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MOVEMENTS OF THE EARTH'S CRUST.*

(BRADYSEISMS, EARTHQUAKES, DIURNAL WAVES, TREMORS.)

By JOHN MILNE, F.R.S., F.G.S.

WHEN we reflect upon the attention devoted to the observation of heavenly bodies, the changes that take place in the atmosphere, and the tides and currents in seas and oceans, it seems remarkable that so little has been done for the study of the movements of the so-called *terra firma* on which we live, and in building foundations to carry instruments which measure and record phenomena which take place above and round about.

If we except earthquakes, which from time to time attract a momentary attention by their violence, the reason that the more universal movements which are in operation beneath our feet receive so little attention is probably that they are not appreciable to our feelings. We cannot see a coast-line sink or rise, but that such things have happened, and that they may yet be in operation, is a deduction based upon a variety of evidence. We do not see tall buildings slowly moving to and fro with a diurnal period; nor do we perceive by any of our senses that there are times when certain instruments behave as if the foundations on which they rested were spasmodically breathing. Although a physicist may tell us that on a certain day a change in level is in operation, our knowledge of this, like that of many other earth-movements, depends upon hearsay.

While saying something about earthquakes, the object of the following short paper is to indicate the character of movements which are either too slow or too small to note with our unaided senses, and to

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point out the scientific and practical advantages which result from their study. We shall refer to them in the order of their relationship to each other—those with an orogenic origin, like bradyseisms and earthquakes, being taken first; whilst those like diurnal waves and tremors, the existence of which may depend upon meteorological conditions, are taken last.

BRADYSEISMS.

The first movements to be touched upon are the *slow* or bradyseismic motions of the Earth's crust which, relatively to sea-level, result in elevation or depression. The manner in which these are produced by a shell too weak to be self-supporting, folding and crumpling as it accommodates itself to a shrinking nucleus, is a theory sufficient to explain the existence of mountain ranges, the uplifting of strata which were once beneath the sea, and many of the more important features of the lithosphere. We shall treat of these movements in relation to continental development, geological history, and to what has been observed to occur during historical periods and a lifetime.

When studying the evidences we have of bradyseismal changes, the first inquiries relate to their magnitude, their form, and the rapidity with which they are performed.

As it is usually only the vertical component of these movements which is measured, and this relatively to ocean-level, a debatable point that presents itself relates to the fixity of this datum. We know that the oceans form a body of water always moving towards a position of equilibrium; that much has been written to show that by absorption a general lowering of level is in operation; that by sedimentation and the release of aqueous vapour from heated rocks, a movement in the opposite direction may be taking place; that by alterations in the position of the Earth's centre of attraction, and by other causes, there may have been changes in the configuration of the oceanic envelope. But putting these considerations on one side—partly because they result in long-continued uniformity of change in one direction—we may ask ourselves how far secular movements have resulted in real elevation or depression, and how far they are only apparent movements due to the rising or falling of the water.

The phenomenon we wish to consider is similar to that which takes place when we raise or lower an apple in a basin of water. When it is lowered the water rises, when it is raised the water falls, and the volume of the immersed solid is equal to the volume of the displaced fluid. If the rim of the basin was flat or saucer-like, over such a surface there would be large horizontal displacements of the water-line.

Applying such ideas to what may possibly have taken place during the growth of the habitable portion of the world—a great part of which we know was at one time beneath the surface of the waters—and

assuming that there was at some particular period in the world's history a universal, or nearly universal, ocean, if we have not considered the matter before, we reach a somewhat unexpected result. Because we know the volumes and areas of the oceans, and the areas and average heights of the continents above sea-level, if the latter have been raised above the former when it extended over the whole globe, then out of an apparent average elevation, usually estimated at about 1000 feet, 250 feet of this would be due to the recession of the waters. A measure of the *area* of existing land surface which may in this manner have been only apparently elevated, may be realized by noticing the area which would be covered if the present sea-level could be raised 250 feet.

Regarding the evolution of continental areas in this manner, we see that the retreat of the ocean may have played a part quite commensurable with that attributed to bradyseismical movement. Should we dismiss, as being improbable, the idea that at any period of continental development there has ever been an almost universal ocean, and only consider the elevations which have taken place within the range of geological history, we still see that secular movements have been accompanied by considerable changes in ocean-level, and still greater in ocean-area. In discussing this question, the *à priori* assumption is, that when any area rose above the waters, it is unlikely that there should have been at the same time, in some other region, a subsidence beneath the water, and even if such contemporaneous but opposite movements had an existence, it is still more unlikely that they should have been volumetrically equal. Granting this hypothesis, as an example of what is likely to have occurred at times well within the limits of the geological horizon, we may take the two great mountain-forming epochs in the world's history. About the close of the Palæozoic era, the Urals in Europe, the Himalayan-like Appalachianians, and other mountain ranges were formed.

In early Tertiary times, the Alps, the Pyrenees, the Carpathians, and the Himalayas were growing upwards, whilst a series of islands were slowly uniting to form the Apennines and the Italian peninsula. The complexity of the folds and the faulted and contorted strata out of which these masses are built, taken in conjunction with the step-like arrangement of sea beaches and terraces, suggest the idea that processes of elevation are intermittent. As these mountains were slowly growing, relatively to the Earth's centre, certain tracts of the rocky crust would rise, others would fall, and there would be a universal contraction in oceanic areas.

With a ratio of land and water areas in early Tertiary times of 1 : 4, and a mean height of the mountains then elevated of 4000 feet, which is the present mean height of Switzerland, the vertical fall in ocean-level would be about 26 feet. This calculation of the fall in the waters

does not include that which would accompany the rise of the extended fold or dome on which the mountains stand, and the figure given is therefore probably much below the truth. The meaning of this retreat of the waters in relation to the history of oceanography is, that at the times when mountains were formed, an intermittent withdrawal of waters, which would be marked on shallow coasts, took place throughout the world, and extensive tracts would be bared, not by the rising of the land, but by the falling of the waters.

Although mountain ranges might, as they rose upwards, increase their distance from the Earth's centre, flanking regions, by approaching this centre at a greater rate than that at which the waters were falling, might be submerged. Accepting the idea of rapid sedimentation at certain points along these intermittently sinking coast-lines, and we have conditions for the accumulation of a series of strata such as are found in many coal-fields, and it is certainly remarkable that these two periods of mountain growth were closely coincident with two great periods of coal-formation. If we do not accept this suggested connection between mountain growth and the deposition of strata accompanying the occurrence of the formation of coal, not only have we to fall back upon the usual explanation that the coal-measures were formed when there was a nicely adjusted balance between the rate at which an area was depressed and the rate at which the same was rising by sedimentation, but we are left to explain why such an adjustment was only marked at two particular epochs in the Earth's history, and why it simultaneously occurred at so many points upon the surface of the globe, which, for carboniferous coal at least, lie between 20° and 60° N. lat. and 20° and 40° S. lat., in regions of bradyseismical action.

Although a relationship might be traced between pronounced secular movements, volcanic action, and other geological phenomena, the main object of the present section of these notes is to show that, although we may take sea-level as a datum relatively to which changes taking place within the historical period may be approximately measured, directly we attempt to measure the magnitude of upheavals with which the geologist has to deal, unless we make our datum at the Earth's centre, or at some fixed distance from the same, it seems possible that some of our results may exceed the truth by 25 per cent.

In Japan, as in many other countries, notably perhaps Italy, bradyseismical movements have, during historical times, taken place with great rapidity. With the assistance of Prof. D. Kikuchi, of the Imperial University of Japan, a few years ago, circulars were sent to officials at all the important seaports and villages round the coast, asking them to collect evidences whether, during recent times or within the memory of the oldest inhabitants, any changes had taken place in the relative positions of the sea or land. The replies, which were numerous, showed that, along the eastern side of the country in

particular, elevation had been in progress, this being particularly noticeable in districts where earthquakes were frequent.

Information gathered in this manner, taken in conjunction with the writer's repeated observations on sea-terraces, shell-borings in rocks well above high-water mark, and other appearances, it may be concluded that movements along certain portions of the Japanese coast have been exceedingly rapid—possibly an inch per year. At one point, where soft tuff rock projects into Yedo bay beneath the bluff at Yokohama, lines of shell-borings can be seen fully 10 feet above high-water mark. Because the rock is so friable and soft, it is difficult to suppose that these markings have been exposed to atmospheric influences for a length of time very much greater than fifty years. Be this as it may, the writer well remembers that nineteen years ago it was impossible to pass round a neighbouring point of similar rock, whilst now at low water it may be walked round, not over drift or shingle, but over a rocky surface. There are no reasons for supposing that these changes in the relative positions of land and water on the coast of Japan which are here referred to, have taken place suddenly. It must, therefore, be supposed that they have either been brought about by the gradual elevation of the land, or by the gradual withdrawal of the water. The Japan current, or Kuro Siwo, which flows up the eastern coast of Japan, and which is comparable with the Gulf Stream in the Atlantic, has, like other oceanic circulating systems, marked seasonal changes in its velocity, and the distance to which it is appreciable.

Although we have no definite data respecting the greater changes which may take place in the magnitude and velocity of ocean currents, owing to gradual but periodic changes in climatic conditions, possibly culminating in periods of glaciation, it is highly probable that such changes have an existence, and if they do exist, it is difficult to suppose that they have been unaccompanied by alterations in the general level of the oceans, and to some degree in variations in the amount of water held back in bays and estuaries, especially those which have narrow entrances.

Notwithstanding these considerations, the occurrence of earthquakes, the crumpled rocks intersected by numerous faults, and other phenomena, incline us to the belief that the eastern coast of Japan is growing in consequence of the movements of the rocky crust rather than by a recession of the waters.

Whether the measurement of these movements which bring about such rapid changes are phenomena of sufficient importance to attract the attention of harbour and other engineers, is a question that cannot be answered until they have been more accurately determined. The importance of forming a trustworthy estimate of the rate at which the larger folds of the Earth's surface have been formed, or by which mountains may be increased or decreased in height, is evident to all students of Earth physics.

The only experimental determinations of these changes are the well-known measurements which were made between marks cut upon certain rocks and sea-level in Sweden. The method, although apparently certain, has its objections. The fact that differences in level can only be observed after long intervals of time is in itself an objection, while the fact that during such intervals, by variations in ocean currents, by sedimentation, elevation or depression at the entrance to a closed sea, like the Baltic, along the shores of which the marks referred to were made, the play of the tides, relative to a phase of which the measurements must be taken, may have suffered alteration.

Results might possibly be obtained in a quicker and more certain manner by differential measurements of the records of three or more tide-gauges referred to neighbouring bench-marks. In a nearly closed bay, like that of Yedo, where the tide is small, it would be possible to choose times when tides had similar phases, and when we could assure ourselves that the surface of the water had the same configuration. Taking observations made at these times, although total rise relatively to a certain phase of tide may be measured, the chief determination would be the relative rising or falling of one point of land as compared with another, together with the axis of such a movement.

Several other methods of obtaining similar results suggest themselves, the simplest of all being the installation underground of several levels parallel and at right angles to the dip of strata. Under these conditions, where changes of temperature would be inappreciable, and where readings would only be required at long intervals, the ordinary spirit-level would be sufficient for the suggested purpose, but, to avoid effects due to the creeping of the soil, the levels should be placed upon the solid rock. With such an installation in Japan, where we know that movements are taking place with comparative rapidity, it is not unlikely that definite measurements of tilting could be obtained in a very few years.

From the observations of levels placed in a cellar, Plantamour has shown that there are long period displacements in the position of their bubbles. Astronomers observe slow changes taking place in solid masonry piers which carry telescopes, and von Rebeur-Paschwitz has recorded the wandering of the zero-point of his horizontal pendulums. In Japan it has been observed that two of these latter instruments, placed 1000 feet apart, have synchronized in the directions of their displacements, slowly creeping for ten or many more days in one direction, and then returning to travel past their starting-point in an opposite direction. Although these instruments may only show changes of 1 or 2 inches of elevation per mile, it is premature to assume that what has been recorded is due to secular changes in the inclination of the Earth's crust. Movements of this nature may be due to the gradual creeping of a layer of soil upon a slope, to the differential loading or removal of moisture on two sides of an observing-station, and possibly to other causes.

Therefore, until levels or horizontal pendulums have been established in duplicate in the suggested manner upon rock, we shall be unable to say that secular movement has been instrumentally measured or recorded.

EARTHQUAKES.

To pass from movements which are accomplished so gently and so slowly that they are neither felt nor seen, to violent disturbances called earthquakes, which in a few seconds may alter the superficial aspect of a country, although the transition is rapid, it is one that is natural.

The greater number of earthquakes may be regarded as announcements that a resistance to secular movement has been overcome, and if such an explanation of earthquake origin is sufficient, then the relationship of the former to the latter is that of a child to its parent. Wherever we find mountains which are geologically young, where the process of rock-folding may yet be in progress, there we find earthquakes. Should these regions of rock-movement be near a sea or ocean, we also find volcanoes. Volcanic eruptions accompany the generation of steam and gaseous pressure beneath lines of yielding; while earthquakes, if we except a few explosive efforts at volcanic foci, tell us that rocky strata, bending under the influence of terrestrial contraction, have exceeded their elastic limit. Although both may occur in the same country, it is seldom that their origins are close together. In Japan it is seen that active volcanic vents chiefly occur along the backbone of the country which forms the upper edge of a huge monocline, whilst the earthquakes are most frequent on the flanks of this fold, or where it sweeps steeply downwards beneath the deep Pacific. The home of the majority of earthquakes is that of the majority of faults, which is a region of monoclinal folding. That a volcano by its eruption acts as a safety-valve for the surrounding district, does not seem to be borne out by observation. Earthquakes and volcanoes are independent, excepting in their parentage, and if between them there is a closer union, we should expect that a relief of pressure following an eruption would result in farther bending of the strata, and an increase in seismic frequency. If it is, therefore, admitted that the majority of earthquakes are the result of fracture resulting from excessive bending, rather than attempting to predict their occurrence by our sensations, the behaviour of lower animals, or the assumption of tides acting on lines of weakness beneath a hardened crust, a more reasonable method of procedure would be to determine whether the earthquakes of a given district are preceded by measurable changes in inclination of the yielding surface. During the last few years of the writer's residence in Japan, with the aid of delicately adjusted horizontal pendulums, some attempt was made towards the solution of such a problem. The results showed that in a number of instances there was an indication of a connection between a uniform and steady change in level and the occurrence of many disturbances.

Because the observations were incomplete, and because there were difficulties in separating earthquakes of a local origin from those which had originated at a distance, the definite solution of this problem remains for future investigations.

From the records obtained in Japan from nearly one thousand observing-stations, we learn that during a period of eight years about nine thousand distinct shocks were recorded, and for each of these the approximate origin and the area that was sensibly shaken have been determined. The analysis of a catalogue of these disturbances shows that Japan may be divided into at least fifteen distinct seismic districts, the records from each of which may be examined separately, the different shocks being taken as numerically equal or have values given to them bearing a relationship to the area which each disturbed. The records from each of these districts give relative measures of the rate at which rock-folding is in progress in such districts, and we are enabled to examine how far these changes are influenced by tidal loads, variations in barometrical pressure, and other phenomena exogenous to the crust of our Earth.

From the study of a series of *after-shocks* which have followed several large disturbances, Mr. Ōmori has shown that, in particular cases considered, the rate at which the broken-up strata settled to a state of equilibrium practically followed the same law, from which it may be concluded that the character of the disjointed materials had been on the average fairly similar. One result of these investigations is that, having observed for a month or so the number of *after-shocks* occurring in a given district, and in this way determined the first part of a curve of frequency, this curve may be completed, and from it we can see how many shocks we may expect in a given number of months, or how many years it will be before the district has returned to its normal state of seismic sensibility.

If we take the records *en bloc*, the only advantage which the Japanese catalogue of earthquakes presents over other lists is its completeness, and the fact that the different records can have "weights" assigned to them. By examining these records, we find that for Japan, as for other countries and for the earthquakes of the world, there is an annual and semi-annual periodicity, the former of which, as Dr. C. G. Knott and Mr. C. Davison point out, may be the result of differences in barometrical stress at two seasons of the year.

For very many of the shocks recorded in Japan, seismographs, writing on stationary or moving surfaces, have given diagrams from which we learn how many vibrations have constituted a given disturbance, the rapidity with which they have occurred, and the extent and direction of each successive movement. The study of these diagrams has led to the conclusion that earthquake-motion, which may be *felt* for periods varying between a few seconds and several minutes, is of

different types, and that each type has a signification. If, for example, we feel a long, easy, rolling motion, at which time the diagram is that of a series of slowly recurring waves, the inference is that the origin of the disturbance causing this movement is at a considerable distance. If, however, an earthquake commences with a series of small but rapid vibrations, followed by a shock or shocks, and irregular sharp motions which die away gradually, then the origin is near, and it appears that the difference in time between the commencement of the tremors and occurrence of the first decided motion is proportional to the distance of the origin from the observing station. The interval of time between the commencement of preliminary tremors and the more violent movements, as shown by an ordinary seismograph, when the distance between the observing-station and the origin of the disturbance is not more than 200 miles, seldom exceeds ten seconds; but if the movement has been propagated to a very long distance, the interval may be many minutes. Should, for example, an earthquake originating in Japan be sufficiently intense that, by means of specially contrived instruments of great sensibility to elastic vibrations and angular displacement, its movements can be recorded at places distant one quarter or more of the Earth's circumference, then it is seen that the tremors appear upon the diagram half an hour before the maximum phases of motion. These latter motions are propagated to these distant places at a rate of two or three kilometres per second, or at about the same rate as they are propagated to places relatively close to an origin. The former, however, assuming that they actually originated at the same time from the same origin as their larger followers, have been transmitted at rates three or four times as quickly, and it becomes difficult to suppose that they have passed through the heterogeneous materials constituting the Earth's crust. To make careful observations on the rate of propagation of these tremors, and to determine the paths they have followed, are two of the most important problems which the seismologist is now asked to solve. Their velocity is somewhat reduced if it is assumed that, instead of passing round our Earth, they pass in straight or curvilinear lines *through* the same; but even with this assumption, we find that the rate of transmission has been greater than it would be had our globe the same constitution as glass or steel.

Our knowledge of the interior of the Earth is at present chiefly based upon the revelations of the thermometer and the plumb-line. Whatever information these may have given us, it does not seem improbable that after a seismic survey has been established for our world, the records of seismographs may add definite information about the effective rigidity of our planet, which, from the little that has already been accomplished, seems to be very much higher than has usually been supposed.

Although many of the investigations relating to earthquakes have apparently only yielded results of value to those engaged in researches

of a purely scientific nature, yet a certain number of them have led to results of practical utility.

From the diagrams of earthquakes, the maximum velocity of a particle and the acceleration or suddenness of motions which are the destructive elements of earthquake movement resulting in projection, overturning, and shattering, have been calculated. That these quantities are real has been verified by numerous experiments, in which columns of brickwork and other bodies have been moved back and forth by a recorded motion, until, by the reaction of their own inertia, they have either been fractured or overturned. The result of these experiments and observations in the field has established the truth of calculations based upon diagrams, and if, after a destructive earthquake, we determine the amount of motion that has been experienced, either from the dimensions and nature of bodies which have been overturned, or from the records obtained from seismographs, we arrive at what are practically identical results. In the great earthquake which, on October 26, 1891, devastated Central Japan, at which time nearly ten thousand people lost their lives, the greatest accelerations recorded varied between 3000 and 4000 millimetres per second per second. Earthquakes which shatter chimneys, partially unroof houses, cause plaster to fall, and which give to an ordinarily built town the appearance that it might present after a bombardment, have a suddenness in their back and forth motions of about one-tenth of the above quantities. From these and other measurements, an engineer, having assumed that a certain quantity of motion may be expected, is now in a position not simply to make a structure strong because an earthquake is strong, but he is able to proportion and distribute his materials to exactly fulfil certain possible conditions. For example, in the building of piers to carry a railway bridge, we know from experience that, when they are sufficiently shaken, fracture first takes place at their base. This form of destruction is identical with that which occurs when a column of brickwork is placed upon a truck which can be moved back and forth at a continually increasing rate. At the same time it is in accordance with what we should expect, which expectations are borne out by the results of theoretical investigations. From observations and considerations like these, we see that walls, columns, and structures like piers and chimneys, require greater dimensions or strength near their base than those given to them in ordinary practice. Forms having equal strength at all their horizontal sections against the effects of horizontally applied motion have been designed; and in Japan, as illustration of these, we have the parabolic brick piers, some of which are 110 feet in height, designed by Mr. C. A. W. Pownall, M.INST.C.E., to carry the Usui railway.

One remarkable observation which seismographic records have confirmed and measured is the fact that, outside an epifocal area, earthquake waves like those of the ocean are somewhat greater on the surface than

they are at a comparatively small depth. The inference from this is, that a building rising from a basement 10 or 20 feet in depth, surrounded by an open area, will receive less motion than a building rising from the surface. Many large and important structures in Japan have therefore been built to rise freely from moderately deep foundations, and on more than one occasion it has been observed that they have not in the slightest degree suffered, whilst their near neighbours have been so far shattered that in certain instances they have required rebuilding.

These are by no means the only beneficial results which have followed seismic investigations. Rules have been formulated for the guidance of an engineer when selecting a site. The unadvisability of having undue top weight, or connecting together structures having differences in their natural periods of vibration, and many other principles to guide the practical builder, have been demonstrated, and it is pleasing to record the fact that the demonstrations have not been altogether unheeded, with the result that, in Japan at least, the security of life and property is greater than it was in former years. Seismometry has directly led to the construction of instruments which faithfully record the jolts and vibrations of railway trains, which show the magnitude and position of irregularities along a line. Modified forms of these contrivances give faithful representations of the jerking due to the want of balance in a locomotive, by correcting which the Imperial Government railways of Japan effect a considerable saving in fuel and repairs. Other instruments, also claiming the seismograph with its steady points as parent, are able to record the peculiar earthquake-like vibrations of bridges and the elastic movements of buildings and steamships.

Although seismology owes its present position to individual efforts made in many countries, standing foremost amongst which are the remarkable results achieved by the late Dr. E. von Rebeur-Paschwitz, a great impetus was given to this study by the establishment of the Seismological Society of Japan, which, during its short existence of hardly fifteen years, issued twenty volumes of original papers. The result obtained by this body of Japanese and European workers acted as an incentive to further investigations in many directions. In Europe seismographs took the place of seismoscopes, whilst the Imperial Government of Japan established a special bureau, which now controls nearly one thousand stations for the purpose of earthquake investigation, and endowed a chair of seismology at its university.

DIURNAL WAVES.

From movements the cause of which are to be sought in the crust of the Earth, we pass to others which are apparently more ubiquitous, and owe their existence to phenomena connected with our atmosphere.

In Germany and Teneriffe, diurnal waves have been recorded and

carefully analyzed by the late Dr. E. von Rebeur-Paschwitz. In Japan, photographic records of these displacements have been obtained at many stations.

The most pronounced movements correspond to a slow tilting of the instruments for ten or twelve hours towards the east, followed by a retrograde motion towards the west. Accompanying this there is a north and south component of motion, which is definite but relatively small.

Von Rebeur found, after a careful analysis of his records, that whatever may have been the chief cause of these displacements, which amount to three or four seconds of arc, but at certain stations in Japan to several times this amount, a slight superimposed lunar effect may be detected.

The records of these movements, like those of tremors and unfelt earthquakes, are obtained by continuously photographing on a moving film the varying position of a horizontal pendulum. When the pendulum remains at rest the diagram is a straight line, but if, during a period of twenty-four hours, it wanders slowly to the right and then back to the left of its normal position, the photogram is a wave-like curve, the amplitude of which varies according to the sensibility of the instrument and the locality where it is installed, from 1 or 2 up to 20 millimetres. In Japan, the localities where pendulums were installed were selected for the purpose of studying these movements under varying conditions. Five sets of diagrams were obtained from instruments placed upon the solid rock in caves, where the daily change in temperature and hygrometric conditions was barely appreciable. At these stations it was observed that the movements due to earthquakes were most pronounced in a direction parallel to the dip, suggesting the idea that this direction is that of least resistance, parallel to which there is a concertina-like yielding in the folded strata. Together with the displacements due to the diurnal wave, the pendulums showed that they slowly wandered, moving several days in one direction, and then returning towards their starting-point. Tremors and daily waves were not visible. Had the sensibility of the pendulums, which, in the experiments in Japan, never exceeded a displacement on the film of 1 millimetre for an angular tilting of $0.1''$, been greater, it is possible that the latter phenomena might have been observed. In Europe similar or corresponding instruments have had sensibilities given to them of $0.01''$ to $0.003''$. The latter degree of sensibility means that changes in inclination of 1 inch in about 1000 miles would be measurable.

Another station was in an underground chamber in the alluvium, where the daily changes in temperature, as in the caves, was extremely small, but where, in consequence of fairly good ventilation, there may have been considerable changes in hygrometric conditions. The depth of this chamber was 12 feet. The records showed wandering of the

pendulums, tremors, and daily waves, all of which were at times quite as pronounced as they were at stations on the surface.

These latter records lead us to the conclusion that diurnal waves are not to be attributed to the immediate effects of any change in temperature close to the instruments.

The remaining stations, where the instruments stood on brick columns with concrete beds, were on the alluvium, which near Tokio forms a layer of reddish stiff soil 50 to 100 feet in thickness, above a soft grey clay-like tuff rock. A locality at which the diurnal wave was hardly appreciable was in a wood. At this place there were high trees for some distance all round the hut in which the pendulum was placed, which protected it from the direct effects of the sun. On an open plain, where on one side of the station there was ploughed ground and on the others green corn, the movements were slight but fairly regular. They apparently indicated that during each day the ground covered with corn rose relatively to that which was bare. At all the other stations where the ground was covered with trees or buildings more upon one side than upon the other, the daily waves were large, and often differed in phase. For example, on two plateaux on the two sides of an open swampy valley, the instrument on one side of this having a protected area on its east side, and those on the other side a somewhat similar area on the west, moved at the same time in opposite directions—that is to say, if the trees on these two opposite scarps followed the movements of the instruments, it may be concluded that on each fine day they bowed towards each other.

A very important observation made at many stations was that *on wet and cloudy days diurnal waves were absent*.

The general conclusions to which the various observations point, is that the movements which take place during the day are due to the removal of a load from the side of the station most exposed to the effects of radiation, and in the alluvium this effect is quite pronounced to a depth of at least 12 feet. This load may be represented by aqueous vapour carried upwards and then dissipated.

On a fine day experiment shows that from moist open ground as much as one ton of moisture may be removed from an area 20 yards square. If an action of this sort is more marked upon one side of an instrument than upon another, then the ground by its resilience rises on the former side, and the pendulum swings away from the area which has been most relieved. In a similar manner, a load composed of men and boys marched up to one side of the station causes the ground on that side to sink, and the movement of the pendulum is towards the loaded side; when they retire, the pendulum returns to its normal position. For reasons like these, the instruments on the two opposite plateaux during the day move in opposite directions, or away from the intervening open valley, where unloading is most marked; while an

instrument on uniformly exposed ground or in a wood shows but little or no motion. That there is little or no motion during rainy or cloudy weather, is evidently due to the fact that at such times there is but little evaporation.

A desirable experiment would be to record the movements of a horizontal pendulum on a uniform and equally exposed prairie-like plain. In this case, because during the morning the sun would take away more moisture from the east than from the west side of the pendulum, until noon or about two in the afternoon, we should expect to find the motion westwards. After a pause, some time in the afternoon, a retrograde movement would set in and continue until some time after sunset, but both movements would be small.

From this we see that a pendulum which has been moving westwards may have the direction of its motion reversed; but the difficulty which presents itself is to explain the manner in which this retrograde motion, having been established, continues during the night, until it nearly returns to the position it had on the previous morning. The explanation of this phenomenon apparently rests on the fact that during the night the area which during the day has lost the greatest load may be the one which gains the greatest load. The establishment of this suggestion depends upon facts and experiments relating to the precipitation and condensation of aqueous vapour. On open ground where radiation is marked, there is a greater precipitation of moisture in the form of dew than there is upon ground which is protected by trees, buildings, or other coverings. The quantity of moisture which is in this way drawn from the atmosphere, or, as Aitken has shown, is trapped just as it rises from the ground, is however small, and cannot be taken as more than one-eighth of that which during the day has been moved by evaporation. Although it may assist in causing the reloading for which we seek, by itself it is insufficient to explain all that is observed; and, further, the retrograde motion of a pendulum may have taken place on nights when dew is not observable. On such occasions, however, a differential loading of two neighbouring areas may have been brought about either by the condensation of moisture on the immediate surface of the ground, beneath leaves and stones, or actually beneath but near to the surface.

If we look beneath a board which has been lying all night upon the grass, it does not unfrequently happen that its under side is wet with moisture, although the grass around may be dry. This observation suggested the idea that just as moisture is condensed beneath a board, a leaf, or a stone, so it may be condensed *in* the ground, within one or two inches of the actual surface. On a hot day moisture is evaporated from soil, and this is perceptibly heated to a depth of about a foot. Shortly after sunset the surface to a depth of one or two inches is chilled, or in winter it may be frozen. The result of this is that

moisture rising as vapour, and by capillarity from water-bearing strata below, is condensed on the under side of the chilled surface. To determine how far superficial soils gain in weight by an action of this description, independently of moisture precipitated from the atmosphere, or condensed as it rises from the ground, the following experiments were made.

Two boxes, each 1 foot 6 inches square, and about 2 inches in depth, were balanced on the extremities of beams carried upon knife-edges. One box had a bottom made of tin, and the other of fine wire netting, and each was filled with earth. Excepting when these were weighed by hanging weights at the other extremities of the beams, they were allowed to rest upon a bed of soft earth. Sometimes it was found that during a night both of the boxes would lose weight, but at other times it was found that the weight of the box with the tin bottom had not changed, whilst the one with the wire netting had gained from 2 to 2·5 ounces, which apparently showed that there had been a condensation of moisture coming up from beneath of 10 ounces per square yard, or about one-eighth of that which had been removed during the day by evaporation.*

Although the retrograde motion of a pendulum during the night is usually less than that which had taken place during the day, thereby causing a creeping of the zero point away from an area of rapid evaporation, the question is whether the precipitation and the forms of condensation which take place between sunset and sunrise are sufficient to produce the observed effects. Our data respecting sub-surface condensation are unfortunately confined to the few observations made by the writer, and many observations have yet to be made before its quantitative analysis has been completed. The greatest effect would be produced when each of these forms of condensation was at a maximum and acted in conjunction.

The difference in the weight of moisture evaporated from two neighbouring areas is apparently sufficient to cause the movements observed during the daytime, whilst the difference in the weights added to such areas from a water-supply common to each, is a phenomenon which may influence the movements observed at night.

These explanations, although they may be sufficient to account for many of the movements observed in Japan, because instances occur where their application is not clear, until they have received more careful attention, can only be received as provisional. At Potsdam, for example,

* In consequence of a fire which occurred at the writer's house, not only were the notes relating to these experiments destroyed, but the experiments themselves had to be terminated. Sub-surface precipitation is evidently closely related to a fact noticed by farmers upon the chalk downs in the Isle of Wight, who find that if the ground is cleared of flints, which means the depriving it of its radiators and condensers, its fertility is impaired.

where Dr. E. von Rebeur-Paschwitz tells me that the ground is equally covered with trees towards the east and west, the motions are quite pronounced, and the same authority has observed extraordinarily large motions on a strongly founded pillar, when there was apparently no motion in its neighbourhood.

An experiment which has yet to be made is to place an instrument upon a pillar, the two sides of which are unequally porous, with the object of determining whether any of the observed movements, especially tremors, which are described in the next section, can be traced to changes taking place in the supporting column.

NOTE.—From the researches of S. H. Miller, F.R.A.S. (Prize Essay on *Evaporation*, published by the Utrecht Society of Arts and Sciences, 1878), it would appear that the average daily quantities of evaporation for *particular* months are approximately as follows :—

Soil (humus; July)	4,243 lbs. per sq. yd.
Water (July, 1869)	8,613 " "
Forest (a spruce)	12,528 " "
Grass (red clover; May)	15,613 " "

These loads, which are removed during twelve hours of daylight, may be either greater or less than the quantities given. They are practically in the ratio of 1 : 2 : 3 : 4.

The greatest daylight displacement of a horizontal pendulum ought, therefore, to be expected when such an instrument was placed on the boundaries of two areas respectively covered with soil and grass. On a fine day the differential evaporation effect on the two sides of the instrument would be equivalent to removing a load of about $2\frac{1}{2}$ tons per 20 yards square from the ground covered with grass, which is quite sufficient to produce many of the observed effects.

EARTH-TREMORS.

The last class of earth-movements to which we have to refer are even more perplexing, and more frequently observed than the diurnal waves.

These are the earth-tremors, earth-pulsations, or microseismic motions, which were first systematically observed by Father Timoteo Bertelli of Florence. The method that Bertelli adopted prior to 1870—which was to observe, by means of a microscope, the movements of the style of a pendulum carefully sheltered from air-currents—is practically identical with the methods yet employed at very many stations throughout the Italian peninsula.

Amongst the more important results obtained by these observers, and confirmed by observations made in other countries, is that tremors were more frequent in winter than in summer, and when the barometer is low rather than when it is high.

In Japan during the last nineteen years these movements have been

studied by the use of a large variety of instruments, whilst for some years past the records have, by photographic or other means, been made continuous.

The analyses of a long series of these latter records have shown that tremors were usually at a maximum when the barometric gradient was steep, no matter whether, at the place where they were observed, the barometer was high or whether it was low. From this it may be concluded that when tremors are pronounced, somewhere or other, either at or within 100 or 200 miles distant from the point of observation, a strong wind may be blowing. This conclusion, which has been verified by an appeal to weather charts, led the writer at one time to regard local or distant winds as the immediate cause of microseismic storms. Although the mechanical action of wind upon buildings, trees, and the surface of the country may produce slight tremors and influence the character of a record, the fact that tremors are sometimes observed at the time of a dead calm around the station, and that they may not be visible when the building in which the instrument which renders them visible is being violently shaken during a heavy storm, has led observers to think that tremors are not the immediate effects of wind. The reason for the existence of tremors was next sought for in fluctuations in barometric pressure. During a typhoon the needle of an aneroid may be observed to pulsate back and forth, whilst the slow change in pressure over an area may, as von Rebeur has shown, produce sufficient alteration in level to be recorded by movements of a horizontal pendulum. When barometrical pressure is changing rapidly over a district, the parts of which offer different degrees of resistance to distortional effects due to varying pressure, the inference is, that such a district might be thrown into a state of irregular agitation sufficiently pronounced to cause the movements called tremors. Although tremors may perhaps be induced by causes such as these, and therefore be really the result of actual movement of the ground, a close inspection of photographs, and a knowledge of the localities where they were obtained and the character of the instrument which yielded the records, give rise to a suspicion that some of these intruders, which may mask effects due to distant earthquakes, and interfere with many delicate physical operations, are, in some cases at least, the result of movements of the atmosphere.

The instruments in the caves, where it was uniformly damp, and many of those situated in huts upon the surface, where the ventilation was so good that it was difficult to understand why the long booms of the horizontal pendulum had not been set in motion by currents of air, either never showed a trace of these movements, or, if they were shown, they were insignificantly small. With other instruments, some of which were well protected inside substantial buildings, and the possibility of their being affected by currents of air from the outside was

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inconceivable, day after day tremors were pronounced. The difference between these two sets of installations was, that the pendulums showing tremors were either longer in proportion to their weight, or actually very much lighter than those which remained steady; and experiments showed that the smaller and lighter a pendulum was, the more closely it approached in character to the imaginary instrument endowed with perpetual motion. The conclusion derived from this observation was, that the so-called Earth-tremors might in some way or other be due to air-currents produced within the containing cases; but there was nothing making it likely that such currents were due to any marked difference in temperature between the parts of an instrument and its enclosing walls.

An experiment which tended to confirm this view was to place a tray of calcium chloride inside the case containing a horizontal pendulum, when it was observed that the pendulum commenced to swing. The meaning of this is that air-currents are produced by rapid desiccation, which is a cause of atmospheric circulation, which has a wide application, but which is seldom emphasized.

Assuming this explanation for the origin of *certain* so-called Earth-tremors to be correct, great difficulties occur when we attempt to explain the peculiarities they exhibit in the times of their occurrence.

If a tremor-storm extends for several days, it is noticed that maxima of movement occur during the night, or from 9 p.m. until 6 a.m. As the disturbance dies out, tremors will only be observed at these hours, until finally the disturbance will end with a little movement about 6 a.m. Some instruments have only shown movements about daybreak, whilst one showing a maximum motion about this time was always on the swing at night (Fig. 9). It will be observed, therefore, that tremors are frequent during the time that the portion of the diurnal wave is most gentle, and that the maximum of tremors occurs about the time when the reversal in the direction of the diurnal swing of a pendulum takes place. Although experiment has shown that the appearance of tremors can be produced by the removal of a heavy load at the distance of 100 feet from a pendulum, at which time it slowly heels over towards the relieved area, because they are often frequent when no daily wave is observable, it does not seem likely that there is any direct connection between these two phenomena.

The conclusion at which we therefore arrive is, that during the night, and especially about daybreak, in consequence of the absorption or giving-off of moisture within more or less closed cases, and possibly to a greater extent outside them, air-currents are produced which are sufficient to move light pendulums, and that some of these movements have been supposed to be caused by an actual movement of the ground.

By no means can all tremors be explained in this simple manner. For example, the horizontal pendulum, now working at Shide, which is

usually adjusted to have a period of seventeen seconds, often shows tremors extending over many hours, which have periods of from one to three minutes. It may be possible that air-currents have produced these movements, the character of which indicates a slow tilting of the instrument; but it seems unlikely, especially when it is seen that for several hours there has been no variation in the period or amplitude of the displacements (Fig. 7). The bulk of tremors seem to have their origin in causes which are meteorological; but we are yet waiting for a more complete explanation of the manner in which they originate.

Although we see in diurnal waves and tremors the results of meteorological phenomena which affect agriculture and forestry, the movements they represent usually present themselves as intruders which have not simply interfered with, but which have hopelessly destroyed certain physical operations.

Tremors brought investigations relating to lunar gravitation at Cambridge to an end; tremors may have been the cause of unsteadiness of images from long focal lenses, rendering accurate astronomical photography uncertain. Times have occurred, when making determinations of standard weights, that balances have been unsteady; and the writer has repeatedly observed delicate forms of these instruments, used in assay work, on the swing and often changing their zero-point. How far tremors may have accelerated or retarded the swing of pendulums in gravitational observations, we do not know. What we immediately wish to do in regard to tremors and diurnal waves is to find means to isolate ourselves from, or at least to minimize, their effects. We can entrench ourselves against the mechanical vibrations of a passing train by means of trenches, and the surveyor in a city can isolate his instrument against the same intruders by a suspension of rubber bands.

How far the study of the tremors which have here been described will enable us to avoid their effects or to destroy them, or to what extent a closer examination of these ill-understood phenomena will prove beneficial, are matters only to be decided after further investigation.

Before the reading of the paper, the PRESIDENT made the following remarks: The paper this evening, which we may expect to be of an extremely interesting and novel character, is by Professor Milne, on the movements of the Earth's crust. I will now call upon Professor Milne to read his paper.

After the reading of the paper, the following discussion took place:—

Sir ARCHIBALD GEIKIE: I think the Geographical Society is to be congratulated on having had from our great authority on earthquakes so luminous and so humorous a description of the subject as he has given to-night. I don't know whether it is a fortunate thing to live in an earthquake country, but Professor Milne's residence of many years in Japan has given him experience of more earthquakes than any other man of science in the world has had, and he has certainly devoted more time to the study of them. But not only has he given attention to

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