Preliminary Note on the Cause of the San Francisco Earthquake of April 18, 1906.

By

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1. ***Introduction.*** The great earthquake of April 18, 1906, which caused an enormous amount of damage in San Francisco, furnished a rare opportunity of studying the different earthquake phenomena, especially the seismic effects on various modern structures. Immediately upon the receipt of the news of the catastrophe, the Imperial Government resolved to dispatch to California Professors T. Nakamura and T. Sano, and myself, for the purpose of making investigations on the great seismic disturbance, each according to his professional point of view. The party departed from Tokyo on May 1st, and arrived at San Francisco on the 18th of the same month, the present writer remaining about 80 days in California.

My special thanks are due to Professor George Davidson, and also to Professors Lawson and Leuschner of the University of California, Dr. Gilbert, of the U. S. Geological Survey, Mr. K. Uyeno, Japanese Consul, and other American and Japanese gentlemen, with whom I came in contact and who gave me most cordial assistance during my stay in California.

2. ***Time of Occurrence.*** The times of earthquake occurrence observed at the Berkeley University and the Lick Observatory were respectively $5^h\ 12^m\ 39^s$ and $5^h\ 12^m\ 12^s$ A.M. (Western States Time, or that of longitude 120° W.); the time of commencement of the

disturbance at the origin itself being probably about $5^h\ 12^m$ A.M.

3. *Area of Destructive Motion.* The area, within which more or less damage was done, was very long, extending over a distance of 550 miles along the Pacific coast, from the vicinity of Salinas on the south to the vicinity of Eureka on the north. The width or the extent from the coast of the strong motion area is probably some 50 miles. The earthquake of April 18th was thus greater, in length, than the large Japan earthquake of 1891, the length of whose area of strong motion was about 400 miles. The intensity of motion in the San Francisco earthquake was, however, less violent than in the other, and the amount of the casualties in San Francisco and the different parts of the strongly shaken zone was small comparatively.

4. *Sea Waves.* When an earthquake of inland origin is large and violent, the waters of ponds, rivers or lakes are more or less disturbed. So similarly a great submarine earthquake is often followed by tidal waves; the time interval between the occurrence of the earthquake shock and the arrival of the destructive sea waves varies from a few minutes to several hours, and depends on the distance of the origin from the shore. Tidal waves which are not to be noticed on high seas are developed most markedly in bays with shallow waters and an open mouth, but are quite insignificant along deep-water straight coasts. Many of the great earthquakes originating off the Pacific coast of Alaska and Central and South America have been accompanied by large tidal waves. But fortunately, this phenomenon which sometimes causes more damage than the earthquake disturbance itself was so far not very destructive along the coast of the United States. The great earthquake of April 18th last produced distinct, but very small disturbances of the bay waters which were clearly recorded on the tide gauge at the Presidio (San Francisco); the amount of the rise and fall of the sea water being only about 6 inches, repeated in about 40 minutes. Now the wave period or periods at a place on a given coast remain constant in all the tidal waves, irrespective of the origin or cause; a destructive tidal wave consisting simply in the increase of the amount of the water motion existing more or less at all times, in consequence of a strong submarine earthquake or eruption, a storm, or some other agency. A seismic tidal wave is caused by the movements communicated from the sea bottom to the superincumbent water mass: a very big water disturbance taking place when the earthquake focus is at the sea bottom itself or at a very small depth below it, accompanied by some changes in the contour of the sea bottom. The absence of any great tidal disturbance on April 18th shows that there was no great submarine depression or vertical dislocation, although it seems probable that the northern half of the epifocal zone was under the Pacific.

5. *Sea Shock.* The steamer "Argo" felt the earthquake shock on sea near Cape Mendocino, the sensation being like that caused by running aground. There were other vessels which experienced the earthquake in a similar manner.

Effects like these, which may be called "sea-shocks," are due to the direct transmission through water of vibratory earthquake movements, and not due to the phenomena of the tidal waves which are developed only along coasts where there is some indentation.

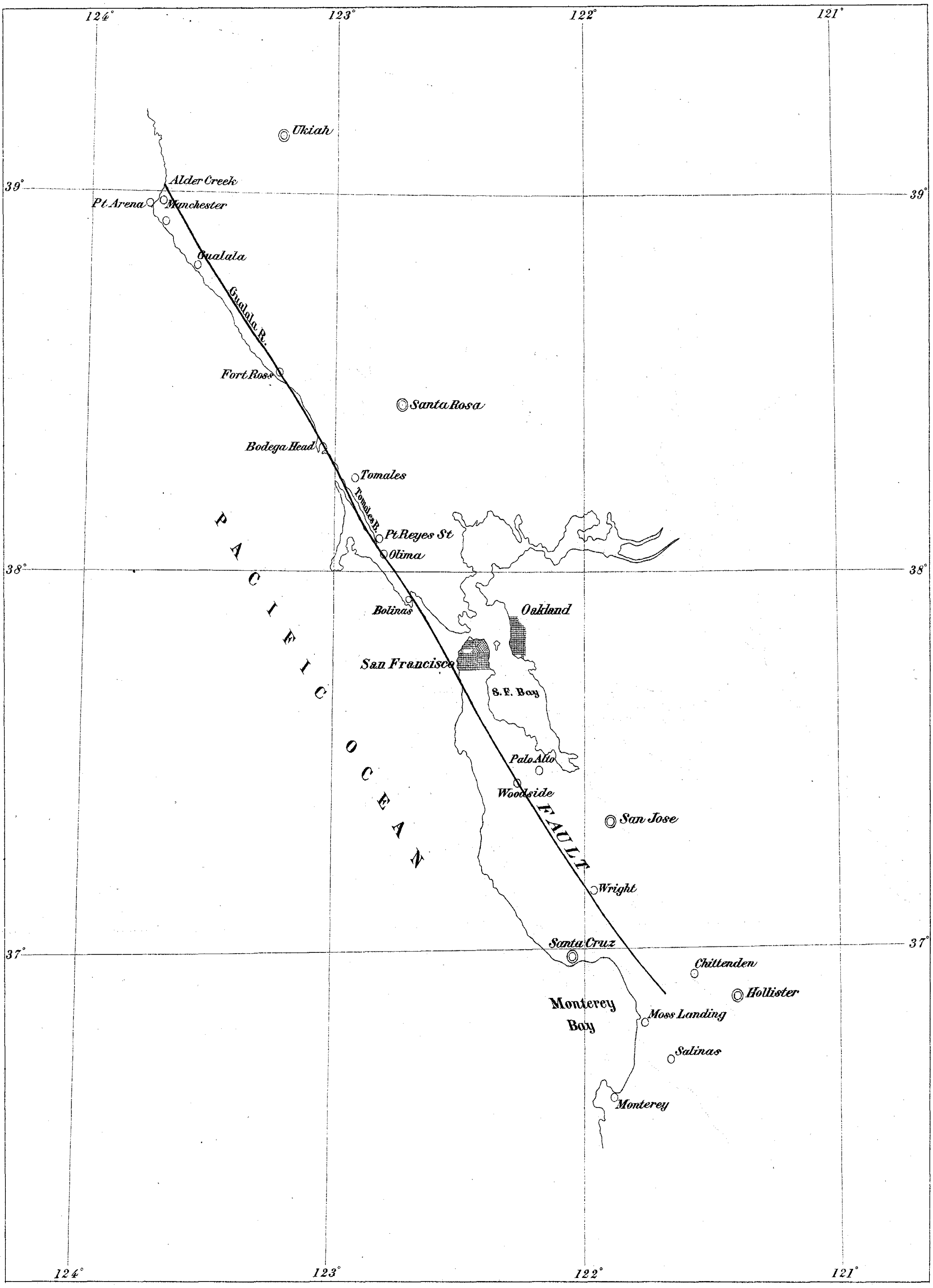
6. *Approximate Position of the Centre of Epifocal Zone.* A *rough* idea as to the position of the most central or principal point in the zone, which forms the origin of the earthquake, may be obtained from a good seismograph record taken at the Lick

Observatory, where the preliminary tremor lasted about 10 or 12 seconds, from which it may be calculated that the distance between the point in question and Mt. Hamilton was about 80 or 90 miles; the predominating direction of motion there being NNW and SSE. These data indicate a place near the Tomales Bay as the most central point of the disturbance. The approximate position of the latter may be assumed to be at a point, *latitude* 38°15′N, *longitude* 123°W.

7. *The Epifocal Zone.* One of the peculiar features in the topography of the State of California is a straight depression whose direction is NNW and SSE and which extends through the valley of the Gualala River, and Tomales and Bolinas Bays, continued further south-eastwards for some distance. This depression, which must have been formed in bygone ages by a great sudden convulsion of the earth's crust, or by the gradual mountain-making force going along the Pacific Coast, shows signs of dislocations caused at no very remote epoch by some great earthquakes, and it is of a special interest that the earthquake of April 18th again produced along the same old weak zone a continuous series of remarkable surface manifestations of cracks, depression, or horizontal slipping, constituting what is called a "fault" in geology. This fault which has been most carefully studied by Dr. Gilbert of the U. S. Geological Survey, Professors Lawson and Branner, and other able geologists of the Berkeley and Stanford Universities, begins on the north at the right-hand mouth of the Alder Creek, near Pt. Arena, and, passes into the ocean at the vicinity of Fort Ross; it again appears at the Bodega Head and at the eastern side of the mouth of Tomales Bay, crosses to Inverness on the west shore of the same bay, and then passes through the vicinity of Pt. Reyes Station, continued to a

Fig. 1. San Francisco and the Vicinity.
Showing the Course of the Great Fault, from Pt. Arena to Chittenden.

PL. I.



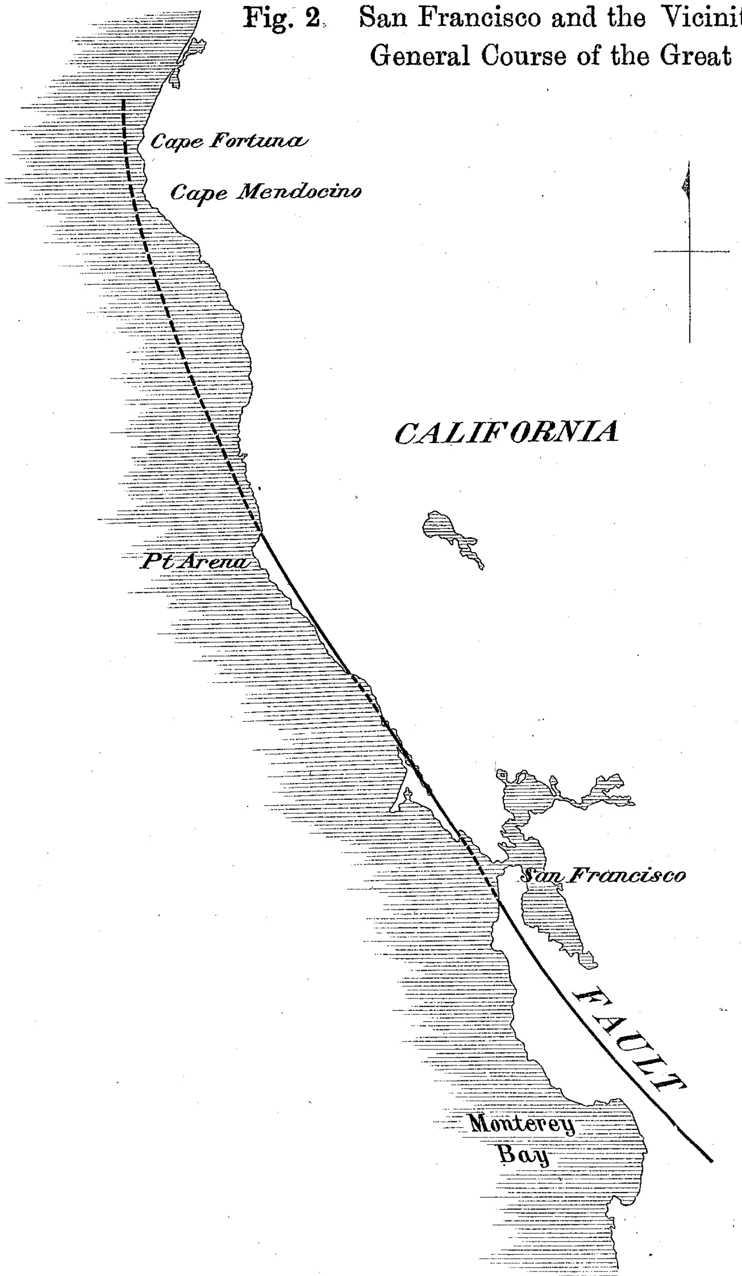


Fig. 2. San Francisco and the Vicinity, showing the General Course of the Great Fault.

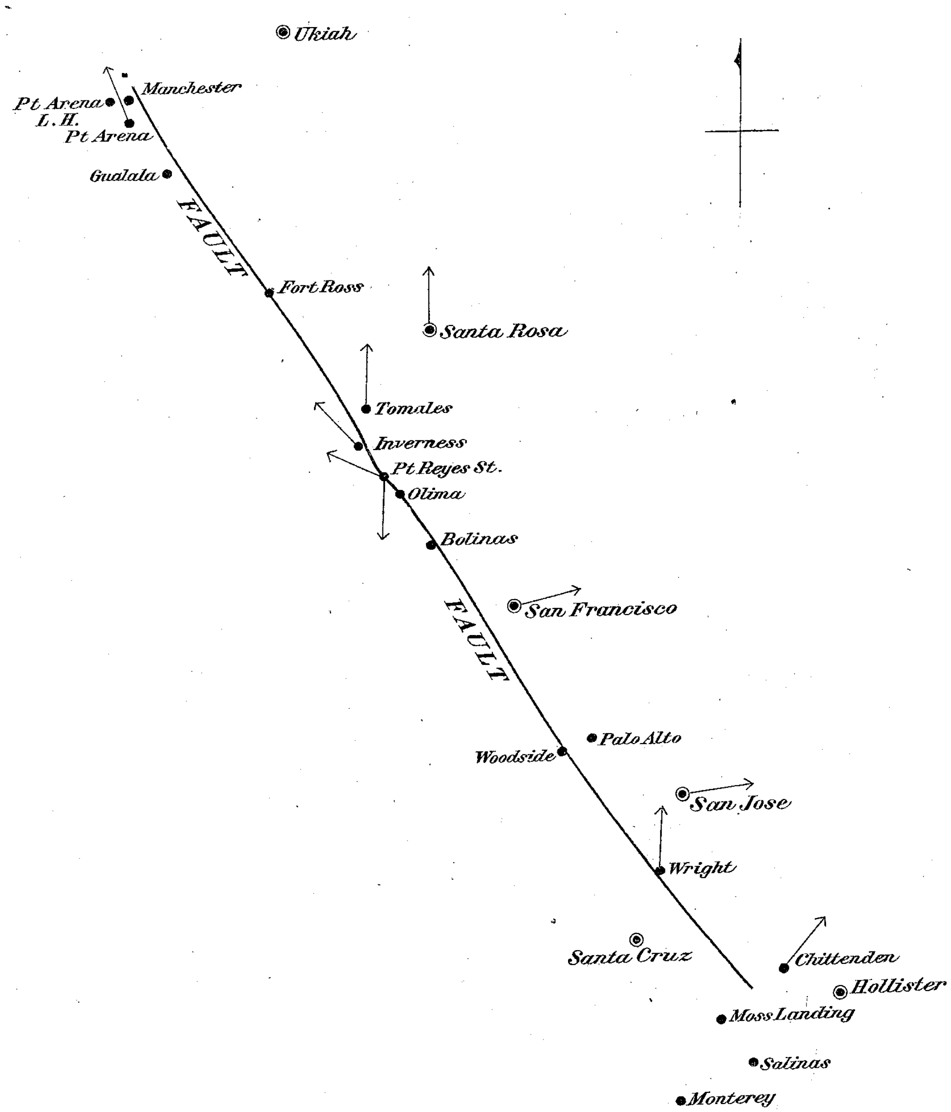


Fig. 3. Directions of Motion at Different places on or near the Great Fault.

place about 4 miles to the west of the Stanford University; marked disturbances of the ground being also distinctly shown to the south-east, in the vicinity of Wright and Chittenden. The length of the visible fault is thus over 150 miles, being three times that of the fault line in the great Japan earthquake of 1891. It is, further, extremely probable that the north-western part of the present fault is continued beyond Pt. Arena under the Ocean some 120 miles more and extends to the vicinity of Cape Fortuna. That the fault was not a mere surface phenomenon is shown by the appearance of the same disturbance across the tunnel near Wright Station, at a depth of some 700 feet below the mountain surface. See fig. 1 (Pl. I) and fig. 2 (Pl. II).

8. *Shear of the Ground.* The shearing movement of the ground produced many remarkable results; roads, fences, and every other thing crossed by the line of disturbance being cut apart and displaced considerably. There were cases, in which even large redwood trees were split by the shearing motion of the ground.

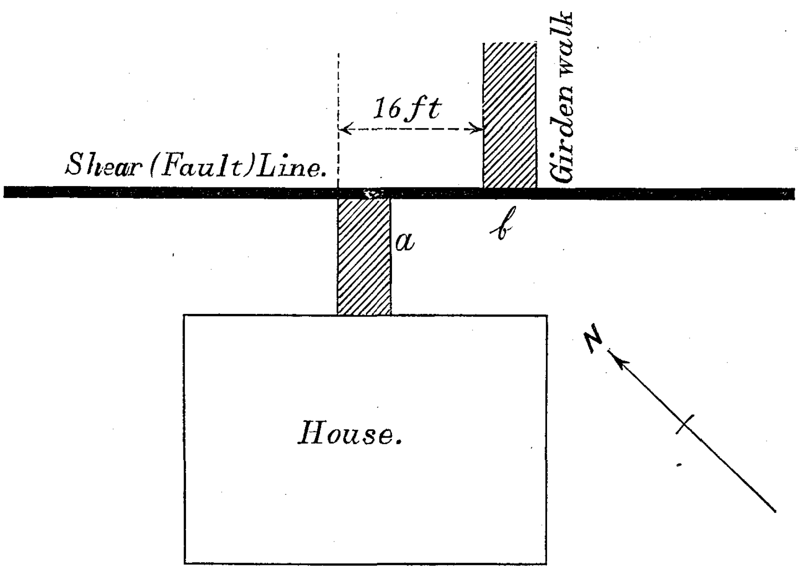


Fig. 4.

Figure 4 relates to the shear effect observed near Olima, a village situated between the Tomales and Bolinas Bays. The fault passed just in front of a house

(Skinner's Ranch) and produced a relative displacement of 16 feet, a girden walk being carried through that distance from *a* to *b*.

Fig. 11 (Pl. III) shows the shearing effects on a pier at Inverness, on the west coast of the Tomales Bay. The end part of the pier was separated from the rest and was displaced about 20 feet towards NNW. The direction of displacement in this particular instance was opposite to the general direction of the relative slip along the great fault line.

Fig. 12 (Pl. III) shows one of the fault cracks produced among the hills above Fort Ross. It will be observed that the new disturbances appeared along a depression marked by a series of small ponds (shown at the right-hand side of the picture), these latter being traces left by a former great earthquake.

Fig. 13 shows the remarkable compression and shear effects along one of the parallel fault cracks, observed on elevated grounds near the town of Manchester, not far from Pt. Arena. A foot-scale placed in the foreground will show the size of the overlapping earth pieces, whose plan is given in fig 8.

9. ***Remarks on Shearing Movements.*** For the sake of illustration, let us first consider cracks of a wall when the earthquake motion is parallel to the latter.

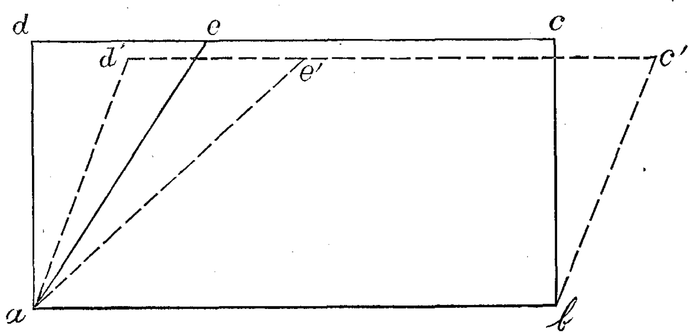


Fig. 5.

Let *a b c d* (fig. 5) be a wall whose bottom side *a b* is fixed, either absolutely or relatively, while the upper side *c d* is brought to the position *c′d′* as the result of a shearing stress in the direction of *a* to *b*. Then the rate of the length change of the line ae, connecting a with any point e on the side cd, will be greatest when the angle dae is equal to 45°. Consequently there will be formed a series of cracks at right angles to the lines of greatest elongation and at an angle of 45° to the base $a\,b$.

Thus, in the case of a strong horizontal motion parallel to the plane of the wall, there will be two sets of cracks at right angles to one another, as in Fig. 6.

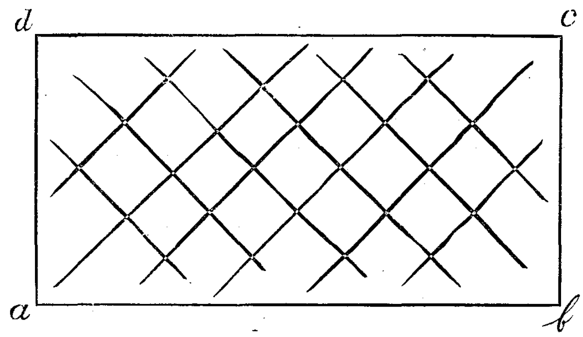


Fig. 6.

Fig. 14 (Pl. IV) illustrates some of the cracks of plastered walls observed in St. James Hotel, San Jose.

Secondary Cracks of the Ground. Along the fault line the ground was, as in other cases, very often bulged up, forming a narrow zone of 1 or 2 feet elevation and some 5 or 10 feet width as if raised up by a gigantic mole creeping underground. This sort of ridge, whose formation was due to the shearing action, combined with a compression along the line of dislocation, showed usually a series of secondary oblique cracks, as is diagramatically indicated in Fig. 7. These ground cracks were perfectly similar to the shear cracks of walls considered above.

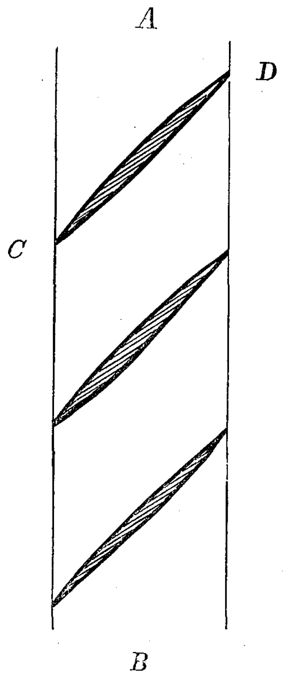


Fig. 7.

AB......Fault Zone.
CD......Shear Cracks.

Figs. 8, 9 and 10, show parts of

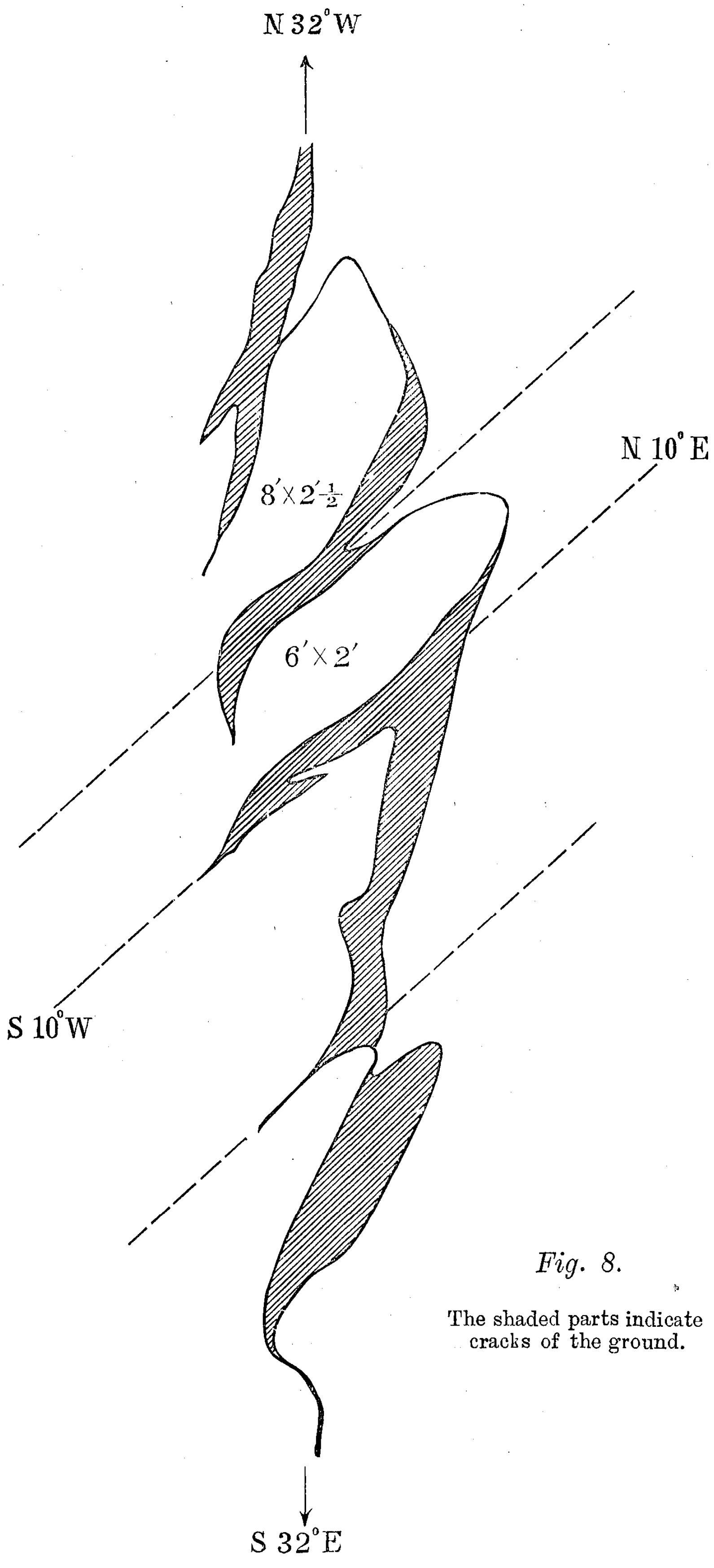


Fig. 8.

The shaded parts indicate cracks of the ground.

the fault lines found near the town of Manchester, not far from Pt. Arena; the dotted lines in each figure indicating the directions of the secondary shear cracks. Fig. 8 is the plan of the remarkable disturbances shown in Fig. 13. In Figs. 9 and 10, the angle between the main fault line and the shear cracks varied between 44° and 47°. In Fig. 8 however, there was evidently a very strong compression, and the shear angle was smaller, namely, 42°.

I have measured the shear angle in 11 other cases, where it varied between 35° and 47°; the total average value being 40°.

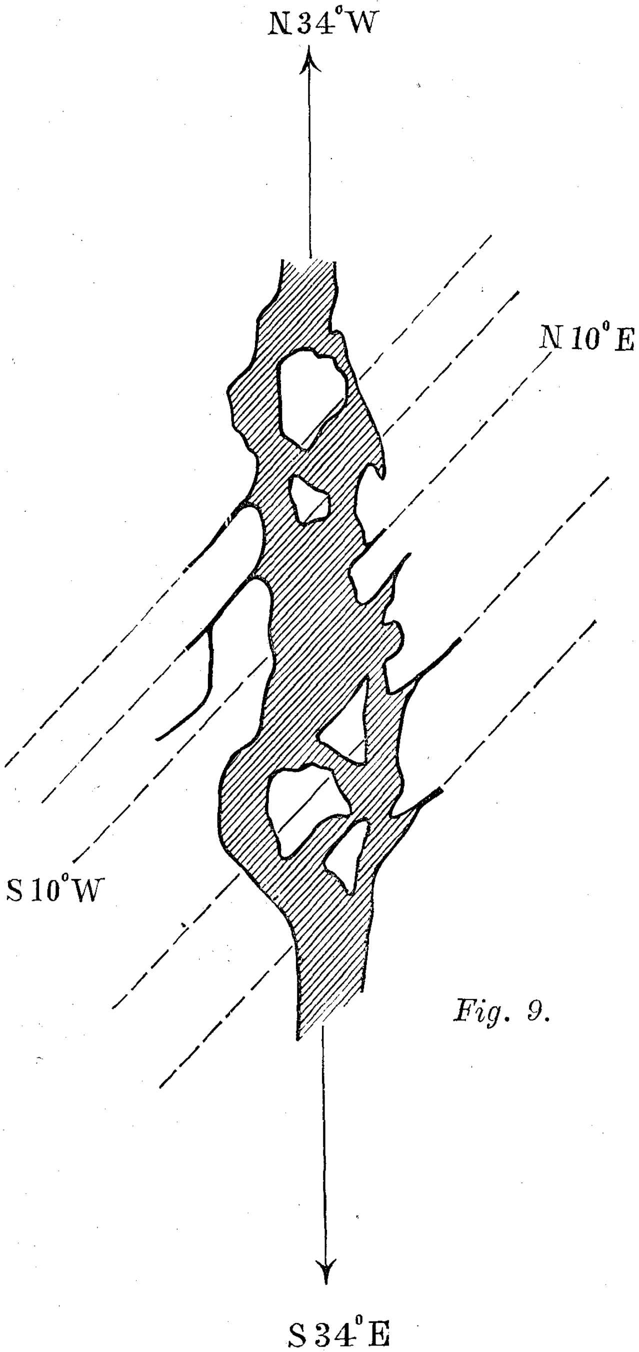


Fig. 9.

If the shear be accompanied by a horizontal compression at right angles to the fault line, the angle between the latter and the shear cracks will be smaller than 45°, as suggested by Professor A. Inokuty, of the Engineering College, Tokyo Imperial University. The coexistence of a tension normal to the fault plane will, on the other hand, make the same angle greater than 45°.

10. *Comparison with the Formosa Earthquake of March 17th, 1906.* The local but very severe earthquake in the Kagi Prefecture, Formosa, on March 17, 1906, produced also remarkable surface dislocations, in which the vertical depression and the horizontal shear each amounted to about 8 feet. The angle between the direction of the main fault and that of the shear cracks was on the average 43°.

11. *Landslips, etc.* In the meizoseismal area, there were great many cases of mountain slides. The most remarkable among these was that which occurred near Cape Fortuna (False Cape), where an enormous quantity of debris was detached from a mountain side and was pushed into the Ocean, creating a new promontary of about 3/4 mile length.

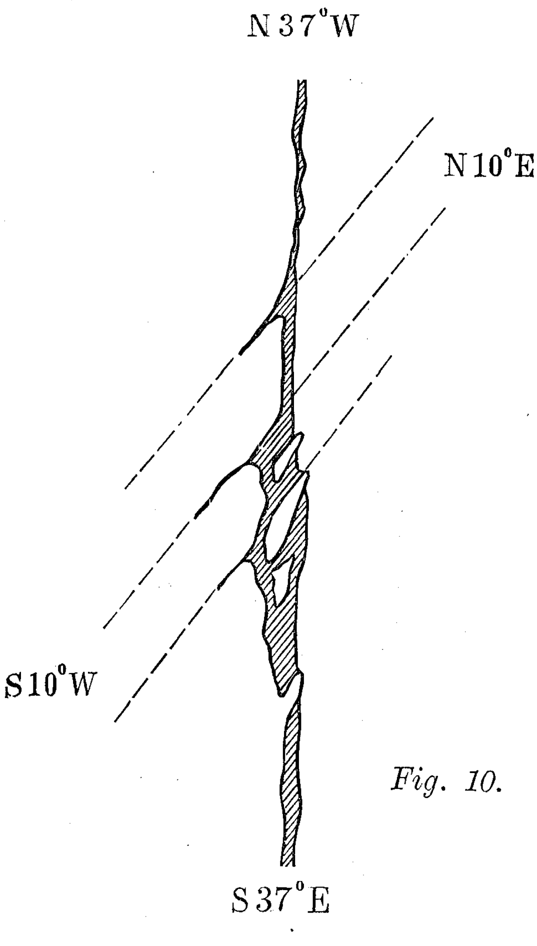


Fig. 10.

At Moss Landing, near Salinas, there were great horizontal disturbances of the sandy ground; the office of the station agent being displaced about 15 feet relative to the adjoining fence.

12. *Direction of Motion in San Francisco.* Fig. 19 (Pl. VII) shows the directions towards which 520 monuments at the different cemeteries in San Francisco and the vicinity were overturned by the earthquake shock. It will be observed that the greatest number of the monuments were overturned towards the east or east slightly north. The mean direction of overturning is N76°E, which may be regarded as the direction *toward* which the greatest horizontal displacement took place.*

See the "Publications," No. 4.

13. *Relation to the Great Fault of the Directions of Motion at the neighbouring places.* The approximate directions of the principal or strongest motion at the different places on or near the fault, each determined from numerous overturned bodies, were as follows:—

A.	San Francisco	N76°E.
	San Jose	N81°E.
	Chittenden	N38°E.
	Watsonville	NE.
	Santa Rosa	N.
	Tomales	N.
	Pt. Reyes Station(East side of Fault)	S.
B.	Pt. Arena	NNW.
	Inverness	NW.
	Pt. Reyes Station (West side of Fault)	WWN.
	Wright	N.

The mean general direction of the fault is N 37° W—S 37° E, this being exactly identical with the direction of the great depression zone before mentioned. The places in Group *A* are situated on the eastern side of the fault line, while those in Group *B* are situated on the western side. It will thus be observed that at the *A* Group places the direction of motion was mostly towards North, North-East, or North-East by East; while at the *B* Group places, the direction was toward North-West, North, or North-West by West. Thus, on the whole, the motion on each side of the fault line had a tendency to diverge, or to be directed away, from the latter. This can be explained on the supposition of a subterranean collapse, or settling down, which would produce an initial inward motion, to be followed by the second and larger outward displacement. Further, the directions of motion at the different places were mostly northward, and not southward. This would mean that the whole meizoseismal zone was first pushed towards SSE, the second or counter motion, which was greater, being consequently directed toward NNW. I presume therefore that the action, which caused the great earthquake of April 18th, was a sudden movement towards South-East by South of the earth's crust at the west coast of California, accompanied by some downward thrust. In this connection it is extremely interesting to note that Mount Tamalpais on the north shore of the Golden Gate has been ascertained, from the trigonometrical measurements, to have moved, between 1851 and 1882, 5.6 feet towards N 12° W, indicating that the earth's crust at this part of America was being strained toward the same direction. The ground on the eastern side of the fault line was generally displaced toward S S E relative to the ground on the other side; the amount of the horizontal slip was maximum at places between Pt. Arena and Pt. Reyes Station and varied from 16 ft. to 20 ft.; the amount of displacement decreasing to about 8 ft. at Woodside, near Stanford University, and to about 4 ft. in the vicinity of Wright. From the uniformity of northward direction of motion it is probable that both sides of the fault line were displaced toward NNW, but the west side was moved more than the east side, the amount of the horizontal slip, or shear, above mentioned being merely relative or differential. In the majority of cases the eastern side was depressed, the maximum amount being 2 ft.

14. From the comparatively very small number of after-shocks, I am inclined to suppose that the main source of the earthquake was situated some considerable depth below the surface. In fact the earthquake seems to have been caused by a

Fig. 11. The shearing effects on a pier at Inverness, on the west coast of the Tomales Bay. The end part of the pier was displaced about 20 feet towards NNW.

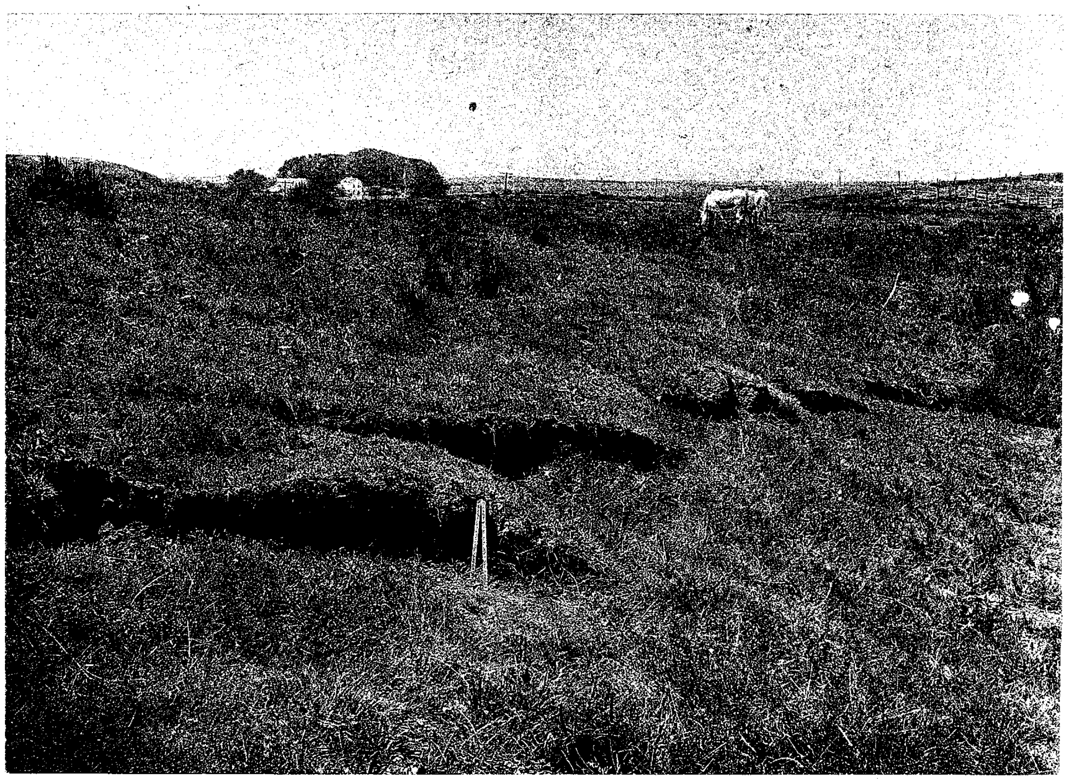


Fig. 13. Remarkable compression and shear effects along one of the fault cracks, produced on elevated grounds near Pt. Arena. A foot-scale placed in the foreground shows the size of the overlapping earth pieces, whose plan is given in fig. 8.

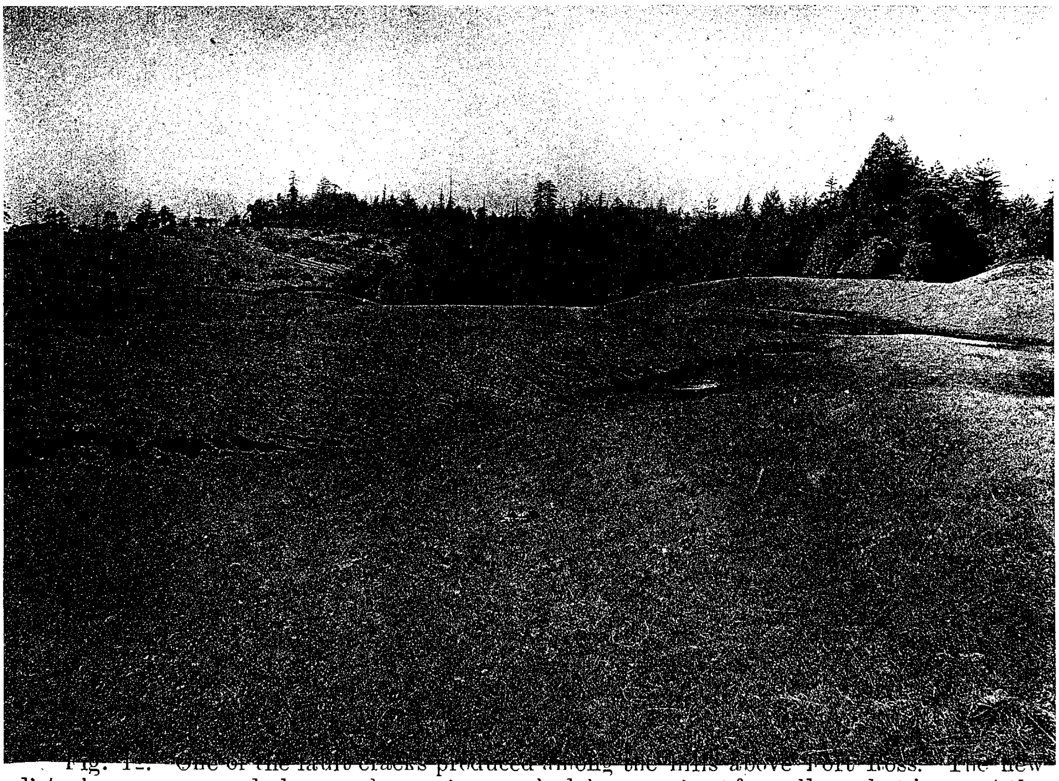


Fig. 12. One of the fault cracks produced along the hills above Fort Ross. The new disturbances appeared along a depression marked by a series of small ponds (shown at the right-hand side of the picture), which are traces left by a former earthquake.

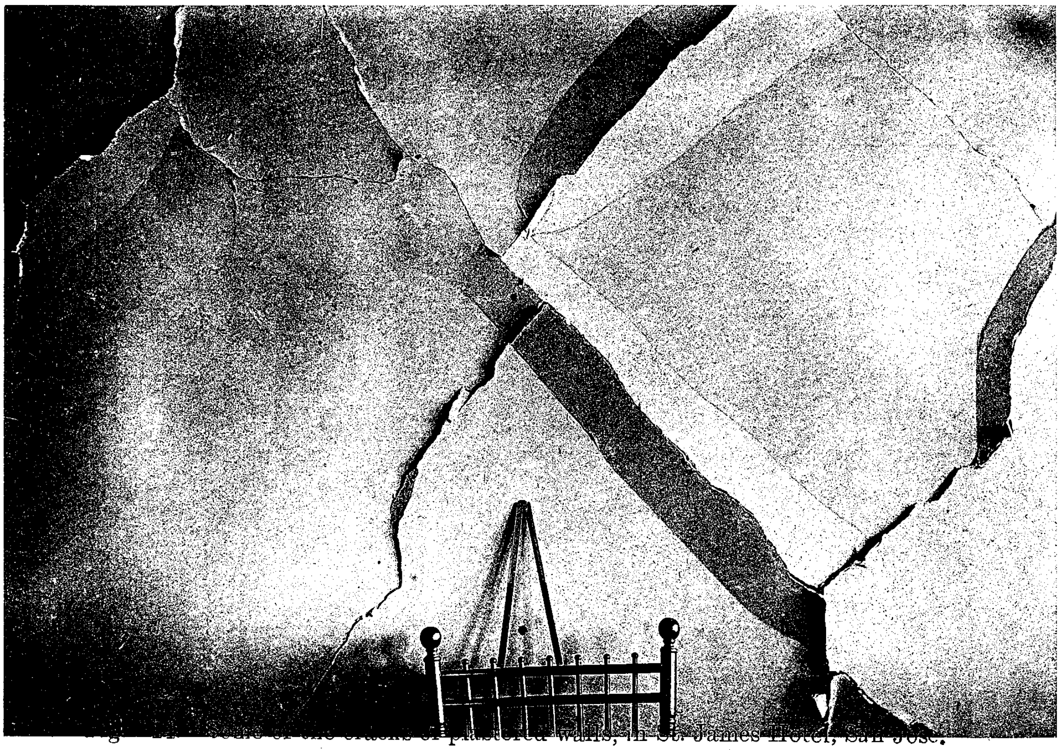


Fig. [illegible]. Some of the cracks of plastered walls, in St. James Hotel, San José.

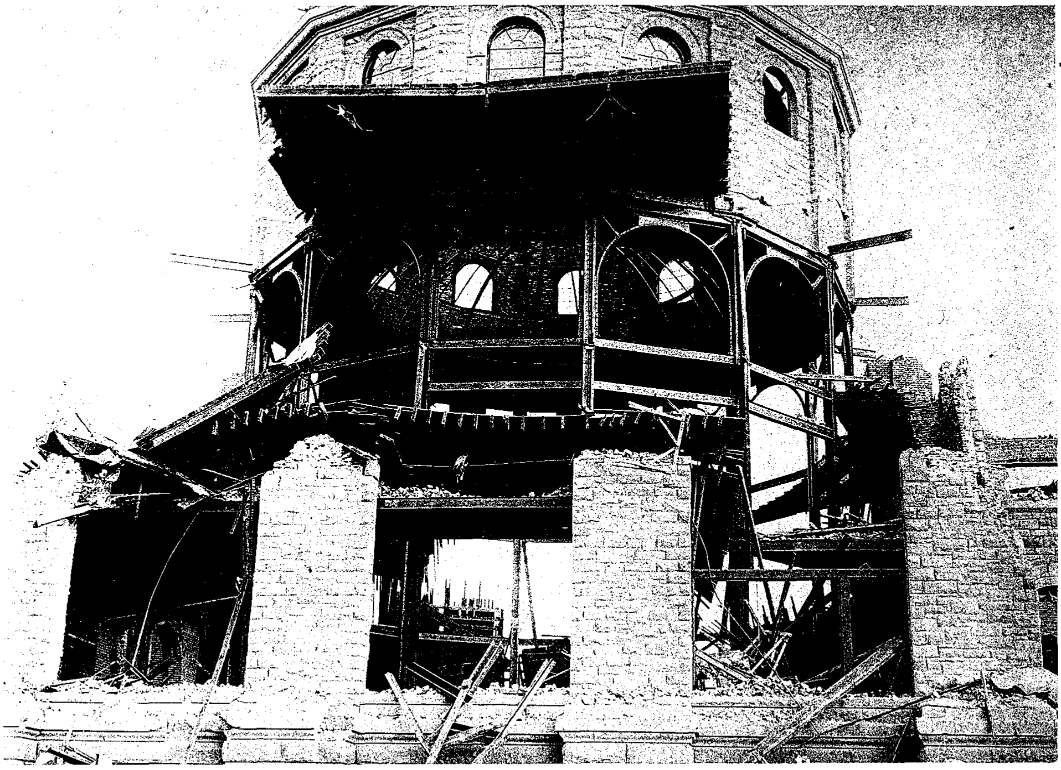


Fig. 15. The damaged condition of the newly erected Library of the Stanford University. The central steel dome behaved as an elastic inverted pendulum.

Fig. 16. The ruined condition of a steel-framed brick house in San Francisco, which was dynamited and then burnt, showing the remarkable effects of the intense heat.

The Observatory on the top of the Strawberry Hill, in the Golden Gate Park, San Francisco, built of reinforced concrete.

Fig. 17. An outside view of the back part.

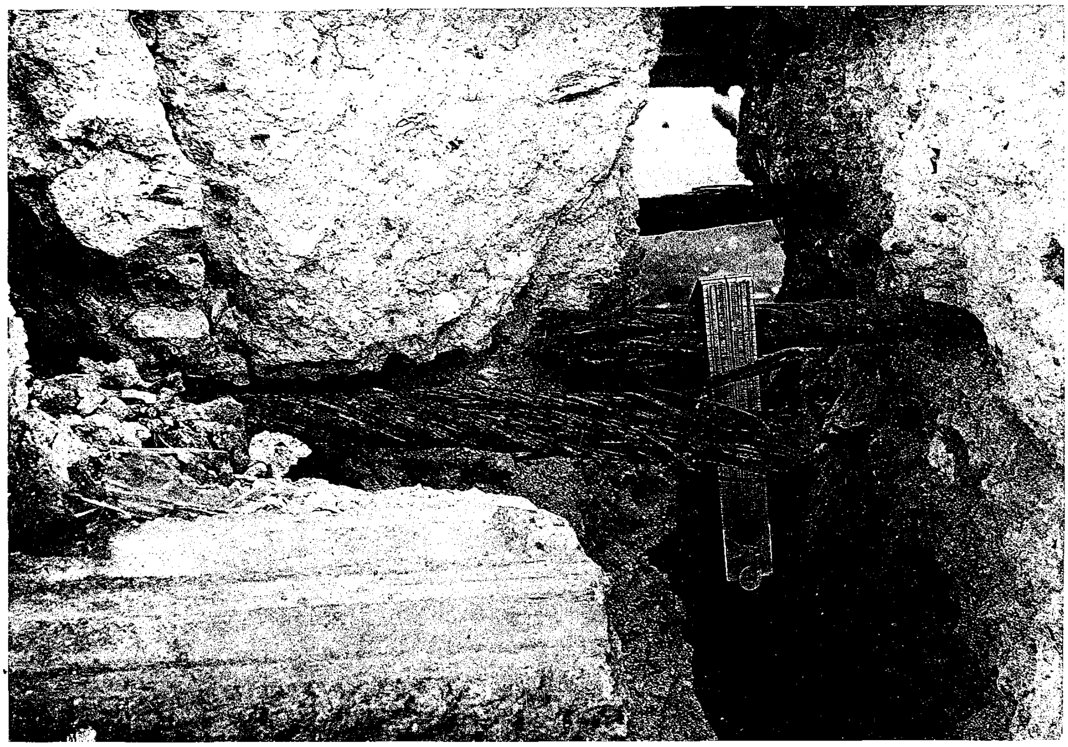


Fig. 18. One of the cracks of the basement wall. The steel cable, one inch in diameter, which was embedded in the concrete, was broken.

disturbance which took place along the old weak line but extended deeper into the earth's crust. The great depth of the main source of disturbance also explains why the intensity of motion was comparatively not very violent, and also why some places such as Santa Rosa, San Jose and Ferndale, not directly on the fault zone, were also badly shaken.

15. *Earthquake Damage.* This earthquake enabled us, for the first time, to study the effects of the shocks on steel-brick and reinforced concrete buildings; there being also numerous other damaged structures, such as ordinary brick, stone and wooden houses, bridges, water-pipes, etc. In San Francisco, the earthquake was followed by fires, which broke out from several places, continued for three days, and entirely destroyed the principal business quarters of the city. The total area of the burnt districts was 4.1 square miles, which is equivalent to 6 times the area of the great London fire of 1666. The amount of casualties was, however, comparatively small, the *ascertained* number of persons killed being about 390. The total number of the killed in the whole earthquake area was probably not more than 1000, the loss of life in Santa Rosa, Stanford University, and other strongly shaken places being slight. In San Francisco, serious damage was confined to the filled-up grounds, where the motion was not so strong as in the cities of Nagoya (max. acceleration=2600 mm. per sec. per sec.), Fukui (max. acceleration =2500 mm. per sec. per sec.), etc., on the occasion of the great Mino-Owari Earthquake of 1891. The double amplitude of motion in San Francisco was probably some 4 inches, and the complete period of vibration about 1 second.

Fig. 15 shows the damaged condition of the newly erected Library of the Stanford University. The central steel dome, which is virtually an elastic inverted pendulum, evidently much vibrated, thereby causing destruction to loosely connected brick and stone parts of the building. The mortar used for cementing the masonry walls was of an exceptionally bad quality.

The damage to the City Hall of San Francisco was also principally due to the same two circumstances, namely, the vibration of its high steel tower, and the bad quality of mortar.

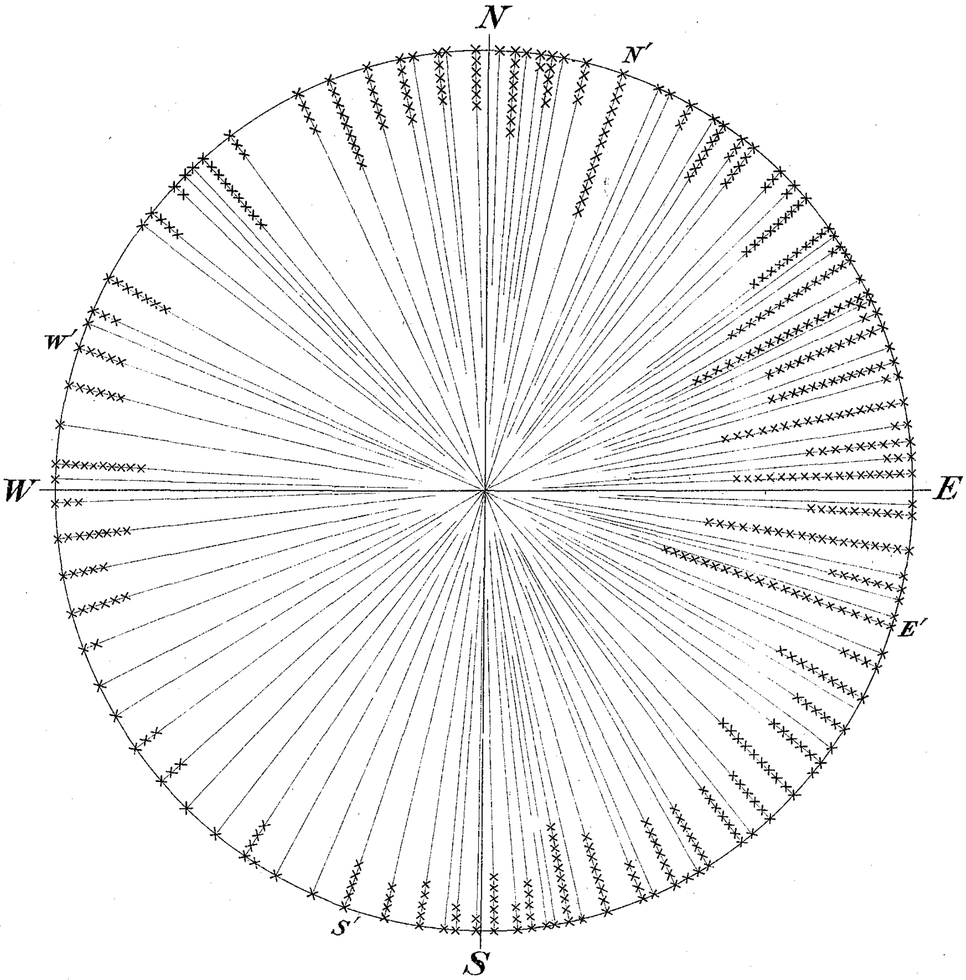
Fig. 16 (Pl. V) shows the ruined condition of a steel-framed brick house in San Francisco, which was dynamited and then burnt. The effects of the intense heat is remarkable, the steel frames being distorted in every possible form as if they had been formed of a soft maleable metal.

Fig. 17 (Pl. VI) gives an outside view of the back part of the Observatory on the top of the Strawberry Hill, in the Golden Gate Park, San Francisco. This building is of reinforced concrete and furnishes a good demonstration of the strength of such structures. The Observatory was indeed seriously damaged and its front portion fell down to the ground, but this was on account of the weakness of the foundation ground which was mostly a filled-up one and was considerably cracked and depressed. Fig. 18 shows, in a larger scale, one of the cracks of the basement wall, similar to that shown in Fig. 17. The steel cable, one inch in diameter, which was embedded in the concrete, was broken. The use of steel cables in concrete walls thus seems to be objectionable, as they are more liable to rusting than solid steel bars. None of the latter used in the concrete walls and floor of the Observatory, whose section was half inch square, was found broken ; the adhesion of concrete and steel being also very good.

16. *Recent Seismic Activity.* Recently there have been a

Fig. 19. Diagram showing the overturning directions of 520 Monuments in San Francisco and the Vicinity.

[Each small cross (×) indicates a monument overthrown in the direction of the radius on which it lies.]



N′, E′, S′, W′, indicate the 4 *magnetic* cardinal directions.

number of great earthquakes in different parts of the world, especially along the following two zones :—

(A). The Pacific coast of North and South America.

(B). Himalayas and North Mediterranean zone.

Next two §§ give a short account of the earthquakes belonging to these two zones.

17. *Earthquakes along the West Coast of North and South America.* Within the 7 years preceding the San Francisco earthquake of April 18, 1906, there were, along the Pacific coast of the American continents, seven great earthquakes, on the dates as follows :—

(i) Sept. 4 and 11, 1899 ; and Oct. 9, 1900.
(ii) Jan. 20, 1900 ; and April 19 and Sept. 23, 1902.
(iii) Jan. 31, 1906.

Of the above 7 earthquakes, the three of group (i) took place off the south-west coast of Alaska, two of them being accompanied by great tidal waves. The three earthquakes of the group (ii) strongly shook Mexico and Guatemala (Central America); while the earthquake of group (iii), which was accompanied by tidal disturbances, caused considerable damage in Panama, and the west coast of Columbia and Equador. The approximate positions of these three groups of earthquakes are marked in Fig. 20 by dotted lines, *1*, *2*, and *3*.

As the west coast of the American continents is one of the great seismic zones on the earth, it is to be supposed that the 7 destructive earthquakes above enumerated were not separate or local phenomena, but were the results of great stresses going on along the Pacific coast zone extending from Alaska to South America, manifested at its north and middle parts. Hence an event most naturally to be expected would have been the exten-

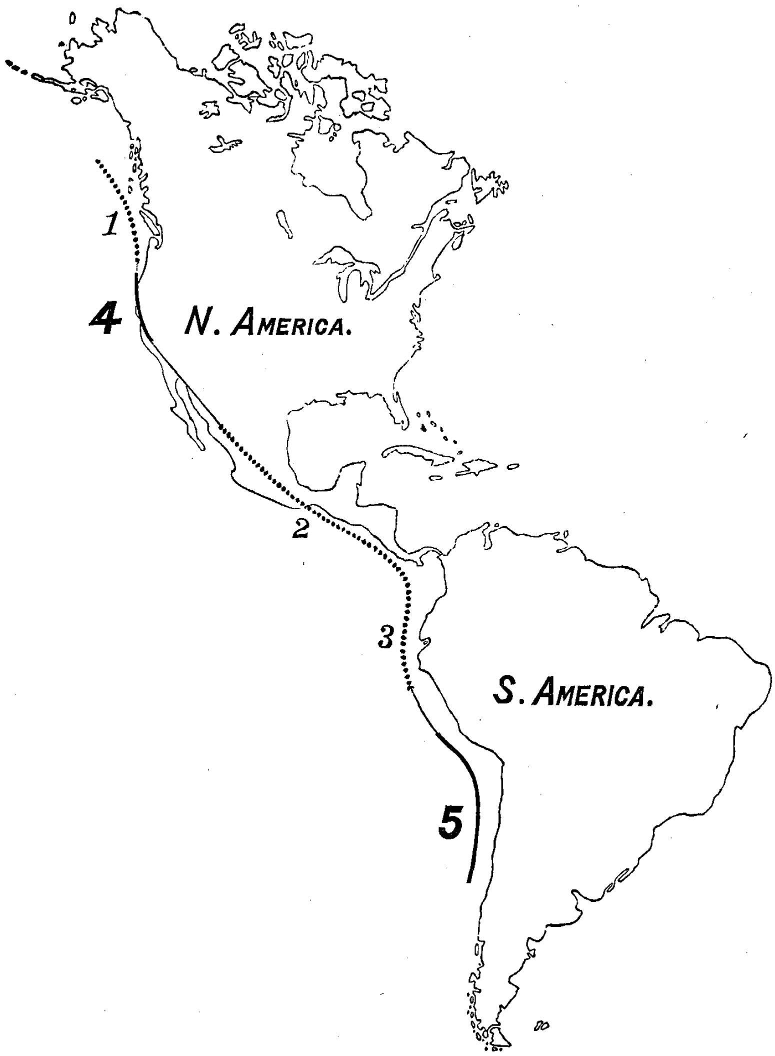


Fig. 20.

sion of the seismic disturbance to the west coast of the United States, which so far had been free from the visitation of disastrous earthquakes. Now this apprehended event has finally taken place on April 8 of this year, the approximate position of the origin being indicated in Fig. 20 by a thick line marked *4*. The great San Francisco earthquake may therefore be regarded as having completed the continuity of the seismic activity along these districts, which latter thus become, for a certain number of years, say 20 or 30 years, seismically a very safe place; *large* earthquakes, which remove a great unstability in the earth's crust, never happening successively at one and the same place.

During my recent stay in San Francisco I explained on several occasions reasonings like the above to newspaper reporters and others, also pointing out that even in the case of a future destructive earthquake, the intensity of motion would not be extremely violent, so that a slight amount of precaution taken in building houses would ensure an almost perfect immunity from earthquake shocks. As to the probable position of the next great shock on the Pacific side of America, I expressed my view that it would be to the south of the equator (that is to say, Chile and Peru),* as it was very likely that the seismic activity would extend to either end along the great zone in question, and as the coast of the countries above named are often visited by strong earth convulsions. I departed on Aug. 4 from San Francisco for home, and arrived on the 22nd of the same month at Yokohama, first there learning of the disastrous shock of Valparaiso, which confirmed my anticipation. The approximate position of the origin of this last earthquake, which took place on Aug. 17 (1906) is indicated in Fig. 20 by a thick line marked *5*.

The great stresses going on along the whole Pacific coast of America, which thus resulted in the occurrence of a series of great earthquakes, seems to be connected with the growth of the Rocky and Andes mountain ranges; the Valparaiso earthquake bringing probably the *great* seismic activity along the zone under consideration for the time to an end.

18. *Activity along the Himalayas and North Mediterranean Zone.* With regard to the seismic activity in Asia and Europe, it is to be noted that the unusually severe eruptions of the Vesuvius, which began on about April 7th this year, lasted about one week, and ended on the 13th of the same month. On the following day, namely, April 14 (1906) there took place the destructive earthquake of Kagi District (Formosa), in which 1249 persons were killed. Four days later on there took place the great San

* This is what I published in the *San Francisco Bulletin* of June 13, 1906.

Francisco earthquake. Whether there existed or not a connection between the Vesuvian eruption and these earthquakes, it is a matter of fact that there was a great seismic activity along the whole length of the zone extending from the north coast of the Mediterranean to the Himalayas, and possibly to Formosa. The different earthquakes belonging to the zone in question, which happened recently, are as follows :—

(i) Assam and Bengal, (India), June 12, 1897.
(ii) Aidin (Smyrna), Sept. 20, 1899.
(iii) Schemacha (Caucasus), Feb. 13, 1902.
(iv) Kashugar (Turkestan), Aug. 22. 1902.
(v) Saloniki (Macedonia), April 4, 1904.
(vi) Kagi (Formosa), April 24, 1904.
(vii) ,, (,,), Nov. 6, 1904.
(viii) Kangra Valley (the Punjab, India), April 4, 1905.
(ix) Calabria (Italy), Sept. 8, 1905.
(x) Kagi (Formosa), March 17, 1906.
(xi) Kagi (,,), April 14, 1906.

Thus great earthquakes took place at the different parts of the zone stretching through Italy, Macedonia, Asia Minor, Caucasus, Turkestan, the outer side of the Himalayas, and Formosa; this proving that the underground stresses were growing along the whole zone. As the seismic disturbances above enumerated occurred in the same epoch as those belonging to the American zone, it is extremely likely that underground stresses reached a maximum all over the earth, resulting in a marked display of seismic disturbances along certain zones of weakness.

19. *Conclusion.* Future studies in various phenomena connected with the movements of the earth's crust might perhaps tend to advance our knowledge respecting the problem of the prediction of great earthquakes, which are often preceded by what may be called "fore-shocks." In the meanwhile, and always, it will be necessary to build houses and other structures strong enough to resist earthquake shocks, a problem which presents no great difficulties.

Tokyo, Nov. 1, 1906.