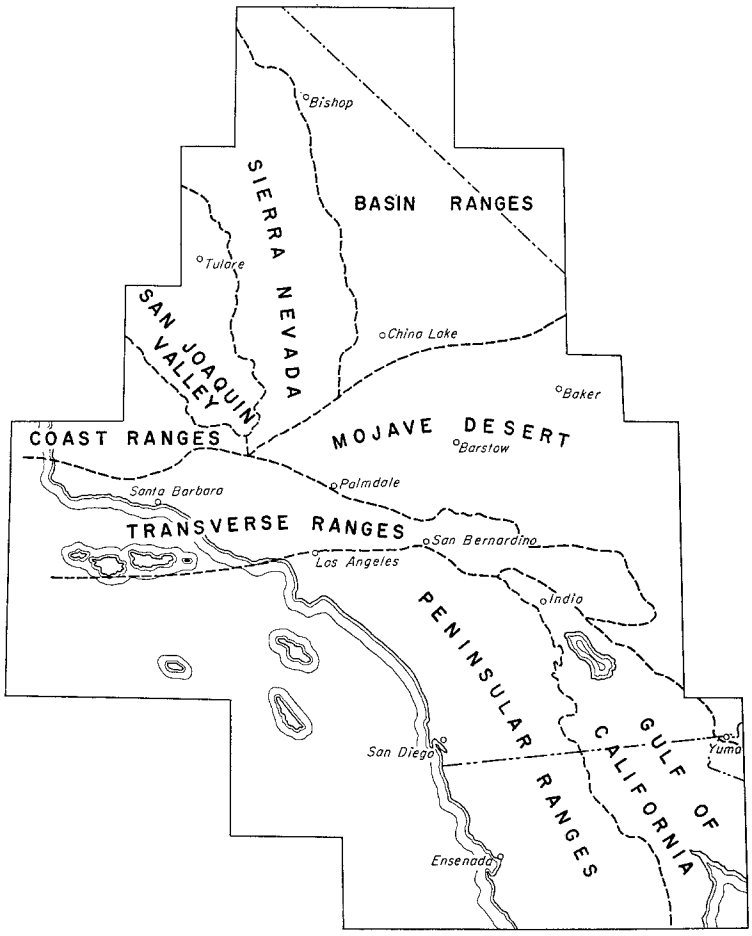

FIG. 2. Major geologic provinces of the southern California region, based on Jahns (1954).

appear to have *left*-lateral components. Toward the eastern end of the province in the region of the San Bernardino Mountains, left-handed faults of the Transverse Range system come into conflict with right-handed faults of the San Andreas system, amidst great structural complications (Allen, 1957). Apparently the San Andreas system is currently the more active of the two, and the eastern extension of the Transverse Ranges has probably been offset somewhat to the southeast by lateral displacements on the San Andreas zone. The only major left-handed fault outside of the Transverse Ranges in southern California is the Garlock fault, which

separates the Mojave Desert and Basin Range provinces, and even it might be considered merly an offset extension of one of the major Transverse Range faults (Hill and Dibblee, 1953). Continuity of east-trending structures into the desert region east of the Coachella Valley is indicated by regional gravity trends as well as by fault patterns (Biehler *et al*, 1964). In addition to left-handed components of displacement on faults of the Transverse Ranges, vertical displacements may have been dominant in many areas. East-trending thrust faults and steep reverse faults are common throughout the Transverse Range province, unlike most of the rest of the southern California region.

In sharp contrast to the Transverse Range province, right-handed faults of the San Andreas system characterize all of the adjacent provinces: Coast Range, Mojave Desert, Peninsular Range, and Gulf of California. Indeed, on the basis of fault patterns alone, these provinces are not readily distinguished from one another and might be expected to have grossly similar patterns of current seismicity. Major branches of the San Andreas system such as the San Jacinto and Elsinore faults can be traced continuously from the Gulf province into and through the Peninsular Range province. Certainly the Gulf of California is not a simple isolated fault-bounded graben as has sometimes been visualized, but instead appears to be another manifestation of continental fragmentation related to *en échelon* faults of the San Andreas system (Biehler *et al*, 1964; Rusnak and Fisher, 1964).

Although the offshore area of southern California south of the Channel Islands has usually been considered part of the Peninsular Range province, it might well qualify as a separate tectonic entity. The Franciscan-type basement rocks that are found at several places in the offshore area are totally different from the predominantly batholithic rocks of the Peninsular Range province. Furthermore, the typical "basin and trough" topography contrasts markedly with that of the adjacent provinces, although one might argue that this is more a function of submarine versus subaerial processes than of truly differing tectonic style. Northwest-trending fault scarps of high relief are particularly abundant throughout the offshore area but are truncated abruptly on the north by east-trending faults represented by the Channel Islands. Faults of the offshore area shown on Plate 1 are adapted from Emery (1960) and are based chiefly on submarine topography.

Faults of the Basin Ranges trend more northerly than those of the other provinces and are associated with greater physiographic relief, as is particularly evident in the Owens Valley and Death Valley areas. Since the days of G. K. Gilbert's classic work in the Great Basin, dominant fractures of this province have typically been considered to be normal faults representing east-west extension, but documentation of this pattern has been fragmentary. On the other hand, a number of major Basin Range faults of Plate 1, such as the Furnace Creek and Panamint Valley systems, have many features in common with the San Andreas zone: great length and linearity, scissoring of Quaternary fault scarps, horizontally offset rock units, and consistently offset streams. Inasmuch as such evidence of horizontal displacements is generally absent farther northwest in the Great Basin, probably the faults of the Owens Valley-Death Valley region represent features that are transitional between true San Andreas and true Basin Range tectonic patterns.

Quaternary volcanism. There are no volcanic centers in the southern California

region that have been active within the historic record; the closest such features are Mt. Lassen, in the southern Cascade Ranges 400 km north of the edge of this region, and Volcán de las Tres Vírgenes, in Baja California 450 km south of the edge of

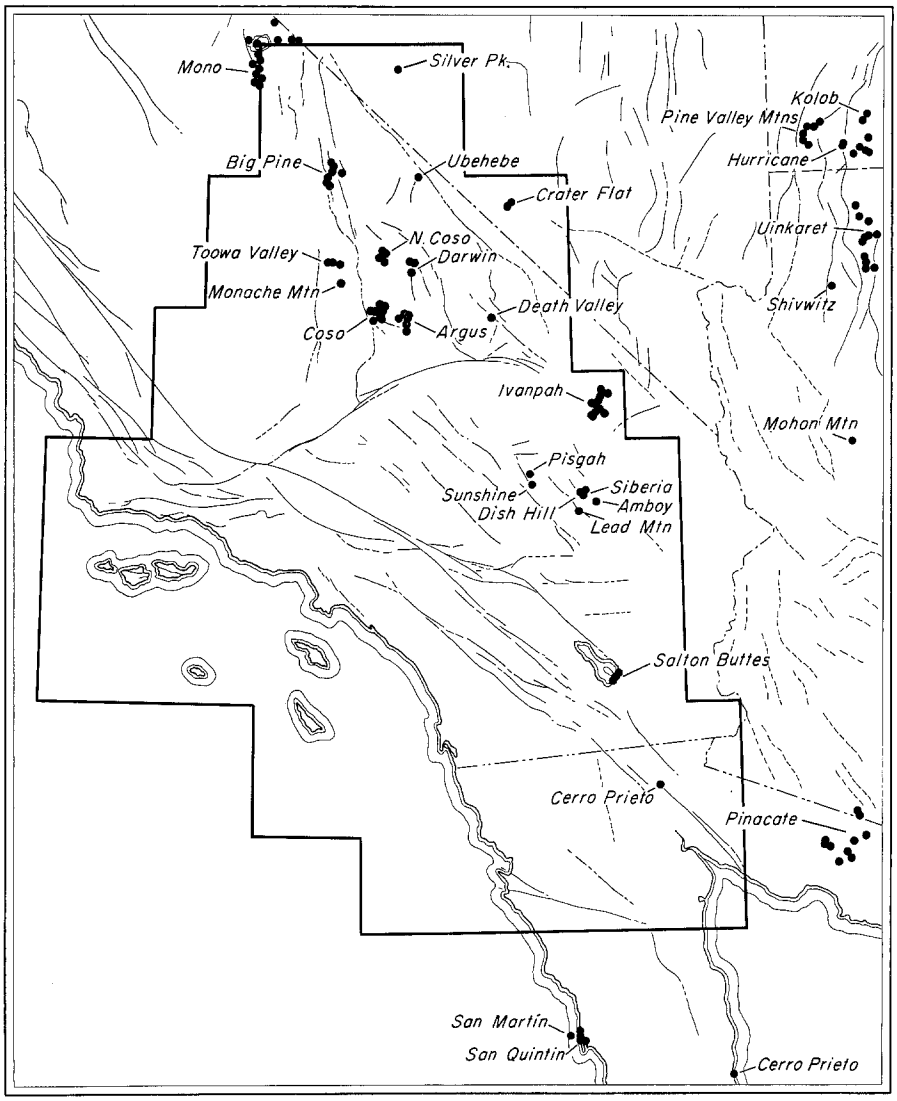

FIG. 3. Centers of Quaternary volcanism (cinder cones, obsidian plugs, craters). Faults outside of southern California region generalized from U. S. Geological Survey and Am. Assoc. Petroleum Geologists (1961).

the area. On the other hand, there are numerous cinder cones, obsidian plugs, and craters within the southwestern United States whose relatively undissected physiographic form suggests that they must be of Quaternary age. A number of these are shown in Figure 3, although it should be emphasized that assignment of many of these features to the Quaternary epoch represents a very subjective judgement.

Probably the most obvious regional significance of the distribution of Quaternary volcanic centers in California shown in Figure 3 is their alignment northwesterly along the extended trend of the Gulf of California, in sharp contrast to the divergent trend of the San Andreas fault system north of the Gulf. Probably this line of activity continues through to the Cascade Ranges of Oregon and Washington and represents a deep-seated tectonic feature of the continental margin. Another more diffuse belt of volcanic activity extends northeasterly from the Gulf of California into the Basin Range and Plateau provinces, only the western edge of which is shown in Figure 3. Either or both of these belts may represent extension of the East Pacific rise into the North American continent (Menard, 1960), but it should be emphasized that trends of historic earthquake activity tend to follow the San Andreas fault system rather than either of these belts. Indeed, a glance at the seismicity map of Plate 1 indicates that there is no striking alignment between the trends of Quaternary volcanism in California and either the gross fault pattern or the seismicity during the past 30 years.

The relationship of individual volcanic centers to particular faults is a more controversial matter. There are a sufficient number of mapped faults in the area of Figure 3 so that there is ample opportunity—if one is so inclined—to relate almost any volcanic activity to one fault or another. There are indeed a number of areas where there can be little question of a direct spatial relation between Quaternary cones and Quaternary faults. Good examples are the cone of Cerro Prieto squarely athwart the extended trace of the San Jacinto fault, 35 km south of Mexicali in Baja California, and the Quaternary (1872?) scarp running squarely between the cones of Red Mountain and Crater Mountain, south of Big Pine in California. On the other hand, there are areas where no such direct relationship is obvious, and it seems unwise to make gross generalizations for the whole region. On a broader scale, Pakiser (1960) has argued for a direct causal relationship between left-handed displacement on the Owens Valley fault system and the large Quaternary volcanic areas at the ends of the valley in the Mono and Coso areas. In view of the lack of other evidence of lateral movement of this sense in the Owens Valley and the widespread distribution of Quaternary volcanic rocks elsewhere in the region, one might also argue that this distribution is fortuitous—or at least not necessarily related to lateral displacements.

Geologic criteria for activity of faults. In the absence of strain-accumulation data or historic records of major earthquakes along a given fault, the only satisfactory criterion for activity lies in geological evidence that displacements have taken place along the fault in the recent geologic past. Even this is not a sure sign of activity or inactivity, in that long-dormant faults may suddenly break anew. For example, the White Wolf fault—locus of the 1952 Kern County earthquake—certainly had not been picked out as particularly active on geologic grounds; indeed, it was shown as a "dead fault" on the 1922 fault map of California (Seism. Soc. Am., 1922). Nevertheless, the over-all historic record, as well as the abundant geologic evidence for recurrent displacements along major fault systems such as the San Andreas, suggests that faults that have been most active in the recent geologic past are the most likely candidates for future activity.

Faults that have had sufficiently recent movement to displace the ground surface

are usually considered active by geologists simply because the ground surface is a very young and ephemeral feature. Such physiographic evidences of faulting (e.g. scarps, sag ponds, offset drainage lines) are powerful tools in identifying and studying active faults, but in practice it is difficult to use these features to compare the degree of activity between different faults or to establish the time interval since the last major displacement. One principal problem is climatic: average annual rainfall varies by more than 25-fold within the area of this study, so that steepness and "freshness" of scarps may be more a function of location that age. As a result of this and other factors, it has not been possible systematically to classify the faults shown on Plate 1 by age or by degree of activity. Most of the throughgoing breaks can be considered active in the sense that they are associated with fault scarps in surficial alluvium, but the ages of most alluvial bodies cannot be well established and must vary over many tens of thousands of years throughout the map area. A few of the major faults have had no significant displacements for some time; these include the western end of the San Gabriel fault, which is covered by late Pliocene sedimentary rocks (Crowell, 1952), and the Kern Canyon fault, the central section of which is truncated and covered by unbroken lavas of 3.5 m.y. age (Webb, 1946; Dalrymple, 1963). Whether even these faults can be considered truly inactive at the present time is questionable, inasmuch as small earthquakes continue to occur near and perhaps along them.

Fault scarps that cut alluvium in southern California have usually been assigned to the Recent epoch. This implies a post-glacial age, and radiocarbon studies of sediments in Searles Lake suggest that the latest Wisconsin glaciation in the nearby Sierra Nevada terminated about 10,000 years ago (Flint and Gale, 1958). There are indeed a few localities in southern California where fault scarps clearly cut latest Wisconsin glacial deposits and are thus undeniably recent in age; Putnam (1962) and Rinehart and Ross (1964) demonstrated this in the central Sierra Nevada and Sharp *et al* (1959) in the San Bernardino Mountains. On the other hand, the great majority of fault scarps in this region cannot be chronologically related to glacial deposits, and their assignment to the Recent epoch must be regarded as questionable. There is growing evidence, in fact, that many scarps are much older than has normally been thought: very fresh-appearing features of the Garlock fault—second only to the San Andreas in regional structural importance—are now thought to date from at least 50,000 years ago (Smith, 1960).

Offset drainage lines resulting from horizontal fault displacements are another very ephemeral feature of faults and therefore indicative of current activity. Streams tend to straighten their courses rapidly after obstructions or offsets have been imposed. Most offsets have thus been considered of Recent age, although it is recognized that the ability of a stream offset to maintain itself will depend not only on age, but also on climate, rock type, depth of stream incision, regional gradient, and rate of fault movement. That many stream offsets along California faults cannot be as young as usually thought is indicated again by Smith's (1960) conclusion that the central segment of the Garlock fault took place more than 50,000 years ago, because consistent stream offsets of more than 600 m occur along the fault less than 40 km both to the west and to the east of Smith's locality (Hill and Dibblee, 1953; Muehlberger, 1954). Although one might attribute the long survival of these offsets

to the sparse annual rainfall, which here averages less than 10 cm, it should be remembered that these offsets and associated scarps have presumably survived through at least one pluvial period, represented by the Tioga glacial stage in the Sierra Nevada. Thus one is forced to the conclusion that if stream offsets and scarps in alluvium are to be used as criteria for activity of faults, then the term "active" must apply to events dating well back into the Pleistocene epoch, perhaps as much as 100,000 years. That physiographic features of faulting very much older than this could survive to the present seems unlikely, however, inasmuch as mid-Pleistocene rocks are highly deformed throughout most of the southern California region.

Stream offsets indicative of active strike-slip faulting are present along at least some of the faults of each of the major geologic provinces of southern California. Numerous right-handed offsets have been well documented by many authors along all segments of the San Andreas fault north of San Bernardino and occur on each of the three major branches of the system farther south as well—Elsinore, San Jacinto, and Banning-Mission Creek faults. Similar right-handed offsets characterize many other faults that are grossly parallel to the San Andreas: Death Valley fault zone (Noble and Wright, 1954); Furnace Creek fault (Curry 1938); Panamint fault (Hopper, 1947); and the Agua Blanca fault of Baja California (Allen *et al*, 1960). Evidence for recent activity along east-west faults of the Transverse Range province is not as impressive as along the San Andreas system, but systematic left-handed drainage offsets have been reported on faults of the Channel Islands (Kew, 1927; Rand 1931), on the Santa Ynez fault (Dibblee, 1950; Page *et al.* 1951), and on the Garlock and Big Pine faults (Hill and Dibblee, 1953). Left-handed stream offsets along the western end of the Santa Cruz Island fault are as systematic and convincing as any in California.

Regional Strain Accumulation and Non-Seismic Strain Release

Regional strain accumulation and release across the major active fault zones of southern California have been observed and analyzed by several techniques. The U. S. Coast and Geodetic Survey has periodically resurveyed a number of first-order triangulation arcs and networks extending for many tens of kilometers across the San Andreas and associated faults, with the objective of studying the rate and distribution of regional strain. In addition, the Survey has established seven traverse lines of about 13 km average length that cross these faults with station spacings as close as 50 m; the objective is to detect possible slippage on the fault planes, as well as to determine very accurately the build-up or release of strain in the very heart of the fault zones. Recently, the California Department of Water Resources has made an effort to measure accumulating strain by using geodimeters rather than traditional optical triangulation methods, with the hope of shortening the time intervals over which significant measurements can be made (California Department of Water Resources, 1963). In addition to the work of these organizations, a number of other less extensive surveys have contributed to the over-all picture.

It is difficult to summarize the results of the Coast and Geodetic Survey work because it covers many different areas, different time intervals, and different surveying techniques; and large parts of the program are still underway and unpublished. Nevertheless, observations in many parts of California, utilizing surveys

dating back to 1882, indicate that right-handed shear is taking place across much of the San Andreas fault zone at a rate given as 5 cm/yr over a width of 50–60 km (Whitten, 1955), or 3 cm/yr over a width of 30 km (Whitten, 1961). This movement has often been thought of as representing accumulating shear strain, as predicted by the elastic rebound theory. Recent re-evaluation of the geodetic data, however, suggests that a significant part of the movement is taking place in some areas by discrete slippage along the fault plane. In the most extreme case yet documented, that in central California near Hollister, the slippage amounts to about 1.7 cm/yr, which is about one-third of the regional strain rate measured between points many kilometers away from and on opposite sides of the fault in this same region (Meade, 1963). Possibly the remaining two-thirds represents accumulating strain, so that slippage should not be considered completely incompatible with the elastic rebound theory, as was implied by Evison (1963).

Within southern California, the most significant Coast and Geodetic Survey network is that near the international border across the Imperial Valley, which here encompasses the several branches of the San Andreas fault system—Elsinore, San Jacinto, and Banning-Mission Creek faults. Right-handed shear is taking place between the San Diego Mountains on the west and the Chocolate Mountains on the east (Plate 1) at about 8 cm/yr, based on surveys in 1935, 1941, and 1954 (Whitten, 1956). The only other resurveyed triangulation arc across the fault zone in southern California that has yielded published information substantiating movement is that between San Luis Obispo and Bakersfield, across the northwest corner of Plate 1. Surveys in 1926 and 1948 tentatively suggest right-handed strain of 4 cm/yr across the San Andreas fault in this region (Whitten, 1955).

It seems geologically reasonable that the San Andreas fault throughout southern California should be characterized by the same sort of right-handed movement that has been measured near Bakersfield and in the Imperial Valley, but there is little additional evidence available. The 13-km closely spaced traverse line near Gorman showed "some indication" of right-handed creep between surveys in 1938 and 1949 (Murphy and Ulrich, 1951, p. 30), but there is no published record of similar distortions of the other closely spaced lines. The Elizabeth Lake Tunnel of the Los Angeles Department of Water and Power carries Owens Valley water for 6 km directly through the San Andreas fault zone about midway between Palmdale and Gorman. Resurveys of this tunnel between 1951 and 1960 suggest that distributed deformation is taking place, although the sense of shear cannot be determined because the end points of the survey are not tied into the regional network. On the other hand, the one resurvey of the triangulation arc between San Fernando and Mojave—across the same region—showed "no evidence of movement" between 1932 and 1952–53 (Meade, 1963), so the possibility remains that strain is not accumulating in this central segment of the fault at a rate comparable to that farther north and south, if at all.

Two other Coast and Goedetic Survey networks within the area of this study are significant in that they likewise show no marked changes between consecutive surveys (Meade, 1963). One of these is the arc between Newport and Riverside, surveyed in 1929, 1934, and 1953, which crosses the southern end of the Los Angeles basin and the Whittier and Elsinore faults. The other is an extensive network across

the Owens Valley extending from Mono Lake to Inyokern; this area includes that of the 1872 earthquake. If strain is accumulating in these areas at the present time, it must be building up at a rate which is at least an order of magnitude smaller than that along the San Andreas zone.

The recent documentation of gradual slippage along the San Andreas fault in central California near Hollister (Steinbrugge *et al*, 1960) has led to a renewed interest in whether similar slippage might not be taking place along other segments of the fault. Indeed, Evison (1963) has suggested that this may well be the "normal mode of movement on faults." From an analysis of both the Imperial Valley and San Luis Obispo-Avenal surveys, Whitten (1960) has argued that slippage is taking place along the Imperial and San Andreas faults, respectively, in addition to the regional shearing. There is no known field evidence of active slippage at either locality although in many undeveloped areas this might easily escape notice at the rates of 0.3 to 0.4 cm/yr suggested by Whitten. Even at these slow rates, however, accumulated slippage in many areas where cultural features cross the fault would certainly be noticed, and it seems clear that slippage such as is occurring at Hollister does *not* characterize all segments of the fault. The closely spaced Coast and Geodetic Survey lines across the fault at Maricopa, Gorman, and Palmdale show no evidence of slippage (Meade, 1963), and buried gas pipelines have been in service since 1932 across the fault near Gorman with no indication of slippage. Furthermore, the concrete lining of the Elizabeth Lake Tunnel beneath the fault farther east has not been broken since it was completed in 1913. Numerous buildings now being constructed squarely athwart the fault in the San Francisco and San Bernardino areas, among other localities, should give further evidence on this point in years to come.

Gradual changes in elevation have been noted at a number of localities in southern California, but it is difficult to separate tectonic effects from those due to withdrawal of groundwater and oil. In at least four areas, these elevation changes have been associated with concurrent faulting:

(1) Gradual slippage on a thrust fault in the Buena Vista Hills east of Taft has been recognized for many years (Wilt, 1958) and is nicely reflected in horizontal displacements of nearby bench marks (Whitten, 1961).

(2) A number of small shallow earthquakes have been associated with subsidence of the Terminal Island area near Long Beach, some of which have sheared-off oil wells (Richter, 1958; Gilluly and Grant, 1949).

(3) A fault scarp with a length of at least 3 km formed late in 1949 about 13 km north of Bakersfield, apparently with no seismic disturbance (Hill, 1954).

(4) The Baldwin Hills Reservoir in Los Angeles failed in December, 1963, bebecause of gradual displacement along a pre-existing fault that passed beneath the reservoir and abutment (Hudson and Scott, 1965). The movement was probably mechanically associated, at least in part, with local subsidence that is well documented in the central part of the Baldwin Hills. Maintenance records at the reservoir suggest that slippage had been taking place at an accelerating rate since the structure was built in 1951, and the culminating event was not associated with any recorded earthquakes in the vicinity.

In the first two of these areas, and perhaps in all of them, subsidence appears

directly related to withdrawal of oil, as has also been true for a number of other areas in Los Angeles (Grant and Sheppard, 1939). Areas of discrete uplift are not so

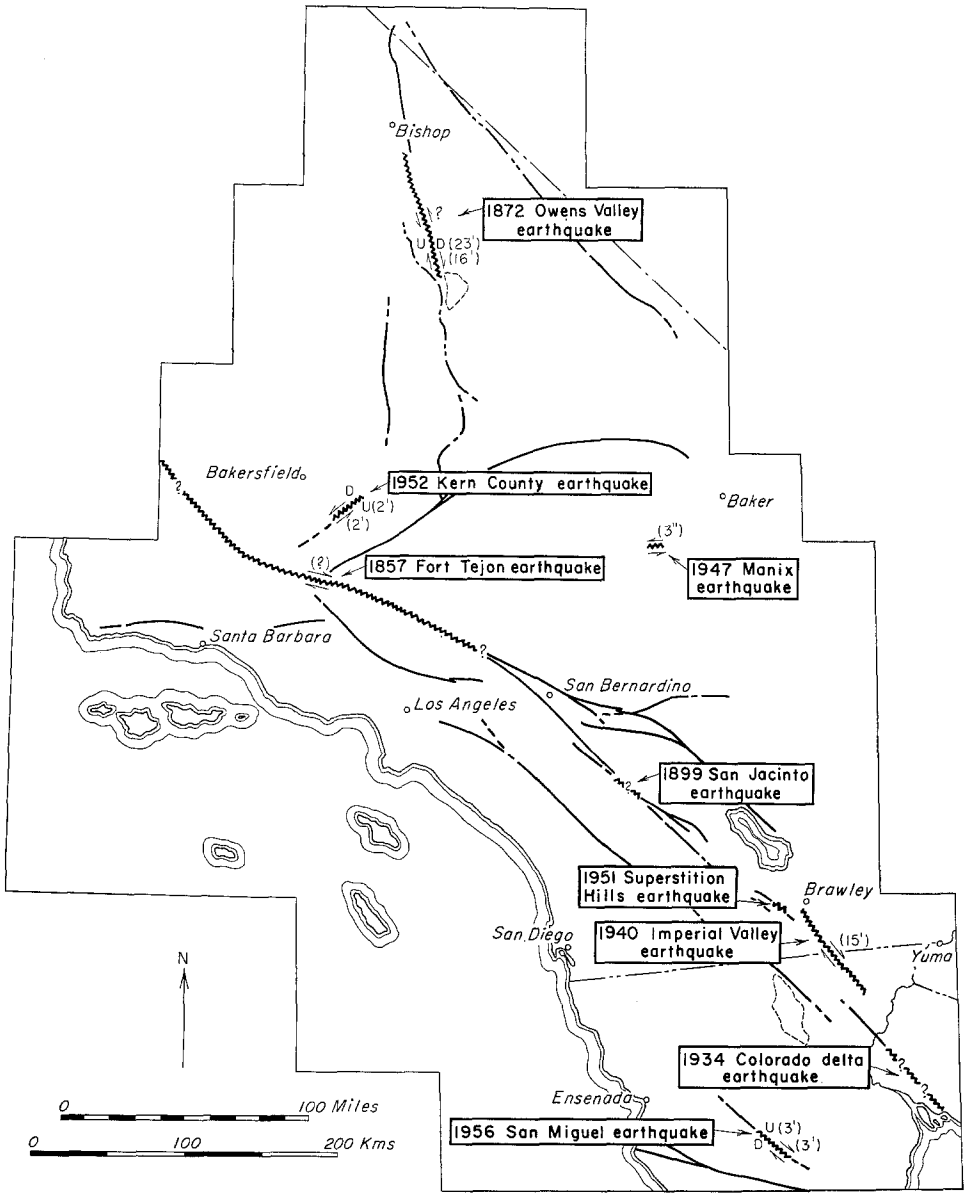

FIG. 4. Map of historic fault breaks and associated earthquakes in southern California region.

easily attributed to human activity. A broad doming northeast of Long Beach seems to have occurred in association with the 1933 Long Beach earthquake (Gilluly, 1949). Three surveys across the San Andreas fault at Cajon Pass between 1906 and 1944 suggest that the area close to the fault is rising at a rate of 0.5 cm/yr (Gilluly, 1949), although somewhat similar surveys across the fault near Palmdale have detected no significant changes (Murphy and Cloud, 1957, p. 39).

Major Historic Earthquakes

Within the historic record, there have been five major earthquakes in the area of this study that have been large enough to be associated with documented surficial fault displacements. That is, well-documented scarps or other surficial offsets were formed in clear association with each of these shocks. In addition, three other earthquakes were probably associated with surficial displacements, and another was associated with ground displacement on a nearby fault that probably was not the locus of the main earthquake. These nine events and their geological environments are discussed briefly in the following section and are illustrated in Figure 4; most have been described in greater detail by Richter (1958).

(1) *1857 Fort Tejon earthquake.* The 1857 earthquake was probably centered near Gorman, and the very widespread area over which shaking was felt compares to that of the 1906 San Francisco earthquake. Contemporary reports leave little doubt that the shock was accompanied by strike-slip displacement for many miles along the fault now recognized as the San Andreas. Although Wood (1955) argues on the basis of an 1876 report that the surface break extended southeast as far as the Colorado Desert (Salton Sea region), it seems more likely that the faulting terminated in the Mojave Desert region near Cajon Pass. We say this on the basis of the freshness of scarplets southeast to Cajon Pass, the lack of reports of disastrous shaking in the San Bernardino area, and the apparent absence of continuous Quaternary scarps through the San Gorgonio Pass area into the Colorado Desert (Allen, 1957). The 1857 earthquake was the last major shock on the San Andreas fault in southern California outside of the Imperial Valley.

(2) *1872 Owens Valley earthquake.* Judging from the extent of the area over which the 1872 earthquake was felt, it was probably the largest earthquake in recorded California history. Contemporary accounts of the faulting accompanying the earthquake are scanty, but the ground was clearly broken along several fault segments extending from near Olancha to north of Big Pine (Whitney, 1872). The most spectacular and well-documented faulting was near Lone Pine, where the scarps are still surprisingly fresh-appearing after almost 100 years. Both left-handed and right-handed strike slips seem to have occurred, although this is a matter of some controversy (see, e.g., Gianella, 1959; Bateman, 1961). The 1872 faulting was not directly along the base of the nearby Sierra Nevada, but the displacements followed older lines of faulting; many pre-1872 scarps in alluvium occur not only within the area of 1872 movements, but north and south of this region as well.

(3) *1899 San Jacinto earthquake.* Reports of surface faulting during the 1899 earthquake are mainly due to Daneš (1907), who described a two-mile fault trace along what is now recognized as the San Jacinto fault in the mountains southeast of Hemet. The features described by Daneš were possibly caused by landsliding, and the exact area has not been relocated; there are, however, numerous very fresh-appearing scarplets along the San Jacinto fault zone between Hemet and Borrego that might well have originated at this time.

(4) *1934 Colorado delta earthquake.* Aerial photographs taken in 1935 along the San Jacinto fault in the tidal flats adjacent to the Gulf of California show a distinct fault trace that has a much fresher appearance than that revealed in subsequent

photographs of the same area (Kovach *et al*, 1962, p. 2348; Biehler *et al*, 1964, Fig. 4). Inasmuch as the earthquake on December 31, 1934 was centered in this very area and was comparable in magnitude to the 1940 Imperial Valley earthquake, it is highly probable that this southeasternmost segment of the San Jacinto fault broke at this time. There is no other substantiating evidence, although the presence of aligned mud volcanoes and hot springs had led Kniffen (1932) to postulate extension of the San Jacinto fault into this region even prior to the 1934 shock.

(5) *1940 Imperial Valley earthquake.* The 1940 earthquake, while only of Magnitude 7.1, was associated with spectacular surface faulting along the Imperial fault for a distance of more than 50 km. Detailed effects have been described by Ulrich (1941) and Richter (1958). The Imperial fault had not been recognized prior to this time and is not marked by older known scarps except possibly at the north end. On the other hand, gravity contours imply that the Imperial fault probably is a deep-seated feature whose history certainly predates 1940 (Kovach *et al*, 1962). Furthermore, it might well be considered merely a branch of the very active San Jacinto fault zone.

(6) *1947 Manix earthquake.* Very small but consistent surface displacements along the Manix fault in 1947 were described by Richter (1958). The movement took place within a fault zone earlier recognized by Buwalda (1914), but the aftershock distribution was along a line almost at right angles to this. Richter feels that the displacement on the Manix fault was a purely secondary feature resulting from the main displacement on a northwest-trending fault that presumably is buried by the local Pleistocene lake beds.

(7) *1951 Superstition Hills earthquake.* Faulting and *en échelon* cracks indicative of slight right-lateral displacement along 3 km of the Superstition Hills fault in the Imperial Valley were noted in early February of 1951 by Joseph Ernst, who had been doing geologic mapping in the area. Ernst reports (personal communication) that the "fault crack cut across low ridges and small gullies as though it were a ruled pencil line," and he concluded that it must have post-dated the last wind- or sandstorm in the area. Examination of the seismic records make it highly probable that the movement originated in association with the Magnitude 5.6 shock of January 23 (not January 29, as suggested by Dibblee, 1945a), reported intensities of which were greatest in this area (Murphy and Cloud, 1953). Revision of errors in the original epicenter now place it in the Superstition Hills (32°59′N., 115°44′W.) rather than near Calipatria, as earlier reported. This is a surprisingly small earthquake to be associated with surficial faulting, but the occurrence is not unique; the 1950 earthquake in northern California near Herlong was of similar magnitude and was associated with minor but well-documented displacements for a distance of more than 8 km (Gianella, 1957). The Superstition Hills fault is probably part of the San Jacinto fault zone and had been recognized and mapped prior to the 1951 earthquake (Tarbet, 1951).

(8) *1952 Kern County earthquake.* The 1952 earthquake, also known as the Arvin-Tehachapi earthquake, was associated with surface faulting along the White Wolf fault between Arvin and Caliente. Detailed effects have been described by Buwalda and St. Amand (1955) and others. The White Wolf fault had been recognized for many years prior to 1952 (e.g., Lawson, 1906), but the subdued and eroded topog-

raphy along its trace would not have led one to believe that the fault was as "active" as many others in southern California.

(9) *1956 San Miguel earthquake.* Ground displacements for a distance of about 20 km along the San Miguel fault during the 1956 earthquake in Baja California have been described by Shor and Roberts (1958). Primarily owing to the remoteness

TABLE 1

EARTHQUAKES OF MAGNITUDE 6.0 AND GREATER IN SOUTHERN CALIFORNIA REGION, 1912–1963. DATA PRIOR TO 1934 FROM RICHTER (1958)

Date	Lat.	Long.	M	Region
6–23–15	32.8	115.5	6¼	Calexico
6–23–15	32.8	115.5	6¼	Calexico
11–21–15	32	115	7.1	Colorado delta
10–23–16	34.9	118.9	6	Tejon Pass
4–21–18	33¾	117	6.8	San Jacinto
7–23–23	34	117¼	6¼	Riverside
6–29–25	34.3	119.8	6.3	Santa Barbara
9–18–27	37½	118¾	6	Long Valley
3–11–33	33.6	118.0	6.3	Long Beach
12–30–34	32–15	115–30	6.5 D	Colorado delta
12–31–34	32–00	114–45	7.1 D	Colorado delta
2–24–35	31–59	115–12	6.0 C	Colorado delta
3–25–37	33–28	116–35	6.0 A	Terwilliger Valley
5–19–40	32–44	115–27	7.1 B	Imperial Valley
12–8–40	31–40	115–05	6.0 C	Colorado delta
7–1–41	34–20	119–35	6.0 A	Santa Barbara
10–21–42	32–58	116–00	6.5 B	Lower Borrego Valley
3–15–46	35–44	118–03	6.3 B	Walker Pass
4–10–47	34–59	116–33	6.4 A	Manix
12–4–48	33–56	116–23	6.5 A	Desert Hot Springs
7–21–52	35–00	119–01	7.7 A	Kern County
7–21–52	35–00	119–00	6.4 D	Kern County aftershock
7–23–52	35–22	118–35	6.1 A	Kern County aftershock
7–29–52	35–23	118–51	6.1 A	Kern County aftershock
3–19–54	33–17	116–11	6.2 C	Santa Rosa Mountains
10–24–54	31–30	116–00	6.0 D	Agua Blanca?
11–12–54	31–30	116–00	6.3	Agua Blanca?
2–9–56	31.7	115.9	6.8	San Miguel
2–9–56	31.7	115.9	6.1	San Miguel aftershock
2–14–56	31.5	115.5	6.3	San Miguel aftershock
2–15–56	31.5	115.5	6.4	San Miguel aftershock

of the area, the San Miguel fault had not been recognized prior to this time, but clear Quaternary scarps and ground-water effects mark the trace of this fault not only within the area broken in 1956, but for some distance to the northwest as well.

If instead of limiting our attention to earthquakes with known surface faulting, we include all earthquakes of Magnitude 6.0 and greater in the last 50 years, the results are tabulated in Table 1 and portrayed in Figure 5. From Figures 4 and 5 it is possible to draw some fairly obvious conclusions concerning the relationship between large earthquakes and geologic structure.

(1) Of the historic earthquakes that have been associated with ground displacements, most were on or very near faults having a previous history of Quaternary

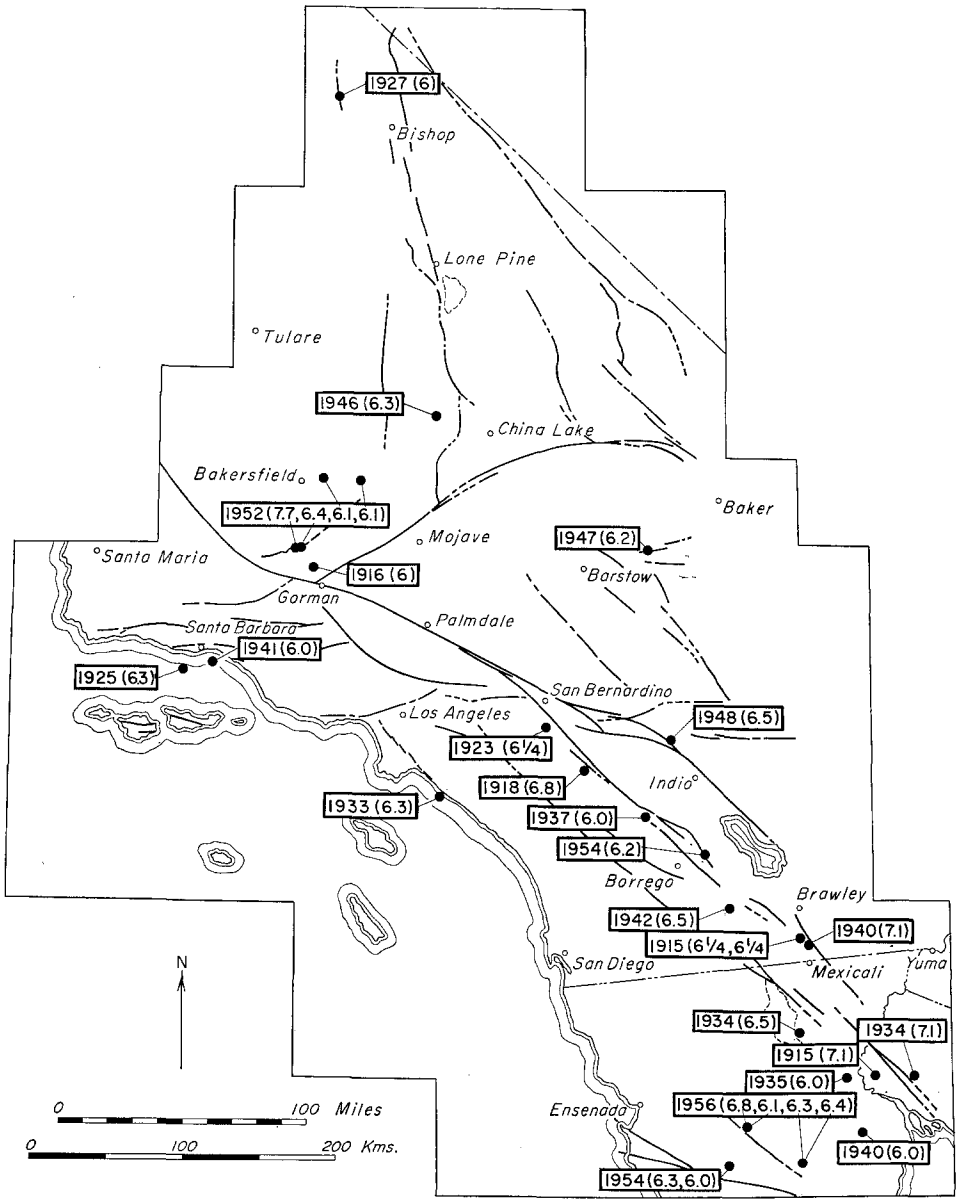

FIG. 5. Earthquakes of Magnitude 6.0 and greater in southern California region, 1912–1963.

movements and whose total lengths were greater than that of the segments broken during the given earthquakes. Possible but unlikely exceptions were the 1940 and 1947 shocks. A history of previous faulting is likewise true for most of the earthquakes of magnitude 6.0 and greater, even where not associated with surface faulting during the particular earthquake.

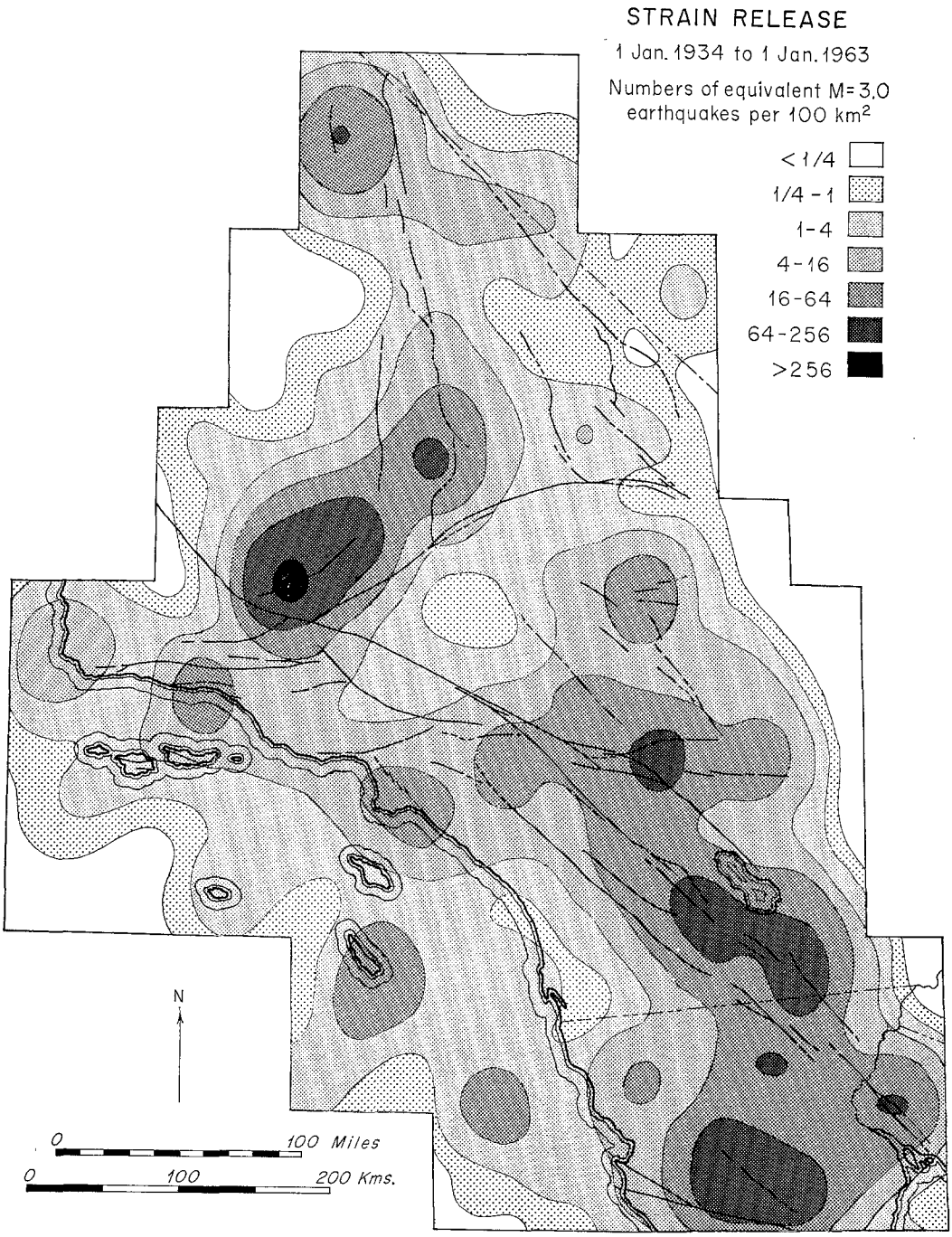

FIG. 6. Smoothed strain-release map of southern California region after ten iterations. Compare with Plate 1, after two iterations.

(2) During the 50-year period from 1912 to 1963, by far the most active fault in the region of this study has been the San Jacinto fault, which has been associated with a number of moderate-sized shocks that have been remarkably evenly spaced along the fault.

(3) With the possible exception of the 1916 Tejon Pass earthquake (Branner, 1917), the San Andreas fault northwest of San Bernardino has been free of large earthquakes during the same 50-year period.

(4) If one were to attempt to draw a fault map solely on the basis of epicenters during the 50-year period, he might pick out the San Jacinto fault zone, but no other valid tectonic lineaments are apparent.

These conclusions and their tectonic implications will be reconsidered in greater detail after discussion of the many thousands of smaller earthquakes that have occurred in this region in part of the same time interval.

Portrayal of Seismicity

Seismicity has been defined and portrayed by various authors in many different ways. An important distinction must be made between seismicity as a measure of seismic events during a given historic time period and seismicity in the more general sense of long-time activity, including expectations for the future. In this paper the term is used in the former sense, as applied to a given period such as the 29-year period during which the Pasadena Seismological Laboratory has been operating. The more general term is referred to herein as secular seismicity. One of the objectives in measuring short-time seismicity is, of course, to aid in formulating a pattern of secular seismicity.

Certainly the simplest presentation of historic seismicity is that of a map of epicenters, with different symbols for earthquakes of various magnitudes or depths (e.g., Figure 7). Severe cartographic problems arise, however, when the number of earthquakes to be represented becomes large, and in recent years a variety of techniques have been used not only to meet this challenge, but also to give a more quantitative representation of the seismic activity. Koning (1952) contoured his maps with "iso-magnitude lines." A number of investigators have used the areal summing of energies from individual shocks, as advocated particularly by Båth (1953). A related technique has been to sum the square-roots of energies from individual shocks, inasmuch as this figure is considered proportional to strain release (Benioff, 1951a); this method has been particularly used by Ritsema (1954), St. Amand (1956), Richter *et al* (1958), Milne (1963) and Niazi (1964). Inasmuch as a clear relationship appears to exist in many areas between frequencies of earthquakes and their magnitudes, another method is that of simply plotting numbers of earthquakes within some statistically representative magnitude range. This has been advocated particularly by Vvedenskaya (1958), and the resulting maps are in many cases only slightly different from those based on energy or strain release (e.g., Fisher *et al*, 1964).

A somewhat different technique aimed more directly at portraying secular seismicity has been suggested by Riznichenko (1958; 1959) and has been widely used in the Soviet Union (e.g. Gzovsky *et al*, 1960; Buné *et al*, 1960) Instead of portraying parameters of individual recorded earthquakes, a level of seismic "activity" is

established for each area on the map from a frequency-energy plot for earthquakes within the given region. The resulting "activity" figures are then contoured in such a way as to express the expected recurrence rate of earthquakes of different energy levels. This method has the advantage of reducing the effects of historic seismic

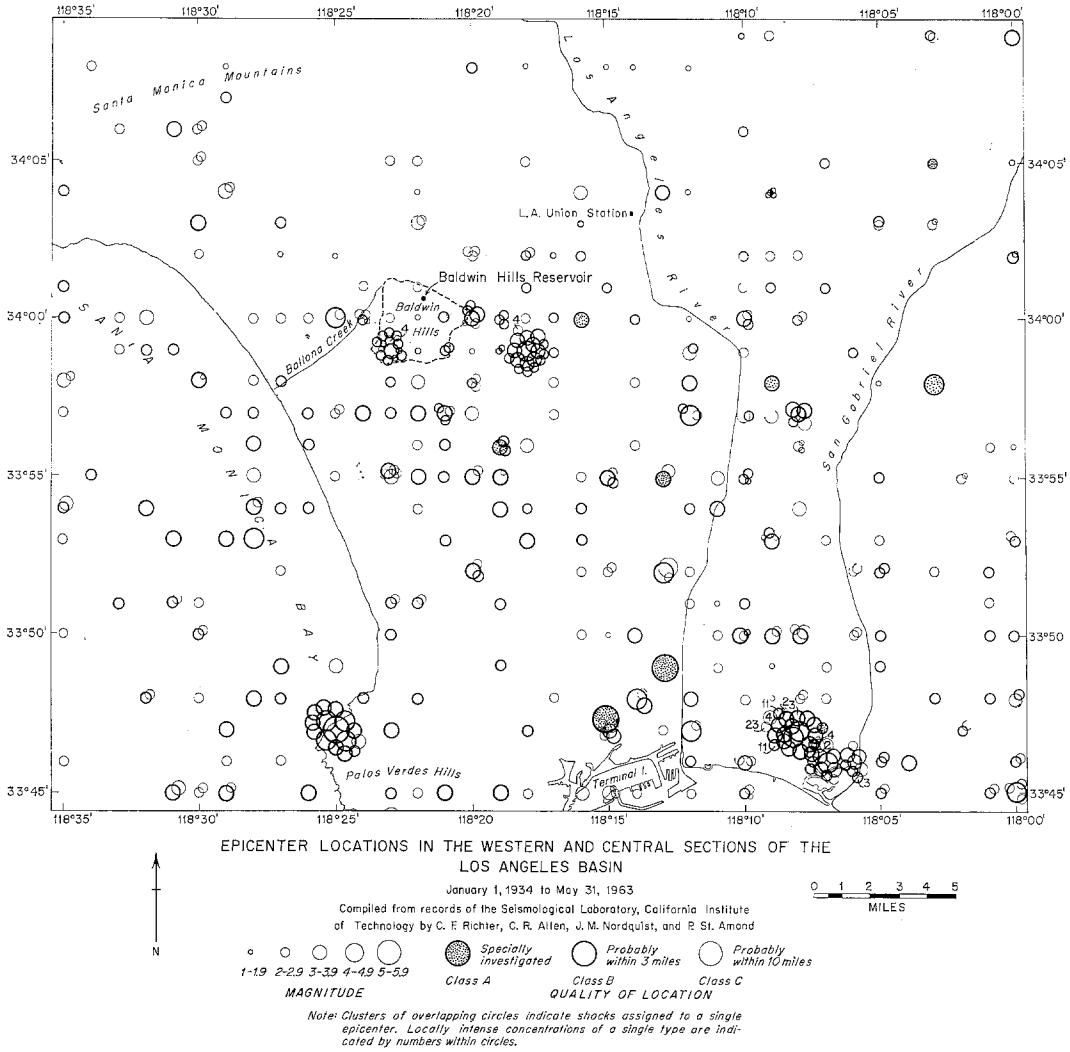

FIG. 7. Epicenters in western and central part of Los Angeles basin, 1934–1963.

events that may not be statistically representative, but a number of important assumptions are involved. In particular, small earthquakes are assumed to occur in association with large ones, and certain parameters of the frequency-energy relationship must be assumed to be constant throughout the region. Thus the resulting "activity" maps have intertwined in them both the recorded data and effects resulting from assumptions of the method, although the general appearance of such maps may be very similar to those of historic strain release for the same region (e.g., Kondorskaya and Landyreva, 1962). For the present study, we prefer to restrict our

seismicity maps of southern California to the historic record of 29 years, and one of our objectives will be to emphasize the hazards of extrapolating this data to the determination of secular seismicity.

As the measure of seismicity for a given area and time interval, we have used the sum of the square roots of the energies of the individual earthquakes, which is a parameter proportional to the strain release (Benioff, 1951a). The reason for using strain release rather than energy is simply that the strain is the one quantity which has geologic reality; geodetic observations in California reveal much concerning the rate and distribution of accumulating regional strain, and it is logical to use a seismicity parameter that can be directly related to this. On the other hand, it should be recognized that the proportionality factor relating strain and square root of seismic energy release is a function of the elastic constants of the rock, the efficiency of conversion of elastic energy into seismic waves, and the volume of the strained rock. Consequently, in visualizing strain release by adding the individual increments of square roots of energies, it is tacitly assumed that this proportionality factor is constant. This is a matter of some controversy, particularly with regard to the volume of the strained rock (Tsuboi, 1956). Nevertheless, the technique has proved useful and significant for the study of widely spread shocks in major earthquake sequences and in aftershock series (Benioff, 1951a; 1951b), and these results suggest that the method should be significant when applied to a region such as southern California which has strong tectonic and seismic unity. Ritsema (1954) has used a similar argument for the Sunda arc.

Strain-Release Maps

Method of preparation. The strain-release map of Plate 1 has been prepared in a manner somewhat similar to that described in an earlier paper (Ritcher *et al*, 1958). Each earthquake was assigned a strain-release figure based on the simplified magnitude-energy relation (Gutenberg and Richter, 1956),

$$\log E = 11.8 + 1.5M$$

which is closely similar to the formula derived independently by Båth (1958) and to those used in Soviet strain-release studies (e.g., Kondorskaya and Landyreva, 1962). Benioff (1951a), Duda (1963), and others, including the present authors, have used a number of earlier formulas, but the differences are not great or meaningful. To avoid using a strain-release figure that involves the elastic constants, we have chosen to represent strain on our maps in terms of the equivalent number of magnitude 3.0 earthquakes, N_3, so that

$$N_3 = 10^{0.75(M-3.0)}.$$

Thus two earthquakes differing by one unit in magnitude will differ by a factor of about 6 in strain release, and a magnitude 7.0 shock will be equivalent to 1000 magnitude 3.0 earthquakes in this sense.

Each of the 4158 five-minute squares of latitude and longitude within the map area was treated as a unit, and strain-release sums were computed independently for

each of these approximately 8 × 9 km squares. Further smoothing was arbitrarily accomplished by a series of computer iterations, in each of which the strain release assigned to a given square was distributed and normalized as follows: 40 per cent remains in the given square, 10 per cent is assigned to each of the four immediately adjacent squares, and 5 per cent is assigned to each of the four diagonally adjacent squares. Plate 1 shows the smoothed strain release after two such iterations; in this case, the effect of a single earthquake is distributed to distances averaging no more than about 24 km from the assigned epicenter, although 85 per cent of the total is within the first 14 km. In view of the problems mentioned in the next paragraph, this is thought to be a realistic smoothing for effective delineation of structural details. Further iterations give a successively more generalized portrayal of strain release, and Figure 6 shows the results of ten such iterations. In this case the effect of each earthquake is distributed to distances as great as about 100 km, although 85 per cent of the strain is still distributed within the first 30 km.

One might question the validity of the arbitrary smoothing of the data. We do this for two primary reasons: (1) most of the earthquakes used in this study have been located only to within 15 km, and many are even more poorly located, particularly in Baja California. (2) Strain is not released from a point during an earthquake, but from a finite volume of rock. According to Utsu and Seki (1954), the area of strain release exceeds that of a 5-minute square only for earthquakes exceeding about $M = 5.9$, but it is these few larger earthquakes that tend to dominate the strain-release map. An added complication, not compensated for in our map, is that the area of strain release in these large earthquakes is markedly non-equidimensional but instead is elongate parallel to the fault system. This has been particularly shown by aftershock distributions of the Kern County earthquake (Benioff, 1955a; St. Amand, 1956) and the Desert Hot Springs earthquake (Richter *et al*, 1958). Were we able to take this factor into account in some way that did not unduly prejudice the results, the strain-release map would presumably have a greater lineation or "grain" parallel to the major fault systems.

The total variation in strain release for different 5-minute squares for the 29-year interval was from 0 to 4630 equivalent $M = 3.0$ shocks. In order to portray this wide variation in a cartographically reasonable manner, contour intervals used in Plate 1 and Figure 6 increase geometrically by factors of 4 and have been normalized to numbers of equivalent $M = 3.0$ shocks per 100 km^2.

Interpretation. Even with the geometrically increasing contour intervals of Plate 1 and Figure 6, it is clear that strain release during the 1934–1963 interval has been dominated by the few large earthquakes. That is, in most parts of the southern California region, there has been an insufficient number of small shocks to greatly alter the pattern of strain release that is given by the large shocks alone. Incompleteness of data still further exaggerates this effect in Baja California, where shocks below magnitude 4.5 have not been as systematically recorded and located as in California itself, although they are presumably equally numerous. The dominance of large earthquakes would be even greater, of course, if the maps were based on energy release rather than strain. As was emphasized in the section on historical earthquakes, most large shocks during this period have occurred on or near major throughgoing faults, and it is obvious that the same relationship must now hold with

regard to total strain release. But the additional data from smaller earthquakes does provide considerable smoothing, and some trends now become apparent that were not obvious on the epicenter map of major shocks.

If one disregards the geologic base of Plate 1 or Figure 6 and attempts to visualize significant trends in seismicity, the following zones might be pointed out: (1) a concentration of activity in the southeast corner of the map, including a general alignment along the axis of the northern Gulf of California province (Salton trough); (2) a broad east-west zone of moderate activity across the center of the map, corresponding roughly to the Transverse Ranges; and (3) a north-trending zone along the east side of the Sierra Nevada, possibly merging southward with (4) a northeast-trending belt of activity between Santa Rosa Island and the southern Sierra Nevada. The first three of these zones clearly correspond to major fault systems and are geologically very reasonable. The fourth zone corresponds to known fault trends only in its northern half, which parallels the Garlock and White Wolf faults; the southern half cuts obliquely across major east-trending faults of the Transverse Ranges and reflects no known structural trend. One might legitimately argue that the alleged belt is fortuitous, at least in its southern half. On the other hand, this northeast-trending belt crosses the San Andreas fault nearly at right angles at the very point of its most abrupt bend within the continent, and even if all earthquakes within this belt have not occurred on faults of northeasterly trend, their localization within the belt might well be related to complications in the regional strain field due to the great bend of the San Andreas. For the moment, however, this must remain speculation.

Certainly the most important question to be asked is whether or not the zones of high strain release on Plate 1 could have been predicted solely on the basis of the locations of "active" fault zones as determined from geologic studies. The answer is a greatly qualified "yes"; virtually all of the major seismic activity has taken place in areas of abundant Quaternary faulting, but the converse is by no means true. The outstanding example is the San Andreas fault itself: south of the Transverse Ranges most of the zone of faulting has also been one of high seismicity, and the concentration of activity along the San Jacinto fault has already been pointed out. Within and north of the Transverse Ranges, on the other hand, the San Andreas fault zone is not at all apparent from the strain-release pattern, and indeed has been characterized by an almost complete absence of even very small earthquakes near the western edge of the map. The relative quiescence of this segment of the San Andreas fault, which is known to have broken in the great earthquake of 1857, is even more dramatically shown by the recurrence curves of frequency versus magnitude, which will be discussed later in this study.

Zones of abundant Quaternary faulting that have been accompanied by high seismicity during the 1934–1963 period include, in addition to the southern San Andreas system, (1) the Agua Blanca and San Miguel fault zones of Baja California, probably extending offshore along the northwestward prolongations of the Agua Blanca system toward San Clemente Island, (2) the central Mojave Desert, (3) the Transverse Ranges, and the southeastern San Bernardino Mountains in particular, and (4) the Owens Valley region east of the Sierra Nevada. The previously mentioned northeast-trending belt marked by the 1952 Kern County and 1946 Walker

Pass earthquakes is the major exception to the general correlation between obvious Quaternary faults and high seismicity, although the White Wolf fault had over 10,000 ft of late Cenozoic displacement that undoubtedly continued at least into Pleistocene time (Dibblee, 1954b).

Areas of low seismicity on Plate 1 and Figure 6 are perhaps more intriguing than zones of high seismicity, because one might argue whether the low seismicity in any given region is temporary or permanent. Is local quiescence during this 29-year period caused by true tectonic stability of the underlying crustal block, or is it perhaps related to major strain accumulation on faults that are locked so tightly that even small earthquakes cannot occur, but which therefore must be considered particularly dangerous for the future? This question will be reconsidered in the following section on recurrence relationships, but in this regard we note that the quiescent areas of Plate 1 can be divided into two groups—those in relatively unfaulted crustal blocks, and those in areas of numerous throughgoing Quaternary faults. Among those in the former group might be placed (1) the southern San Joaquin Valley, (2) the Oceanside-San Diego-Tijuana region, (3) the triangular wedge of the western Mojave Desert between the Garlock and San Andreas faults, and (4) the easternmost Mojave Desert. In view of both the geologic and seismic patterns, these areas are probably seismically stable relative to adjacent blocks, although problems of seismic zoning that are considered in the final section of this study suggest little distinction from adjacent areas in terms of potential hazard from shaking. Indeed, in the past 10 years San Diego has been shaken (with intensity IV M. M. or over) more frequently than other large cities of the region, though usually by shocks centered much farther south in Baja California.

A number of areas can be pointed out on Plate 1 where remarkably little seismic activity has occurred between 1934 and 1963 despite an abundance of evidence of throughgoing Quaternary faults. These include particularly the San Andreas fault zone within and north of the Transverse Ranges, and the entire Garlock fault zone, which seems to have served more as a boundary between seismic provinces than as a locus of seismic activity. In addition, two areas of peculiar relative quiescence within otherwise very active belts are the Banning-Mission Creek fault zone between the Imperial Valley and the northern Coachella Valley, and the central Owens Valley, which is interesting because the relative quiescence is centered squarely on the area that was broken in the great earthquake of 1872. In years to come, it will be particularly interesting to see if these and other "holes" in the strain-release map along major active fault systems are gradually filled in.

In contrast to our emphasis on major throughgoing faults, many of the recent Soviet efforts in the field of seismo-tectonics have tended to emphasize correlation between seismicity and geologic features other than active faults (e.g., Gzovski, 1957; 1962). Particular importance has been placed on velocity gradients of vertical movements, both at the present time and during geologic history, and on boundaries between regions of differing geologic histories. To some degree the same criteria would apply to the southern California region, except we would emphasize that the large vertical velocity gradients are almost all across faults that would be considered "active" on other more obvious geologic grounds, and it is these faults that form boundaries between areas of differing geologic histories. In general, it is much easier

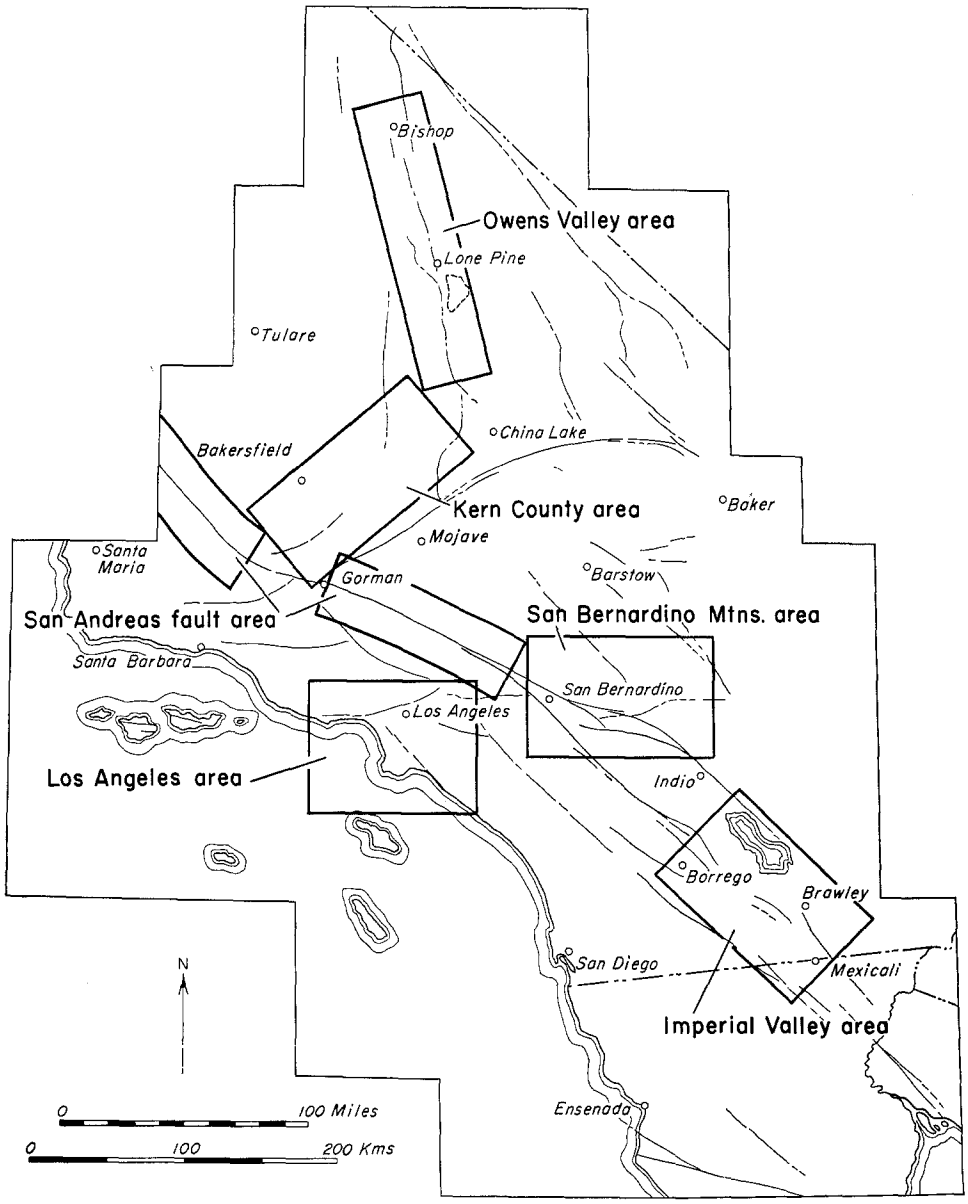

FIG. 8. Areas covered by frequency-magnitude studies.

and more realistic to map the faults themselves than to attempt to compute rates of vertical displacement in the geologic past or to measure such displacements at the present time. In addition, we have the problem of horizontal displacements clearly being dominant over vertical displacements in most parts of the region—an idea that is dismissed in most Soviet studies. And as has been demonstrated by 50 years of intensive geological mapping in southern California, it is a far more difficult task to determine geological histories of horizontal displacements than those of vertical

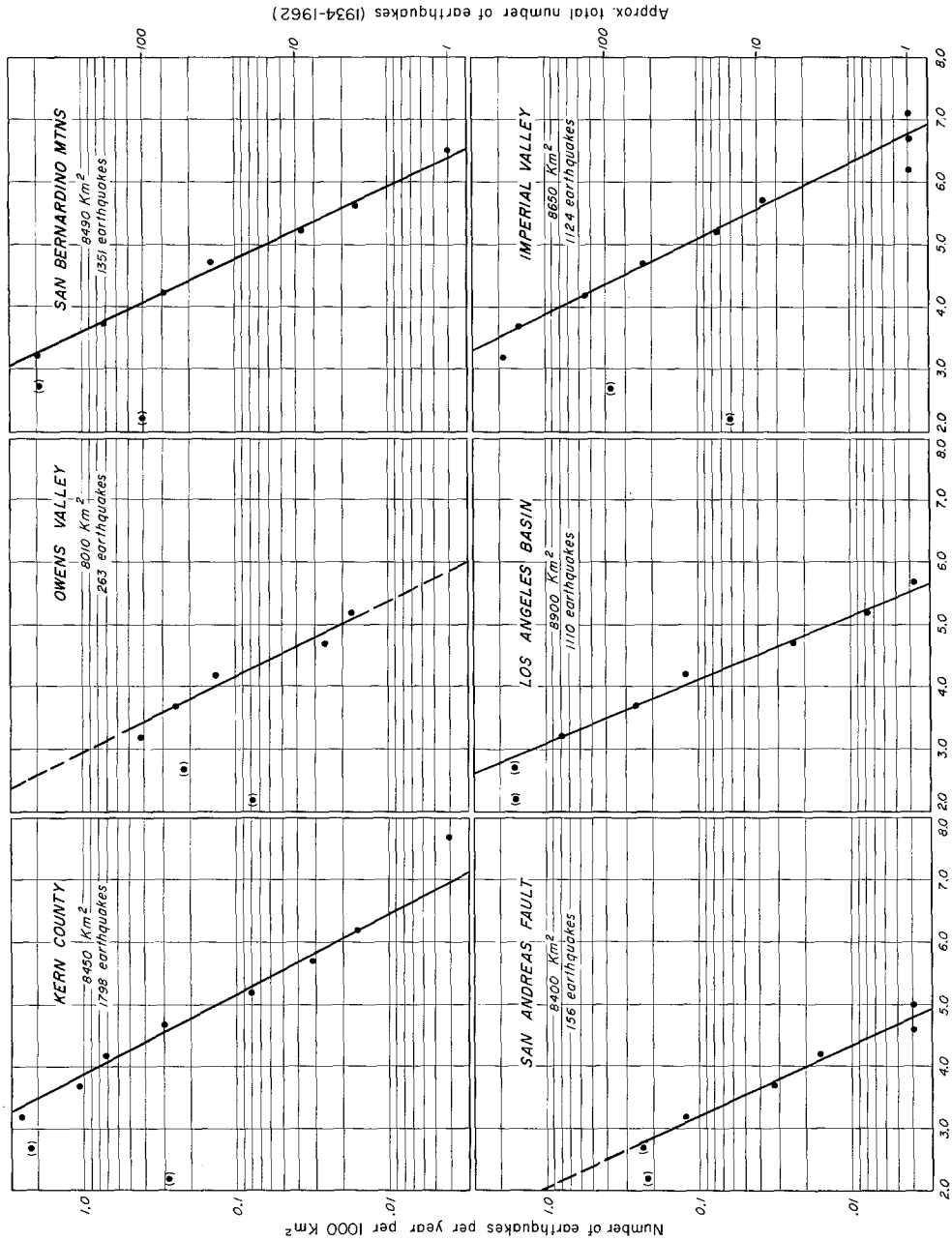

FIG. 9. Recurrence curves for individual areas of Figure 8.

displacements. We do agree that if adequate geodetic control were available on contemporary rates of vertical and horizontal displacements throughout the southern California region, or if widespread instrumental data were available on the associated strain field, this would be a most important step forward to those persons attempting to predict future seismicity.

Magnitude versus Frequency Relationships

Another approach to the problem of delineating seismicity is to plot curves of earthquake magnitude versus frequency of occurrence—so-called recurrence curves. If this is done separately for different areas, the levels of activity reflected by the various curves can be compared; indeed, if a sufficient number of such recurrence curves can be established, it may be possible to contour the levels of activity in the manner suggested by Riznichenko (1958; 1959) and carried out in several areas of the Soviet Union. As was pointed out earlier, this technique has the advantage of averaging many events and reducing the effects of isolated nontypical events, but if the resulting curves are extrapolated to longer time intervals and larger magnitude ranges than those represented in the sample period, a number of important and debatable assumptions are involved.

As an example of this technique, six southern California areas of approximately equal area (Figure 8) have been selected on the basis of their geologic homogeneity and interest. Recurrence curves have been plotted for each of these areas separately for the 29-year period from 1934 to 1963 (Figure 9). Because the Seismological Laboratory assigned magnitudes only to the nearest half-unit until 1944, it has been necessary to group all magnitude assignments in this way. Two parameters have been determined for each curve (Table 2): b is the slope of the curve defined by Gutenberg and Richter's (1954) magnitude-frequency relationship, $\log N = a + b(8 - M)$. A_{3+} represents the position of the curve, somewhat similarly to Riznichenko's (1959) "Seismic Activity," and is here expressed as the extrapolated annual number of earthquakes of $M \geqq 3.0$ per 1000 km^2. (A_{3+} has been determined from cumulative curves derived from those of Figure 9, in order to avoid dependence on the method of grouping magnitude assignments.) One might question the validity of drawing straight lines through the points of Figure 9, which in several cases are more compatible with several *en échelon* segments than with a single linear curve. Such curves have been drawn only to facilitate comparison with those other regions, rather than in the attempt to prove the logarithmic frequency-magnitude law. Indeed, Tsuboi (1958) has questioned the theoretical validity of such a relationship, but this subject is beyond the scope of the present study.

Gutenberg and Richter (1954) obtained a value of b of 0.88 for southern California, closely comparable to the value of 0.86 obtained herein from the much larger amount of data. These authors, and also Miyamura (1962), have emphasized the possible tectonic significance of regional variations in b, which range from 0.4 for Australia to 1.8 for the East Pacific Ocean; the southern California value is typical of other active circum-Pacific areas such as Japan (Tsuboi, 1952; Utsu, 1961). Riznichenko (1959), on the other hand, argues for a relatively uniform value of b for a variety of world-wide areas, including California. Using $\log E = 11.8 + 1.5\,M$, his average value corresponds to about $b = 0.65$, but direct comparisons are difficult in view of

the necessary magnitude–"energy level" conversion. Regardless of comparison with other regions, however, it is significant that most of the recurrence curves for southern California have slopes that are closely similar to one another (Figure 10), which suggests mechanical homogeneity throughout the region. The extensive Soviet Tadjik Complex Seismological Expedition emphasized the same phenomenon for different sub-zones of the Garm and Stalinabad regions (Buné *et al*, 1960; Riznichenko and Nersessov, 1961). Of the southern California recurrence curves

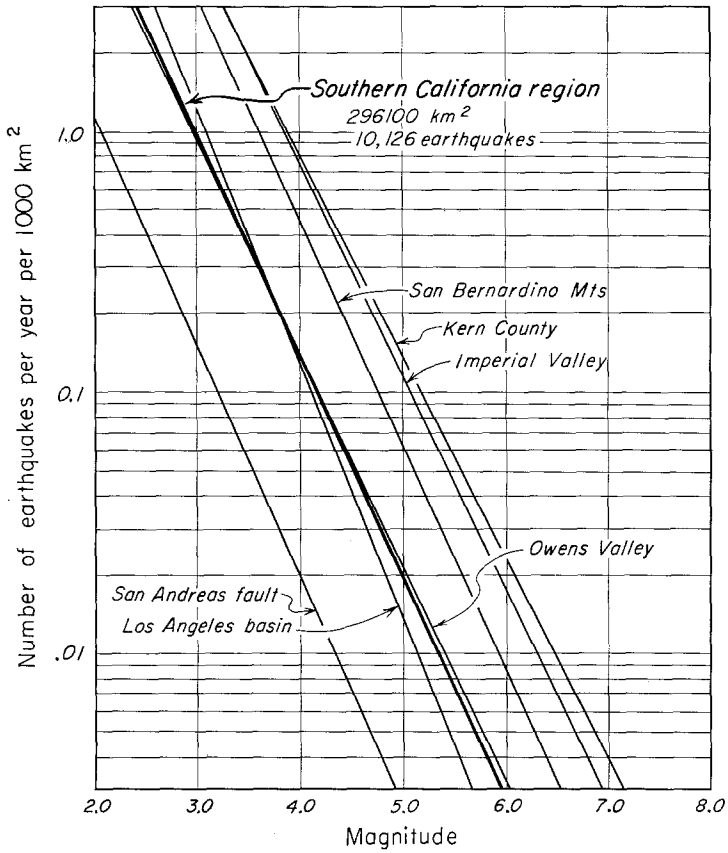

FIG. 10. Comparison of recurrence curves.

only the curve for the Los Angeles basin is markedly steeper than the others, and this may be due in part to the fact that numerous small aftershocks of the 1933 Long Beach earthquake are included but none of the larger shocks of the series, inasmuch as our sample period starts with January 1, 1934.

Whether or not the linear recurrence curve can legitimately be extrapolated to magnitudes higher and lower than those represented in the sample period is an important question, but one to which this study adds little new data. Gutenberg and Richter (1954) pointed out that the curve must somehow terminate at the upper end, inasmuch as earthquakes larger than magnitude 9 simply do not seem to occur. Studies by these authors and many others, however, suggest that the curve may be

linear at least as high as magnitude $7\frac{1}{2}$ or 8 in some areas. At the lower end of the scale, special studies using ultrasensitive seismometers in selected areas of Japan, the Soviet Union, and the United States (New Mexico) indicate that recurrence curves may be linear down to magnitudes well below zero (Asada, 1957; Buné *et al*, 1960; Sanford and Holmes, 1962), but no studies of similar scope have been carried out in southerm California. Richter and Nordquist (1948) noted that small earthquakes near the Riverside station increased "regularly" in number with decreasing magnitude at least down to magnitude 0.4; but a 1959 series of shocks near the China Lake station appeared to have a clear cutoff below about magnitude 0.7 (Richter, 1960). All of our southern California recurrence curves shown in Figure 9 drop off very rapidly below $M = 3.0$ but this is simply caused by the fact that the Seismological Laboratory has made no consistent effort to locate such small shocks in a systematic manner.

It is obvious from Figure 10 and Table 2 that the Kern County area has been the most active of the six southern California regions during the 1934–1963 period, and

TABLE 2

EXTRAPOLATIONS FROM RECURRENCE CURVES OF FIGURES 9 AND 10

Region	Area $km^2 \times 10^3$	b Slope of curve	$A_{3.0}$ No. of Shocks 3.0 per year per 10^3 km^2	"once per year" earthquake M	"once per 100 year" earthquake M	Interval between M = 8.0 shocks yrs
Kern County	8.45	.80	9.4	5.3	7.7	160
Imperial Valley	8.65	.82	8.6	5.2	7.6	173
San Bernardino Mtns.	8.49	.85	4.7	4.8	7.2	491
Owens Valley	8.01	.82	1.2	4.2	6.6	1340
Los Angeles basin	8.90	1.02	1.5	4.2	6.3	3740
San Andreas fault	8.40	.90	0.2	3.3	5.6	18300
Southern California	296.1	.86	1.5	6.1	8.2	52

the San Andreas fault area has been the least active. It is tempting to extrapolate these curves to determine what might be the largest earthquake which might be expected per year or per 100 years, and what might be the expected interval between $M = 8.0$ earthquakes. These extrapolations are shown in the last 3 columns of Table 2 and apply in each case to the entire region, not per 1000 km^2. They have been obtained from cumulative curves derived in turn from Figure 10 and assume no earthquakes larger than $M = 8.5$. The validity of such extrapolations, on the other hand, is seriously open to question, but the arguments are somewhat different for each region and are discussed separately below.

Kern County area. The activity of this region is high because of the 1952 Kern County earthquakes, and to a lesser extent because of the 1946 Walker Pass earthquakes (Figure 5). Thus the 29-year period from 1934 to 1963 can hardly be considered typical, and extrapolations are meaningless if based solely on these data. Indeed, if we consider only earthquakes during the 12-year period prior to 1946 (i.e., prior to the Kern County and Walker Pass earthquakes), the extrapolated recurrence rate for $M = 8.0$ shocks is about 1700 years. Judging from the lack of geological evidence for abundant recent activity, this recurrence rate is probably much more realistic than the 160-year period derived from the 1934–1963 data.

Imperial Valley area. In contrast to Kern County, the Imperial Valley region has experienced numerous relatively large but independent earthquakes during the 1934–1963 period, so that the extrapolations of Table 2 probably have more significance. It is interesting that despite the high seismic activity of the Imperial Valley, no truly great earthquakes ($M \geqq 7.7$) have occurred here within the historic record, and one might well question whether the recurrence curve for this province does not drop off sharply above magnitude 7.0. Indeed, the present rate of occurrence of moderate-sized earthquakes may be sufficient to relieve the accumulating regional strain without the occurrence of intermittent great earthquakes, as is suggested by the following argument.

The Imperial Valley is unusual in that it is not only a coherent geologic and seismic unit, but it is also a region for which good geodetic data on strain accumulation exist. Following an argument similar to that used by Benioff (1955a) for the Kern County earthquakes, and assuming that strain accumulates throughout a 35-km crust, the average yearly strain release represented by the 1124 earthquakes in the 1934–1962 interval is 3.7×10^{-6}. This compares with the yearly strain accumulation across the same area of one-tenth second of arc (Whitten, 1956), corresponding to a strain of 4.8×10^{-7}. Thus, if one believes these figures, strain was being seismically released during this period at a rate almost 8 times as great as that of the strain accumulation, even without any great earthquakes during the interval. If Byerly and DeNoyer (1958) are correct in their calculation that the depth of the 1940 Imperial Valley earthquake fault break was only 12 km, indicating a shallower zone of strain accumulation that we have assumed above, the discrepancy is even greater. Several very debatable assumptions are involved in our line of reasoning, however, and it does not seem possible at present to decide whether the large discrepancy is the result of fallacious assumptions or whether this particular 29-year period is simply nonrepresentative of the secular seismicity.

Owens Valley area. Although seismicity of parts of the Owens Valley area appears relatively low during this 29-year period, it should be remembered that the largest earthquake in California's recorded history occurred in the very center of this area in 1872. Indeed, the strain-release map (Plate 1) shows that the area of faulting at that time is now the quietest area within the Valley. Inasmuch as little is known about possible strain build-up in this region, it is difficult to say whether or not the extrapolations of Table 2 have any real significance in the long-term outlook. It should be noted, however, that if we assume the 1872 shock was of magnitude 8.5 and was associated with an average 10 ft of uplift over one-third the length of Owens Valley, then the extrapolated recurrence rate of 4800 years for earthquakes of similar magnitude implies an uplift of the Sierra Nevada scarp at a rate of 700 ft per million years. This is in sharp contrast to Axelrod's (1962) estimate of 9000 ft of uplift across the Sierran scarp in this same region during the last million years (i.e., post-Pliocene), which suggests either that the seismic extrapolation is unwarranted or that the present epoch is distinctly less active than was most of Quaternary time.

Los Angeles basin area. Probably a sufficient sampling of earthquakes in the Los Angeles basin has been made during the 1934–1963 period so that the recurrence extrapolations of Table 1 have some reality, although it was mentioned previously that aftershocks of the 1933 Long Beach earthquake may somewhat bias the curve

in the lower magnitudes. It is interesting to note that according to this extrapolation the Long Beach earthquake ($M = 6.3$) would qualify as a "one-hundred-year earthquake." Whether or not earthquakes as large as magnitude 8 occur in this area under present tectonic conditions is unknown, although fresh and throughgoing fault scarps that might be associated with such earthquakes are probably less numerous here than in any of the other five regions. The northern part of this area lies within the Transverse Range province, in which at least one earthquake as large as magnitude 7.5 has occurred in recent years (1927, off Point Arguello).

San Bernardino Mountains area. Much of the apparent high activity of this area is caused by a single major event, the 1948 Desert Hot Springs earthquake and its aftershocks (Richter *et al*, 1958). For this reason alone, we tend to be skeptical of the extrapolations of Table 2. In addition, major branches of the San Andreas fault system pass through this area, so that many of the arguments discussed in the next section probably hold here too.

San Andreas fault area. That the San Andreas fault zone should be one of the most seismically quiescent areas of southern California is surprising to most people, but this is clearly demonstrated by Figure 10 and Table 2, which illustrate the primary hazard in extrapolating long-term activity from relatively short-term records. The San Andreas fault area shown on Figure 8 is a strip 40 km wide centered on the fault, and it is split into two segments because the 1952 activity related to the White Wolf fault would otherwise extend into this strip. The southern segment extends roughly from Cajon Pass to Quail Lake, and the northern segment from Cerro Noroeste to the northern end of Carrizo Plain. Carrizo Plain has often been thought of as the most diagrammatic segment of the San Andreas fault, and photographs of this "active" area illustrate many textbooks (e.g., Richter, 1958, p. 2), yet within the history of the Seismological Laboratory only 12 small earthquakes have been recorded and located in this northern segment. Despite the present quiescence, it is clear that the great 1857 earthquake was centered in this region (Wood, 1955), and abundant scarps leave no doubt that many other similar shocks have occurred along this line in the recent geologic past. Even in the southern segment, most of the activity represented by the curve of Figure 9 has come from the periphery of the 40-km strip, and no earthquakes have been clearly attributed to the San Andreas fault itself.

We should perhaps point out that the San Andreas fault zone near the western edge of the region is in a part of our seismograph network where small earthquakes may not have been as systematically recorded as in other areas. Possibly more small shocks have occurred here than we realize, and studies are now under way using ultra-sensitive seismometers to test this possibility. On the other hand, we feel confident that few shocks above magnitude 4.0 have escaped detection in this area, so that if an inordinate number of very small shocks is indeed occurring the recurrence curve for this area must depart markedly from linearity—a situation that has been observed nowhere else and seems unlikely to us.

The current quiescence along the San Andreas fault might be explained in three different ways: (1) elastic strain was fully relieved during the 1857 earthquake and has not yet built up again to the point where even small earthquakes occur; (2) the cohesion across the fault in this segment is so great that accumulating strain cannot be relieved by small earthquakes and will instead be released by a great earthquake

at some time in the future; or (3) gradual slippage along the fault is continually relieving the regional strain.

Alternative (3) can probably be eliminated for most of this segment of the fault on the basis of undisplaced survey lines, tunnels, and pipelines at Maricopa, Gorman, Elizabeth Lake, and Palmdale. In the absence of complete geodetic data for this part of the fault, it is difficult to choose between the remaining alternatives (1) and (2), but inasmuch as parts of the fault farther north where strain is known to be accumulating are likewise seismically quiescent, we prefer alternative (2). But regardless of whether one visualizes an impending great earthquake on this segment of the fault, there can be no doubt that numerous great earthquakes have occurred here in the geologically recent past as compared to other parts of southern California, and the 18,300-year recurrence rate suggested by the magnitude-frequency curve (Table 2) is grossly misleading. Everything that is known about the geology of southern California indicates that the San Andreas fault zone should be at the top of the list in Table 2 rather than at the bottom, and this emphasizes the dangers in attempting to extrapolate from a record of only 29 years in an area of only 8400 km^2. The suggestion that secular seismicity evaluations can be made from records of only 1 or 2 years over areas of only 1000 km^2 (Gzovsky *et al*, 1960) leaves us exceedingly skeptical, at least for regions tectonically similar to southern California, and similar skepticism has recently been expressed in the Soviet Union by Gubin (1964). Likewise, we question the local applicability of Asada's (1957) conclusion that one can locate "a part of the crust where destructive earthquakes will never occur by making observations of micro-earthquakes and determining whether they occur there or not." Indeed, a map of parts of the southern California region based on these principles might well give an exactly *inverse* picture of secular seismicity.

The principle is further illustrated by a number of recent examples from other areas:

(1) The great 1960 Chilean earthquake occurred in an area which Gutenberg and Richter (1954) had specifically pointed out as one of low seismicity in the previous 1904–1952 period for which seismograph records existed. Munoz Gallegos (1960) reports that most people interviewed in the Province of Cautén, one of the areas most heavily afflicted with aftershocks, had never felt an earthquake before, not even a light tremor. Considering the great earthquakes of 1575, 1835, and 1960 in this region, relative quiescence in a seismically active zone may be more a cause for apprehension than for comfort.

(2) The disastrous Niigata, Japan, earthquake of 16 June 1964 ($M = 7\frac{1}{4}$) was centered in a pocket of lowest "expectancy of maximum acceleration," based on Japanese historical records (Kawasumi, 1951).

(3) Although the area of the great 1964 Alaskan (Prince William Sound) earthquake had not been completely quiescent in the years prior to 1964, it had nevertheless experienced no truly great earthquakes within the historic record, and most of the more moderate activity was concentrated in a belt lying northwest of the area broken in 1964 (Davis, 1963). Furthermore, the linear zone of 1964 aftershock activity was bracketed on both ends by epicenters of the great earthquakes of 1899 and 1938.

(4) The Iranian earthquake of 1962 ($M = 7\frac{1}{4}$) created total disaster in an area

where even the oldest inhabitants had never before felt tremors strong enough to alarm them (Ambraseys, 1963), yet the region is one of active tectonism with archeological evidence of previous earthquakes, and much of the 1962 break was along pre-existing faults that have been active in late Cenozoic time (Mohajer and Pierce, 1963).

Southern California region. Unlike the six individual areas that have been discussed above, the recurrence curve and extrapolations for the southern California region (Figure 10; Table 2) are based on the entire 296,100-km^2 area and 10,126 earthquakes with the "Pasadena Local Area" and "Baja California Extension" of Figure 1. Although the premise that big earthquakes occur where little ones do apparently breaks down when considering areas as small as 8000 km^2, probably a sufficient area and a large enough number of earthquakes are included in the entire southern California region so that the extrapolations of Table 2 have some real meaning in this case. This viewpoint is substantiated by the known occurrences of great earthquakes during the historic record: judging from the areas over which they were felt, there have been three, or possibly four, great earthquakes in this region since 1800. These are the 1812 earthquake in the Santa Barbara Channel of questionable magnitude, the 1872 Owens Valley earthquake, the 1857 Fort Tejon earthquake, and the 1892 earthquake in northern Baja California (possibly on the Agua Blanca fault). Inasmuch as all of these shocks were probably in excess of magnitude $7\frac{3}{4}$, their frequency during this period corresponds roughly with the extrapolated frequency of 52 years for such shocks given by the 1934–1963 records.

Changes of Seismicity With Time

Yearly cumulative strain release in the southern California region is shown in Figure 11, and it is obvious that within the history of the Seismological Laboratory the rate of strain release has been relatively constant with the exception of a few years during which large earthquakes occurred. The main "jumps" in the curve are caused by the 1940 Imperial Valley earthquakes, the 1952 Kern County earthquakes, and the 1956 San Miguel earthquakes. One might expect that if the regional recurrence curve of Figure 10 indeed has validity, the strain-release curve of Figure 11 should be accurately reflected in the numbers of earthquakes recorded yearly. Table 3 indicates that this is true in a general way, but departures from exact correspondence are numerous. These are apparently due to the facts that (1) small aftershocks continue into years beyond those of the main shocks, (2) not all aftershocks sequences have been equally well investigated, and (3) one year is evidently not a sufficiently long sample time for strict adherence to the recurrence curve for shocks greater than $M = 3.0$ in this region, even in the absence of aftershock sequence complications.

If there were a sufficiently long-time record to establish the average slope of the curve of Figure 11, one might be able to predict the equivalent size of earthquake necessary in any given year to bring the curve back to the average, as has been done for long-term regional data by Benioff (1955b). We do not feel, however, that the 1934 through 1962 time interval represents a long enough time span to establish a meaningful average level of activity. It does seem likely that the average level is somewhat higher than that represented by the post-1956 segment of the curve

(including, now, activity through 1964), so that a large earthquake in the southern California region would certainly come as no surprise, based on this line of reasoning alone.

Benioff (1951b) has argued for quasi-periodic changes in the level of world-wide seismic activity since the turn of the century, and Gutenberg (1956) has pointed out the rather sudden decrease in world-wide seismicity following 1906. If such secular changes have taken place in the southern California region alone, however, they are not obvious to us; neither the 1934–1963 seismographic data nor the limited pre-1934 records substantiate any significant secular changes in either the level or geographic distribution of southern California seismicity within recorded history.

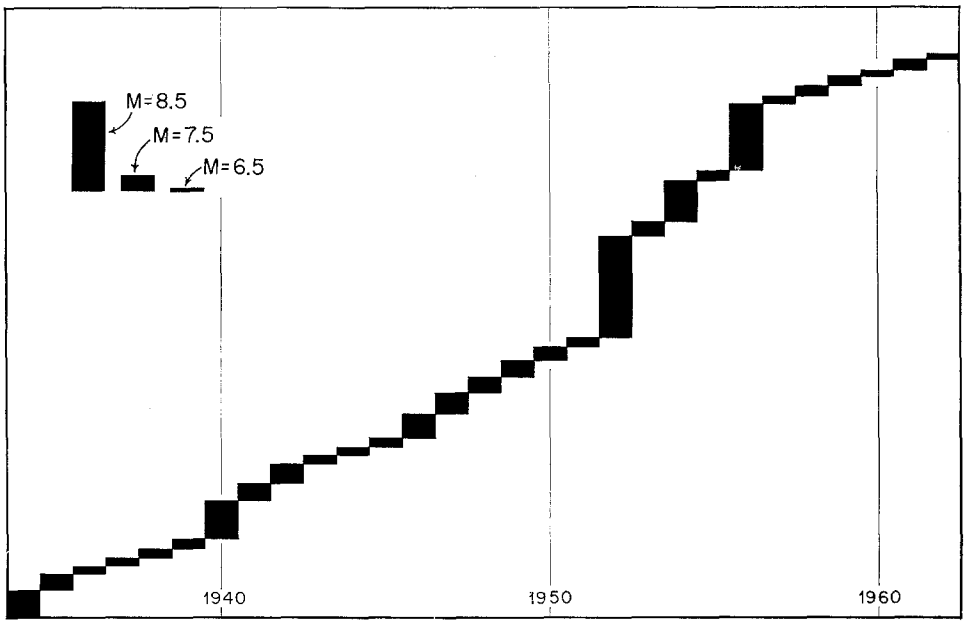

FIG. 11. Cumulative strain release in southern California region as a function of time, 1934–1963. Bars at upper left show equivalent strain of single earthquakes.

FAULTING AS THE CAUSE OF EARTHQUAKES IN SOUTHERN CALIFORNIA

Faulting as the basic cause of earthquakes has recently come under serious attack from Evison (1963), who argues the converse point of view that faulting "should be regarded as a form of earthquake damage" rather than as the cause of earthquakes. Earthquakes themselves are relegated to an independent and more obscure cause, perhaps phase changes at depth. Since much of Evison's discussion concerns southern California earthquakes, we feel obligated to evaluate his conclusions in the light of our study. Among the major lines of evidence used by Evison to support his point of view are:

(1) There has been no adequate demonstration that earthquake foci do indeed lie on active faults.

(2) "Only a small proportion even of large shallow earthquakes are accompanied by significant fault movement at the surface," and the associated faulting in many

cases has been much more complicated than one would expect from the simple elastic rebound theory.

(3) Major segments of "active" faults are apparently without earthquakes, even of small magnitude.

Several other important lines of evidence are mentioned by Evison, but we feel that our data from southern California have particular bearing on these three, which are discussed separately below.

Evison correctly points out that "since in seismically disturbed regions it is common for active faults to occur every 20 km or so, there is mostly ample opportunity to assign any particular epicenter to some fault or other." But whether or not the "opportunity" exists, we feel confident that the vast majority of our instrumental epicenters have been located free of geological prejudice, particularly

TABLE 3

NUMBERS OF RECORDED AND LOCATED EARTHQUAKES OF MAGNITUDE 3.0 AND GREATER WITHIN THE SOUTHERN CALIFORNIA REGION, BY YEARS

1934	171	1949	310
1935	317	1950	212
1936	209	1951	136
1937	179	1952	379
1938	178	1953	324
1939	209	1954	391
1940	269	1955	187
1941	215	1956	279
1942	235	1957	156
1943	173	1958	147
1944	158	1959	177
1945	97	1960	123
1946	302	1961	181
1947	290	1962	154
1948	207		

since 1937. Indeed, a glance at our detailed map of the Los Angeles basin (Figure 7) is sufficient to demonstrate that most earthquakes in this part of southern California clearly have *not* occurred along major faults. On the other hand, the distribution of large earthquakes is distinctly different (Figure 5): as was pointed out in the discussion of major historic earthquakes, there are only a few instances of shocks of magnitude 6.0 and greater for which a reasonable argument cannot be made for association with a given pre-existing fault. The exceptions include (1) large aftershocks of the Kern County earthquake, (2) a number of large shocks in Baja California for which neither the epicenters nor the local geology are well known, and (3) possibly the 1946 Walker Pass earthquake and the 1947 Manix earthquake. All of the instrumentally located epicenters of other large shocks are closely associated with major faults, at least within the limits of location errors. Of particular note is the alignment along the San Jacinto fault zone; even if one neglects the 1915, 1918, and 1923 locations (which are based partly on macroseismic data), the remaining epicenters clearly delineate the fault zone. All in all, in contradis-

tinction to Evison's skepticism, we remain impressed with the association between large earthquakes and major active faults in southern California, although we recognize that there may be exceptions and that the southern California pattern does not necessarily apply to all other regions.

Evison's second argument claims that only a small proportion of large shallow earthquakes have been associated with fault movements on the surface. This overlooks the fact that most large earthquakes are submarine, and many others have originated in remote areas where faulting could not have been observed. Moreover, Evison's point certainly cannot be maintained for southern California; every major earthquake in this region that was carefully investigated in the field and that might reasonably have been expected to be associated with fault displacement (i.e., $M > 6.5$) has indeed been so associated. These earthquakes have all been discussed earlier in this study. Only in the case of the 1947 Manix earthquake do we feel that there is serious doubt as to the direct relationship between surficial faulting and faulting at depth (Richter, 1958), but inasmuch as this shock was of very marginal magnitude for associated faulting ($M = 6.3$), it does not seem fair to extrapolate phenomena of this event to all larger earthquakes.

It is certainly true that the causal relationship between the 1952 Kern County earthquake and the movement on the White Wolf fault has not been established unequivocally, but we cannot agree with Evison that it constitutes a "feat of imagination" to relate directly the two. He argues that low-angle thrusting, such as was observed along the White Wolf fault, is "usually regarded as a shallow phenomenon" and was perhaps strictly a secondary effect resulting from surficial "spreading" of the Tehachapi Mountains over the adjacent lowlands. On the other hand, thrust faults that steepen rapidly with depth are the rule rather than the exception in southern California, and would be the expected result of vertical displacement at depth (Sanford, 1959). Furthermore, well-located aftershocks that occur throughout the region of the White Wolf fault average 8 km in depth (Cisternas, 1963); even in the absence of an adequate theory of aftershocks, this distribution with depth would seem most accidental if the faulting were entirely surficial. Evison says that Gutenberg (1955a) assumed the fault plane to dip steeply in his solution, but it appears to us that he assumed only the strike of the fault and the direction of dip; the steep (63°) dip is the result of his solution. Evison further infers that because the epicenter was 20 km from the nearest point of surface faulting, unjustified extrapolation is required to relate the two to the same fault. But it should be emphasized that very clear geophysical evidence from oil exploration indicates that the White Wolf fault does indeed extend in the subsurface toward the epicenter (Buwalda and St. Amand, 1955), and extrapolation of the fault to and through the epicentral region is far more reasonable than any other course. These, plus other lines of evidence that Evison does not discuss, such as the areal distribution of aftershocks (Richter, 1955) and the northeasterly propagation of the source disturbance (Gutenberg, 1955b), lead us to the firm conclusion that the fault theory still provides the most likely and reasonable explanation of the 1952 events.

In his third argument, Evison points out that even small earthquakes are not occurring along parts of the Alpine fault in New Zealand, which is otherwise looked upon by geologists as a very active fault (Suggate, 1963). This "discrepancy be-

tween seismicity and fault evidence" is thus used as an argument against the "fault hypothesis of earthquakes." Evison might just as well have pointed to parts of the San Andreas fault in California, where current seismicity likewise is nil. But we have the advantage in California of knowing that shear strain is continuing to build up in many of these areas, as well as the knowledge of great historic earthquakes in 1857 and 1906 along parts of the fault that are now relatively quiescent. Thus, in our opinion, temporary seismic inactivity along segments of "active" faults is a powerful line of evidence in favor of the fault theory rather than against it.

While defending the fault origin of earthquakes in southern California, we should emphasize that this does not necessarily constitute a defense of the classical elastic rebound theory in the sense of overcoming frictional resistance. Mechanical deficiencies in the frictional basis of the elastic rebound theory for earthquakes deeper than a very few kilometers have recently been pointed out by Orowan (1960) and Griggs and Handin (1960). Whether the mechanism of faulting be by brittle fracture, by creep instability, or by propagation of flaws, we only argue that in some way this must represent a sudden loss of cohesion within a shear zone (i.e., a fault) following a period of elastic strain accumulation.

Implications for Seismic Zoning

It is not the purpose of this study to attempt to establish seismic risk zones for the southern California region, but we feel obligated to point out a number of severe problems in seismic zoning that are emphasized by this work and other related studies:

1. Determination of the relative "activity" of faults on the basis of geologic evidence alone is difficult, and no part of the southern California region is very far removed from one or more faults that have a demonstrable history of Quaternary displacements.

2. We have emphasized repeatedly that frequency-magnitude and strain-release studies in this region indicate that large earthquakes do not necessarily occur where small ones do, at least as sampled during a 29-year period. Thus, short-time seismic history is not a valid guide to future seismicity except in a very gross sense. A far better criterion of expected activity would be a precise measurement of strain buildup, but insufficient geodetic and strain-meter data are now available to draw many significant conclusions.

3. Proximity to active faults is by no means the only criterion of seismic hazard. Louderback (1942), Gutenberg (1957), Richter (1959), and others have emphasized the importance of local ground conditions, which have not been considered in this study. Furthermore, Benioff (personal communication) has argued that even under similar geologic conditions, shaking during a great earthquake may be more intense at some distance from a fault than very close to it, particularly in the long-period vibrations. Benioff argues that the ground motion at the fault is essentially a unidirectional heave that becomes transformed into an oscillatory wave train of increasing duration as the wave propagates away from the fault.

4. Shallow aftershocks of a major earthquake may do more damage in a local area than the main shock itself, and aftershocks of a major earthquake are dis-

tributed over a much wider area than many people appreciate. For example, a local aftershock of the 1952 Kern County earthquake caused far more damage in the city of Bakersfield than did the main shock (40 km away) one month earlier. A more dramatic example of this phenomenon is illustrated by Figure 12, which shows the major aftershocks of the 1960 Chilean earthquakes (based on Fisher *et al*, 1964)

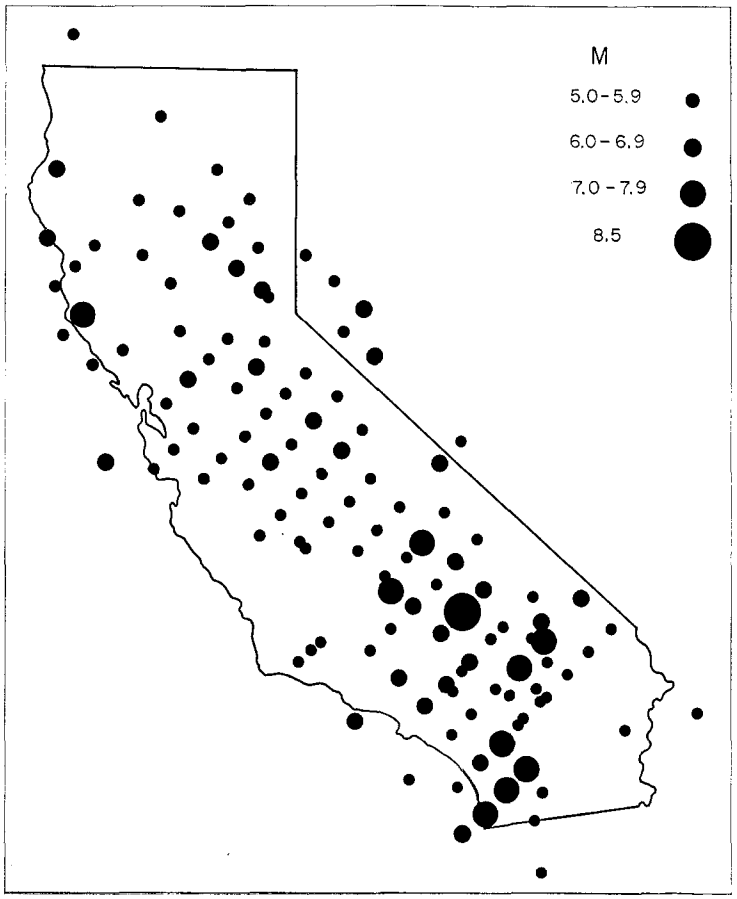

FIG. 12. Epicentral distribution of 1960 Chilean earthquakes during first six months of activity, superposed on map of California at same scale. Principal epicenters are arbitrarily assumed in southern part of state, with northward progression of faulting. Chilean data from Fisher *et al* (1964).

superposed on a map of California at the same scale. It is particularly noteworthy that on this map shocks as large as the disastrous 1933 Long Beach earthquake are relatively evenly spread over almost the entire state of California; one aftershock of magnitude 7.1 occurred more than 800 km from the epicenter of the initial shock, and presumably not on the same fault. Inasmuch as great historical earthquakes in California have not been associated with breaks as long as the 1000-km length of the Chilean earthquake (Press *et al*, 1961; St. Amand, 1961), such a widespread aftershock distribution for great California earthquakes is probably unlikely,

but Figure 12 does emphasize the fallacy in predicting seismic hazard solely on the basis of the locations of active faults or of the epicenters of great earthquakes themselves.

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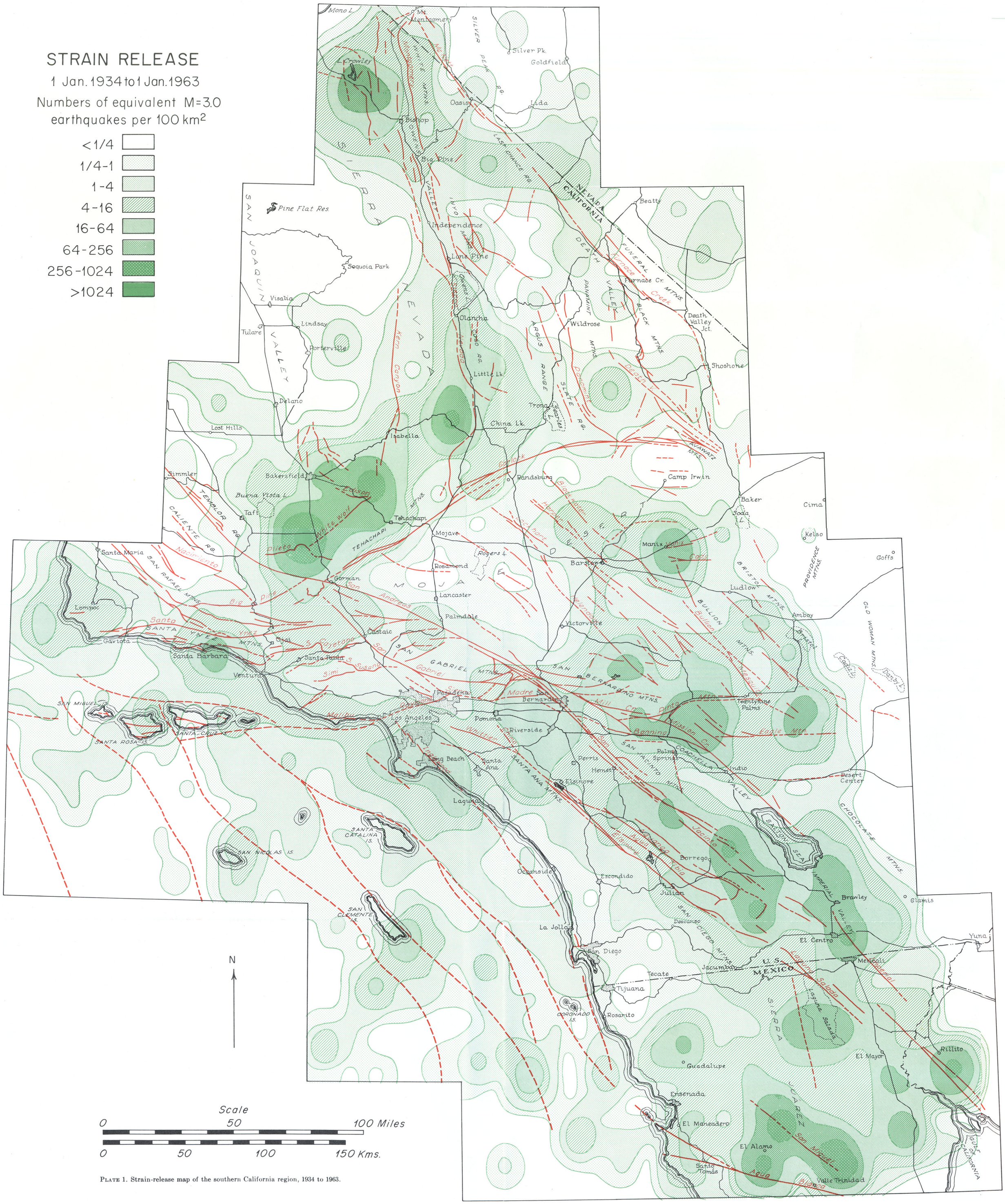

PLATE 1. Strain-release map of the southern California region, 1934 to 1963.