section i., and part vii.). He perceives that the present area of land on the earth's surface is the result of the balance of two antagonistic processes—the destruction caused by superficial agents on every portion of land exposed to their influence, and the periodic elevation, by subterranean action, of the land so wasted, or of new land from beneath the sea.

5. *Distribution of Animal and Vegetable Life.*—It is usual to include in treatises on physical geography an outline of the distribution of plants and animals, with an account of the great regions or provinces into which zoologists and botanists have divided the continents. The question naturally arises why the distribution should be as it is. Two answers obviously suggest themselves—1st, climate, and 2d, the power possessed by plants and animals of diffusing themselves. Yet climate only explains a part of this problem, and it is evident that migration cannot possibly account for the diffusion of innumerable organisms. There is a large residuum of unexplained phenomena on which much light is thrown by geological inquiry. Thus, for example, the presence of living Arctic forms of vegetation on the mountains of central Europe can be connected with the occurrence of the remains of Arctic animals in the superficial deposits of that region, and with other facts which make it clear that at no very distant date an Arctic climate prevailed over most of Europe, that at that time a northern vegetation spread southwards and covered the plains and heights of Europe even as far south as the Alps and Pyrenees, and that as the climate gradually ameliorated the northern vegetation was extirpated from the low grounds by the advance of plants better suited to the milder temperature, but continued to maintain its ground amid the congenial frosts and snows of the mountains, where to this day it still flourishes (see DISTRIBUTION). (A. GE.)

GEOLOGY

GEOLOGY is the science which investigates the history of the earth. Its object is to trace the progress of our planet from the earliest beginnings of its separate existence, through its various stages of growth, down to the present condition of things. It seeks to determine the manner in which the evolution of the earth's great surface features has been effected. It unravels the complicated processes by which each continent has been built up. It follows, even into detail, the varied sculpture of mountain and valley, crag and ravine. Nor does it confine itself merely to changes in the inorganic world. Geology shows that the present races of plants and animals are the descendants of other and very different races which once peopled the earth. It teaches that there has been a progress of the inhabitants, as well as one of the globe on which they dwelt; that each successive period in the earth's history, since the introduction of living things, has been marked by characteristic types of the animal and vegetable kingdoms; and that, however imperfectly they have been preserved or may be deciphered, materials exist for a history of life upon the planet. The geographical distribution of existing faunas and floras is often made clear and intelligible by geological evidence; and in the same way light is thrown upon some of the remoter phases in the history of man himself. A subject so comprehensive as this must require a wide and varied basis of evidence. It is one of the characteristics of geology to gather evidence from sources which at first sight seem far removed from its scope, and to seek aid from almost every other leading branch of science. Thus, in dealing with the earliest conditions of the planet, the geologist must fully avail himself of the labours of the astronomer. Whatever is ascertainable by telescope, spectroscope, or chemical analysis, regarding the constitution of other heavenly bodies, has a geological bearing. The experiments of the physicist, undertaken to determine conditions of matter and of energy, may sometimes be taken as the starting-points of geological investigation. The work of the chemical laboratory forms the foundation of a vast and increasing mass of geological inquiry. To the botanist, the zoologist, even to the unscientific, if observant, traveller by land or sea, the geologist turns for information and assistance.

But while thus culling freely from the dominions of other sciences, geology claims as its peculiar territory the rocky framework of the globe. In the materials composing that framework, their composition and arrangement, the processes of their formation, the changes which they have undergone, and the terrestrial revolutions to which they bear witness, lie the main data of geological history. It is the task of the geologist to group these elements in such a way that they may be made to yield up their evidence as to the march of events in the evolution of the planet. He finds that they have in large measure arranged themselves in chronological sequence,—the oldest lying at the bottom and the newest at the top. Relics of an ancient sea-floor are overlaid by traces of a vanished land-surface; these are in turn covered by the deposits of a former lake, above which once more appear proofs of the return of the sea. Among these rocky records lie the lavas and ashes of long-extinct volcanoes. The ripple left upon the shore, the cracks formed by the sun's heat upon the muddy bottom of a dried-up pool, the very imprint of the drops of a passing rain-shower, have all been accurately preserved, and yield their evidence as to geographical conditions widely different from those which exist where such markings are now found.

But it is mainly by the remains of plants and animals imbedded in the rocks that the geologist is guided in unravelling the chronological succession of geological changes. He has found that a certain order of appearance characterizes these organic remains, that each great group of rocks is marked by its own special types of life, and that these types can be recognized, and the rocks in which they occur can be correlated even in distant countries, and where no other means of comparison would be possible. At one moment he has to deal with the bones of some large mammal scattered through a deposit of superficial gravel, at another time with the minute foraminifers and ostracods of an upraised sea-bottom. Corals and crinoids crowded and crushed into a massive limestone where they lived and died, ferns and terrestrial plants matted together into a bed of coal where they originally grew, the scattered shells of a submarine sand-bank, the snails and lizards which lived and died within a hollow tree, the insects which have been imprisoned within the exuding resin of old forests, the footprints of birds and quadrupeds, the trails of worms left upon former shores—these, and innumerable other pieces of evidence, enable the geologist to realize in some measure what the faunas and floras of successive periods have been, and what geographical changes the site of every land has undergone.

It is evident that to deal successfully with these varied materials, a considerable acquaintance with different branches of science is needful. Especially necessary is a tolerably wide knowledge of the processes now at work in changing the surface of the earth, and of at least those forms of plant and animal life whose remains are apt to be preserved in geological deposits, or which in their structure and habitat enable us to realize what their forerunners were. It has often been insisted upon that the present is the key to the past; and in a wide sense this assertion is eminently true. Only in proportion as we understand the present, where everything is open on all sides to the fullest investigation, can we expect to decipher the past, where so much is obscure, imperfectly preserved, or not preserved at all. A study of the existing economy of nature ought thus to be the foundation of the geologist's training.

While, however, the present condition of things is thus employed, we must obviously be on our guard against the danger of unconsciously assuming that the phase of nature's operations which we now witness has been the same in all past time, that geological changes have taken place in former ages in the manner and on the scale which we behold to-day, and that at the present time all the great geological processes, which have produced changes in the past eras of the earth's history, are still existent and active. Of course we may assume this uniformity of action, and use the assumption as a working hypothesis. But it ought not to be allowed any firmer footing, nor on any account be suffered to blind us to the obvious truth that the few centuries wherein man has been observing nature form much too brief an interval, by which to measure the intensity of geological action in all past time. For aught we can tell the present is an era of quietude and slow change, compared with some of the eras which have preceded it. Nor can we be sure that, when we have explored every geological process now in progress, we have exhausted all the causes of change which, even in comparatively recent times, have been at work.

In dealing with the Geological Record, as the accessible solid part of the globe is called, we cannot too vividly realize that at the best it forms but an imperfect chronicle. Geological history cannot be compiled from a full and continuous series of documents. From the very nature of its origin the record is necessarily fragmentary, and it has been further mutilated and obscured by the revolutions of successive ages. And even where the chronicle of events is continuous, it is of very unequal value in different places. In one case, for example, it may present us with an unbroken succession of deposits many thousands of feet in thickness, from which, however, only a few meagre facts as to geological history can be gleaned. In another instance it brings before us, within the compass of a few yards, the evidence of a most varied and complicated series of changes in physical geography, as well as an abundant and interesting suite of organic remains. These and other characteristics of the geological record will become more apparent and intelligible as we proceed in the study of the science.

In the systematic treatment of the subject the following arrangement will here be followed:—

1. *The Cosmical Aspects of Geology.*—Under this head we may consider the evidence supplied by astronomy and physics regarding the form and motions of the earth, the composition of the sun and planets, and the probable history of the solar system.

2. *Geognosy,—an Inquiry into the Materials of the Earth's Substance.*—In this division we deal with the parts of the earth, its envelopes of air and water, its solid crust, and the probable condition of its interior. Especially, we have to study the more important minerals of the crust, and the chief rocks of which that crust is built up. In this way we lay a foundation of knowledge regarding the nature of the materials constituting the mass of the globe, and may next proceed to investigate the processes by which these materials are produced and altered.

3. *Dynamical Geology* embraces an investigation of the various agencies whereby the rocks of the earth's crust are formed and metamorphosed, and by which changes are effected upon the distribution of sea and land, and upon the forms of terrestrial surfaces. Such an inquiry necessitates a careful study of the existing geological economy of nature, and forms a fitting introduction to the investigation of the geological changes of former periods. This and the previous section include most of what is embraced under Physical Geography; and for the reason stated under that heading the subject will here be treated more in detail than is usual in geological treatises.

4. *Structural Geology, or the Architecture of the Earth.*—We now advance to consider how the various materials composing the crust of the earth have been arranged. We learn that some have been formed in beds or strata on the floor of the sea, that others have been built up by the slow aggregation of organic forms, that others have been poured out in a molten condition or in showers of loose dust from subterranean sources. We further find that, though originally laid down in almost horizontal beds, the rocks have subsequently been crumpled, contorted, and dislocated, that they have been incessantly worn down, and have often been depressed and buried beneath later accumulations.

5. *Palæontological Geology.*—This branch of the subject deals with the organic forms which are found preserved in the crust of the earth. It includes such questions as the relations between extinct and living types, the laws which appear to have governed the distribution of life in time and in space, the relative importance of different genera of animals in geological inquiry, the nature and use of the evidence from organic remains regarding former conditions of physical geography. This subject will be more properly discussed in the article PALÆONTOLOGY, and will therefore be only cursorily treated in the following pages.

6. *Stratigraphical Geology.*—This section might be called geological history. It works out the chronological succession of the great formations of the earth's crust, and endeavours to trace the sequence of events of which they contain the record. More particularly it determines the order of succession of the various plants and animals which in past time have peopled the earth, and thus ascertains what has been the grand march of life upon the planet.

7. *Physiographical Geology*, starting from the basis of fact laid down by stratigraphical geology regarding former geographical changes, embraces an inquiry into the origin and history of the features of the earth's surface—continental ridges and ocean basins, plains, valleys, and mountains. It explains the causes on which local differences of scenery depend, and shows under what very different circumstances, and at what widely separated intervals, the hills and mountains, even of a single country, have been produced.

PART I.—COSMICAL ASPECTS OF GEOLOGY.

Before geology had attained to the position of an inductive science, it was customary to begin all investigations into the history of the earth by propounding or adopting some more or less fanciful hypothesis in explanation of the origin of our planet, or even of the universe. Such preliminary notions were looked upon as essential to a right understanding of the manner in which the materials of the globe had been put together. To the illustrious James Hutton (1785) geologists are indebted for strenuously upholding the doctrine that it is no part of the province of geology to discuss the origin of things. He taught them that in the materials from which geological evidence is to be compiled there can be found "no traces of a beginning, no prospect of an end." In England, mainly to the influence of the school which he founded, and to the subsequent rise of the Geological Society (1807), which resolved to collect facts instead of fighting over hypotheses, is due the disappearance of the crude and unscientific cosmologies by which the writings of the earlier geologists were distinguished.

But there can now be little doubt that in the reaction against those visionary and often grotesque speculations, geologists were carried too far in an opposite direction. In allowing themselves to believe that geology had nothing to do with questions of cosmogony, they gradually grew up in the conviction that such questions could never be other than mere speculation, interesting or amusing as a theme for the employment of the fancy, but hardly coming within the domain of sober and inductive science. Nor would they soon have been awakened out of this belief by anything in their own science. It is still true that in the data with which they are accustomed to deal, as comprising the sum of geological evidence, there can be found no trace of a beginning. The oldest rocks which have been discovered on any part of the globe have probably been derived from other rocks older than themselves. Geology by itself has not yet revealed, and is little likely ever to reveal, a trace of the first solid crust of our globe. If then geological history is to be compiled from direct evidence furnished by the rocks of the earth, it cannot begin at the beginning of things, but must be content to date its first chapter from the earliest period of which any record has been preserved among the rocks.

Nevertheless, though geology in its usual restricted sense has been, and must ever be, unable to reveal the earliest history of our planet, it no longer ignores, as mere speculation, what is attempted in this subject by its sister sciences. Astronomy, physics, and chemistry have in late years all contributed to cast much light on the earlier stages of the earth's existence, previous to the beginning of what is commonly regarded as geological history. But whatever extends our knowledge of the former conditions of our globe may be legitimately claimed as part of the domain of geology. If this branch of inquiry therefore is to continue worthy of its name as the science of the earth, it must take cognizance of these recent contributions from other sciences. It must no longer be content to begin its annals with the records of the oldest rocks, but must endeavour to grope its way through the ages which preceded the formation of any rocks. Thanks to the results achieved with the telescope, the spectroscope, and the chemical laboratory, the story of these earliest ages of our earth is every year becoming more definite and intelligible.

Relations of the Earth in the Solar System.

Before entering upon the study of the structure and history of the earth, we may with advantage consider the general relations of our planet to the solar system, especially in view of its origin and history. It is now regarded as in the highest degree probable that all the members of that system have had a common origin. The investigations of recent years have revived and given a new form and meaning to the well-known nebular hypothesis, in which Laplace sketched the progress of the system from the state of an original nebula to its existing condition of a central incandescent sun with surrounding cool planetary bodies. He supposed that the nebula, originally diffused at least as far as the furthest member of the system, began to condense towards the centre, and that in so doing it threw off or left behind successive rings which on disruption and further condensation assumed the form of planets, sometimes with a further formation of rings, which in the case of Saturn remain, though in other planets they have broken up and united into satellites.

According to this view we should expect that the matter composing the various members of the solar system should be everywhere nearly the same. The fact of condensation round centres, however, indicates at least differences of density throughout the nebula. Mr Lockyer has, indeed, suggested that the materials composing the nebula arranged themselves according to their respective densities, the lightest occupying the exterior and the heaviest the interior of the mass. And if we compare the densities of the various planets, they certainly seem to support this suggestion. These densities are shown in the following table, that of the earth being taken as the unit :—

Density of the Sun	0·25
,, Mercury	1·12
,, Venus	1·03
,, Earth	1·00
,, Mars	0·70
,, Jupiter	0·24
,, Saturn	0·13
,, Uranus	0·17
,, Neptune	0·16

There is not indeed a strict progression in the diminution of density, but the fact remains that, while the planets near the sun are about twice as heavy as they would be if they consisted of such a substance as granite, towards the outer limits of the system they are composed of matter as light as cork. Again, in some cases, a similar relation has been observed between the densities of the satellites and their primaries. The moon, for example, has a density little more than half that of the earth. The first satellite of Jupiter is less dense, though the other three are found to be more dense than the planet. Further, in the condition of the earth itself, a very light gaseous atmosphere forms the outer portion, beneath which lies a heavier layer of water, while within these two envelopes the materials forming the solid substance of the planet are so arranged that the outer layer or crust has only about half the density of the whole globe. Mr Lockyer finds in the sun itself evidence of the same tendency towards a stratified arrangement in accordance with relative densities, as will be immediately further alluded to.

There seems therefore to be much probability in the hypothesis that, in the gradual condensation of the original nebula, each successive mass left behind represented the density of its parent layer, and consisted of progressively heavier matter. The remoter planets, with their low density and vast absorbing atmospheres, may be supposed to consist of metalloids like the outer parts of the sun's atmosphere, while the interior planets are no doubt mainly metallic. The rupture of each planetary ring would, it is conceived, raise the temperature of the resultant nebulous planet to such a height as to allow the vapours to rearrange themselves by degrees in successive layers, or rather shells, according to density. And when the planet gave off a satellite, that body would, it might be expected, have the composition and density of the outer layers of its primary.[1]

For many years the only evidence available as to the actual composition of other heavenly bodies than our own earth was furnished by the *aerolites*, *meteorites*, or falling stars, which from time to time have entered our atmosphere from planetary space, and have descended upon the surface of the globe. Subjected to chemical analysis these foreign bodies show considerable diversities of composition; but in no case have they yet yielded a trace of any element not already recognized among terrestrial materials. Upwards of twenty of our elements have been detected in aerolites, sometimes in the free state, sometimes combined with each other. More than half of them are metals, including iron, nickel, manganese, calcium, sodium, and potas-

[1] Mr Lockyer communicated some of his views to Professor Prestwich, who gave them in his interesting *Inaugural Lecture* at Oxford, in 1875. He has further stated them in his Manchester Lectures, *Why the Earth's Chemistry is as it is.*

sium. There occur also carbon, silicon, phosphorus, sulphur, oxygen, nitrogen, and hydrogen. In some of their combinations these elements, as found in the meteoric stones, differ from their mode of occurrence in the accessible parts of the earth. Iron, for example, occurs as native metal, alloyed with a variable proportion (6 to 10 per cent.) of metallic nickel. But in other respects they closely resemble some of the familiar materials of the earth's rocky crust. Thus we have such minerals as pyrite, apatite, olivine, augite, hornblende, and labradorite. No more reliable proof could be desired that some at least of the other members of the solar system are formed of the same materials as compose the earth.

But in recent years a far more precise and generally applicable method of research into the composition of the heavenly bodies has been found in the spectroscope. By means of this instrument, the light emitted from self-luminous bodies can be analysed in such a way as to show what elements are present in their intensely hot luminous vapour. When the light of a burning metal is examined with a properly-arranged prism, it is seen to give a dark band or *spectrum* which is traversed by certain vertical bright lines. This is termed a *radiation-spectrum*. Each element appears to have its own characteristic arrangement of lines, which retain the same relative position, intensity, and colours. Moreover, gases and the vapours of solid bodies are found to intercept those rays of light which they themselves emit. The spectrum of burning sodium, for example, shows two bright yellow lines. If therefore white light from some other source passes through the vapour of sodium, these two bright lines become dark lines, that portion of the light being exactly cut off which would have been given out by the sodium itself. This is called an *absorption-spectrum*.

By this method of examination it has been ascertained that many of the elements of which our earth is composed exist in the state of incandescent vapour in the atmosphere of the sun. Among these are some of our most familiar metals—iron, zinc, copper, nickel, with sodium, magnesium, barium, calcium, and vast quantities of free hydrogen. Moreover, as Mr Lockyer has pointed out, these elements appear to succeed each other in relation to their respective densities. Thus the coronal atmosphere which, as seen in total eclipses, extends to so prodigious a distance beyond the orb of the sun, consists mainly of sub-incandescent hydrogen and another element which may be new. Beneath this external vaporous envelope lies the chromosphere where the vapours of incandescent hydrogen, calcium, and magnesium can be detected. Further inward the spot-zone shows the presence of sodium, titanium, &c.; while still lower, a layer (the *reversing* layer) of intensely hot vapours, lying probably next to the inner brilliant photosphere gives spectroscopic evidence of the existence of incandescent iron, manganese, cobalt, nickel, copper, and other well-known terrestrial metals.[1]

The spectrosope has likewise been successfully applied by Mr Huggins and others to the observation of the fixed stars and nebulæ, with the result of establishing a similarity of elements between our own system and other bodies in sidereal space. In the radiation spectra of nebulæ Mr Huggins finds the hydrogen lines very prominent; and he conceives that they may be glowing masses of that element. Sir William Thomson and Professor Tait have suggested, on the other hand, that they are more probably clouds of stones in rapid motion, perhaps in an atmosphere of hydrogen. Among the fixed stars absorption spectra have been recognized, pointing to a structure resembling that of our sun, viz., a solid or liquid incandescent nucleus, surrounded with an atmosphere of glowing vapour.[2] According to Mr Lockyer, those stars or nebulæ which have the highest temperature have the simplest spectra, and in proportion as they cool their materials become more and more differentiated into what we call elements. He remarks that the most brilliant or hottest stars show in their spectra only the lines of gases, as hydrogen. Cooler stars, like our sun give indications of the presence, in addition, of the more stable metals—magnesium, sodium, calcium, iron. A still lower temperature he regards as marked by the appearance of the other metals, metalloids, and compounds, so that the older a star or planet is the more will it lose free hydrogen till, when it comes to the condition of our earth, all its free hydrogen will have disappeared.[3] According to this view the atoms of all the elements existed originally in the nebula dissociated from each other by reason of the intense heat. As the nebula gravitated towards its nucleus and cooled, the atoms came together, and the elements appeared in a certain order, beginning with hydrogen, and passing on through the metals and metalloids into compounds such as we find on our globe. The sun would thus be a star considerably advanced in the process of differentiation or association of its atoms. It contains, so far as we know, no metalloids or compounds, while stars like Sirius show the presence only of hydrogen, with but a feeble proportion of metallic vapours; and on the other hand, the red stars indicate by their spectra that their metallic vapours have entered into combination, whence it is inferred that their temperature is lower than that of our sun.

Further confirmation of these views as to the order of planetary evolution is furnished by the form and structure of the earth. Reference has already been made to the fact that the outer crust of our planet possesses only about half the density of the whole mass. It consists largely of metalloids—oxygen, silicon, carbon, sulphur, chlorine. On the other hand, lavas and mineral veins, which are believed to have been supplied from some considerable depth, contain abundance of metallic ingredients.

The form of the globe likewise points to a former fluid condition. As the result of computations from ten measured arcs of the meridian made by different observers between the latitudes of Sweden and the Cape of Good Hope, Bessel obtained the following data for the dimensions of the earth :—

Equatorial diameter	41,847,192	feet, or	7925·604	miles.
Polar diameter	41,707,314	,,	7899·114	,,
Amount of polar flattening,	139,768	,,	26·471	,,

The equatorial circumference is thus a little less than 25,000 miles, and the difference between the polar and equatorial diameters (nearly $26\frac{1}{2}$ miles) amounts to about $\frac{1}{300}$th of the equatorial diameter.[4] More recently, however, it has been shown that the oblate spheroid indicated by these measurements is not a symmetrical body, the equatorial circumference being an ellipse instead of a circle. The diameter of which the vertices touch the surface of the globe in longitudes 14° 23′ E. and 194° 23′ E. of Greenwich is nearly two miles longer than that at right angles to it.[5]

In obedience to the influence of rotation on its axis, our planet would tend to assume exactly such a flattening at the poles as it has been proved to possess. This was discovered and demonstrated by Newton, and the amount of

[1] On the constitution of the sun see Roscoe's *Spectrum Analysis*; Lockyer's *Solar Physics*, 1873; and memoirs in *Proc. of Roy. Soc.*, by B. Stewart, Loewy, and De la Rue.

[2] Huggins, *Proc. Roy. Soc.*, 1863–66, and *Brit. Assoc. Lecture* (Nottingham, 1866); Huggins and Miller, *Phil. Trans.*, 1864.

[3] Lockyer, *Comptes Rendus*, Dec. 1873.

[4] Herschel, *Astronomy*, p. 139.

[5] A. R. Clarke, *Mem. Roy. Astron. Soc.*, xxix.; Herschel, *Astron.*, p. 691. See also a more recent paper by Colonel Clarke, *Phil. Mag.*, August 1878.

the ellipticity was actually calculated by him, long before any measurement had confirmed such a conclusion.

The tendency of modern research is thus to give probability to the conception that not only in our own solar system, but throughout the regions of space, there has been a common plan of evolution, and that the matter diffused through space in stars, nebulæ, and systems is substantially the same as that with which we are familiar. Hence the study of the structure and probable history of the sun and the other heavenly bodies comes to possess an evident geological interest, seeing that it may yet enable us to carry back the story of our planet far beyond the domain of ordinary geological evidence, and upon data not less reliable than those furnished by the rocks of the earth's crust.

II. The Movements of the Earth in their Geological Relations.

We are here concerned only with those aspects of the earth's motions which materially influence the progress of geological phenomena.

1. *Rotation.*—In obedience to the impulse communicated to it at its original separation, the earth rotates on its axis. This movement is completed in about 24 hours, and to it is due the succession of day and night. So far as observation has yet gone, this movement is uniform, though recent calculations of the influence of the tides in retarding rotation tend to show that a very slow diminution of the angular velocity is in progress. This velocity varies relatively in different places, according to their position on the surface of the planet. At each pole there can be no velocity, but from these two points towards the equator there is a continually increasing rapidity of motion, till at the equator it is equal to a rate of 507 yards in a second.

To the rotation of the earth are due certain remarkable influences upon currents of air, which circulate either towards the equator or towards the poles. Currents which move from polar latitudes travel from parts of the earth's surface where the velocity of rotation is small to others where it is great. Hence they lag behind, and their course is bent more and more westward. An air current quitting the north polar or north temperate regions as a north wind is deflected out of its course and becomes a north-east wind. On the opposite side of the globe a similar current setting out straight for the equator is changed into a south-east wind. This is the reason why the well-known trade-winds have their characteristic westward deflexion. On the other hand, a current setting out northwards or southwards from the equator passes into regions having a less velocity of rotation than it possesses itself, and hence it travels on in advance and is gradually deflected eastward. The aerial currents blowing steadily across the surface of the ocean produce currents in its waters which have a westward tendency communicated to them indirectly from the effect of rotation. A certain deflexion is said to be experienced by such rivers as flow in a meridional direction, like the Volga. Those which flow polewards are asserted to press upon their eastern rather than their western banks, while those which run in the opposite direction are stated to be thrown more against the western than the eastern. The reality of this action may be doubted.

2. *Revolution.*—Besides turning on its axis the globe performs a movement round the sun, termed revolution. This movement is accomplished in rather more than 365 days. It determines for us the length of our year, which is, in fact, merely the time required for one complete revolution. The path or orbit followed by the earth round the sun is not a perfect circle but an ellipse, with the sun in one of the foci, the mean distance of the earth from the sun being 92,400,000 miles. By slow secular variations the form of the orbit alternately approaches and recedes from that of a circle. At the nearest possible approach between the two bodies, owing to change in the ellipticity of the orbit, the earth is 14,368,200 miles nearer the sun than when at its greatest possible distance. These maxima and minima of distance occur at vast intervals of time. The last considerable eccentricity took place about 200,000 years ago, and the previous one more than half a million of years earlier. Since the amount of heat received by the earth from the sun is inversely as the square of the distance, eccentricity must have had in past time much effect upon the climate of the earth, as will be pointed out further on (section 7, p. 218).

3. *Precession of the Equinoxes.*—If the axis of the earth were perpendicular to the plane of its orbit, there would be equal day and night all the year round. But it is really inclined to that plane at an angle of $23\frac{1}{2}°$. Hence our hemisphere is alternately presented to and turned away from the sun, and in this way brings us the familiar alternation of the seasons—the long days of summer and the short days of winter. Again, were the earth a perfect sphere of uniform density throughout, the position of its axis of rotation would not change. But owing to the protuberance along the equatorial regions, the attraction chiefly of the sun and moon tends to pull the axis aside, or to make it describe a conical movement like that of the axis of a top round the vertical. Hence each pole points successively to different stars. This movement, called the precession of the equinoxes, in combination with other planetary movements, completes its cycle in 21,000 years. At present the winter in our northern hemisphere coincides with the earth's approach to the sun, or *perihelion*. In 10,500 years hence it will take place when the earth is at the farthest part of its orbit from the sun, or in *aphelion*. This movement acquires great importance when considered in connexion with the secular variations in the eccentricity of the orbit (see section 7).

4. *Change in the Obliquity of the Ecliptic.*—The angle at which the axis of the earth is inclined to the plane of its orbit does not remain strictly constant. It oscillates through long periods of time to the extent of about a degree and a half, or perhaps a little more, on either side of the mean. According to Dr Croll,[1] this oscillation must have considerably affected former conditions of climate on the earth, since, when the obliquity is at its maximum, the polar regions receive about eight and a half days more of heat than they do at present—that is, about as much heat as lat. 76° enjoys at this day. This movement must have augmented the geological effects of precession, to which reference has just been made, and which are described in section 7.

5. *Stability of the Earth's Axis.*—That the axis of the earth's rotation has successively shifted, and consequently that the poles have wandered to different points on the surface of the globe, has been maintained by geologists as the only possible explanation of certain remarkable conditions of climate, which can be proved to have formerly obtained within the Arctic Circle. Even as far north as lat. 81° 45′ abundant remains of a vegetation indicative of a warm climate, and including a bed of coal 25 to 30 feet thick, have been found *in situ*. It is contended that where these plants lived the ground could not have been permanently frozen or covered for most of the year with thick snow. In explanation of the difficulty, it has been suggested that the north pole did not occupy its present position, and that the locality where the plants occur lay in more southerly latitudes. Without at present entering on

[1] Croll, *Trans. Geol. Soc. Glasgow*, ii. 177.

the discussion of the question whether the geological evidence requires necessarily so important a geographical change, let us consider how far a shifting of the axis of rotation has been a possible cause of change during that section of geological time for which there are records among the stratified rocks.

From the time of Laplace[1] astronomers have strenuously denied the possibility of any sensible change in the position of the axis of rotation. It has been urged that, since the planet acquired its present oblate spheroidal form, nothing but an utterly incredible amount of deformation could overcome the greater centrifugal force of the equatorial protuberance. It is certain, however, that the axis of rotation does not strictly coincide with the principal axis of inertia. Though the angular difference between them must always have been small, we can, without having recourse to any extra-mundane influence, recognize two causes which, whether or not they may suffice to produce any change in the position of the main axis of inertia, undoubtedly tend to do so. In the first place a widespread upheaval or depression of certain portions of the surface to a considerable vertical amount might shift that axis. In the second place an analogous result might arise from the denudation of continental masses of land and the consequent filling up of sea-basins. Sir William Thomson freely concedes the physical possibility of such changes. "We may not merely admit," he says, "but assert as highly probable, that the axis of maximum inertia and axis of rotation, always very near one another, may have been in ancient times very far from their present geographical position, and may have gradually shifted through 10, 20, 30, 40, or more degrees, without at any time any perceptible sudden disturbance of either land or water."[2] But though, in the earlier ages of the planet's history, stupendous deformations may have occurred, and the axis of rotation may have often shifted, it is only the alterations which can possibly have occurred during the accumulation of the stratified rocks that need to be taken into account in connexion with former changes of climate. If it can be shown therefore that the geographical revolutions necessary to shift the axis are incredibly stupendous in amount, improbable in their distribution, and completely at variance with geological evidence, we may reasonably withhold our belief from this alleged cause of the changes of climate during geological history.

It has been estimated by Sir William Thomson "that an elevation of 600 feet, over a tract of the earth's surface 1000 miles square and 10 miles in thickness, would only alter the position of the principal axis by one-third of a second, or 34 feet."[3] Mr George Darwin has shown that on the supposition of the earth's complete rigidity no redistribution of matter in new continents could ever shift the pole from its primitive position more than 3°, but that, if its degree of rigidity is consistent with a periodical re-adjustment to a new form of equilibrium, the pole may have wandered some 10° or 15° from its primitive position, or have made a smaller excursion and returned to near its old place. In order, however, that these maximum effects should be produced, it would be necessary that each elevated area should have an area of depression corresponding in size and diametrically opposite to it, that they should lie on the same complete meridian, and that they should both be situated in lat. 45°. With all those coincident favourable circumstances, an effective elevation of $\frac{1}{300}$ of the earth's surface to the extent of 10,000 feet would shift the pole $11\frac{1}{3}'$; a similar elevation of $\frac{1}{20}$ would move it 1° $46\frac{1}{2}'$; of $\frac{1}{10}$, 3° 17′; and of $\frac{1}{2}$, 8° $4\frac{1}{2}'$. Mr Darwin admits these to be superior limits to what is possible, and that, on the supposition of intumescence or contraction under the regions in question, the deflexion of the pole might be reduced to a quite insignificant amount.[4]

Under the most favourable conditions, therefore, the possible amount of deviation of the pole from its first position would appear to have been too small to have seriously influenced the climates of the globe within geological history. If we grant that these changes were cumulative, and that the superior limit of deflexion was reached only after a long series of concurrent elevations and depressions, we must suppose that no movements took place elsewhere to counteract the effect of those about lat. 45° in the two hemispheres. But this is hardly credible. A glance at a geographical globe suffices to show how large a mass of land exists now both to the north and south of that latitude, especially in the northern hemisphere, and that the deepest parts of the ocean are not antipodal to the greatest heights of the land. These features of the earth's surface are of old standing. There seems, indeed, to be no geological evidence in favour of any such geographical changes as could have produced even the comparatively small displacement of the axis considered possible by Mr Darwin.

In an ingenious suggestion Dr John Evans contended that, even without any sensible change in the position of the axis of rotation of the nucleus of the globe, there might be very considerable changes of latitude due to disturbance of the equilibrium of the shell by the upheaval or removal of masses of land between the equator and the poles, and to the consequent sliding of the shell over the nucleus until the equilibrium was restored. This hypothesis starts on the assumption of a thin crust enclosing a liquid or viscous interior—an assumption which, as will be shown in subsequent pages, is negatived by considerations in physics. The Rev. O. Fisher has suggested that the almost universal traces of present or former volcanic action, the evidence from the compressed strata in mountain regions that the crust of the earth must have a capacity for slipping towards certain lines, the great amount of horizontal compression of strata which can be proved to have been accomplished, and the secular changes of climate—notably the former warm climate near the north pole—furnish grounds for inquiry "whether a fluid substratum over a rigid nucleus would not be compatible with mechanical considerations, and whether, under those circumstances, changes in latitude would not result from unequal thickening of the crust."[5]

6. *Changes of the Earth's Centre of Gravity.*—Though no known geological operation seems to have been capable of producing an effective change in the position of the axis of rotation of the earth, there may have been variations in the position of its centre of gravity. Any change of that kind must affect the ocean, which of course adjusts itself in relation to the earth's centre of gravity. The enormous accumulation of ice at one pole during the maximum of eccentricity will displace the centre of gravity, and, as the result of this change will raise the level of the ocean in the glacial hemisphere,[6] Dr Croll has estimated that, if the present mass of ice in the southern hemisphere is taken at 1000 feet thick extending down to lat. 60°, the transference of this mass to the northern hemisphere would raise the level of the sea 80 feet at the north pole. Other methods of calculation give different results. Mr Heath puts the rise at 128 feet; Archdeacon Pratt makes it more; while the Rev. O. Fisher gives it at

[1] *Mécanique Céleste*, tome v. p. 14.
[2] *Brit. Assoc. Rep.* (1876), Sections, p. 11.
[3] *Trans. Geol. Soc. Glasgow*, iv.

[4] *Phil. Trans.*, November 1876.
[5] *Geol. Mag.*, 1878, p. 552.
[6] Adhemar, *Revolutions de la Mer*, 1840.