PRESIDENT'S ADDRESS.

THE EARTH'S FRAMEWORK.

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The Nestor of American Geologists once replied to a criticism of a minor detail of his profound theories of diastrophism, that if he desired to understand the architecture of a great cathedral, he would not begin by examining the key-hole. One should begin such an investigation by standing back where a view of the grand ensemble may be obtained. Such a view will almost certainly suggest the proper line of procedure in the gradually narrowing scrutiny of the details; and should inhibit at the outset the tendency to frame hypotheses too cramped to accommodate the larger relationships of the structure.

The Earth is so vast a body that a distant and detached vantage-point is difficult of attainment, and is, of course, in the literal sense impossible. It is not impossible, however, for the scientific imagination to carry us out to any point in space that may seem to us convenient for our purposes, or to translate us backward or forward in time to any instant that may best serve our interest. It is necessary to adopt this method for the reason that every attempt to proceed from the particular to the general in the study of the Earth, without first comprising it in some comprehensive view, has resulted in failure.

THE EXTERNAL FORM.

It is a fact appreciated by even the least informed that the Earth is a nearly spherical body. It is, to be more precise, an ellipsoid of revolution having an axial diameter very slightly less than the equatorial diameters. How the gross form of the Earth has been ascertained is in itself a fascinating story; but it cannot be told here. It will be far more interesting to tell how and why the Earth differs in detail from any exact mathematical figure.

The departures of the Earth from any exact figure of revolution, about which I now propose to speak, are excessively minute fractions of Earth radii. It is impossible to represent them in true scale on any globe of manageable size. Even the polar flattening, amounting to 1/297 of the radius, would not be noticed by you if represented on the largest globe that could be placed in this room. The maximum relief difference of 12 miles, between the top of the highest mountain and the bottom of the deepest abyss of the oceans, if represented on the common 18-inch globe of the school room, would amount to 1/40 inch, or the thickness of a good coat of paint. Small as are these departures from perfect regularity of form, they are nevertheless of vast importance to an understanding of the history and architecture of the Earth; and they have stimulated the curiosity, and exercised the highest abilities of many of the greatest geologists, geodecists and physicists of the world.

The most noteworthy surface features of the Earth are the continents and ocean basins. An observer stationed on the Moon would see upon the silvery disc of the Earth, at full, the outlines of these grander features, as we see the "face in the Moon", and if he were to watch patiently from hour to hour, as the Earth turned on its axis, he would gradually become aware of certain curiously repeated forms. One of the most striking, as Suess long ago pointed out, is the southward tapering of the continents and great peninsulas—North and South America, Africa, Greenland, the peninsulas of India and Farther India. Another is the roughly triangular shape of the land masses, and the approximately circular or polygonal form of the oceans. Again he would note certain contrasts. If he were a careful observer he would see that the oceans are set opposite the continents. Toward the south pole he would note a concentration of the waters of the Earth, and toward the north pole, of the lands.

If now we can imagine that our observer's vision penetrates the watery envelope of the Earth, as though it were perfectly transparent, and that he turns upon it a telescope of moderate power, he would note at once that the continents are margined by belts of land, the continental shelves, only slightly veiled by shallow seas. At places, as along the northern and eastern shores of North America, the northwestern coasts of Europe, the eastern front of Asia and the southern end of South America, he would see a marked widening of these shallows, sometimes with crescentic fringes of islands along their outer margins. They would appear in some cases to almost or quite connect the continents—northern North America to Asia on the west and Europe on the east; South America with Antarctica; southeastern Asia with Australia; Australia with Antarctica.

As the Earth passed through its phases, illumined by the slanting rays of the Sun, there would come into view upon its continents a marvelous wealth of details: great narrow ridges, winding in sweeping curves along the western edges of the two Americas; beautiful crescents festooned one outside the other from central Eurasia to the island-dotted margins; long low parallel ridges, in graceful curves near the eastern coast of North America; vast level stretches in the interior marked here and there with subdued elevations. These are the great mountains and lowlands of the Earth. Upon these in turn our observer, with a powerful telescope, might make out a bewildering complex of details etched out by some mysterious agencies that he would scarcely understand, for these are the work of air and water, which the Moon lacks.

We have outlined the Earth's grander surface features. The ruddy lands with their margining shoals and sinuous mountain ridges are the continental platforms. The silvery seas between are the ocean deeps; the great basin-shaped depressions of the lithosphere. The rest are the mountains, the islands, the plateaus and plains, the valleys and divides, hill and dale, upland and lowland, the finer filigree of the Earth's vast tracery.

The strand-line, where sea and land meet, is not the true edge of the continents. In some cases, as off the western coast of Africa, North and South America, the strand and the continental edge are not far apart, and sometimes they nearly coincide. Along the eastern and northern coasts they are often separated by wide stretches of shallow water, seldom over a hundred fathoms deep. These areas are the epicontinental seas. Sometimes these latter send long embayments in upon the continents. Such are Hudson Bay, the North Sea and the Baltic. These are the epeiric seas. The strand is determined by the degree to which the oceans at any particular time overflow the continents, or are drawn down upon the continental slopes. A lowering of sea-level by 600 feet, one thirty-five thousandth of the Earth radius, would lay bare in most parts of the world, the true margin of the continents. This same reduction of sea-level would attach most of the marginal or continental islands to the mainlands. The Artic islands, the British islands, Newfoundland, East Indies, Japan, Cuba, Sicily, and many others, belong with the continents. Oscillations of the strand much greater than this have often occurred during the Earth's past.

The continents are elevated platforms, standing on the average in mean altitude about three miles above the smoothed floor of the ocean basins, and separated from them by somewhat abrupt slopes. Except for the polar flattening and equatorial bulge, these are the greatest departures of the Earth from perfect sphericity.

Within the area of the ocean basins there is in general a topographic monotony far exceeding anything on the lands. The sea-floor is commonly spoken of as though it were approximately level. There are, however, many significant departures from levelness. The most striking are the so-called deeps. Of these there are two sorts, the troughs or *fore-deeps* and the broad or *central deeps*. The fore-deeps of Suess are all located along the margins of the ocean basins, in front of folded mountain arcs, and are practically confined to the Pacific and Indian oceans, although sediment-filled fore-deeps may be present in the Atlantics also.

The average depth of the Pacific is about 2,400 fathoms (2.7 miles). The Aleutian deep, in front of the Aleutian islands, sinks to a depth of 3,000 to 4,000 fathoms. The great Tuscarora deep, in front of Japan, descends to 4,600 fathoms. The Philippine trough, extending in front of the Philippine islands from Riu Kiu islands to Tulur, reaches a depth of 4,700 fathoms; while the Aldrich deep between the Samoa islands and New Zealand, ranges from 4,000 to 5,160 fathoms, nearly six miles, and is one of the deepest abysses of the oceans. Off the coast of Northern Chile depths as great as 4,100 fathoms are found comparatively near shore in a series of deep pits constituting a somewhat interrupted trough. In the central deeps, which in contrast to the fore-deeps are broad, basin-like depressions far from land, depths of over 3,000 fathoms are common. The most noteworthy of these are in the areas to the north and south of the Sandwich islands, and between the Gilbert islands and the Christmas island group.

The Atlantic basins—North and South—differ from the Pacific basin in a number of significant respects. In the first place, with the exception of the San Juan trough north of Porto Rico, there are no fore-deeps. Central deeps, both in the North Atlantic and South Atlantic go down to depths greater than 3,000 fathoms. Another striking and unique feature of the Atlantics is the mid-Atlantic, or Dolphin, ridge, which runs through the middle of these oceans from Greenland southward to the south polar sea. Bending strongly to the east between Africa and South America, it maintains a general parallelism with the margins of the two Atlantic basins. Near its southern end it sends off branches towards both Africa and South America. The South Atlantic basin is separated from the North Atlantic by the constriction between Africa and Brazil, with depths of about 2,000 fathoms, and from the Pacific by a submerged ridge of moderate depth, which joins the South American platform with Antarctica. It should be remarked here that a similar shoal joins Australia with Antarctica.

The Indian Ocean, of roughly circular form, contains fore-deeps on its eastern margin athwart Australia and the East Indies, and an island-dotted ridge of significant character between the southern point of India and Madagascar.

The continental platforms have a very special character. Their average height above sea level is only about one-fifth the average depth of the ocean basins. Five-sixths of the total smoothed relief of these platforms is, therefore, hidden beneath the waters of the seas. If the continents and the ocean basins were smoothed out to an average level surface, this surface would lie about 9,000 feet, or one and five-ninths miles, below sea-level. That is, there is enough water to produce, under appropriate conditions, a universal ocean more than a mile and a half deep. In area the continental platforms cover about one-third of the Earth's surface, and the ocean basins the other two-thirds.

Dana's generalization that a continent consists typically of a basin or lowland bordered by mountains, is approximately true of all, although Africa is, with the exception of portions of the northern Saharan region, more like a great plateau of comparatively recent elevation. North America best illustrates this conception of a continent, and evidently suggested the idea to Dana. The Appalachian ranges on the east and the great bordering cordillera on the west are separated by the extensive interior lowlands of the Mississippi Valley, Great Lakes, Hudson Bay and the Great Plains. In South America the Andean system narrowly borders the Pacific edge, and the highlands—ancient worn-down mountains—of Brazil and Guiana, the east. Between are the interminable lowlands of Argentina, Paraguay and the Amazon. If we eliminate from Eurasia the two spurious elements, Arabia, which belongs geologically with Africa, and India, a fragment of an ancient dismembered continent, the rule holds. In the east and southeast mountain crescents extend in concentric loops from the island chains of the Kurile, Japan, Riu Kiu, Phillipines and the East Indies, back into the heart of Mongolia. On the west the ancient Caledonides form the border from Spitzbergen to Ireland. Along the Mediterranean the complicated folds of the Alps, Carpathians and Balkans are joined on the east by the Taurides and highlands of Anatolia, Armenia, Iran and Afghanistan, uniting finally with the huge bulk of the Himalayas. Between stretch the vast plains and steppes of Siberia, Turkestan and Russia, broken only by the singular ridge of the Urals. In Australia the Great Dividing Range outlines the east coast, and a subdued ridge, culminating in Mt. Bruce, 4,000 feet high, lies not far back of the west coast. Between are lowlands on the east, merging into plateau heights in the Great Sandy desert region of central and western Australia. Thus, mountains and highlands characterize the continental margins, as deeps do the borders of the Pacific. They seem often to be the reciprocals of each other. Around the Pacific the mountains fringe the coast and determine its trend; but along the Atlantic they descend into the sea and seem to be abruptly cut off at the strand. So the Caledonides enter the sea in Scandinavia and Ireland, and the Appalachians in Gaspe and Newfoundland.

Hidden, as it were, within the depths of the continents, unnoticed by the layman, but of supreme interest to the geologist, are the *shields*—areas, usually of subdued topography, occupied by ancient rocks and the roots of by-gone mountains. These are the nuclei of the continents. The region surrounding Hudson Bay, and including Labrador and Greenland, suggested the name to Suess, and is the prototype of all the shields. Among its gnarled rocks of gneiss and greenstone are some of the most ancient of the world. The Greater Antilles and Mexico, wreckage of an ancient continent; Brazil and Guiana; Africa, south of the Sahara; Finland and eastern Scandinavia; Angara in eastern Siberia; Australia west of the eastern lowlands; India south of the Indo-Gangetic valley; and Madagascar, are others. About them the continents have been built, and against them the waves of encroaching seas have beaten and the mountain crescents of later times have been thrust. They have borne the brunt of the Earth's uneasy struggles; and strengthening their sinews with the age-long strife, have become the strong defenders of the lands against the invading seas. Though it has been, on the whole, a losing fight, these hardened veterans still bear witness to the grand extent of their old domain. On the Pacific front they still press on to victory. In the Atlantic and Indian areas their scattered cohorts straggle in defeat.

One further element of the Earth's external form, though apparently dominated by the lands, belongs with the oceans. It is the mediterraneans. The Roman Mediterranean, between Europe and Africa, not only bestows its name upon seas of this type, but is by far the best example. Though almost completely land-locked, it descends to oceanic depths of over two thousand fathoms. It is divided by the toe of Italy, Sicily, and Cape Bon in Tunis, into an eastern and a western basin. The Roman Mediterranean, and the Black and Caspian seas, are remnants of a grander mediterranean, Tethys of the geologists, that once extended far to the east over the area now occupied by the plateau of Iran and the Himalaya mountains. It is a mountain-bordered region of great geologic changes.

The Caribbean and Gulf of Mexico, lying between North and South America, constitute another mediterranean. This sea also lies in a region of great geologic uneasiness. Its eastern, central and western deeps descend to over 2,000 fathoms, and are separated from each other by shallower ridges.

I regard the series of deeps between Borneo and New Guinea, in the East Indies, as another mediterranean. Here again there are three deeps, the Sulu, the Celebes, and Banda-Molucca seas, separated by shallow ridges. Once more this is a region of geologic unrest, characterized by volcanoes, earthquakes, and tiltings of the Earth's crust.

THE INTERIOR.

The interior of the Earth is not open to direct observation, and in consequence, has been for centuries the fertile mother of myths and eerie speculations. Even among competent physicists, geologists and astronomers, unproved and unprovable hypotheses have too often covered up the lack of knowledge. Fortunately this altogether sterile and unsatisfactory period of Earth science is rapidly drawing to a close. We have today methods of investigating the Earth's interior which give us precise information on some important points; and we are nearing the time when many of the mysteries will be solved. I shall discuss the data in regard to the Earth's interior without reference to any particular theory of its origin.

The view was almost universally held by geologists and physicists a few decades ago that the Earth's interior is a molten mass upon which the comparatively thin crust floats. When we examine carefully the grounds for this conclusion, we are somewhat surprised to find that it rests upon temperature observations extending through a few hundred, or at the most a few thousand feet of the Earth's surface materials, and upon the La Placian hypothesis of the Earth's origin. Added to this is the tacit assumption that volcanoes must be in communication with a fluid interior.

The La Placian hypothesis is now pretty generally discredited, while the explanation of volcanic lava effusions requires no such mechanism as a fluid Earth. In fact such an explanation creates more problems for the vulcanologist than it solves. We may, therefore, reject all other suppositions and examine very briefly the validity of the projected temperature gradients, which have been asked to prove so much.

From a multitude of temperature observations in deep wells and mines it has been determined that to the depth of observation, some 7,500 feet, the temperature increases on the average at the rate of about 1 degree F. for every 60 or 70 feet of descent. By a rectilinear extrapolation of this observed gradient, it can easily be shown that at a comparatively slight depth, say 20 to 30 miles, the temperature is high enough to melt any known substance, and at less than 200 miles it is beyond the critical temperature of all substances. But what are the grounds for the assumption that the temperature continues to increase at the same rate to indefinite depths? Chamberlin, Barrell and others have pointed out the fact that this again rests either on preconceived notions of the Earth's origin and history, or on the assumption that the small-scale conditions of the laboratory must necessarily hold within the unknown depths of the Earth. As Barrell says, speaking of the conclusions of Arrhenius: "There is no demonstration as to why this rectilinear extension is assumed, whether it is to be regarded as an adiabatic temperature curve produced by condensation under pressure, or produced in some other way. The influence of cooling throughout geologic time in changing the outer gradient is not considered; nor the influence of rising magma." The effect of radioactivity alone is sufficient to cause a revision of all the older opinions of the Earth's temperature gradient. Even if a fairly high temperature gradient be granted, there is no guarantee that material would be fused, except locally, because of the great elevation of fusing points by the pressure.

The evidence that the interior of the Earth is not fluid, but extremely solid and rigid, is, however, of an entirely positive sort. It rests upon three principal lines of investigation: the reaction of the Earth to forces and stresses of extraterrestrial origin, such as tides and precession; the way in which the body of the Earth transmits elastic waves; and direct experimentation upon rock materials under high temperatures and pressures.

The fact that the Earth continues to rotate at all is evidence of rigidity. Kelvin illustrated this by attempting to spin raw eggs about their longer axis. The failure to spin is due to the internal friction of the liquid material. The hard-boiled egg will spin easily. But the axis of form and the axis of rotation of the Earth do not exactly coincide; and consequently the Earth spins with a quick weaving or top-like vibration because the axis of figure continually revolves about the axis of rotation, the two coinciding only near the center of the Earth. This is known as the Eulerian motion. According to Euler's computations, based upon the assumption of perfect rigidity, the Eulerian motion should have a period of 306 days, or about ten months. Astronomers were unable to discover such a period in the changes of latitude involved; but in 1890 Chandler, by a careful study of all the recorded changes of latitude, discovered a period of 427 days (14 months); and Newcomb and Hough proved that if the Earth be assumed to have a rigidity somewhat greater than steel, the discrepancy is accounted for. The precessional movement of the Earth's axis, a slow weaving movement having a period of 25,800 years, and caused by the action of extraterrestrial forces upon the equatorial bulge, is also a measure of rigidity, and its evidence is accordant with that just discussed. Newton, Kelvin, Hough and Love have investigated the ellipticity of the Earth, due to rotation, and have shown that on the assumption of perfect fluidity a figure of about 1/230 is derived, whereas the actual ellipticity as determined from various sources is nearly 1/297, and indicates a high degree of rigidity.

The most exact study of the reaction of the Earth to stresses of outside origin, is Michelson and Gale's elegant investigation of the Earth's body tide. Unless it is perfectly rigid the solid Earth must respond to the attraction of the Moon and Sun somewhat as the watery envelope does, but to an infinitesimally smaller degree. Many attempts have been made to measure this body tide, but with only partial success. The problem was finally solved by Michelson and Gale by an ingenious application of the interferometer to the measurement of water tides in pipes buried in the ground and half filled with water. The difference between the observed and computed tides in the water of these pipes is a measure of the body tide of the Earth. It indicates that the Earth is slightly more rigid than solid steel.

Further evidence of the rigidity of the Earth is derived from earthquakes. An earthquake is a complicated network of elastic waves originating at a locus of sudden disturbance upon or within the Earth, and propagated through the materials of the Earth in directions and with velocities determined by the nature of the waves and the density-elasticity modulus and structure of the media in which they travel. When a record of an earthquake is received on the recording drum of a distant seismograph, it will be found to be divided into three easily recognizable parts: the preliminary tremors, the principal tremors, and the end tremors. With the last we have no particular concern. The preliminary tremors consist of two phases, known as first and second preliminary tremors. The principal tremors are due to waves of rather large amplitude that appear to have traveled within the Earth's crust, not far below the surface, and have consequently pursued a circumferential path. The preliminary tremors, on the other hand, have traveled along chords, or more likely along somewhat curved paths within the Earth, and so may have penetrated the Earth to any depth. There is considerable evidence that the first preliminary tremor is due to waves of compression and the second to waves of distortion or transverse waves.

Now the rate of transmission of these waves is a direct measure of the density-elasticity modulus of the Earth; and the fact that waves of distortion are transmitted at all is an indication of solidity. They indicate, again, a rigidity greater than steel. Earthquake waves have the added advantage that they enable us to explore the interior of the Earh to varying depths. As Klotz has phrased it "Seismograms are the Roentgen rays of the interior of the Earth". We shall see later what information they convey.

All of these lines of evidence agree in indicating that the Earth has an average rigidity greater than that of solid steel. Since the materials of the outer shell or lithosphere have a rigidity considerable less than that of steel, it follows that the deep interior must have a rigidity considerably greater than steel.

Finally the careful experiments of Adams, King and Bridgman on the behavior of rocks under very high pressures and temperatures, indicate that the strength of rocks is enormously increased by high confining pressures, and that the fusing points are enormously elevated. Adams demonstrated that granite under a confining pressure of 26,000 pounds to the square inch is four times as strong as when subjected to atmospheric pressure alone. That is, if the granite be confined in a close fitting steel jacket, pressures that would completely crush it in air are not able to close small cavities in the rock. The increased closeness of fit of the crystals and the increased internal friction have greatly increased the strength. Bridgman has subjected rocks to pressures as high as 30,000 atmospheres.

It is perhaps well at this point, by way of caution, to call attention to the distinctions that should be kept in mind between strength and rigidity, and also between viscosity and plasticity.

Rigidity is resistance to change of form, or the resistance to distortion from a unit shearing stress. Strength is measured by the elastic limit. Rubber may be very strong; but it has very low rigidity. To say, therefore, that the Earth is as rigid as steel does not mean that it is as strong as steel. There may be within it zones of little strength, or zones of weakness as they are commonly called by geologists. Viscosity is strictly a property of fluids, and is an internal friction or resistance of the molecules to motion over each other. It may be small or great, as in syrup or asphalt. Plasticity is a property of solids, and is related to elasticity of form. Under sufficient stress solids may flow, either by distortion of the component crystals, or by progressive recrystallization. This is plasticity. Barrell has called attention to these distinctions in his conclusion that the Earth may possess a zone of weakness beneath a zone of strength. To this zone of weakness he has given the name of *Asthenosphere* (*astheneo*, to be weak). But before discussing this characteristic of the Earth, let us review the data as to the probable composition of the interior.

It was pointed out a moment ago that seismograms—the records of earthquake waves—enable us to explore the interior of the Earth. Great earthquakes shake the entire Earth. Such an earthquake as that of San Francisco in 1906, or the terrific Japanese earthquake of 1923 writes its autograph on all the seismographs of the world. If the preliminary tremors travel approximately on chords, they traverse the Earth to all depths. For example, if the receiving instrument is at 120°of arc from the focus of the shock, the deepest part of the chord will lie at 2,000 miles below the surface, or one-half the Earth's radius. At 60° the chord will reach something over 500 miles below the surface. Although the changing density with depth causes these wave-paths to curve slightly, it is possible by the study of a large enough number of records to determine approximately what these paths are. Having determined this point and knowing the velocity of the waves from observation of the time of the shock and the time of arrival of the disturbance at the receiving instrument, the density and elasticity of the Earth become known at all depths.

The bearing of these investigations on the nature of the Earth's interior has been discussed by Oldham, Wiechert, Gutenberg, Knott, Davisson and others. Knott's latest conclusion is, as summarized by Davisson, that:

(1) The outer heterogeneous crust is clearly thin compared with the radius of the Earth, about one two-hundredth part of the radius, or 20 miles.

(2) Beneath this outer crust lies a thick and practically homogeneous layer, in which the primary and secondary waves become separated, owing to their different velocity, and at a depth of about three-tenths Earth radius the wave velocities become nearly constant.

(3) This elastic rigid shell extends to about five-tenths Earth radius.

(4) Beyond 120° from the focus the secondary (distortional) waves seem to disappear, indicating that some rather abrupt change in the material has taken place, and that there may be a non-rigid nucleus of measurable compressibility.

There is no doubt but that the wave velocity is reduced in this central core. There is some difference of opinion as to whether the secondary waves traverse it or not. In any case it probably consists of material somewhat different from that of the middle, highly elastic zone. Since the average density of the Earth is 5.6, and the average surface density 2.7 or 2.8, it follows that the core and the intermediate shell must consist of heavy material. Hobbs concludes that there is a central core with a radius of 2,200 miles composed of material similar to the meteoric iron-stones, and specific gravity 6.9. Outside of this he places an intermediate zone 1,000 miles thick consisting of nickel-iron, with density 7.6. The outer shell, 800 miles thick, is supposed to consist of material similar to meteoric stone, with density 3.6. The superficial shell above this with density 2.7 is very thin.

The most recent and in many respects the most adequate discussion of the composition of the Earth's interior, is an elaborate paper by H. S. Washington on the chemical composition of the Earth. He says: "Of the many and somewhat varied suggestions that have been made as to the distribution of matter in the Earth, that which supposes a solid core of nickel-iron surrounded by a series of solid progressively varying silicate shells now meets with the general acceptance of geophysicists. Such a distribution has been advocated for example by Oldham, Wiechert, Gutenberg, Suess, Daly, Clarke, Adams and Williamson, and the present writer [Washington]...............This concept of the Earth's interior has been arrived at through several lines of evidence; especially the velocities of transmission of earthquake waves through the interior; analogy with meteorites considered as fragments of a cosmic body; the density, rigidity, moment of inertia, magnetism, and other physical characters of the Earth; the compressibility of minerals and rocks; and the chemical and mineral characters of igneous rocks. These lines of evidence are convergent and they are mutually corroborative."

Washington's suggested distribution of matter in the Earth is as follows: At the center is a core of nickel-iron of density 10 and radius of about 2,100 miles. This passes gradually into the lithosporic shell, consisting of magnesium and iron silicates, probably olivine, scattered through a sponge of metallic nickel-iron, the whole having a composition resembling the meteoric pallasites. The average density of this shell is 8, and its thickness about 440 miles. This shell in turn passes outward into the ferrosporic shell by diminution of the amount of metal and increase in that of silicate. This shell is composed chiefly of olivine and hypersthene with 25 per cent or less of nickel-iron. It resembles the chondritic stone meteorites. The average density of this shell is 6 and its thickness 440 miles. The ferrosporic shell grades outward into the peridotic shell, by the gradual disappearance of the nickel-iron and increase of ferromagnesian minerals and labradorite. It is essentially a peridotite, and its composition is similar to that of the achondritic meteorites. Its average density is 4, and its thickness 900 to 1,000 miles. Above the peridotic shell is a basaltic shell of density 3.2 and about 25 miles thick, overlain by the acid granitic shell 9 to 12 miles thick and having a density of about 2.8. The overlying layer of sedimentary rocks is too thin to be considered in the calculations. The computed average density of these shells is 5.49, and the known density of the Earth 5.52. The correspondence is therefore good.

On the basis of the above analysis the central core would comprise 27.3 per cent of the mass of the Earth; the lithosporic shell 8.51 per cent; ferrosporic shell 22.55 per cent; peridotic shell 40.08 per cent; basaltic shell 1.08 per cent, and the granitic shell 0.48 per cent. Also, iron would comprise about one-third of the total mass of the Earth, oxygen coming next with 27.71 per cent and silicon third with 14.53 per cent. Iron, oxygen, silicon, magnesium, nickel, calcium and aluminum would make up 98.2 per cent of the mass of the Earth. Washington finds a comparable relative abundance of the elements in the Sun's atmosphere, although calcium seems to be more abundant there than iron.

It is next necessary to discuss the distribution of mass in the Earth's outer shell. The data on this point are largely derived from observations of the direction of gravity in different parts of the world, and from pendulum observations of the intensity of gravity.

From the well-known statement of the law of gravitation it follows that any mass of the Earth which stands above its surroundings should exert a lateral pull upon all adjacent masses, and that if there are any masses within the Earth of superior or inferior density, they in turn must change the direction of gravity. Now continental platforms, mountains and other eminences do stand above their surroundings, and consequently every determination of the direction of gravity should have a topographic component. The plumb-line seldom points straight toward the center of the Earth. In the determination of the astronomic latitude and longitude of a place, this is called the "station error".

If now there is no deficiency of mass within and beneath the elevated blocks of the Earth's crust, their effects upon the direction of the vertical can be computed provided their volumes are known. When, however, the Himalaya mountains were weighed in the balance by means of the plumb line, they were found wanting; and Airy, Pratt and Petit drew the conclusion that the Earth's crust in the Himalayan sector must be of abnormal lightness. The mountains seemed to float in the Earth's crust, much as an iceberg floats in the water, because of their smaller density. In 1889 Major Dutton gave the name *isostasy* to this state of balance which seems to exist between adjacent blocks of the Earth's crust. The idea of isostasy is one of the most important concepts in geology, and there has rapidly grown up around it an enormous technical literature contributed by geologists, geodecists, astronomers and mathematicians.

The term isostasy is often applied both to the state of balance existing between adjacent blocks of the Earth's crust of equal surface area but different altitude, and to the general theory of isostatic balance. The isostatic state may be illustrated very simply. Suppose a prism of stone and one of iron, each having the same area of horizontal cross-section and the same weight, to be stood on a thick sheet of heavy plastic material; then in time they will sink into the yielding medium until they float in equilibrium. The prism of stone will, however, project out of the medium farther than the prism of iron, because its excess of mass above the yielding medium is compensated by a deficiency of mass beneath. At some level beneath the surface the superincumbent mass in one column is the same as that in the other. This is the level of compensation. It is obvious that the lighter prism above the level of compensation is longer than the denser. If now we substitute a suboceanic prism of the Earth for the prism of iron and a continental prism for the prism of stone, and conceive of them as resting on a yield-zone, or asthenosphere—to make use of Barrell's conception—we have precisely similar relationships of the two prisms, providing they differ in density.

It should be possible to determine the relative density of adjacent masses of the Earth, no matter whether they are above or below sea level; and as a matter of fact this has been done on a large scale by Hayford and Bowie in the United States, and by Burrard and others in Asia and Europe. The pendulum method of gravity determinations has been applied, particularly to oceanic stations; but the geodetic method of Hayford has been most extensively used on the continents. It consists essentially of a systematic study of the station error, or discrepancy between geodetic and astronomic determinations of latitude and longitude. From such studies Hayford and Bowie concluded that within the area of the United States the discrepancies are so small that topographic features must be almost completely compensated by subsurface deficiencies of density, and that the continent as a whole is compensated by the superior density of the adjacent ocean floors. They concluded that the level of compensation is about 76 miles (122 kilometers) beneath the surface. Later determinations by Bowie give about 80 miles. While the depth of compensation cannot be exactly determined, Barrell concludes that under any tenable hypothesis all the compensation lies within the outer one-fiftieth of the Earth's radius.

Barrell has elaborately reviewed the data of Hayford and Bowie, in his monumental study of "the strength of the Earth's crust", and concludes that while minor topographic features are probably not completely compensated, but stand up largely because of the strength of the Earth's crust, nevertheless masses of regional extent are compensated. He favors Gilbert's generalization that: "Mountains, mountain ranges and valleys of magnitude equivalent to mountains, exist generally in virtue of the rigidity of the Earth's crust; continents, plateaus and oceanic basins exist in virtue of isostatic equilibrium in a crust heterogeneous as to density."

It is not feasible to review here any part of the enormous mass of technical details that leads to this conclusion, and to the further conclusion that the rigid and strong crust is underlain by a solid, but weak, zone of great thickness, the *asthenosphere;* but it can be stated that both conclusions rest upon a very substantial foundation of observation and close analytical reasoning. The apparent paradox of high rigidity and zones of weakness will disappear if we recall the distinction between rigidity and strength already stated. The asthenosphere is characterized by high pressure, high temperature, and a delicate balance between temperature and pressure such that any lessening of pressure through deformations of the rigid shell above may cause some of the material of these two shells to pass into the fluid state, thus initiating the accumulation of *magma reservoirs.*

Mountains.

To the layman mountains are merely conspicuous topographic features with limited summit area. They are surface features. But to the geologist they are, with few exceptions, the results of failure of the rigid crust under stresses originating in the interior. They are intimately related, therefore, to the constitution and dynamics of the Earth's interior, and are the outward manifestation in folding and fracturing, of very slow secular changes that are in progress below the surface. For this reason the discussion of mountains has been postponed till after the description of the interior.

A mountain range or crescent is an elongated zone of folding or wrinkling and fracturing of the Earth's crust. It seems to represent in the main a strain resulting from compressive stress. This is illustrated when sheets of paper are caused to buckle and slide over each other by pushing against their edges. If long sheets of wax, plaster of paris or clay, be placed in a box, loaded with shot, and compressed by moving the movable end of the box against them with a powerful screw, as in the experiments of Bailey Willis, the types of folds and fractures found in mountains can be very accurately reproduced. By a proper application of compressive force to layers of plastic material, curved or crescent-shaped wrinkles, similar to the mountain loops of the Alps and eastern Asia, can be produced. It is, therefore, generally conceded that mountains are the result of the action of thrust or tangential compression in the Earth's crust.

Since the Earth is a spherical body, a condition of compressive stress in the crust must be related to radial shortening or shrinkage of the entire mass; to expansion of the crust from heating or the release of confined material; to the movements of magma; to the sagging of basin-shaped depressions in which sediments are accumulating; to the down-sinking and wedging action of heavy sectors; to creep, slump, etc; to changes in the Earth's figure due to changes in the rate of rotation or the position of the axis of rotation; to the operation of stresses of extraterrestrial origin; or to various combinations and associations of these causes.

This is not the place to discuss the intricacies of mountain structure; but a few of the more significant features may be noted. Seen in plan, mountain ranges and systems usually trend in sweeping curves or crescents. The Asiatic loops already often referred to, illustrate this very perfectly. The uninitiated will most readily detect this in the magnificent island crescents of the Aleutians, Kurile, Japan, Philippine islands, Andaman islands and Sumatra, and in the colossal bow of the Himalayas. The Lesser Antilles, bordering our own Caribbean are another beautiful example. In Asia the oldest crescents are in southern Siberia and outer Mongolia, parallel with the old shield-land of Angara. The youngest are the outer island loops. Between are the great loops of the Altai, Tianshan, Great Khingan, Kuenlun, Himalayas and the coast ranges of eastern Asia, all approximately concentric with the ancient border, and arranged like giant festoons throughout eastern and southeastern Asia. The Alps and Apennines, Carpathians and Balkans, and in Asia Minor the Taurides, carry out the plan. In America the ranges of the central Rockies remind us of the great loops of the East Indies. The Alaskan and Endicott ranges of Alaska, the Coast ranges, the swinging curves of Mexico and Central America, the symmetrical mountain border of South America; even the mighty sweep of the Appalachian ridges from Newfoundland to Alabama, and the subdued ranges of Brazil conform to this wondrous scheme.

In vertical cross-section mountain systems exhibit series of up-and-down folds—anticlines and synclines—cut by great fracture-planes or faults, upon which the folded slices of the crust have been slid over each other, often to an unbelievable extent. In the arena of greatest disturbance the folds are usually tipped over to one side, or overturned, in the direction toward which the principal thrusting and sliding of the slices or nappes has tended. The amount of overthrusting or horizontal displacement of the slices is prodigious, amounting in the Alps to 80 or 100 miles. Keith estimates that in the southern Appalachians the thrusting and folding combined indicate a total compression of this Earth-segment by as much as 200 miles. The total compression or shortening of the Earth's crust during the entire history of the Earth can only be measured by hundreds, and probably by thousands of miles. Unless these localized compressions have been compensated by extension of the crust in other regions, of which there is little evidence, the Earth's diameter has been shortened one mile for every 3.14 miles of crustal shortening. It is obvious that the Earth has been growing smaller.

When we decipher the history of a mountain system, such as the Appalachians, we discover one further remarkable fact, first brought to the attention of geologists by James Hall, though suspected by Babbage and Herschell; namely that every great mountain system stands where once a great depressed trough or geosyncline lay below the sea, accumulating sedimentary deposits throughout vast periods of time. These *geosynclines*, as Dana called them, sink as they are filled with sediments, sometimes until tens of thousands of feet of sediments have accumulated, and until finally the weakened crust gives way and brings in play the mighty compressive mechanism that slowly buckles them up into a mountain system.

The great geosynclines of North America and South America according to Schuchert seem to have lain between the ancient shields and extensive marginal lands or border-lands, now foundered beneath the margins of the adjoining oceans—dragged down by their subsiding deeps. Thus have disappeared ancient Appalachia on the east, and Cascadia on the west of North America; and an old land that once lay off the west coast of South America.

HYPOTHESES AND SYNTHESIS.

There are many hypotheses of mountain building and the origin of the continents, but they nearly all agree on one point, that shrinkage of the Earth is the dominant factor. How this shrinkage has been caused, and by what specific mechanism the vertical descent of the Earth's mass toward the core has been transformed into tangential thrust sufficient to fold and slice the contorted crust and compress it by hundreds of miles, is a problem still awaiting final solution. I shall refer briefly to the main hypotheses.

To the ancients, sudden catastrophic upheaval seemed a sufficient explanation of all the Earth's diversified topography, and seemed to fit well with the volcanoes and earthquakes of the eastern Mediterranean home of the elder civilizations. It was not until the close of the 18th century that considered theories of the origin of the Earth and its physiognomy began to emerge out of the fog of fable and ecclesiastical repression. Lehmann and Füchsel, Humboldt and Von Buch, Pallas and de Saussure laid the foundations of more modern conceptions; but they generally appealed to forces of upheaval rather than to tangential thrust as the cause of mountains. Hutton appealed to the expansive force of internal heat; and Babbage, Lyell and de la Beche accepted this view. Elie de Beaumont, in the first half of the 19th century, was the first to suggest that contraction of the Earth as a result of cooling would produce a state of compression in the rigid crust; and this theory of the cause of mountains has been the dominant view ever since. de Beaumont, however, regarded the action as sudden and of the catastrophic order.

It remained for Hall, Dana, and LeConte, in America to put the theory of tangential thrust on a sound basis and to point out the importance of regions of sedimentary accumulation—geosynclines—as a preparation for mountain building. Hall believed that loading of the crust caused subsidence, and that the rise of internal heat into the sediments, together with the pinching resulting from the sagging of the trough, caused the folding. Dana pointed out the inadequacy of this as a cause of folding, and appealed to secular cooling of the Earth as an adequate explanation. This view became little short of a dogma in 19th century geology.

The pentagonal reseau of deBeaumont and the tetrahedral theory of Lowthian Green, I need not discuss.

As the prodigious amount of crustal compression became known, geologists began to doubt the adequacy of secular cooling, and Osmond Fisher showed it fallacy. It is interesting that one of the latest books on Earth genesis, by Harold Jeffreys, returns to this well-worn theory, and tries by a new mathematical analysis to show that it is adequate. He greatly underestimates the amount of compression to be accounted for.

With the general abandonment of the theory of secular cooling, some returned to the geosynclinal theories of Babbage and Hall, while others sought for additional causes of shrinkage. Still others have appealed to changes in the ellipticity of the Earth, shifting of the axis of rotation, suboceanic spreading and continental creep, and drifting of the continents. Suess, in his magnificent analysis of the Face of the Earth, represents the continent of Asia as creeping outward over the margins of the subsiding deeps in response to a thrust acting toward the oceans. He appealed to general contraction, however, as the cause of the thrust. Hobbs believes the thrust came from the oceanic side. Taylor and Wegner have attempted to prove that the continents tend to slide toward the equator with a southward and westward movement, and that their margins are mashed and crumpled by the resistance of the subjacent zone. Wegner's theory is the most elaborate of this type. He supposes that the present continents once constituted a large continuous land mass, and that this split, and North and South America drifted away from Eur-Africa toward the west, the light *sial* of the continent floating on the heavy *sima* beneath it. Australia pulled loose and lagged behind toward the east. The island crescents of eastern Asia are the ravelings pulled off the eastern border of the drifting residual mass.

With the general acceptance of the theory of isostasy has come another revision of theories of mountain-making and continental origin. Bowie, Burrard and others have tried to find in isostatic readjustments a *vera causa* of mountain folding; but most geologists have written the word inadequate across this explanation. Bailey Willis believes in the interaction of many light and heavy masses. Chamberlin, whose profound planetesimal theory of Earth origin is now generally accepted, argues from the gradual manner in which he believes the Earth to have been built up, that it would have had such a degree of primitive heterogeneity as to permit a very large amount of subsequent gravitative condensation, because of extensive chemical, mineralogical and subatomic reaggregations of matter within it, as compression gradually increased in the growing Earth.

Chamberlin further argues that the Earth very early in its history achieved a major segmentation as a result of which the superior density of the suboceanic or master sectors was produced, and that the oceanic areas have as a consequence always been areas of subsidence, with the continents, or squeezed sectors, pinched between them. He considers this pinching as the direct and adequate cause of mountain folding and its marginal location, and of the final foundering of the ancient borderlands. If, however, isostatic compensation is complete at a depth of 80 miles, and below this depth lies a yielding asthenosphere, it is difficult to see how direct wedging pressure of the oceanic sectors, sufficient to produce the extraordinary amount of compression observed, can be brought to bear. The comparatively thin rigid crust would not be stiff enough to administer the terrific push. This objection lies against all theories of sub-oceanic spreading. Chamberlin, to be sure, tries to escape it by making his solid wedges extend to the core of the Earth; but as Barrell has pointed out, this virtually denies isostasy. Nevertheless the origin of the thrust must be deep-seated, and I believe that Chamberlin is right in regarding the heavy oceanic sectors as the main reservoir of the mountain-making force.

Recently Keith has suggested a mechanism which in part escapes this dilemma, namely the tangential pressure of rising wedges of fluid magma invading the rigid shell. Subsidence of the oceanic sectors is appealed to as a source of the hydrostatic pressure which sets the magma in motion and lifts it into the crust. Keith's theory leaves much to be desired, but I believe that with slight modification it is a serviceable hypothesis.

Suess and Hobbs have shown that the island arcs of Asia, faced by fore-deeps, are backed by volcanic belts. A similar arrangement is found in other mountains. Hobbs has further shown that the rising mountain ridge, of which the islands are only the crest, tilts backward away from the fore-deep. As the anticlinal ridge rises, the synclinal fore-deep sinks, and underthrusts it. There must certainly be a lateral movement of material from beneath the deep into the region under the anticline. We may now assume that the pressure of the subsiding oceanic wedge against the continental margin has been sufficient to initiate the bowing and folding of the rising arch. With the first lifting of the arch the pressure is relieved below it to a slight extent, and the subjacent material, always at the critical boundary between the melting urge of high temperature and the restraining hand of pressure, will begin to liquify and form a magma reservoir. This will be encouraged by dilatation of the material of the rising arch, as recently suggested by Mead. Rising into the anticline through the shear zone and pursued by the heavy solid material moving plastically through the asthenosphere, from beneath the subsiding ocean floor, the magma will flow under the folding sedimentary beds, dragging them on its back, shoving and folding them, and finally wedging and eating its way to the surface, and emerging to the light of day in the row of volcanic vents.

In the Atlantic and Indian areas the sinking oceanic sectors have dragged the former continental margins down with them. Thus has India been severed from Africa and Africa from South America; while the encroaching Indian, Pacific and Atlantic deeps have whittled off the southern ends of South America and Africa, separating them from Antarctica. Along the eastern and western coasts of North America and western coast of South America the ancient border-lands have foundered into the abyss; and the continent of Antillia has been rent asunder.

Let us try now to gather the bewildering details of the Earth's interior and exterior architecture into a consistent scheme. Let us stand once more at a point removed, where facade and transept, tower and dome, column and pilaster and corbel, arch and buttress and window blend into harmonious beauty. Let us walk through its lofty corridors, where nave and bay and aisle, altar and choir and chancel, apse and chapel fit into the groined and pillared framework. Only so shall we comprehend the building of this mighty edifice.

The continents and ocean beds are the primordial light and heavy sectors of the Earth's framework, balanced, but striving against each other in eternal search for that isostatic adjustment which is continually disturbed by the shifty play of wind and rain, weather and stream and ice, wave and current upon their surface; and by the uneasy Titans of heat and pressure and chemical and atomic transformation that heave and groan deep beneath the crust. The mountains and plateaus, the fore-deeps and the central sags, the shifting strand, the troughs and geosynclines, the ragged outlines of the mediterraneans with their shoals and deeps surrounded by the flotsam and jetsam of disrupted lands, the wreckage of continents and shields strewn about the borders of the Indian and Atlantic seas, the sunken reefs of the Pacific, the foundered borders and the tapering southlands are the visible expression of the age-long struggle to build the framework of the Earth.