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EARTHQUAKE FORECASTS[1]

INTRODUCTION

THERE was a time when the weather belonged to the gods. Storms and drought were inflicted on man in punishment or for vengeance, man strove to avert them by sacrifice or prayer, and the priest was his intercessor. Now the weather belongs to nature, and the priestly robe has fallen on the Weather Bureau. Man's new agent, however, is not an intercessor; he does nothing to placate; he makes no attempt to control the course of nature; but inspired by science he foretells the coming changes so that his lay client may take warning and be prepared. The crops are harvested before the rain, the herds escape from the lowland before the flood, the ships reach harbor before the gale; and man chants a hymn of praise to science.

There was a time when the earthquake was equally enveloped in mystery, and was forecast in the enigmatic phrases of the astrologer and oracle; and now that it too has passed from the shadow of the occult to the light of knowledge, the people of the civilized earth—the lay clients of the seismologist—would be glad to know whether the time has yet come for a scientific forecast of the impending tremor. The outlook for earthquake forecasting is my theme to-day.

As you are aware, I am not a seismologist. My point of view is that of the geologist and general geographer. I speak as

[1] Presidential address to the American Association of Geographers, read at Baltimore, Md., January 1, 1909.

a layman, and present impressions acquired chiefly during somewhat amateurish work on the physical history of the San Francisco earthquake. That event was so far unforeseen that no seismologists were at hand, and the duty of investigation fell, in the emergency, on a volunteer corps of geologists and astronomers. For me it proved a fascinating subject, and interest did not cease with the completion of the special task.

But while this much is offered by way of explanation, and to prevent misunderstanding, you are not to infer that an apology is made because I tresspass on fields to which I have no title, for I am an advocate of the principle of scientific trespass. The specialist who forever stays at home and digs and delves within his private enclosure has all the advantages of intensive cultivation—except one; and the thing he misses is cross-fertilization. Trespass is one of the ways of securing cross-fertilization for his own crops, and of carrying cross-fertilization to the paddock he invades. Hypotheses, the trial theories which compete for development into final theories, spring by the principle of analogy from earlier and successful theories, and the broader the investigator's knowledge of explanatory science the greater his opportunity to discover hypotheses that may be applied to his own problems. Progress is ever through the interaction of the sciences one on another; and scientific trespass is one of the profitable modes of interaction. The trespasser brings with him a mental attitude and a mental equipment which are new to the subject, and whether or no the idea he contributes eventually "makes good," its contribution creates a new category for observation and opens a new avenue of inquiry. And he carries back with him the pollen of new ideas.

Next to verity, the factors which give value to an earthquake prediction are definiteness as to time and place. If the geologist Whitney, in warning San Franciscans forty years ago that their city would suffer by earthquake, had been able to specify the year 1906, and to convince them that he had warrant for his prophecy, the shock, when it came, would have been a phenomenon only and not a catastrophe. If any of those mysterious oracles who were said to have predicted earth convulsions in 1906 had named San Francisco, and told their reasons, the course of history might have been different.

PLACE

Let us consider first the possibility of scientific forecast as to place, and in so doing let us assume the point of view of the resident. The factor in which he is personally interested is the factor of danger—danger to life, danger to property, danger to the present generation. Except as a matter of curiosity, he is not concerned with faint tremors and minor shocks, nor with violent shocks likely to come after centuries of immunity. It will be convenient, at least for this day and hour, to embody our point of view in a concise term, and the adjective *malloseismic* will be used to designate localities likely to be visited several times in a century by earthquakes of destructive violence.

Experience.—The most important of all bases for the indication of earthquake localities is experience. Where tremors have been frequent in the past, there they are to be expected in the future. This premise hardly requires discussion, for it is founded on our confidence in the continuity of the great processes concerned in the evolution of the earth. We recognize indeed that continuity may fail in any particular case, but we always assume it as far more probable than discontinuity.

Other bases for forecast are connected with our conceptions as to the origin of earthquakes. The theory of earthquakes now generally accepted ascribes them to the sudden breaking or slipping of rocks previously in a condition of shearing strain. Exception should probably be made of some of the shocks accompanying volcanic eruptions, but volcanic shocks constitute a class by themselves to which it is not important to extend the present discussion. In non-volcanic, or ordinary, examples it is believed that the strains arise in connection with those tectonic or diastrophic changes which are exhibited superficially in the deformation of the surface, and that their accumulation is gradual. Fracture occurs when and where the internal stress exceeds the strength of the rock, and a fault results. Slipping takes place when the stress along the plane of a preexistent fault exceeds the force of adhesion. In either case it is the instantaneous character of the separation which occasions the jar.

The earthquake being thus a concomitant of tectonic change, its regions of frequency should be found in areas of diastrophic activity, and its occurrence should be rare and sporadic in areas of diastrophic sluggishness. This corollary is so well recognized that seismic activity is commonly regarded as the specific criterion of relatively rapid crustal change. Other criteria of such change are physiographic and geologic, and these may be applied in regions whose earthquake history is unknown. They may also be used, in the absence of seismic records, to give approximate indication of malloseismic localities.

Bold and High Ranges.—It was pointed out by Powell that, because erosion is greatly stimulated by altitude and high declivity, lofty mountains must be regarded as young; and under the principle of continuity young mountains created by uplift are presumably still growing. They are, therefore, phenomena of diastrophic activity and presumably belong to malloseismic districts. The conspicuous example is Mt. St. Elias, which rises boldly 20,000 feet from its base, which was shown by Russell to have continued its growth during the life of the existing marine fauna, and which recently has been signalized by earthquakes of the first class.

Fault Scarps.—Along the bases of block mountains the lines of their limiting faults are sometimes marked by fresh scarps demonstrating recent increase of uplift. In the Great Basin these scarps traverse the alluvium of the piedmont slopes, a surface of such simple type that their presence or absence can be observed with confidence. Their absence suggests diastrophic inactivity or sluggishness, for their effacement is a time-consuming process. Their presence suggests diastrophic activity, and the suggestion is strengthened when their relation to phenomena of weathering and erosion is such as to show that they were produced by a series of recent uplifts instead of one only.

Rifts.—A third physiographic criterion is illustrated in California and was brought to general attention by the San Francisco earthquake. The slip causing that shock occurred on the plane of a fault which outcrops at the surface and has been traced for hundreds of miles. The attitude of the plane is vertical, but the displacement along it was horizontal; and there is reason to think that earlier movements on the same plane were horizontal also, for the fault does not separate a ridge of uplift from a valley of depression but traverses both valleys and mountains. At all points it is included within a belt of peculiar topographic habit, which the investigating geologists have designated as "the rift." Within this belt, which ranges in width from a fraction of a mile to several miles, are numerous ridges and troughs, long or short, level or inclined, and approximately parallel to the trend of the belt. Each of these represents a dislocated tectonic block, and the dislocation is of so recent date that the disturbed drainage has made little progress toward the restoration of normal conditions. Lakelets are numerous, and streams wander irregularly. Without delaying to attempt a fuller and more adequate description, which may be found in the report of the California Commission,[2] I content myself with an assurance to physiographers that the topographic expression of the rift belt is distinctive, so that it can readily be recognized in other localities by those who have made its personal acquaintance in the field. Other belts of the same character have already been found in California[3] and their discovery elsewhere may confidently be expected.

Rift topography appears to be the surface expression of a species of repetitive horizontal faulting, just as the fault scarp is the surface expression of vertical faulting, and the two types, which with present knowledge are apparently distinct, will doubtless eventually be found to intergrade. The features of the San Andreas rift—the one associated with the San Francisco earthquake—were neither created nor greatly modified at the time of that shock, but such modifications as were made were of such character as to accentuate and perpetuate the peculiarities of the belt. The belt itself would be the natural result of a long series of such events, succeeding one another with such rapidity as to dominate minor aqueous agencies in the modeling of the surface. These considerations, together with the fact that earthquakes are known to have repeatedly originated in the rift belts of California, serve to establish the rift topography as a criterion for the recognition of malloseismic districts.

Geologic Formation.—Fault scarps and rift belts serve to indicate some of the foci of past and future earthquakes. Other foci lie wholly within the earth's crust. Whether the rupture occurs above or below, its jar is propagated through the crust in all directions and affects a large area of the surface. Within this area the intensity of the shock varies primarily with distance from the origin, but it varies also with the character of the geologic formation at the point of emergence. The variation with formation has less range than the variation with distance, but is not less important to the resident and the sojourner, the architect and the engineer—that is to say, it is equally important in forecasting areas of dangerous energy. The portion of San Francisco most intensely racked by the shock of 1906 stood farther from the fault line than the portion least affected, but it stood on less coherent soil. Wood has carefully mapped the distribution of intensity in the San Francisco peninsula, as evidenced by the injury to

[2] California earthquake of April 18, 1906; report of the State Earthquake Investigation Commission; published by the Carnegie Institution, Washington, 1908, pp. 25–52.

[3] The only rift belt beside the San Andreas which has yet been traced for any distance is one which follows in a general way the western base of the Berkeley hills. In the vicinity of Oakland its position is indicated by a trough among the lower hills two or three miles back from the piedmont plain. At Haywards it coincides with the western base of the hills, and at Irvington, with the western base of a projecting spur. In Berkeley also its line follows the base of the hills, but a little northward it climbs to the summit of the first ridge. The principal fault occasioning the earthquake of 1868 was in this rift belt, running from Haywards southward, and it is probable that some of the earlier recorded earthquakes were associated with the same belt. The fault of 1868 is described, and the rift belt is mentioned, in the "Report of the California Earthquake Commission," Vol. I., Part II., pp. 434–5 and 447.

buildings, and shown its close correlation with the distribution of underlying material;[4] and similar, though less detailed, correlations have been made in other regions. On the theoretic side the subject is almost untouched, and there is great need of experimentation, but the empiric results already available have much practical value and enable the geologist and engineer to distinguish broadly, within the limits of a malloseismic district, the tracts more likely, and the tracts less likely, to be affected disastrously by the passing earthquake wave.

On the whole that factor of earthquake forecast which consists in the indication of locality is in a satisfactory condition. In long inhabited regions experience designates certain districts as malloseismic. Newly settled regions may be classified, provisionally and less perfectly, by the data of physiography. And malloseismic districts will eventually be subdivided with confidence by means of geologic criteria.

TIME

Turning now to the time factor in forecasting, and retaining the point of view which emphasizes the element of danger, let us inquire what methods are available for the prediction of the time of occurrence of a destructive earthquake at a given locality or in a given district. Rational attempts to solve this problem have been connected (1) with the idea of rhythm, (2) with that of alternation, (3) with that of the trigger or starter, and (4) with that of the prelude; and each of these lines of approach is worthy of examination.

Rhythm.—Because we are surrounded by and immersed in the rhythms of art and nature, and because the earthquake is a recurrent phenomenon, it is easy to infer that the interval between the last shock and the next will be similar to that between the last and its predecessor. Reasoning of this general tenor probably underlies the greater number of lay forecasts, and is in particular responsible for the wide-spread popular belief that a place recently devastated is *ipso facto* immune for several decades, or at least for several years. A similar belief prevalent among men of science has a slightly different origin, but is even more strongly held; and there is little exaggeration in saying that our guild recognize it is a duty, when the terror-stricken inhabitants of a racked and ruined city seek safety in the open spaces, to assure them that the danger is past and urge them to return to their homes. Now, it is not at all true that either the great shocks or the small shocks affecting a particular locality, or affecting a district, or affecting the earth as a whole, are separated one from another by regular or approximately regular intervals; and it is not at all true that immediate danger is past when a great shock has wrought its havoc; and yet I am prone to believe that the rhythmic principle does hold place in the mechanics of earthquakes. On that point something further will be said, but I shall first invite your attention to the general phenomena of earthquake sequence, selecting examples from the American record because we are most interested in the phenomena of our own territory.

The United States has one well-known malloseismic district, a district including central and southern California, with areas in Mexico and the Pacific Ocean, and possibly extending northward. Alaska also contains a district, and there may be a third in Utah. Since the beginning of the last century, Alaska has experienced at least nine shocks of destructive rank; but the record is fragmentary and may

[4] "Report of the California Earthquake Commission," Vol. I., Part II., pp. 220–45, and atlas, maps 17–19.

omit more than it includes. For the California district eleven are listed, within the same period, the record being somewhat vague, and possibly incomplete, for the first half of the century. To these we may tentatively add the Oregon or Klamath earthquake of 1867 and the Sonora and Arizona earthquake of 1887, raising the number to thirteen. In other parts of the United States were the New Madrid (1811–12), the Charleston (1886), and a relatively weak but probably destructive shock in the New Madrid region in 1865.

The average interval between the individuals of the California series was nine years, and the separate intervals, in order, were: 12, 24, 3, 18, 8, 2, 1, 4, 15, 5, 6 and 8 years. As the centers of disturbance were scattered through the whole district and the areas of dangerous violence were of moderate dimensions, the danger record for any single locality was smaller, and the intervals correspondingly larger. In San Francisco, for instance, the last five destructive shocks have been separated by intervals of 26, 3, 30 and 8 years.

While it is manifest at once that neither of these sequences constitutes a rhythm, it is quite conceivable that they represent in some way a system of rhythms. They might, for example, be composed of several independent rhythms, each beating with its own period; or they might contain imperfectly recorded rhythms, each requiring for its interpretation some of the less violent shocks not included in the destructive class. And if it were possible to group the shocks according to place of origin, it might be found that each earthquake center has its orderly law of sequence. But while the existence of such a systematic arrangement seems within the range of possibility, I regard it as altogether outside the field of probability; and I feel sure that any attempt to discriminate rhythmic series on numerical grounds, without any other basis for classification, would prove unprofitable.

The single element of order which unquestionably belongs to the sequence of quakings is implied by the term after-shock. Every great shock is followed by a train of minor shocks, the length of the train being roughly proportional to the magnitude of the initial shock, and the average strength and frequency of the shocks diminishing with the lapse of time. Usually also the great shock is preceded by faint tremors, or by a few small shocks. The prelude, the great shock and the train of after-shocks, together constitute a typical seismic event, and if their sequence could be absolutely depended on, the terror of the great shock might rationally be palliated by the thought that the worst is over. But unfortunately there are exceptions, and the character of the exceptions is not reassuring. Occasionally the prelude includes a shock of great power, and occasionally the train of after-shocks, instead of being wholly subordinate in intensity, includes one or more major shocks, rivaling the initial shock in violence. Of the twenty-five American examples fourteen were normal and two abnormal, the others remaining unclassified because too little is known of them. It is possibly significant that the two abnormal earthquakes were of exceptional power, the New Madrid heading the list for the United States, and the Yakutat, of Alaska, being of the same order of magnitude. The New Madrid event began with a shock of great violence at 2 o'clock on the morning of December 16, 1811, and this was followed by a long series of vigorous after-shocks, among which eight were noted as of special strength and three were reported as equalling or exceeding the initial shock. Of the last-mentioned, one followed the initial shock after an interval of five hours, and the others severally after 38 and 53 days.[5] The Yakutat series began with a strong shock September 3, 1899, "and there were shocks at intervals until September 10, when, at 9:20 A.M., they began to be alarming. There were fifty-two shocks, culminating in one of great violence at 3 P.M. . . . There was another violent earthquake September 15 and other shocks until September 20."[6]

In view of these facts the promptings of terror when a great shock comes may well be seconded by the admonitions of wisdom, for even though it be probable that the worst is over, a substantial possibility remains that the worst is still to come. American experience suggests that as often as one time in eight a powerful shock, instead of being the climax of the earthquake, may be only the forerunner of the climax; and when life and limb are at stake the odds of seven to one in favor of safety form but a slender basis for mental serenity.

Turning now from the statistics of sequence to the question of underlying causes, I wish to present a conception of earthquake mechanism which has developed gradually during the study of California phenomena. The block movements associated with earthquakes in California are dominantly horizontal, and the fault planes along which the blocks slide are vertical. For this reason my mental picture of the system of faults (habitually drawn with two dimensions only) is a map instead of a section on a vertical plane. Imagine a large tract of the earth's crust superficially divided by faults into acute-angled blocks, which have a prevailing trend in one direction. In composition the blocks are heterogeneous, including stratified, metamorphic and igneous rocks, with complicated structure. The fault surfaces are not mathematically plane, but gently undulate, so that movement among the blocks involves more or less distortion of the blocks themselves. Imagine also that the tract is subject to external horizontal force of such nature as to induce internal shearing strains and the associated shearing stresses; and that the application of external force is continuous, making the internal stress cumulative. The internal stress is not uniformly distributed, because the more plastic rocks relieve the strain by flowage. When the stress along some part of a fault surface becomes greater than the adhesive force a slip occurs. When the stress within an elastic rock becomes greater than the shearing strength fracture takes place. In either case there is an instantaneous redistribution of stress. Relief of stress in the rock adjacent to the rupture is accompanied by increase of stress about the edges of the surface of parting, with the result that the area of the parting grows; and the growth is continued until regions of small stress are reached. The magnitude of the resulting earthquake depends chiefly on the quality of energy released by the relief of accumulated strain and stress.

If the quantities are large there are important after-effects. The discharge of strain causes a new arrangement of strains and stresses through a large tract; this leads to flowage and the local concentration of stress, especially in the more elastic rock; and this in turn causes fractures, of which the surface manifestations are after-shocks.

When finally equilibrium is restored, and the train of after-shocks is complete, the system of stresses, not only in the immediate neighborhood of the fault, but throughout an extensive tract, is mater-

[5] MS. of report on New Madrid earthquake by M. L. Fuller.

[6] "Recent Changes of Level in the Yakutat Bay Region," by R. S. Tarr and Lawrence Martin, *Bulletin Geol. Soc. Amer.*, Vol. XVII., p. 31.

ially different from what it was before the earthquake. In places, and especially near the fault, the general stress is less; in other places it is greater. The region of maximum stress is ordinarily shifted, so that when stresses imposed by external force again overtax the resistance, the new point of yielding is at some distance from the last.

In view of the complexity of the conditions and the intricacy of the interaction among strains, it is not to be supposed that the status at any one epoch will ever be exactly repeated. Nevertheless, its main features may recur, and whenever they do a cycle will have been completed. Such a cycle, however, would be indefinitely long, and would be too difficult of discovery to be available for purposes of forecast.

It is conceivable also that in some limited portions of the general district the local conditions may give rise to repetitive collapses somewhat independent of the general progress of events. In such case the successive earthquakes would originate in the same place and their systematic character could be recognized through that fact.

There is a class of natural and artificial rhythms in which energy gradually passes into the potential form as internal stress and strain and is thus stored until a resistance of fixed amount is overcome, when a catastrophic discharge of energy takes place. The supply of energy being continuous and uniform, the discharges recur with regular intervals. The frictional machine for generating electric sparks in the laboratory is the type; other examples are the geyser, water gurgling from a bottle, and the alternate adhesion and release of the violin bow in contact with the string. The earthquake is a repetitive catastrophe belonging to the same mechanical group, and if its mechanism were as simple as that of the electric machine its rhythm would be as perfect. If the stresses of an earthquake district affected only homogeneous rock and were always relieved by slipping on the same fault plane, the cycle of events would be regular; but with complexity of structure and multiplicity of alternative points of collapse, all superficial indication of rhythm is lost. If rhythmic order shall ever be found in the apparent confusion, it will be through an analysis which takes account of the points of origin of all important shocks.

Alternation.—The principle of alternation in the occurrence of earthquakes has already been touched. When a large amount of stored energy has been discharged in the production of a great earthquake and its after-shocks, it would seem theoretically that the next great seismic event in the same seismic district was more likely to occur at some other place, and that successive great events would be distributed with a sort of alternation through the district. This hypothesis I used twenty-five years ago, in predicting that the next slip on the fault at the base of the Wasatch range, instead of occurring in the locality of the last previous slip, would take place at a different point;[7] and it has been more recently applied by Omori, Hayes and Lawson in forecasting earthquakes on the western coast of the two Americas. These geographers agree in regarding the entire coast either as a single seismic district or as a portion of a greater district, in which there is interdependence of parts. Omori pointed out that in the period of six years from 1899 to 1905 there were extensive disturbances in Alaska, Mexico, Central America, Colombia and Ecuador; stated that the gap thus left between Alaska and Mexico had led him to anticipate an early

[7] Monograph I., U. S. Geological Survey, p. 362.

rupture in that tract of coast; and suggested, after his first anticipation had been realized by the San Francisco earthquake, that the next disturbance might be south of the equator—where the Valparaiso earthquake soon afterward occurred.[8] Hayes, after the San Francisco and Valparaiso earthquakes, suggested Mexico as a probable locality for the next rupture; and after the earthquake which devastated the state of Guerrero in southern Mexico, made a similar suggestion as to Colombia.[9]

[8] In an interview published by the San Francisco *Bulletin* of June 13, 1906, F. Omori says: "Between 1899 and January 1 of this year (1906) there have been several extensive earthquakes along the coast of Alaska, Mexico, Central America, Colombia and Ecuador. These disturbances are not to be regarded as separate or unconnected phenomena, but were the result of great stress which was taking place all along the west coast of North and South America. The Pacific slope of the United States remained comparatively quiet all this time, so it was most natural to expect a continuation of the disturbance in these parts.

"As it has finally happened this time I believe it is over and the adjustment complete. . . .

"The center of a future earthquake, due perhaps to the same causes as this, will probably be different, and may take place as far away as the other side of the equator."

In a bulletin of the Imperial Earthquake Investigation Committee of Japan, published in January, 1907, Vol. I., pp. 21 and 23, he continues the subject, illustrating the distribution of seismic disturbances by a map, and concludes thus:

"The great stresses going on along the whole Pacific coast of America, which thus resulted in the occurrence of a series of great earthquakes, seem 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."

The forecast of an earthquake between Alaska and Mexico was verified by the California shock of 1906 and the forecast of a disturbance south of the equator by the Valparaiso earthquake of 1906. The forecast of immunity for some decades in the Mexico-Central America group was shown to be erroneous by the Mexican earthquake of 1907. The success or failure of the prediction of immunity for other parts of the coast remains to be determined. It is to be noted (1) that the Mexican earthquake, occurring in a district for which Omori predicted immunity, was forecast by both Hayes and Lawson; (2) that Lawson forecasts disturbance in a region north of California for which Omori forecasts immunity, and that Hayes forecasts disturbance for a region south of Mexico for which Omori forecasts immunity. See the following notes.

[9] C. W. Hayes is thus reported in the Washington *Times* of April 16, 1907:

"At least one man, who has studied seismic disturbances, has succeeded in predicting the locality of an earthquake months before the shock occurred.

"He is Dr. Charles Willard Hayes, of the United States Geological Survey, who made a report for the government on seismic conditions in Nicaragua in 1899. In this report he made the statement after the recent destructive earthquake at Valparaiso that he would not be surprised if the next section of the American continent to be visited by a seismic disturbance would be somewhere between San Francisco and Valparaiso, probably in Mexico.

"Dr. Hayes would not be surprised if the next earthquake should occur in the United States of Colombia, South America.

"In speaking of the earthquake in Mexico yesterday Dr. Hayes said to a *Times* reporter this morning:

"'While it is impossible to predict with any accuracy the location and time of the occurrence of an earthquake, our knowledge of the geological structure of the earth enables us to determine within certain limits the probable areas where seismic disturbances are most likely to occur. The course of these disturbances may be expected to follow a general line of adjustment of the earth's crust along the western slope of the two American continents, the line being somewhat broken in Central America.

"'The course from South America extends north to the islands in the Caribbean Sea, and that from North America is traceable down through Mexico and Central America. This course extends north along the coast of Alaska across the Aleutian Islands, down the Siberian coast, through Japan and thence across the Indian Ocean.

"'The disturbance in Alaska a few years ago was the first of the series that has afflicted the western hemisphere recently. It was natural to

Lawson mentioned breaks in the continuity of recent demonstrations, between the southern part of California and Central America, and between the northern part of California and Alaska, and suggested the probability of early visitations in Mexico and the Oregon-Washington region. In this forecast he anticipated by a few weeks the Guerrero earthquake.[10] Omori went farther and expressed the opinion that the Valparaiso earthquake was the final term of a series, and that the whole Pacific coast of America would be exempt for a time from *great* seismic activity. He expected for San Francisco a period of immunity of thirty to fifty years and for coastal regions from Alaska to Ecuador of twenty to thirty years.

It will be observed that this idea of a series, breaking on the American coast in the course of a few years, and followed by a comparatively long interval before the arrival of another series, an idea apparently shared by Hayes and Lawson, combines rhythm with alternation in the theory of forecasting.

Prediction and verification are the test of hypothesis, and this group of predictions—albeit tentative and advanced with judicious caution—embodying, as they do, the diverse views of independent investigators, who approach the subject from both seismologic and geologic sides, constitute a valuable contribution to seismic forecasting. The outcome in verification will have bearing not only on theories of alternation, rhythm and rhythmic immunity, but on the order of magnitude of the seismic district within which effective mechanical interaction takes place, and also on the profounder earth problems with which the question of the ultimate cause or causes of earthquakes is involved. If it shall appear as highly probable that yieldings to crustal stress in remote parts of North America have a direct influence on the dates of similar events in South America, the primary sources of the stresses can hardly be of such local nature as the shifting of load through degradation and aggradation or the outward flow of continental excess of matter, but should be sought rather in forces tending to deform the planet as a whole.

Trigger.—The third general principle applicable to prediction is that of the trigger—or the principle involved in the parable of the last straw, which broke the camel's back. As the growing earth stress

expect the next one at some distance, and, as it happened, this occurred at San Francisco. Then the Valparaiso disturbance being so far to the south it was probable that the next shake would be somewhere between the two. The shock at Jamaica was probably connected with the Valparaiso earthquake, being in the same course with it. That in Mexico is more likely to be connected with the course of disturbance from Alaska down.'

"Dr. Hayes, when asked if he would venture to predict the locality in which the next earthquake might occur, said that he did not wish to go on record as making any prediction on a matter concerning which scientific knowledge was so limited, but was of opinion that it would not be unreasonable to look for one in northern South America in the United States of Colombia. Asked whether a disturbance there would be likely to affect the region of the Panama canal, he thought that Panama might feel tremors from a considerable shock, but that it was unlikely any damage would result."

[10] A. C. Lawson, in a lecture read to the National Geographic Society, March 29, 1907, attributed the California earthquake to a series of ruptures that had been traveling along the western coast of America. "So far it has occurred everywhere along the coast except in a stretch between the southern part of California and Central America and an area between the northern part of California and the southern part of Alaska. These stretches, I believe, will be visited before long and then the long line of this earthquake will be complete from Chili to Alaska." This statement preceded by a few weeks the occurrence of the Guerrero earthquake in Mexico, and its prognostication was thus promptly verified as to the district south of California. It awaits verification for the district north of California.

little by little approaches the limit of the resisting force there is a critical period during which a relatively small additional stress arising from some other source may precipitate the catastrophe. A number of possible sources for the additional stress are known, the influence of several has been fairly demonstrated in a statistical way, and it is on the whole probable that a large majority of earthquakes owe their precise dates to such contributory causes. Many of the precipitating factors are periodic in their character, and the times of their maxima, or other favorable phases, are known; so that, granting their influence, they serve to restrict prediction to certain epochs. They are not of primary importance in forecasting, but when the approximate date of a future earthquake shall have been learned by other means, they will serve to refine the estimate of time.

The principal known causes of periodic variation of stress are bodily tides of the earth; oceanic tides, which alternately load and unload the sea bed near the shore; the winter load of snow on parts of the land; annual and diurnal variations of atmospheric pressure; diurnal variations of barometric gradient; and the wandering of the earth's axis of rotation. The relative importance of the several influences can not yet be indicated, but it is known that their absolute importance is not the same in all places. Three belong to the coastal belts, two to the land; and two belong to land and sea, but vary with latitude. Their relative importance in any particular locality may depend also on the direction of the slowly growing tectonic stress of the crust; for in order to be effective the temporary or adventitious stresses must be of such character as to augment the tectonic stresses. Let me illustrate this point.

The tidal sway of an oceanic basin raises and lowers the surface very little where the water is deep, but has a much greater effect on the shoals bordering coasts. The strip of sea bed following the coast is subjected twice a day to the addition of a heavy load of water, and in the intervening hours is relieved of pressure by the same amount. On the seaward side of the strip there is a gradual change in pressure, and on the landward side, just at the water edge, an abrupt change; and these pressure differences cause strains and stresses in the crust beneath. The directions of the induced strains lie in vertical planes at right angles to the coast, and are competent to increase or diminish tectonic stresses having similar directions. On the coast of Alaska near Mt. St. Elias the tectonic changes in progress include an uplift of mountains parallel to the coast, and the main tectonic stresses may be assumed to lie in vertical planes normal to the coast; so that here the oceanic tides are competent to precipitate earthquakes. But on the California coast near San Francisco, where the directions of the main tectonic stresses are horizontal and are approximately parallel to the coast, the stresses from oceanic tides may be ineffective. On the other hand the stresses created in the crust by the shifting of the axis of rotation are probably better calculated to augment tectonic stresses at San Francisco than at Mt. St. Elias.

Unfortunately the value to the forecaster of the periodic stresses is impaired by the occurrence of other transient stresses which are not periodic. The barometric gradients and extremes of pressure connected with cyclonic storms are of this class, and so are the pressure changes arising when the sea is pushed against the land or drawn from it by strong wind; and all these storm effects are at times much greater than the rhythmic changes of corresponding character. If storms are really earthquake-breeders—instead of the traditional calm, sultry, so-called "earthquake weather"—then the shocks they precipitate can be foretold only so long in advance as the storms themselves are foreknown.

The most potent of all precipitants of earthquakes is also useless to the forecaster because its action is unforeseen. It is the earthquake wave emanating from a nearby focus. The response to such an impulse follows the initial shock so closely that the two shocks are combined in a single seismic event—an earthquake with two foci, or a "double-earthquake."

Prelude.—The forecasting of earthquakes by means of prelude has nothing in common with other methods, but resembles rather the forecasting of the weather for the day by a glance at the sky in the morning. It depends on the recognition of premonitory signs, and also, to some extent, on the recognition of the earliest phases of the event itself.

When a fracture or other parting of the rock takes place, the jar which is communicated to surrounding portions of the crust is not a simple impulse, but a congeries of vibrations differing in amplitude and period, and in speed of transmission. At any point of the focus they begin together, but traveling through the rock at different rates, they arrive at any distant point at different times; and the greater the distance the greater their separation. The strongest of the vibrations, or those said to constitute the principal shock, are not the first to arrive, but are preceded by vibrations which are much weaker, and are known as the preliminary tremors. At a point twenty miles from the origin the preliminary tremors are felt four or five seconds before the principal shock. There are also vibrations too minute to be felt, and not yet recorded by the most delicate seismographs, but of such frequency that they fall within the register of the ear and are perceived as sounds, and these usually begin to arrive before the preliminary tremors. The sounds and faint tremors are notes of warning, and to him who not only hears and feels but understands they give command of precious seconds. People who live in earthquake countries and are familiar with these warnings acquire the habit of instantly taking precautionary measures.

Still earlier than the sounds and tremors with which the earthquake begins, are sometimes sounds, tremors or minor shocks, and it is suspected that phenomena of this sort may betray growing seismic activity and thus constitute premonitory symptoms of the final rupture. Little is known of them in any exact way, because they occur at a time when attention is not directed to such matters; and nearly all records are made from memory after the occurrence of the earthquake. If they are veritable preludes, connected in a systematic way with the mechanics of the earthquake, they are probably analogous to the cracklings and crepitations observed in strained beams and strained blocks of rock before collapse occurs. With reference to the possibilities of forecasting, expectation centers especially on faint tremors such as are occasionally perceived a few minutes or a few hours before an earthquake shock. They are more frequently inferred from the peculiar behavior of animals; and after making much allowance for the influence of imagination on the memory of observers, there is still reason to think that various animals are affected by vibrations to which man is insensible, and that their reported uneasiness before earthquake shocks is real and is occasioned by premonitory vibrations.

The scientific study of preludes belongs to the future, and especially to such adaptations of seismographic appliances and methods as we may confidently anticipate. Feeble tremors, ascribed to minute crepitations of the crust, have already been made audible by means of the microphone, so that the ear could be applied to a sort of seismic stethoscope; and the next step will perhaps be to construct a seismograph of such delicacy as to record these minute vibrations, and install it where it will be undisturbed by tremors of artificial origin.

RÉSUMÉ

Summarizing briefly, many of the malloseismic districts or areas of earthquake danger are known from records of past experience, and others are being recognized by physiographic characters. Within them are tracts of special instability because of the incoherence of the underlying formation, and these can be both characterized in general terms and locally mapped. The general relations of danger to place are so well understood that an early solution of their outstanding problems may be assumed. Of the relations of danger to time much less is known and there is less promise for the immediate future. The hypothesis of rhythmic recurrence has no sure support from observation, and is not in working order for either large or small areas. Its corollary of local immunity after local disaster is more alluring than safe. The allied hypothesis of alternation between parts of a district is being tested by a great example, but the verdict belongs to the future. The hypothesis of precipitation by accessory forces which are in large part periodic and foreknown, has a good status and is being developed on the statistical side. It promises to make the date of prediction more precise if ever the approximate time shall be achieved by other means. The hypothesis of an intelligible prelude has barely been broached and the means to test it are not yet in sight. In a word the determination of danger districts and danger spots belongs to the past, the present and the near future; the determination of times of danger belongs to the indefinite future. The one lies largely within the domain of accomplishment; the other still lingers in that of endeavor and hope.

We may congratulate ourselves that it is not the place factor which lags behind, for knowledge of place has far more practical value than knowledge of time. In fact I see little practical value in any quality of time precision attainable along lines of achievement now seen to be open. Suppose, for example, that a prediction based on rhythm or alternation should indicate an earthquake as due in a certain year, and that tides should be recognized as the most potent accessory cause; then for several days each month, and possibly for many months, expectation would be tense, and the cost in anticipatory terror would be great. Or suppose that prelude phenomena should be found to afford real warning; the forecaster on duty would still have to deal in probabilities, and when in doubt would often sound vain warnings, in the conscientious effort to escape the greater error of omission at the critical time—and again nervous strain would be wasted. And even if warning were definite, timely and infallible, so that peril of life could be altogether avoided, property peril would still remain unless construction had been earthquake-proof. If, on the other hand, the places of peril are definitely known, even though the dates are indefinite, wise construction will take all necessary precautions, and the earthquake-proof house not only will insure itself but will practically insure its inmates.

MORAL

It remains to draw the moral. In view of these facts as to forecasting, and of the further fact that we have in our land a district subject to strong earthquakes, there are duties to be recognized and policies to be advocated. It is the duty of investigators—of seismologists, geologists and scientific engineers—to develop the theory of local danger spots, to discover the foci of recurrent shocks, to develop the theory of earthquake-proof construction. It is the duty of engineers and architects so to adjust construction to the character of the ground that safety shall be secured. It should be the policy of communities in the earthquake district to recognize the danger and make provision against it.

The general fact of local danger spots, where the agitation during strong earthquakes is peculiarly violent, has long been familiar. It is known that they are commonly found in lowlands where the underlying formation is a deep deposit of alluvium or other unconsolidated material, and that such material, while it aggravates great shocks, absorbs and quenches small ones. It is also known that the local phenomena are in some way connected with the transformation of earthquake waves in passing from elastic to inelastic material. But a mechanical theory of the phenomena is yet to be supplied. For economic, as well as scientific purposes, this is one of the important fields for investigation. In Japan, where earthquakes are much more frequent than in any portion of our own land, the subject has been studied and may still advantageously be studied, by the observation of natural shocks. In America the problem can be more readily studied by means of artificial earthquakes in the laboratory, continuing the line of experimentation begun by Rogers.[11] When the underlying principles have become known, it will be comparatively easy for geologists, engineers and architects to estimate the danger factor in places to be occupied by buildings.

The San Andreas rift,[12] now traced through so much of its length as traverses inhabited areas, is recognized as a danger belt of a peculiar character, to be avoided especially by water conduits and railways. Although it is probably the most extensive rift belt in the country, it is not the only one, and the positions of all others should be determined and mapped. The foci or epicenters of recurrent earthquakes are also localities of special danger, even though the underlying formation is firm and elastic. So far as the earthquake faults reach the surface of the ground, the epicentral tracts coincide with the rift belts and fault scarps; but some of the foci are doubtless wholly subterranean and need for their discovery a seismic survey like those conducted in Japan, Italy, England and, since the Valparaiso earthquake, in Chili. In Japan, which now takes first place in the study of earthquakes, the survey is conducted by a system of seismographic observatories in cooperation with a large body of local correspondents—a mode of organization quite analogous to that of our Weather Bureau, with its system of thoroughly equipped stations and its wide-spread corps of volunteer observers.

Much progress has already been made

[11] Professor F. J. Rogers, of Stanford University, gave harmonic motion in a horizontal direction to a box of sand, and found that under certain conditions a body resting on the sand received motion which was not harmonic, and which had greater amplitude and a much greater maximum acceleration than the motion of the box. His experiments are described in the "Report of the California Earthquake Commission," Vol. I., Part II., pp. 326–35.

[12] "The California Earthquake Investigation Commission," Vol. I., Part II., pp. 25–53.

in determining the principles of earthquake-proof construction. After each great earthquake which in modern times has devastated a city, there has been engineering study of the buildings which successfully resisted the vibrations and of those which succumbed, so that the construction of the future might profit by the experience of the past. In various countries, and especially in Japan, there have been series of experiments either for determining the mechanical character of earthquake shocks, or for testing the ability of different types of construction to withstand them. The results of these observations and experiments have helped to determine the building regulations and building methods in various earthquake districts. For our own purposes there are needed, not merely a complication of the principles developed elsewhere and of the deductions from recent experience in California, but special lines of investigation, covering, theoretically and experimentally, the materials and architectural methods employed in this country at the present time. In the line of experiment, we may well follow the example of our oriental neighbors, by constructing a machine which will give to a platform all the motions characteristic of a violent earthquake, and using the platform as a testing ground for types and materials of construction.

The proposition that it should be the policy of the inhabitants of an earthquake district to recognize the danger and make provision for it appears self-evident, but I regret to say that its soundness is not universally recognized in California. As long ago as 1868, Whitney, speaking of the Pacific states, said:

> The prevailing tone in that region, at present, is that of assumed indifference to the dangers of earthquake calamities—the author of a voluminous work on California, recently published in San Francisco, even going so far as to speak of earthquakes as "harmless disturbances." But earthquakes are not to be bluffed off. They will come, and will do a great deal of damage. The question is, How far can science mitigate the attendant evils, and thus do something toward giving that feeling of security which is necessary for the full development of that part of the country.[13]

This policy of assumed indifference, which is probably not shared by any other earthquake district in the world, has continued to the present time and is accompanied by a policy of concealment. It is feared that if the ground of California has a reputation for instability, the flow of immigration will be checked, capital will go elsewhere, and business activity will be impaired. Under the influence of this fear, a scientific report on the earthquake of 1868 was suppressed.[14] When the organization of the Seismological Society was under consideration, there were business men who discouraged the idea, because it would give undesirable publicity to the subject of earthquakes. Pains are taken to speak of the disaster of 1906 as a conflagration, and so far as possible the fact is ignored that the conflagration was caused, and its extinguishment prevented, by injuries due to the earthquake. During the period of after-shocks, it was the common practise of the San Francisco dailies to publish telegraphic accounts of small tremors perceived in the eastern part of the United States, but omit mention of stronger shocks in the city itself; and I was soberly informed by a resident of the city that the greater number of the shocks at that time were occasioned by explosions of dynamite in the neighborhood. The desire to ignore the earthquake danger has not altogether prevented the legitimate influence of the catastrophe on building regulations and building practises, but

[13] "Earthquakes," by J. D. Whitney, *North American Review* for April, 1869, Vol. CVIII., p. 608.

[14] "California State Earthquake Investigation Commission," Vol. I., Part II., p. 434.

there can be little question that it has encouraged unwise construction, not only in San Francisco but in other parts of the malloseismic district.

The policy of concealment is vain, because it does not conceal. It reflects a standard of commercial morality which is being rapidly superseded, for the successful salesman to-day is he who represents his goods fairly and frankly. It is unprofitable, because it interferes with measures of protection against a danger which is real and important.

To understand the practical importance of the earthquake danger, let us for a moment consider it from the insurance point of view. To determine rate of premium, an insurance company first computes the risk, and this computation is based on past experience, comparing the actual losses with the amount exposed to loss. We know, with fair approximation, the loss of life by earthquake in California from the year 1800, and can compare it with the population. As to the property loss, our knowledge is relatively indefinite, but it suffices for the present purpose.

Consider first the value of insurance against the danger of death by earthquake. Seven hundred and nine deaths are reported to have been caused by the San Francisco earthquake, and about 76 deaths by earlier earthquakes, making a total of 785.[15] The total annual population for the same period, that is to say, the sum of the populations for the several years, was about 51,500,000.[16] Using these data, the annual premium on a policy for $1,000, payable only in the event of death by earthquake, is computed at one cent and a half, plus the cost of doing the business and the profit of the company. The minuteness of the earthquake risk may be further indicated by saying that it is one tenth of the risk of death by measles. If a timid citizen of California should emigrate in order to escape the peril from earthquake, he would incur, during his journey, a peril at least two hundred times as great, whether he traveled by steamship, sailing vessel, railway car, motor car, stage, private carriage, or saddle; and if in emigrating he removed from San Francisco to Washington City he would incur, by change in environment as regards typhoid fever, an increment of peril eighteen times as great as the earthquake peril he escaped.[17]

The danger to property is much more serious. Using the same method of computation as before, and availing myself of the expert knowledge of local statisticians, I have made a parallel estimate of the earthquake risk to buildings in California, and find it to be about five hundred times as great as the risk to life. If a company were to undertake the insurance of buildings against injury by earthquake, and base its premium on the experience of the state from 1800 to 1908, the average premium on a policy of $1,000 would be about $7, plus the cost of doing the busi-

[15] The casualties in 1906 are given as reported by the State Board of Health; those in earlier years were compiled from Holden's "Catalogue of Earthquakes on the Pacific Coast, 1769 to 1897."

[16] To obtain this figure the populations of the state on census years were platted on section paper and a curve of population drawn through them, thus graphically interpolating estimates for intervening years. For years earlier than 1850 estimates were based on data contained in Hittell's "History of California." The census returns do not include Indians. In making estimates of the population previous to 1850 the Mission Indians were included. The estimate includes the year 1908.

[17] The U. S. Census returns for the years 1901–5 give the following death rates, per 100,000, from typhoid: San Francisco, 27.0; Washington, 56.6. The statement in the text of course applies only to the risk of death from typhoid; the death rate from *all* causes was higher, in the same years, in the western city than the eastern.

ness.[18] This is nearly twice as large as a similar figure expressing the fire risk for the United States, as based on the accumulated experience of underwriters. Just as in the case of fire insurance, the premium on earthquake insurance would be adjusted to the local conditions; it would be higher for houses on soft ground than for those on bed rock, relatively high for houses near known earthquake foci, and very low for houses classed as earthquake-proof.

In making this estimate the fire damage occasioned by the earthquake damage of 1906 was treated as part of the earthquake damage. Had the direct earthquake damage alone been considered, the computation would have yielded a figure materially smaller, though still comparable with the basal fire insurance factor. But there seems no good reason for excluding the fire damage, for not only was the San Francisco conflagration caused wholly by the earthquake, but fire is a frequent sequel of the wrecking of buildings by seismic shocks. Nearly all our appliances for heating, cooking and lighting are sources of fire danger when deranged by violence to the containing buildings, and if the agent of violence affects a large area, as in the case of earthquakes, the appliances for extinguishing fires are apt to be disabled at the same time.

It is possible that the estimate of the building risk is exaggerated by reason of its having been made just after the great disaster of 1906. It certainly would have been materially smaller if made by the same method just before that disaster. But this qualifying circumstance is largely if not wholly offset by the fact that various shocks of the same physical rank as that of 1906 wrought comparatively little havoc because at the time of their occurrence the areas shaken were sparsely populated—at least by house-building races. The Inyo earthquake of 1872, having its origin in Owens Valley, demolished the village of Lone Pine with a completeness not paralleled in 1906, and the falling walls crushed to death a tenth part of the village population. The shocks of 1812, affecting a tract on which Los Angeles, Santa Barbara and other large towns are now built, were limited in their destructive effect to the Spanish Missions because those were then the only houses; but the mission buildings fared badly, and it is related that thirty or forty mission Indians lost their lives. The earthquake hazard indicated by these occurrences was certainly not less than that emphasized by the recent disaster in a populous district,

[18] In assembling data for this estimate I was greatly assisted by Professors C. C. Plehn and A. W. Whitney, of the University of California, but these gentlemen are not to be held responsible for the estimate itself. The estimate involves, among others, the following assumptions: (1) in that part of San Francisco burned over in April, 1906, the loss from destruction and injury of buildings amounted to one third the entire loss; (2) the ratio of sound value to assessed value of buildings in San Francisco in 1905 was 1.7; (3) the similar ratio for the entire state was 2.0; (4) the average value of buildings per capita in California was the same for the entire period 1800–1908 as for the single year 1905. Some of the elements of the estimate are as follows:

Damage to buildings in burned district of San Francisco in 1906 (= 1/3 × $350,000,000)	$117,000,000
Damage to buildings in San Francisco, outside burned district, 1906	7,000,000
Damage to buildings outside of San Francisco, 1906	15,000,000
Damage to buildings in California, 1800–1905	20,000,000
Total earthquake damage to buildings in California, 1800–1908	$159,000,000
Total corresponding "exposure" (= sum of annual value of buildings in California 1800–1908)	$22,000,000,000
Basal insurance factor (= ratio of total loss to total exposure)	0.00723
Risk on policy of $1,000	$7.23

and yet the absolute losses they occasioned were so small as to have little influence on the totals used in the computation.

On the whole, weighing these and other factors of the problem as well as I am able, I am disposed to adhere to the estimate, not, indeed, claiming for it a high measure of precision, but regarding it as a fair approximation to the truth, and possibly as good as may be derived from the available facts.

It is needless to carry further the discussion of insurance rates. Its purpose has been served in showing that the earthquake risk to buildings in California is comparable with the fire risk and equally worthy of serious consideration. There is no present question of earthquake insurance, of which the function would be merely to distribute earthquake losses, but there is a question of the prevention of earthquake damage.

Earthquake damage is at least as preventable as fire damage. It is possible so to construct houses that they will neither collapse nor otherwise be vitally injured by such shocks as have visited California in the past. In a house so built there will be small danger from earthquake-started fires because they will be both accessible and quickly detected. It is wreckage that prevents the prompt extinguishment of the initial blaze. In a house so built there will be little damage to furniture, merchandise and other valuable contents. With houses so built the life risk will become a vanishing quantity, for practically all earthquake casualties are directly due to the failure of buildings. And in a community thus protected in life and property the terror of the mysterious unheralded temblor—a factor far outweighing the actual personal peril—will gradually wear away.

In saying that earthquake damage is preventable I would not be understood to imply that the subject of earthquake-proof construction is at all adequately developed. Competent modes of construction are known, but the best modes, the most economic modes, the modes best adapted to American materials and conditions remain to be determined, and there is much need of investigation.

It should be the policy of the people and state of California to see that the necessary investigations are made, and that the results are embodied in the building regulations of all cities as well as in the entire building practise of the state. And, in order that the methods of construction may be properly adjusted to the very unequal local requirements, provision should be made for a seismic survey and the mapping of tracts of special earthquake danger.

G. K. Gilbert

JEAN ALBERT GAUDRY[1]

From time to time as honored chieftains fall in the front ranks of the world's intellectual forces that are making for scientific progress, and bent on the conquest of new realms of knowledge, it befits men of a younger generation to take note of the passing of these heroes, these veteran standard-bearers who now rest from their labors, leaving a splendid memorial of their lifework behind them. Upon such occasions it is well to call to mind some of the more notable achievements of these patient searchers after truth, and to bethink ourselves what manner of men were they who contributed largely to widening the bounds of human understanding, whose lives were consecrated to the service of the sovereign mistress of truth.

An occasion of this kind has recently befallen us. Geological and biological science mourn the loss of Professor Albert Gaudry, foremost of the modern school of French paleontologists, a man of remarkable and versatile talents, in-

[1] Presented before the American Society of Vertebrate Paleontologists at the Baltimore meeting, December 30, 1908.