Note :- For accompanying fault map see C.S. B-852

THE BULLETIN OF THE
SEISMOLOGICAL SOCIETY OF AMERICA

VOL.XIII MARCH, 1923 No. 1

A FAULT MAP OF CALIFORNIA

By Bailey Willis

Another title, and perhaps a more obvious one, would be an "Earthquake Map of California." The map is designed to show the lines on which earthquakes may occur and which, therefore should be avoided by structures liable to damage by earthquakes. But since tectonic earthquakes occur only on faults, a map of the faults which traverse the mountains of the state includes those on which there may be earthquakes. We are more nearly sure of including the earthquake lines, if we map faults than if we map only known earthquakes, because no one knows on what fault the next slip may come. Possibly some day we shall be able to keep a record of the elastic vibrations of the earth's crust along danger lines and thereby forecast a shock as we now do the coming storm, but that ability, if it come at all, must await patient investigations to be extended over years. Earthquakes are still strange phenomena, for we have been too much afraid of them to become intimate with their causes. We do know, however, that they originate on faults and this is a map of the faults which traverse the rocky foundations of California and may be the origin of earthquake shocks.

A fault is a break in the rocks. The faults shown on this map are breaks which are usually many miles long; some of them are several hundred miles long; they are thus features which resemble those of mountains in magnitude and, in fact, faults usually define the mountain ranges of California. We do not know how deep into the earth faults extend, but their depth is probably commensurate with their length. The smaller branches may not go deeper than a mile or two, but the depth of the greater ones is probably tens of miles. The lines on the map thus represent surfaces of fracture of the earth's crust. They outline large blocks which are mountains or even mountain ranges. They penetrate the rocks to depths where they are firmer and much more highly elastic than they are at the surface.

An earthquake is an elastic shock, which originates in a slip on a fault, where the rocks have been held by friction, under increasing strain, until they yield. Slipping suddenly, like an elastic spring, they send vibrations through the globe.

Such are the earthquakes of California and of many other regions where there are no active volcanoes. Volcanic activity also gives rise to shocks and it is not impossible that one kind of earthquake may pull the trigger for the other, where elastic strain and volcanic conditions exist simultaneously. In California, however, we have only the elastic, so-called tectonic, earthquake.

The intimate connection existing between faults and earthquakes was clearly established by the researches carried out by the geologists who investigated the shock of April, 1906, that set fire to San Francisco; especially by the studies of Lawson, Branner, Gilbert, and Reid. The line of the fault was traced for one hundred and fifty miles by them and their assistants. The nature of the displacement and its amount were determined and the explanation of the shock, as having been due to elastic strain and rebound, was placed beyond doubt.

These who may wish to know what the evidence and the deductions were should consult the report of the State Earthquake Commission, published by the Carnegie Institution of Washington. That report contains a map of the principal earthquake faults of California, but on a small scale and not complete enough to be of practical use.

Dr. Branner was particularly impressed with the duty which the conditions in California place upon geologists to investigate earthquakes and inform the people of the Commonwealth with a view to diminishing the inevitable risks attending them. He, together with many of his colleagues, regarded those risks as greatly exaggerated by the failure to take reasonable precautions in building, as well as in locating structures, and he looked upon the location of active faults as the most immediate means of promoting security. The Fault Map which accompanies this text may be regarded as inspired by him, for he bequeathed the obligation to his successor in geology at Stanford.

A combination of circumstances made the realization of Dr. Branner's purpose possible. The base map of the State had been prepared by the U.S.Geological Survey, especially to enable the Division of Irrigation under Professor Frank Adams of the University of California, to present to the people of the State the facts regarding irrigation, and Professor Adams arranged for the use of the map as a base for the Fault Map.

The Carnegie Institution of Washington, through its Advisory Committee on Seismology, encouraged the work and Mr. H. O. Wood, Research Associate in Seismology, compiled the map of the faults for the southern part of the State.

A number of public spirited businessmen of San Francisco, appreciating the practical nature of the work, subscribed the funds necessary to execute surveys where the fault lines had not been traced. This work was done under the auspices of the Seismological Society of America, so far as was possible within the time and with the means available.

Thus the Fault Map is a product of cooperation of several agencies. The writer, however, as President of the Seismological Society, is responsible for the form in which the map appears and for presenting to the public a draft which is less complete than would be desirable. It is a statement of progress in the execution of surveys, which should be continued and perfected for the benefit of the people of the Commonwealth.

With this much of explanation of the purpose and origin of the Fault Map we may proceed to describe its features more in detail.

By reference to the legend it will be seen that two classes of faults are distinguished: active and dead. These terms are used very much in the sense in which we speak of active volcanoes or dead volcanoes. An active fault is one on which a slip is likely to occur. A dead fault is one on which no movement may be expected. Both kinds are found and, obviously, it is desirable to distinguish between them.

The distinction between active and dead faults appeared to be obvious when the execution of the map was undertaken, but unfortunately it proved to be capable of two different interpretations. these became incorporated in the map and could not be altered after it had been drawn. There is therefore an inconsistency between the northern and southern sections, which appears in the use of the terms active and dead.

Mr. Wood designated as active all faults on which there has been a movement within historic time, and also all faults upon which physiographic evidence of recent surface dislocation - "trace" phenomena - could be obtained.

Mr. Willis connected the faults with the growth of the mountains. It is the general opinion of geologists that the mountains of California, including both the Sierra Nevada and the Coast Ranges, are still being pushed up and that earthquakes are direct evidence of that activity in mountain growth. The growth of a mountain takes very many centuries. The mechanical effects, which are manifested, in part, by faulting, are very complex and are not within reach of analysis by human investigation. We cannot know the conditions of pressure and friction which hold the masses steady or cause them to slip. Hence any fault that is related to a growing mountain is reasonably subject to the suspicion of being an active fault in the sense that a slip may occur. The northern half of the map, north of San Luis Obispo, is drawn on this basis.

Active faults, according to the historic point of view, include the great San Andreas rift, the Elsinore and San Jacinto rifts, and others connected with less well known, but recorded earthquakes. According to the geologic interpretation not only these, but also the faults which surround Mt. Tamalpais, traverse the Santa Clara Valley, the Santa Lucia Range, the Santa

Ynez Valley, and those that extend thence southeastward, passing northeast to Los Angeles, are potentially active.

For the information of those who may care to know more in detail of the method of securing data with which to compile the map some further explanation is offered. Mr. Wood gathered information for all parts of the State south of San Francisco from geologists, mining Engineers, oil companies, and other available sources. The facts by which any fault was located were commonly, displacements more or less directly observed in the strata, traced by geologic surveys or noted in mining or drilling. It was impossible to distinguish an active fault from a dead one, except by personal observation in the field and that recourse, unfortunately, was not open to the compiler in a majority of cases. He therefore cloassed as active only those rifts on which earthquakes had been recorded or upon which physiographical evidence of recent dislocation could be obtained. Many of these Mr. Wood traced personally, especially in the region round about Los Angeles.

Mr. Wood's data were far more complete for the southern part of the State, south of San Luis Obispo, than north of that district. Mr. Willis undertook to supplement the compilation by making a geologic reconnoissance between San Luis Obispo and Santa Rosa, and the work was carried out by himself and Mr. Robin Willis. The method used was based on observation of the mountain forms. Throughout the Coast Ranges it is usually possible to recognize a topographic surface, an old landscape, which is older than the present mountains and which has been warped or faulted during their elevation. The old surface was a hilly lowland, not a plain, but its features are distinct from those of the landscape that is now being sculptured. To identify it, whether on the summit of a range or on the slope from ridge to valley, or where it passes under the modern valley-fill, one needs to consider the actual work of the winds, rains, and streams and to recognize the remnants of the older lowland, so far as it has not yet been attacked.

Thus the orchards which adorn the summit of the Santa Cruz mountains west of Stanford University grow in the deep soil characteristic of the old surface. A view across the northern portion of the Santa Lucia Range shows the landscape of the old lowland, there elevated to more than three thousand feet above sea, but not faulted. He who drives the highway along the Santa Clara Valley from San Jose to Gilroy may see it in the flat slopes of the Mount Hamilton Range, which are being cut to pieces by the little modern ravines. Along there it slopes to the valley and passes under it, but if one ascends to the ridge and tries to trace the old surface eastward he finds it faulted down. The continuation in the Mount Hamilton Range is in a separate mountain block beyond a fault and at a different level.

It is not desirable, in this brief account of the Fault Map, to pursue the description of the method further. It is not a new method since it was employed by Davis and by Hayes in studies of the Appalachian uplift more than thirty years ago and has been applied by the writer to the investigation of many ranges, but its extensive use to trace out the fault systems of the Coast Ranges is not so generally practiced as it might be.

An active fault is also recognized by minor features of the landscape, "trace" phenomena, the accidents of its activity, provided the last movement be not too long past. The case is again similar to that of a volcano. We see in the graceful perfection of outline of a Fujiyama the evidence of its recent activity. Erosion has not had time to destroy the form. Along an active fault we observe landslides, swamps, ponds, trenches, ridges, and valleys, which by their peculiar forms and relations betray their relation to the rift and the recency of their origin.

None of these local features is peculiar to an earthquake rift. Landslides may occur on any steep hillside. Swamps and ponds are due to various conditions. Trenches, ridges, and valleys are the usual effects of erosion. But the repetition of these accidents along a definite line points to a common cause, a condition inherent in the underground structure. Sometimes a stratum of unusually hard rock fixes the position of a ridge and of an adjacent valley, giving to both a linear character, but such cases are easily identified. They are, furthermore, comparatively rare in the Coast Ranges, where the rocks vary greatly in character in short distances, and they are apt to be of small extent along the mountain trend as compared with the rifts, which run for tens or hundreds of miles.

The alignment of minor accidents of the landscape is thus a prime means of identification of an earthquake rift. If topographic maps of sufficient detail and accuracy have been made they may facilitate a preliminary study of possible lines, to be verified by examination in the field. Where we have as yet no topographic surveys, adequate to show the details of the landscape, it has been found impossible to follow the active faults, except by an expenditure of time and money which was beyond our means. This is the reason why the rifts have not been traced northward beyond Santa Rosa, although they undoubtedly extend on through Humboldt County and are possible causes of danger.

Special studies were made of the San Andreas Rift with a view to determining the character of the surface appearances of an active fault. It was examined in detail immediately after the shock of 1906 and the observations, recorded in the Report of the State Earthquake Commission, constitute a valuable source of information as to its features at that time. It was, however, desirable to ascertain to what changes had been effected in fifteen years and it was necessary that observers who had not previously had an opportunity to note these characteristics of a fault should be trained to recognize them. The writer found this experience very enlightening for the Rift does not present certain aspects which he anticipated and does offer others that were not looked for. We may proceed to describe some of the more characteristic sections of the San Andreas Rift.

Tomales and Bolinas bays cover an easily accessible section in which the fault zone is probably a mile or more in width, as described by G. K. Gilbert. An observer is struck by the absence of any evidence of displacement. The shores of the bays slope gently down to the water, with a profile that is slightly convex upward, and though, as we shall see, this convexity is significant, it would not attract attention to the existence of the Rift.

The valley between Tomales and Bolinas bays, like that which follows the Rift for twenty-five miles from Mussel Rock to Searsville Lake, has the cross-section of an open valley of erosion. The peculiarities which these valleys exhibit, the undrained sections, the central ridges the swelling slopes, are all readily attributable to the irregular distribution of the harder or softer rocks of the Franciscan terrane. No geologist who was not aware of its character would be prone to assume that it was a fault-valley instead of an erosion valley; yet such is the case, as was conclusively demonstrated in 1906. That fact being established we recognize that it is remarkably straight, considering the heterogeneousness of the rocks which it traverses, and careful observation reveals the displacement of the old lowland surface or datum plane.

We shall refer several times to this old lowland surface, which is now warped, faulted, and elevated to the mountain summits, or depressed beneath the valleys, and it will be convenient to call it by the name which is already in use among the geologists who have recently studied it most widely. It is known among them as the Santa Cruz lowland because it was first described as it occurs in the Santa Cruz mountains.

Following the San Andreas Rift southward beyond Searsville Lake we trace it over Black Mountain, down the valley of Stevens Creek, along upper Los Gatos Creek, and just west of the peak of Loma Prieta, the highest point in this part of the Coast Range. The Rift here shows a character not uncommon along the active faults. After following a valley, of which it is the direct cause, it crosses the highest part of the range, splitting the mountain peaks. A common notion is that a fault forms one side of a long unsymmetrical ridge, the steep or scarp side, and defines the base of the scarp. Diagrammatic faults in textbooks do and so do some natural ones, but they do not in the Coast Ranges. There a scarp is the exception, the rifts often follow a valley or run along the summits.

In Loma Prieta we have a short section of the Rift on which there is no obvious displacement, but only a zone of pronounced crushing. It is a pivot section along which the opposite sides of the Rift have twisted past each other, so that the crest of the range to the northward is west of the fault, whereas to the southward the crest is east of the fault. One can get a good idea of this movement by placing the palms of the hands together, with the fingers out straight, and turning one hand past the other on the balls of the forefingers. If you face north and rotate the hands so that the fingers of the left hand rise higher than those of the right, you will get the relations as they are in the Santa Cruz mountains north and south of Loma Prieta.

The San Andreas Rift presents a very interesting aspect in the section which lies along the eastern side of the Carrizo Plains, a desert district in which the effects of erosion are very slight. The movement of 1857 there produced a trench that looks like a large irrigation ditch and as seen from an aeroplane can be followed ten or fifteen miles into the distance until lost in the haze.

From Tejon Pass southeast to the latitude of San Bernardino the Rift follows the margin of the desert and the features characteristic of the fault are well preserved. The line passes through Elizabeth lakes and from both shores rise very gentle slopes, which are slightly arched sections of the Santa Cruz surface, if we may carry the name so far from its origin. The slopes closely resemble those which border Tomales Bay. Southeast of Elizabeth lakes the fault zone is wide and the displacements are complex. In the middle of the valley is a pronounced ridge with a fault on both sides of it, a structure which geologists call a horst. Southward along the Rift are numerous depressions, valleys, and visible faults, characterized by wide differences in the ages of strata that are brought into juxtaposition by the movements. This section has been examined in detail by Mr. L. F. Noble, Geologist of the U. S. Geological Survey, and is one of the best-known portions of the San Andreas.

Still further southeastward, beyond San Bernardino, the San Andreas Rift seems to branch and to enclose the depression of the Salton Sea between its arms. Our knowledge of it in the desert region is very incomplete, but it will be noted that the rift which gave rise to the earthquake at El Centro in the Imperial Valley is apparently the southern branch. It has been called the San Jacinto Rift.

Among the results of observation of the features characteristic of the Rift it is of geologic interest to emphasize the absence of steep fault scarps, already referred to, and the frequent occurrence of uparching slopes. The latter commonly exhibit the sculpture of the Santa Cruz surface, but the datum is arched in a more or less pronounced curve that cannot be due to erosion of the heterogeneous rocks. It is attributed by the writer to a bulging of the underlying rock masses as they shear under compression. It is most marked in masses of serpentine, which are the most readily distorted by pressure. If one makes a cut in the skin of an orange and presses the edges tightly together, causing the parts to bulge up on each side, he will have an effect similar to that which may be observed along many sections of the Rift.

The absence of the fault scarps and the pinching of the edges of the rifts, as if they were pinched down against one another, suggest that the larger components of displacement have always been horizontal, as they were in 1906. There must, however, have been notable vertical components also, since strata which are normally separated by many thousand feet are brought into contact along some sections. We cannot but recognize that we are only on the threshold of the investigation of these remarkable rifts.

There are certain special localities where the possibility of earthquakes, even at long intervals apart, affects large interests because of the local concentration of population or of property or of both. San Francisco and Los Angeles are obvious instances and it is appropriate that the reasons for the accepted mapping of the faults in the vicinity of these cities should be stated.

The position of the San Andreas Rift west of San Francisco and its activity were made evident in 1906 beyond question. The line passes along the Crystal Springs Lakes, the San Andreas Valley, out to sea at Mussel Rock, and back along the margin of the land in Bolinas Bay. The movement of 1906 amounted to a displacement of twenty feet horizontally and one and a half feet vertically. The shock was not a very severe one, but the neglect of precautions against destruction of the water mains by earthquake left the city at the mercy of the fire which ensued. The earthquake of 1906 was the third considerable one in a hundred years and precautions which were initiated immediately after the great catastrophe were wisely planned. They should be vigilantly maintained and augmented as the city grows.

The San Andreas is the main rift, not only of this section, but of California. It has many branches, several of which are to be traced in the vicinity of San Francisco. A long one, which presumably branches off from the San Andreas at a considerable depth beneath the surface, runs along the base of the foothills west of the Santa Clara Valley and San Francisco Bay, passing about four miles west of Palo Alto and close to, or through Lake Merced. It is recognized chiefly on physiographic grounds, by the warping and displacement of the Santa Cruz surface, and appears not to have been the locus of any slipping for an indefinitely long time. It is, however, a branch of the active system.

A short fault passes through Colma, along the western side of Twin Peaks, and across the Golden Gate. The southern end, which was mapped by Professor Lawson in the San Francisco folio, is shown as dead, but is probably not distinct from the northern portion. The latter shows a well-defined fault scarp or cliff, facing west, and the elevated ridge carries modern dune sands on its summit. They indicate the recency of displacement. The manner in which this fault curves toward the east indicates that it dips eastward away from the San Andreas. Thus while it is to be regarded as a minor element of the general system, it apparently is not directly connected with the great Rift. It very likely branches near the Presidio and sends a fork (not shown) along the western short of the Marin Peninsula, while the other form continues the trend toward Sausalito.

Sausalito Bay, like Bolinas Bay, corresponds to a sunken block between faults on which the adjacent masses of Tamalpais and Tiburon have been pushed up. The evidence of faulting is more obvious, however, along the shores of Sausalito Bay, where no movement has been recorded by history, than along Bolinas. The warping of the Santa Cruz surface back of Sausalito and the scarps along both sides of the bay, the horst of Belvedere Island, the depression of Mill Valley, the bold eastern face of Tamalpais, and the dislocation of the Santa Cruz surface on the northern slope of the mountain past Lagunitas Lake, these features all combine to demonstrate the rifted character of the peninsula.

Tiburon point lies between two rifts, which presumably extend into San Francisco Bay as far as Goat Island. The presumption that faults extend along their trend beneath the waters of the bay can not, of course, be verified by direct observation, but it is supported by the fact that relatively depressed areas in general in the Coast Ranges are bounded by planes of deplacement. Adjacent blocks have been pushed up, as a rule, as Tamalpais, Tiburon, and San Francisco Peninsula have been.