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JOSEPH BARRELL
1869-1919

BY

CHARLES SCHUCHERT

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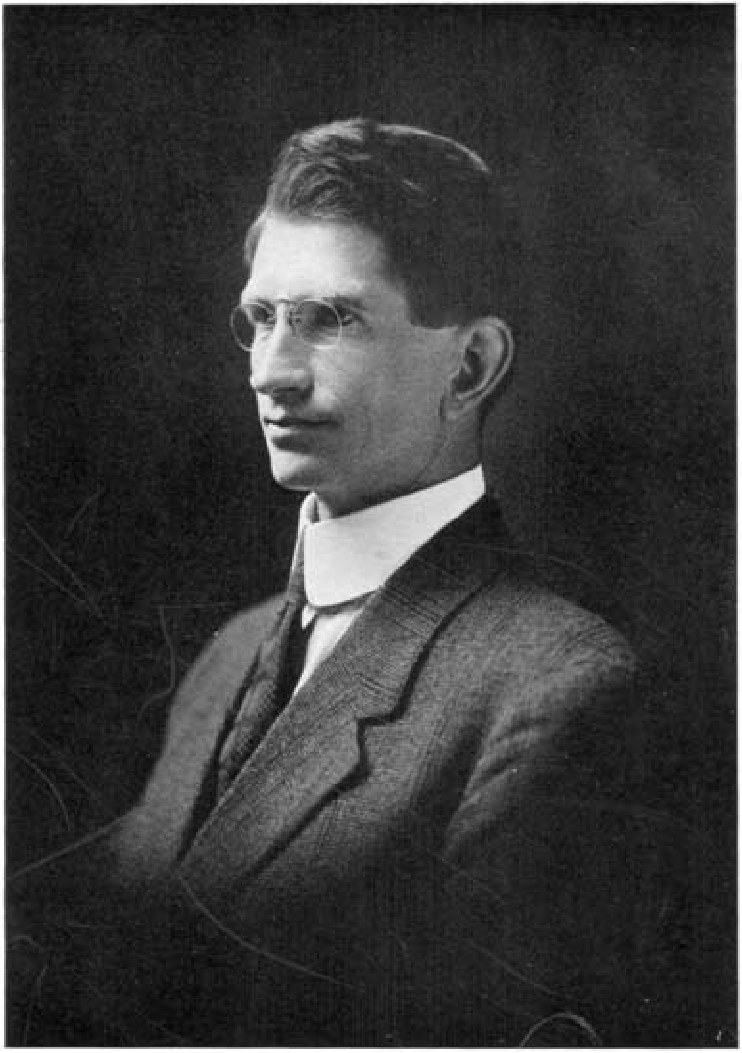

Joseph Barrell

JOSEPH BARRELL, ENGINEER-GEOLOGIST

1869-1919

BY CHARLES SCHUCHERT

JOSEPH BARRELL'S scientific life coincided with the "Golden Era" of Geology in America, and in him American Geology has lost a leader who promised to stand as high as the highest. "Those whom the gods love, die young." His period of educational preparation, balancing of personal characteristics, and storing up of fundamental experiences was back of him. Had he lived longer he would have become the chief exponent in the subjects of geologic sedimentation, metamorphism, structural geology, the geologic bearings of isostasy, and the genesis of the earth. T. C. Chamberlin writes: "We had come to look upon him as one of the most promising leaders in the deeper problems of earth science"; Bailey Willis, that "there is unanimous recognition of the fact that Barrell was one of the strongest of the younger leaders and a man of great promise"; John M. Clarke, that Barrell's death "is a truly overwhelming disaster for American Geology."

Upon his colleagues at Yale, Barrell's death, following so soon after that of Irving, fell as a heavy blow. Coming to us as a matured and highly educated young man, we saw Barrell grow into a leading geologist who exceeded our hopes and more than justified our choice of him to fill the chair of Structural Geology created for him at Yale. He was a power among us, and it was around him that our graduate courses in Geology were built. Personally, we are bereft of a friend and councillor whose place can not be filled—one whose simplicity of nature and strength of character were unique. His great fund of knowledge was always gladly placed at our disposal, and his constructive criticism and fertility of suggestion have been the stimulus to more of our work than we shall ever realize. We rejoice that the privilege was ours of working with him, and in our hearts there will always remain the grateful memory of his inspiring personality.

Barrell's death occurred in New Haven, Connecticut, on May 4, 1919, after a week's illness with pneumonia and spinal meningitis. He left a wife, Lena Hopper Bailey, and four sons, Joseph, Herbert Bailey, William Colburn,* and Richard Lull. Standing 5 feet 10.5 inches in height, of the blue-eyed Nordic type, with a full head of wavy light brown hair, he was pale and spare of build, and yet of great muscular strength—the "strong man" of his class at Lehigh. Once seen, he was easily remembered, and he was quickly picked out in a crowd. This was due in part to his tall slender build, his long and awkward stride, and his confident bearing, but more especially to the strength of character reflected in his large features, particularly the wide mouth and long, narrow nose, concave in profile. He prided himself on the longevity of his ancestors, and from a careful study of insurance tables held the unshakable belief that some thirty years of active life were ahead of him.

Modest and optimistic, with a strong independence of mind, he prized true worth highly, and was easily aroused to criticism of posers and social climbers, and of shams and errors. Simple in attire, and fond of simple living, his intellectual ideals were of the highest. He cared little for popularity, or for adverse criticism, and not much more for praise. His colleague, Professor Gregory, says that what he valued most was "uninterrupted time for research and intellectual fellowship established through writings. His intellectual power was so obvious and so continuously displayed that twenty years of intimacy has left on me an impression of a mind rather than of a man. His mind was of surpassing fertility, imagination, and machine-logic." In appearance and mentality, Barrell reminded his older colleagues at Yale of James D. Dana; whatever subject these two great geologists touched was made clearer and the way indicated for new lines of research.

A man of science, and especially one deeply interested in generalizations, should be endowed with imagination under restraint. Barrell had a great deal of this quality, and loved to speculate under the limitations of the "multiple hypothesis." No man ever had better developed the power of detachment

* Since deceased.

from his own views. He could examine his conclusions from all angles. As Davis says, "He interested himself in thinking about how he thought, and tried to evaluate the results of his thinking. He was as careful and critical in this respect as he was fertile and ingenious in mental inventions."

An omnivorous reader and a very hard worker, Barrell never tired of unraveling the intricacies of earth structure, and having a marked faculty for picturing his thoughts, he not infrequently expressed an idea in graphic form before he put it in writing. His method of presenting a subject was to prepare his reader for what was to come, and then to set forth in detail the processes and principles that underlie the results sought for. This is why most of his papers are lengthy and in places tedious. His earlier articles were not well written, and he constantly sought to improve this weakness.

In the scheme of instruction at Yale, Barrell had charge of two classes: a half-year undergraduate course in Historical Geology, and a full-year course, primarily for graduates, in Dynamical and Structural Geology. At times he also took part in teaching small groups in Field Geology, and nearly every year he gave a special course to graduate students in which the literature and the solution of problems along structural and dynamic lines constituted the subject-matter. Before the class, Gregory says, "he was the geologist rather than the teacher of untrained minds. . . . The recognition of the average undergraduate viewpoint played little part in his teaching." Accordingly, in his earlier career at Yale the boys found him too statistical, and on the campus he was known as "Old Bathylith" and "Interstitial Relations"; later, however, these friendly nicknames vanished.

In graduate teaching, Gregory continues, "where analytical thought, mental invention, breadth and depth of knowledge make the successful instructor, Barrell had few equals." The more mature his students, the more enthusiastic they were in his praise, and he gave them much that was not to be found in books. Difficult his course was, and exacting his examinations, but the student who completed them was thoroughly grounded in the principles of Dynamical and Structural Geology.

FAMILY HISTORY [1]

The name Barrell, spelled in many ways, had its origin among the ancient land-holding knights of Normandy, and appears in England for the first time with the battle of Hastings and William the Conqueror in 1066. The first of the family to migrate to America was George Barrell, a cooper by trade, who arrived at Boston from St. Michaels, Suffolk, in 1637, and died there in 1643. He became a freeman of the Boston parish on May 10, 1643, and owned a house and a half acre of ground (for which he paid 31 pounds) on what is now the southeast side of Hanover Street between Elm and Washington. He had but two sons, and one of them, John, also a cooper by trade, married Mary, daughter of William Colburn, one of the twelve original founders of the colony. It is from this union that all of the American Barrells of colonial origin have sprung.

Until recently, the Barrells have been in the main sea-going people, ship-owners and merchants. The second John Barrell was a mariner, and his son John a well educated man and a successful shipping merchant. Professor Barrell in his genealogy of the family says of John III: "The hazards of travel and of residence in tropical lands, however, told severely upon their number, so that notwithstanding several large families of sons, his descendants bearing the name have remained few in number and widely scattered."

The most widely known and wealthiest was Joseph Barrell of Boston (1739/40-1804), after whom the subject of our sketch, his great grandson, was named. He married three times and had twenty children. This Joseph Barrell was an original thinker and a good speaker and writer. He is said to have "early espoused and firmly maintained the cause of his country," and for a time represented the town of Boston in the State Legislature. He lived well, and it was in his splendid home that General Washington was entertained during his visit to Boston. He was also one of the group of men who fitted out the ship "Columbia" and sent her into the Pacific,

[1] Taken from a genealogy of the Barrell family prepared by Professor Barrell, but not published.

where in 1792 her crew discovered the Columbia River. Later they purchased of the Indians the territory about this stream, and in this way began the colonization of what have since grown to be the Northern Pacific States of the American Union.

The father of Professor Barrell, Henry Ferdinand, was born in New York City, October 3, 1833. His son says he "grew up with a strongly developed taste for books, for nature, and for life in the country." Henry Ferdinand's father bought him a farm near Warwick, Orange County, New York, and it was here that he met his wife, Elizabeth Wisner, whom he married on March 15, 1858. The Wisners, originally from Switzerland, had been real estate holders for 150 years and officers in the colonial and later wars. In 1864, Henry Ferdinand Barrell sold this farm and bought another at New Providence, New Jersey, and here from 1875 to 1895 he served as chairman of the trustees of the public library and of the public school in which the subject of this sketch received his primary education. He had nine children, of whom Joseph was the fifth child and the fourth son.

ACADEMIC CAREER

Joseph Barrell, the subject of this memoir, was born at New Providence on December 15, 1869. As a child, he was more interested in books on natural history, astronomy, and history, than on general literature. His mother, after whom he takes, related to the writer that frequently he would get a volume of the Encyclopedia Brittanica and sit for hours reading it. At the age of ten years, he was given a planisphere and often at night would take it and a book on astronomy, along with a lantern, and then lie on his back gazing at the stars, and so learn their names with the aid of the planisphere. Joseph attended the public school until he was sixteen years old, and two of his teachers prepared him privately for college. Before going to college, however, it was necessary for him to earn some money, and so he taught school during 1886-1887. For this he received two hundred dollars, and with further assistance from his parents he attended the Stevens Preparatory School at Hoboken the following year. Here he won a scholarship for Stevens Institute, but preferred a college course at

Lehigh University, which he began in September, 1888, and completed four years later with high honors. In 1893 he received from the same university the E. M. degree, in 1897 its M. S., and in 1916 its doctorate of science.

In a sketch of himself written for the twenty-fifth anniversary of his graduation at Lehigh, Barrell says that in 1893, when he received his engineering degree, "I regarded myself as lucky in securing an instructorship at Lehigh in mining and metallurgy." This position he held for four years, teaching mechanical drawing, mining and metallurgical design, making shop visits to various metallurgical plants, and practising surveying with students in the anthracite mines. "Teaching," he goes on to say, "is always better training for the teacher than for the taught. . . . The summers were put in in gaining experience, parts of the winters were employed in studying Geology and practical Astronomy, for which Lehigh gave me the degree of M. S. in 1897." His thesis in fulfillment of the requirements for this degree is 419 pages long, and is entitled "The Geological History of the Archean Highlands of New Jersey, including their Extension in New York and Pennsylvania." In it appear some of the problems on which he later worked so much.

In 1898, Professor E. H. Williams, Jr., contemplating a division of his work at Lehigh, persuaded the university to hold vacant for two years the position of assistant professor of Geology, provided Barrell would spend that time at Yale in advanced work. Barrell says that this opportunity "was a most generous one. I spent the following two collegiate years at Yale and the summers working in Montana for the U. S. Geological Survey in general and mining Geology." In 1900 Yale gave him the degree of Ph. D., and tradition has it that he was the ablest student of Professors Penfield, Pirsson, and Beecher. In this way, as Barrell says, "a mining and metallurgical education, combined with a panic year on leaving college, had led logically into a career as a geologist. The initial engineering education and the experience of the eight years following 1892 formed the broad and solid base on which the following work has been built."

For three years after 1900, Barrell taught Geology at Lehigh, with Zoology as a side issue. In 1902, he was married there to Lena Hopper Bailey. The three summer months of the year preceding were spent in Europe with Professors Herbert E. Gregory and Charles H. Warren, travelling "by foot, by bicycle, and by third-class trains, the object being to see the countries and study Geology rather than to do sightseeing in the cities."

"What better course," says Gregory, "could be devised for a man set aside as a physical geologist than that chosen for and by Barrell: elementary school and high school in a rural village, a year at a city preparatory school, four years of engineering studies, six years of mining practice combined with teaching of mathematics, astronomy, mining and metallurgy, and capped by two years of graduate study of field and laboratory problems? Few men at the age of thirty-one have built such a broad and solid base for a future scholarly career."

In 1903, Barrell was asked to come to Yale to develop the field of Structural Geology, and his decision to accept the invitation was the turning point in his career, since by it he turned his back on the more profitable field of mining engineering and set his face toward graduate teaching and research. He was at first assigned to the Sheffield Scientific School, but Professor Gregory's classes in Geology in Yale College had grown so rapidly that Barrell was transferred to that department of the University in the following year. Needing still more help, the College in 1905 appointed Isaiah Bowman to teach Physiography and Geology, and two years later Ellsworth Huntington came to give work in Geography. All of this teaching was done in the Peabody Museum, where E. S. Dana, Charles Schuchert, and R. S. Lull also had their offices. This group of men reacted intellectually on one another in their daily intercourse, and here the extent of Barrell's dynamic influence can not be measured, except as the printed product of the other men in the decade between 1905 and 1915 bears testimony to it.

Barrell was a member of the honorary scientific society of the Sigma Xi, and president of the Yale Chapter in 1914. He was also elected to the Phi Beta Kappa Chapter of the same University. He was a fellow of the Geological Society of America, the Paleontological Society, and the American Association for the Advancement of Science, and a member of the American Academy of Arts and Sciences. Only four days before his death, there came to him the news of the highest honor that can be given to an American scientist, election to the National Academy of Sciences.

As a lecturer, Barrell was often called on by other universities. In 1912 he gave a series of five lectures at the University of Illinois, dealing with "The Bearing of Geology on Man's Place in Nature" and "The Measurements of Geologic Time." In 1914 he gave a course of three Sigma Xi lectures at the Universities of Missouri and Kansas. At Columbia two years later he gave six lectures on isostasy, and at Yale he presented before the Sigma Xi and Phi Beta Kappa societies his interesting talk on "The Habitability of Worlds."

WRITINGS

An analysis of Barrell's writings shows that he progressed from simpler relations to the most complex of geologic problems. It is also clear that his best results were obtained through generalizing from the publications of others. He loved to assemble the published data derived from field and laboratory, and along with his own observations, subject all to the test of multiple hypotheses, so as all the better to ascertain the correct explanation of the facts examined. As Willis has said, Barrell was first an engineer in Geology, since his training had led him to precise habits of thought, and it is this characteristic that especially distinguishes his work. He himself has said that "geologic research in the past generation has been passing out of the qualitative stage and has partaken notably of the quantitative character."

Barrell's first publications, in 1899 and 1900, deal in mining, but those since 1901 have nearly all had to do with Geology. His bibliography, if completed in detail, would take note of about 150 notices and reviews of books, most of which appeared in the *American Journal of Science*. Of these, nineteen contain original matter and are therefore included in the bibliography which accompanies this sketch; in general they deal with isostasy, the origin of the earth, and metamorphism, the subjects with which he was most familiar. When he set himself to write a review of a book, he produced a lucid analysis, with discussions of the conclusion attained by the author.

Of short papers and longer memoirs, his bibliography includes about sixty, totalling nearly 2000 pages.

MINING ENGINEERING

Barrell's first experience as a mining engineer was in 1894, with the engineering corps of the Lehigh Valley Coal Company, at Wilkesbarre, Pennsylvania. In June, 1897, he joined the staff of the Butte and Boston Mining Company of Butte, Montana, and worked with them and the Boston and Montana Company for over a year. "The work was interesting," he says, "and involved difficult problems in the plumbing of crooked shafts, and the measurements of amounts of ore extracted from old workings." These experiences led to his publishing in *Mines and Minerals* during 1899 and 1900 a series of five papers which he wrote while at Yale studying for the doctor's degree. These papers have to do with the methods and errors of mine surveying,—instrumental errors, methods of keeping stope books, and choice of survey instruments. They abound in mathematics and in diagrams, and thus foreshadow two of Barrell's future tendencies in Geology.

REGIONAL GEOLOGY AND METAMORPHISM

During the summer months of 1899, Barrell was field assistant to W. H. Weed of the United States Geological Survey, mapping the ore-bearing formations of the Elkhorn Mining District of Montana. This work, Barrell states, was done alone, much of it on horseback, in the mountainous region between Butte and Helena. It involved a study of the great successive intrusions of molten rock which in the early Tertiary had broken up the crust and brought in the wealth of gold, silver, and copper. The first result of these field studies was the publication of the "Geology and Ore Deposits of the Elkhorn Mining District," by W. H. Weed, with an "Appendix on the Microscopical Petrography of the District," by Barrell.

These observations Barrell made the basis of a dissertation for the doctorate when he returned to Yale in the autumn of 1899. Under the guidance of Professor Pirsson, he made an elaborate petrographic study of the rocks, along with the geology of the Elkhorn area, resulting in a dissertation which was entitled "The Geology of the Elkhorn Mining District."

This Elkhorn work contained a chapter on "The Physical Effects of Contact Metamorphism," which was published in abstract in the *American Journal of Science* in 1902. In this paper Barrell discussed the changes of mass and volume through metamorphism, and stated, among other things, that the shrinkage in rock of certain compositions may be "from 25 to 50 per cent in volume, attended with the evolution of great quantities of gases which at surface pressures and temperatures would amount to several hundred times the volume of the original sediments."

In the summer of 1900, Barrell was again employed by the United States Geological Survey in a two months' reconnaissance of the surface geology of the Deerlodge region of Montana, and of the underground geology of Butte. The next year he began, again under the direction of Weed, a three months' geological survey of the surface and underground geology of the Marysville mining district, Montana. These results, also worked out at Yale and published as "Geology of the Marysville Mining District, Montana: a Study of Igneous Intrusions and Contact Metamorphism," reveal a mastery of petrography and chemical mineralogy. The region was one of the noted gold-producing centers of Montana, and the mines were situated around the margins of the irregular Marysville bathylith of quartz diorite. The Marysville bathylith is "but 6 miles at its nearest point from the exposed surface of the far greater Boulder bathylith, a granitic mass which is petrographically a quartz monzonite in normal composition. The Boulder bathylith possesses a general rudely rectangular form, occupying about 60 miles in latitude by about 35 in longitude, and holds within its confines the mining city of Butte, from which for many years past has poured a flood of silver and a quarter of the world's copper. Other smaller mining centers also lie within this large granitic area, while such important ore deposits as those of Elkhorn and Unionville, south of Helena, have been found about its margin."

The Marysville report has now become one of the classics in Geology, and of it Pirsson in a review in the *American Journal of Science* says: "The special character of this work lies in the detailed investigation of the bathylithic body, of the method of intrusions, of its form, and of its relations to the surrounding rock masses both past and present." The intrusion Barrell could not explain by the accepted methods, and did so by a new theory, that of magmatic stoping. Daly, in his book "Igneous Rocks and their Origin," states that "It was in the Cordilleran region, at Marysville, Montana, that Barrell independently originated the stoping theory of magmatic emplacement."

Because of the large scale on which the Boulder and Marysville bathyliths are exposed, and because of the forceful presentation of the field relations and the clearness of Barrell's inferences therefrom, Suess, in his great work, "The Face of the Earth" was led to say that the Marysville report is "one of the most instructive works produced in modern times" connecting granitic invasions with volcanoes.

In 1904 appeared Van Hise's epochal "Treatise on Metamorphism." Great in volume and depth of thought, this book made a profound impression on Barrell, and his copy of it was read and re-read so often that it soon fell to pieces. All of Barrell's students also had to do much reading in this book, and in 1905 he wrote an extended review of it for the *American Journal of Science,* in which he states that Van Hise has made of metamorphism "an exact science," that its phenomena express the "chemical and physical laws operating within the crust of the earth," and that they are here presented "in the most systematized form." The book is a "landmark of a new era." To Barrell, however, Chapter 11 was the most interesting, since it treats of the relations of metamorphism to the distribution of the chemical elements, and in his notice he devotes more than one half of the space to it.

Metamorphism always remained one of Barrell's foremost lines of study, and as late as 1914 he wrote "Relations of Subjacent Igneous Invasions to Regional Metamorphism."

This paper was published in 1921 under the editorship of Professor Frank F. Grout. Some of its summations are as follows: Bathyliths come into place either accompanied by crustal compression, as in the Appalachians, or without folding, as in the Cordilleras. The features of metamorphic rocks are due in the main to bathylithic invasion and compression; to a less extent to movements of solutions, selective crystallization, lit-par-lit injection gneisses, and the alternation of injection and mashing. Magmatic solutions are not of meteoric origin, and the results in minerals depend upon equilibria,—largely on the presence of H_2O and CO_2.

EROSION, SEDIMENTATION, AND CLIMATOLOGY

After some years as an instructor of graduate students in Dynamic Geology, Barrell's ideas in regard to processes of erosion, sedimentation, the formation of deltas, and the discerning of ancient climates in the sediments took form, and it was on these subjects that he next wrote. He it was, more than any other, who led geologists away from the prevalent idea that nearly all strata are of marine origin, and toward what Coleman has called "dry land geology," namely, to the recognition that one fifth of the present lands are mantled by continental deposits. Nearly one fourth of his publications follow these lines. As Vaughan says, Barrell organized the principles of sedimentation "into a consistent body of usable criteria, and applied them to the interpretation of many formations." He also did much to build up the science of Paleoclimatology, and in Paleogeography he established principles for discerning the shore-lines of the seas, and the extent and elevation of the ancient lands that were furnishing the marine sediments. Had he lived longer, he would have done much more, for an unusually stimulating opportunity had come to him as chairman of the newly founded Committee on Sedimentation in the National Research Council.

In 1906, Barrell published a series of three papers on the "Relative Geological Importance of Continental, Littoral and Marine Sedimentation" in the *Journal of Geology*. Here, as in most of his papers on sedimentation, he is dealing with fresh-water deposits, those of deltas, and those of the littoral region of the seas. To have a correct knowledge of marine sediments one should of course know their origin and nature on the lands, and while this logical sequence for study had much to do in leading him to work mainly with continental formations, the fact of his environment probably had most to do with these predilections. Barrell was raised on Triassic strata that are composed of conglomerates of fresh-water origin, and as a teacher of students at Yale his excursions were largely to fresh-water and estuarine strata. James D. Dana had long been explaining the Triassic strata in eastern North America as of estuarine origin; to-day everyone sees that their genesis came through fresh water in areas between the mountains of Permian making, and under semiarid climates.

In these three papers, Barrell sets forth a quantitative view as to the relative geologic importance of continental, littoral, and marine types of sediments, and the criteria for separating them. It is a study of facts already assembled in the geologic literature, and an application of changing and cyclic geographies to stratigraphy. Among other things he develops the criteria for discerning subaerial delta deposits, and shows that such attain their greatest development after epochs of mountain making unaccompanied by notable uplift of the continental platforms. "The ratio of continental to marine sediments," he says, "should have fluctuated widely through geological time. Following an epoch of continental uplift with mountain-making, the deposits formed in interior basins should attain a maximum, especially the deposits made under desert conditions." Finally, when the lands are greatly reduced, the burden of the rivers is largely that of solution materials, resulting in the wide spread of shallow-water marine deposits.

He also emphasizes the cyclic relations between continental and marine sedimentation in geologic history. The wide and cyclic significance of mud-cracks in association with other features indicating flood-plain deposits is discussed at length and applied to the interpretation of Proterozoic deposits in Montana and the Grand Canyon of the Colorado.

The significance of desert deposits becomes very striking when one notes that one fifth of the present land surface is desert tracts. Barrell estimates that the subaerial deposits of piedmont waste, of continental basins, and of deltas cover about one tenth of the emerged continental surfaces. Adding these "to the estimate of the deposits of arid climates would give a fifth of the land surface as mantled by continental formations." The lands, in the course of the geological ages, are, however, warped and elevated into mountain ranges, so that the geological record "should show a far less proportion of thin and superficial land deposits." On the other hand, basin and delta deposits should be quantitatively as great as those laid down upon the floor of the epeiric seas.

Having developed the principles of sedimentation for continental and shallow-water marine deposits, Barrell applied them in 1907 to a late Mississippian formation in the paper entitled "Origin and Significance of the Mauch Chunk Shale," in which he concludes that "In the anthracite region, more surely in the southeastern and eastern portions, the whole formation [which is about 3000 feet thick], from top to bottom, was a subaerial delta deposit laid down under a semiarid climate." The nearest approach to-day to a similar area is the highly arid Punjab region near the base of the Himalayas and the lower plains of the Indus River. "These comparisons, while not intended to convey the idea that the Appalachians were ever of Himalayan magnitude, are suggestive of a more massive range of mountains and a wider land area to the eastward of the Pennsylvanian geosyncline than is customarily thought of as existing in Upper Devonian and Carboniferous times."

Having seen much of the Carboniferous of eastern Pennsylvania, Barrell had asked himself, "To what extent have the tectonic movements and climatic variations caused the great contrasts seen here in the Lower and Upper Carboniferous formations?" To solve this problem, he took up in detail the principles that have to do with the relations between climate and terrestrial deposits and published his results in a paper bearing that title. He writes: "The environment of the lands may be classified into three fundamental and independent factors—the relations to the surrounding seas, the topography which forms their surfaces, and the climates which envelope them; each of major importance in controlling the character of the lands." Fundamental are the relations of the continental fluviatile deposits to the climates, and they may be successfully used in determining those of the geologic past. "This is exclusive of the significance of salt and gypsum deposits on the one hand or of glacial deposits on the other, which are of course universally recognized, but these are the marks of climatic extremes."

The first part of the paper under review has to do with the relations of sediments to regions of erosion. It deals with the relation of physiography to erosion and the consequent supply of waste as sediments to the formations. Then he takes up the relations of sediments to regions of deposition, and finally the relations of climate to fluviatile transportation. These parts lead to the conclusion that "Climate is a factor comparable to disturbances of the crust or movements of the shore-line in determining the nature and the variations in the stratified rocks of continental or offshore origin, thus playing a part of large, though but little appreciated, importance in the making of the stratigraphic record."

Along with many other things, Barrell finds that "While the varying powers of erosion and transportation are delicate stratigraphic indicators of *climatic fluctuations*, the chemical and organic control accompanying the deposition are the more secure indicators of the *average climatic conditions*."

Finally, what was the origin, environment, and significance of the conglomerate and sandstone formations intercalated between others of different nature? Barrell's answer is that these coarse materials have three origins: first, marine conglomerates and sandstones; second, tectonic conglomerates and sandstones; third, climatic conglomerates and sandstones.

"Changes in volume of ocean waters, earth movements, and atmospheric activities are the three mixed and fundamental causes by which the three classes of deposits become possible, but the records which they embody are largely distinct and independent. By separating conglomerates and sandstones into these three classes, the sedimentary rocks, therefore, present a threefold record, the marine conglomerates giving that of the variable relations of land and sea; the tectonic conglomerates, the record of variable vertical uplifts; the climatic conglomerates, the record of variable temperature and rainfall."

In 1910, Professor Sherzer published a valuable paper on the "Criteria for the Recognition of Various Types of Sand Grains." He found seven types, and in the application of the ascertained principles to the Sylvania sandstone, he came to the conclusion that it is of eolian origin. In a review of the paper in the same year, Barrell thinks this conclusion is not warranted, because as yet too few sands, modern and ancient, have been studied enough in detail.

Barrell's next study was on "Some Distinctions between Marine and Terrestrial Conglomerates," the gist of which he presented before the Geological Society of America in 1908. A half-page abstract appeared in the Society's *Bulletin* and in *Science* in 1910, but the paper as a whole was not printed until 1925. Its conclusions are as follows:

The truly terrestrial forces produce vastly more gravel, pile it in thicker formations, spread it far more widely, and provide more opportunities for accumulation than do the forces of the marine littoral areas. Conglomerates are, therefore, dominantly of terrestrial origin; they are as characteristic of continental deposits as the limestones are dominantly marine.

The present volume rates of denudation Barrell finds to be, for marine areas, between .02 and .10 cubic miles per year; while fluviatile denudation yields as marine or as continental deposits 1.50 to 3.00 cubic miles per year. In other words, the total annual erosion is from about 3.00 to 6.10 cubic miles.

Marine denudation attains its "highest absolute and relative value at times of great marine transgressions. . . . Its absolute value may readily have been twice the present amount, and its value relative to subaerial denudation may have attained even twenty times the present ratio."

In regard to gravels, he says: "The gravels supplied by fluviatile erosion are some tens of times greater in quantity than the gravels produced by the erosive action of the sea."

Concerning the distribution of marine gravels, Barrell's conclusions are: "On open coasts with fixed shorelines marine gravels commonly range from about 1 fathom above high-water level to 4 or 5 fathoms below. They are kept against the coast and seldom extend more than from 1 to 3 miles from shore. . . . Marine gravels . . . may under exceptional circumstances, extend to ten times these limits."

Marine conglomerates rarely attain a thickness of 100 feet, and even this depth is exceptional and local. On the other hand, terrestrial conglomerates are often many hundreds and sometimes thousands of feet thick.

"Rivers commonly move gravels down descents of hundreds of feet from their regions of origin and along horizontal distances of tens of miles. . . . Under favorable conditions, moreover, rivers may sweep gravels from far inland mountains to the margin of a continent and down descents of thousands of feet. Consequently, rivers, as agents of gravel distribution, may be a hundred times more effective than the shore activities."

"In conclusion, it is seen that gravels of either marine or terrestrial origin require stable conditions for their development. They are local and not widely distributed formations. Marine gravels are most restricted, since they are limited to the margin of the sea. River gravels, on the other hand, may occur over all parts of the lands, but do not tend to attain the sea. Finally, in order that gravel may remain as conglomerate formations, either of terrestrial or marine origin, it must be progressively buried below the zone of erosion."

Having finished the paper on conglomerates, Barrell now sought out a thick and unfossiliferous conglomerate-sandstone series whose age relations were obscure. Such a series he found in the southern Appalachians, and upon this he made another study that was published during 1925. The conglomerates, sandstones, and slates of the Ocoee and Chilhowee groups of Tennessee, North Carolina, and Alabama have long been a stumbling block in correlation, because it is only near the top of the thick series that fossils have been found. On the basis of these fossils, Keith finally referred all of the Ocoee and Chilhowee to the Lower Cambrian. Barrell discussed the many formations of this series, aggregating between 9000 and 13,000 feet in depth, and concluded that the lower part, with a maximum thickness of 7500 feet, is of terrestrial origin. The middle formations, with a thickness of 3400 feet, are in part at least a terrestrial deposit, though a part is probably estuarine. The remaining 2700 feet are entirely of marine origin.

As to the nature of the geosyncline in which these Ocoee-Chilhowee deposits were laid down, he concludes that it lay between mountains, had a very irregular bottom, and that its crustal subsidence shifted at first from place to place. Most of the deposits came from the areas of maximum deposition, tens of miles away. In regard to the geanticline that supplied the Ocoee-Chilhowee formations, he thinks that at the close of the Proterozoic an Alpine-like mountain system stood on what is now the Piedmont Plateau of the southern Appalachians. Finally, late in Lower Cambrian time, the region passed into topographic old age. The climate, he holds, was at first cool, with moderate rainfall, and later considerably warmer.

In 1912, in continuation of his studies of sedimentary formations, Barrell published the paper entitled "Criteria for the Recognition of Ancient Delta Deposits." He defines a delta as "a deposit partly subaerial built by a river into or against a body of permanent water." This study concerns the detailed structures of deltas, the physiography of the lands that furnished the detritus, and the cyclic nature of the erosion of the rivers and therefore also of the delta accumulations. It is a difficult study because of the great variability in the extent of deltas, in the character of their sediments, in the size and streaming power of the river or rivers that bring the material, and finally in the wave and streaming forces of the water body and the depth of the water in which and in front of which the deltas are laid down.

In 1913-1914 followed the application of the criteria of the previous paper to the Upper Devonian delta of the Appalachian geosyncline. This is one of Barrell's best pieces of work, and a very philosophic one, for it brings out the relations of the Appalachian delta, both to the interior sea and to the extensive eastern land Appalachia and the Atlantic Ocean beyond. The volume of this extensive delta Barrell computed at about 16,500 cubic miles for Middle Devonian and 63,000 cubic miles for Upper Devonian time. "This is an impressive measure of the volume of the adjacent land which was eroded in Upper

Devonian times. But it is a minimum measure, since that part of the rocks which was taken into solution was carried farther away, and of the mechanical sediments it represents only that part which was carried westward into the trap of the geosyncline."

This Devonian delta implies a much greater Appalachia than is usually assumed, and one which must have exceeded the present Sierra Nevada in elevation. Barrell thinks that this old land was not confined to the limits of the present continental shelf, but probably extended out into the Atlantic for an unknown distance where there is now deep ocean. Accordingly, great parts of eastern Appalachia must have been fragmented and sunk into the depths of the Atlantic during Mesozoic time.

As early as 1905, Barrell began to ask himself, What were the geographic and climatic conditions which controlled the nature of the Old Red Sandstone deposits? In 1906 he wrote out his views but withheld them from printing, thinking that he and the present writer would find means of visiting Scotland. As this opportunity did not come, he presented his ideas in 1916 in the paper "Dominantly Fluviatile Origin under Seasonal Rainfall of the Old Red Sandstone." A copy of this paper was sent to Professor T. G. Bonney of University College, Cambridge, England, and his letter of thanks to Barrell opened with the word "Eureka!" Truly, here is the correct explanation of the origin of the Old Red Sandstone.

"The central conclusion reached in this paper is that the Old Red Sandstone formations were not deposited in lakes or estuaries, nor are they of desert origin." They are "river deposits accumulated in intermontane basins," "exposed to air in times of drought," and "similar to the basin deposits of the western United States laid down in the Tertiary period between the growing ranges of the Cordillera." There was "an alternation of seasons of rainfall and drought—a climate with an arid season, but not an arid climate." "The Great Valley of California may therefore in the present epoch, both in physiography and in climate, be cited as a striking illustration of the nature of the Old Red Sandstone basins."

In 1915, R. W. Sayles presented a paper on "Banded Glacial Slates of Permocarboniferous Age, showing Possible Seasonal Variations in Deposition." In discussing this paper, Barrell pointed out that he had noticed similar stratigraphic banding in argillites associated with the oldest of all known tillites, those of the Huronian of Ontario. He says: "At the south end of Cobalt Lake occurs a thick bed of argillite delicately banded, indicating rhythmic deposition. The bands are grouped in series which show larger rhythms. If the bands are annual, the rhythmically recurring groups show climatic fluctuations covering periods of years. . . . The association of these banded argillites with iceberg deposits and ground moraine indicates, therefore, the existence of summer melting and winter freezing during the Huronian glaciation."

In 1908, Professor Schaeberle published his conclusion that most of the postulated theories of geological climates are upset by his theory of temperature of space, that is, they are invalid because they are based upon an adopted value for the temperature of space which is too great by nearly three hundred degrees of the centigrade scale at the earth's distance from the sun." To this sweeping dictum Barrell, in a short notice in *Science,* "Schaeberle and Geological Climates," replied that ancient climates "are based not upon considerations of the temperature of space, but upon detailed studies of the geological record." "Manson's hypothesis of an earth self-heated and protected by a cloud envelope until the Tertiary, which Schaeberle considers that he has demonstrated as a true theory, must be regarded as in no measure adequate to explain the facts."

Paleoclimatology as derived from the nature of the sediments was Barrell's special field, and he was the recognized leader in it. His article on the relation between climate and terrestrial deposits (1908), discussed more fully on page 16, "traces," according to Willis, "the complex variations of temperature and rainfall and their effects upon sediments with such keen analytic power, such wealth of illustration, and such logic as to lay firmly the foundations of interpretation of terrestrial stratigraphy in terms of climate."

PIEDMONT TERRACES OF THE NORTHERN APPALACHIANS

While an undergraduate student at Lehigh, Barrell became interested in the physiography of the highlands of New Jersey and Pennsylvania. He had studied Davis' works, but on account of the peculiarities of the wind gaps and the rivers that flow through the ridges with which he was familiar, he concluded that much of the area must have been beneath the sea and covered by sedimentary deposits. This was in opposition to the prevalent opinion that the present rivers were incised in the "Cretaceous peneplain." His views were formulated for the first time in his Lehigh thesis of 1897, but it was not until 1913 that he presented the matter in more mature form before the Geological Society of America. The assumed Mesozoic terrestrial peneplain of southern New England he finally showed to be in reality of marine origin and "stairlike or terraced in its character, facing the sea." It was this study that was absorbing his last years, and his death made impossible what would have been his *magnum opus*. In 1915 he demonstrated his theory in the field before the New England Intercollegiate Geological Association, as leader of a characteristically well planned and carried out excursion to the critical areas in Connecticut, in the course of which he met with equanimity the frequent questions and objections of a party which included Davis, Johnson, Miss Bascom, and many others with vigorous ideas of their own on the subject.

Regarding this intricate and far-reaching study, Barrell left a mass of manuscript notes and drawings, which H. H. Robinson put into order for publication during 1920. Barrell had not, of course, gone far enough with his studies to develop his ideas completely, but he laid the foundations for others to build upon. The subject is a fascinating one, and all the more so since Barrell's views are decidedly at variance with the generally accepted views of geologists, both as to the number of erosion cycles and their ages. The following is taken from Robinson's editorial review of Barrell's work:

"The physiographic history of the Appalachian region has rested on the recognition of a topographic plane of reference, commonly known as the Cretaceous peneplane, above which rose older residual masses, below which were locally cut secondary topographic levels of Tertiary age representing temporary stillstands of the land following periods of uplift, and on the outer margin of which rested the great unlithified series of Mesozoic and Neozoic sediments. The underlying assumption was that all peneplaned surfaces were the result of fluvial denudation and that remnants of all remain so little reduced as to permit the former surfaces to be restored with assurance.

"In most parts of the province three cycles of peneplanation were recognized and correlated in a general way, as the Cretaceous, the early Tertiary, and the late Tertiary. In some localities an older erosion surface, the Jurassic peneplain, was recognized."

Barrell held, at least for New England, that the various terraces are "initially the result of marine denudation," that most of them are of post-Miocene age, and "that the terraces could be restored from their existing remnants." Gradually he came to the conclusion that there were eleven such benches, all of marine origin. "The names, elevation [in feet] of the inner restored margins, and the age of the terraces are as follows:

"Becket	2450	Cretaceous
Canaan	2000	Cretaceous
Cornwall	1720	Oligocene
Goshen	1380	Pliocene
Litchfield	1140	Pliocene
Prospect	940	Pliocene
Towantic	740	Pliocene
Appomattox	540	Pliocene
New Canaan	400	Pleistocene
Sunderland	240	Pleistocene
Wicomico	120	Pleistocene"

Robinson concludes: "A careful study of the profile and maps both topographic and geologic, coupled with some acquaintance with the region, has left the definite impression that Professor Barrell's conclusion as to the marine origin of the terraces below the Cornwall is well taken." The two older terraces, however, Robinson regards as of early Tertiary origin rather than as of Cretaceous time.

RHYTHMS AND GEOLOGIC TIME

Barrell was one of the participants in a symposium on the interpretation of sedimentary rocks at the Albany meeting of the Geological Society of America in 1916. Here he presented a part, but only the smallest part, of a study on "Rhythms and the Measurements of Geologic Time." This is his most important work, and will remain a source of information and stimulation to research along several lines of philosophical thought.

He had long been attracted by the cycles of sedimentation: "Nature," he says, "vibrates with rhythms, climatic and diastrophic." The viewpoint of the six parts of the study is geological, with the emphasis on the pulsatory nature of uplifts and subsidences, though the evidence furnished by radioactivity is thoroughly reviewed. Part I treats of the rhythms in denudation, and shows that "erosion is essentially a pulsatory process" and that "a single rhythm is the erosion cycle; and small partial cycles are superimposed on larger." Here then is developed the hypothesis of compound rhythms. This part leads to the conclusion that the present rate of denudation is high, in fact, "very much greater than the mean for geologic time." Part II deals with rhythms in sedimentation, and shows that sedimentation "is not a continuous process, even during a stage of crustal depression." Therefore the stratigraphic record is replete with "breaks" of varying time lengths, the non-seeable greater disconformities and the lesser but more numerous diastems.

J. M. Clarke in "L'Île Percé" says: "My lamented friend, Joseph Barrell of Yale, wrung the music from a wall of rock of water-laid sediments, by showing how the record, if correctly read, is a succession of rests and beats. The quiet waters lay down their deposits in uninterrupted conformity, till a storm wave of short length and greater height breaks them. The high note passes and subsides into the lower beat, again recorded in unbroken deposits. Slowly the sea bottom is raised above the waves and the hardened sands and clays are worn jagged and rough by the rains and streams; slowly the land sinks beneath the waters and on its uneven strata are again laid the even deposits of the quiet sea. Thus about him everywhere, if one will read and listen, lie the symphonies of the rocks."

Part III treats of the estimates of time based on geologic processes, on erosion, sedimentation, hypothesis of compound rhythms, amount of oceanic salt, and on the loss of primal heat. In this presentation we get a more adequate idea of the quantitative lengthening of geologic time. "Measurements of Time based on Radioactivity" is the subject of Part IV, which is a worthy associate of Holmes's "Radioactivity and the Measurement of Geological Time," published in 1915. Finally, in Part VI, "Convergence of Evidence on Geologic Time and its Bearings," the geological and physical arguments are bound together into a unity, resulting in the conclusion that at least 550 million, and a maximum of 700 million, years have elapsed since the beginning of the Cambrian. This is, moreover, less than one half of geologic time, for the Laurentian or post-Ladogian granites, the oldest great invasions of igneous magmas into vast thicknesses of sedimentary formations, have an age as great as 1,400,000,000 years. "Combining the indications regarding the present high rate of denudation with the evidence of the halting and discontinuous nature of past deposition, it is seen that geologic time is certainly much longer—perhaps ten or fifteen times longer—than the estimates based on strictly uniformitarian interpretation." This paper, Holmes (1925) says, is "the most careful study of geologic time yet published."

Harlow Shapley, the astronomer, accepts Barrell's geologic time estimates, and says: "We may study the stars, indeed, with the aid of fossils in terrestrial rocks, and acquire knowledge of atomic structure from the climates of Precambrian times." "In the growth of our concepts of the age of the earth, Barrell's discussion is likely to mark an epoch because of its consistent carefulness, its great expansion of geologic time beyond the commonly accepted limits, and its decided rebellion against the stringent limitations set by Kelvin and later physicists."

ISOSTASY

Barrell's most philosophic works have to do with isostasy and the genesis of the earth. It was in 1904 that he began to write on the former subject, in a review of T. M. Reade's book, "The Evolution of Earth Structure." Two years later he wrote a review of J. F. Hayford's "The Geodetic Evidence of Isostasy," giving also a brief historical review of the place of this subject in geological literature and of the problems upon which it bears. Finally, in 1914, he reviewed briefly the status of the hypothesis of polar wandering, concluding that "Closer examination tends to cut down more and more even those moderate limits of polar migration set by Darwin. It would appear that the assumption of polar wandering as a cause of climatic change and organic migrations is as gratuitous as an assumption of a changing earth orbit in defiance of the laws of celestial mechanics."

During the years 1914 and 1915, Barrell published in the *Journal of Geology* a series of eight papers that were later collected and bound in one volume under the title "The Strength of the Earth's Crust." The first part of this series of articles treats of the geologic tests of the limits of strength. In Parts II and III is discussed the "Regional Distribution and Influence of Variable Rate of Isostatic Compensation." Part IV deals with the "Heterogeneity and Rigidity of the Crust as Measured by Departures from Isostasy," while Part V is on "The Depth of Masses producing Gravity Anomalies and Deflection Residuals." Part VI is devoted to the "Relations of Isostatic Movements to a Sphere of Weakness—the Asthenosphere," and Part VII to "Variation of Strength with Depth, as shown by the Nature of Departures from Isostasy." The final part has to do with the "Physical Conditions Controlling the Nature of Lithosphere and Asthenosphere."

This work at once placed Barrell high among geodesists and geologists. Willis says: "Barrell's analysis covers every part of the subject exhaustively, dissociates all its elements, weighs them, and recombines them. It is the product of extraordinary industry, activity and thoroughness." Arthur Holmes writes of it as a "remarkable series of papers, which is worthy of the most careful study, and constitutes a valuable and stimulating contribution to terrestrial dynamics." According to Pirsson, "They constitute probably the most serious and profound discussion, which has yet been attempted, of the facts which are known and of the theories which have been deduced from them, concerning the strength of the earth's outer shell."

The year of Barrell's death, there simultaneously appeared two papers, "The Nature and Bearings of Isostasy," which is a non-technical summary of the subject, and "The Status of the Theory of Isostasy." These papers, which may be regarded as Barrell's mature views on isostasy, are reviewed in *Nature* for February 12, 1920, and from that review the following excerpt is quoted: Barrell here maintains "that surface inequalities of contour and mass are accompanied by inverse inequalities of density beneath the surface, so that at a depth of about 120 kilometers equal areas have equal masses superposed." He "contends that over limited areas there are large deviations—amounting to 1000 feet over an area 200 miles in diameter (about 3°), or even more. He regards the upper part of the earth's crust as sufficiently strong to sustain uncompensated loads of this amount, the vertical magnitude of the departure being, of course, inversely proportional to its areal extent; it can thus support individual mountains or limited ranges, as well as erosion features of considerable magnitude, such as the Nile and Niger deltas. Under greater and more widely extended loads, however, the crust is supposed to bend in gentle curves involving but little crustal stress; this bending is accompanied by yielding in a lower, weaker layer, which brings about isostatic compensation."

Barrell's work on isostasy, Bowie states, "was far-reaching and thorough, and threw much light on the relation of isostasy to geology. In fact, Barrell did more, in my estimation, to bring the geodesists and geologists together in the science of isostasy than did any other investigator."

GENESIS OF THE EARTH

In 1907, Barrell reviewed W. H. Pickering's paper, "The Place of Origin of the Moon." This place the latter thought to be the Pacific Ocean, thus giving rise to that basin. Barrell shows that oceanic basins could not have arisen in this way.

Chamberlin's very important book, "The Origin of the Earth," appeared in 1916, and Barrell was looking for it. After reading it, he wrote a five-page review which was printed in *Science* for August 18, 1916. "The subject is vast," he says, "and the evidence on many aspects is somewhat vague. A variety of subhypotheses could be raised for comparison." Regarding the size of the planetesimals, Barrell states: "It seems a debatable question to the reviewer if such a large proportion of the added material was necessarily dust-like and capable of being distributed by the primitive atmosphere and ocean. Upon the mean size of the incorporated units various subhypotheses of consequences may be built up."

Chamberlin's hypothesis of juvenile shaping "is, of course, like the other steps in the development of the planetesimal hypothesis, dependent upon the basal postulates. It is not clear that earth-strains due to the causes invoked could initiate such a primary segmentation . . . in fact, calculations on the stresses which the reviewer has made to test this subhypothesis pointed to quite a different method of yielding. The distribution of continents and oceans does not accord very closely with it, and the evidence of isostasy does not indicate that the density differences between continents and ocean basins reach below the outer fiftieth of the earth's radius."

In Barrell's opinion, however, "The Origin of the Earth" is "a notable constructive addition to thought upon this fundamental subject. . . . The names of Chamberlin and Moulton must rank high among those scientists who have dealt constructively with that vast, vague and remote problem—the Origin of the Earth."

When Chamberlin's book appeared, Barrell was getting ready for a lecture to be delivered on November 23, 1916, before the Yale Chapter of the Sigma Xi, the introductory one in the course on "The Evolution of the Earth and its Inhabitants" (later issued in book form by the Yale University Press). The manuscript finally grew far beyond the content of his lecture, and eventually appeared in part in three different places: as the first chapter in the book resulting from the lectures; as Chapters

VIII, IX, and XI in the first edition of Schuchert's "Historical Geology"; and in the *American Journal of Science* during 1927.

In the summer of 1916, Barrell wrote on the "Significance of the Equatorial Acceleration in the Sun's Rotation." This short paper will not be published, but is preserved for future reference in the library of Peabody Museum, Yale University. It was followed by an extended paper entitled "Geological Relations of Earth Condensation and Resulting Acceleration in Rotation," which was published in 1925 and 1926. He begins with the questions: "(1) Is the earth smaller now than it was in the early geological periods? If so, what has brought about that condensation? (2) Has tidal retardation by moon and sun effectively increased the rotation period of the earth since the Archeozoic, or has this been a geologically negligible factor? (3) Has condensation produced an acceleration in rotation? If so, how much more oblate would the earth become? (4) Could such a change of figure be recognized by a change of sea-level and to what amount, or would it be inappreciable in effect? (5) What distortions would be given to the crust and would these be wholly masked by the orogenic and epeirogenic movements due to other causes? (6) How would the stresses due to change in figure be distributed through the earth? Where and how would failure occur? (7) Are regional joint-systems related to the planetary stresses? (8) Lastly, can these forces have reached a higher order of magnitude during the formative period of the earth, and if so, may they have had an influence in determining the arrangement of the larger features of the earth?"

His conclusions are divided into two groups. On the one hand, so far as stresses in the earth's body are concerned, those due to change of oblateness would appear to be wholly submerged beneath those due to change of volume. It is difficult to see in these results either a basis for a segmentation of the earth into great conical sectors, or a recognizable cause for the shifting of epeiric seas. On the other hand, it appears probable that planetary strains occur in the outermost shell of the crust, the zone of fracture, which may constitute one of the major factors in determining the nature of regional joint systems. These stresses may also coöperate with local forces in helping to determine the trend of normal fault systems.

"The paper is written chiefly on account of its suggestiveness toward further work, rather than because of any finality in conclusions. In a field where so little is directly known, as in that of the deep interior of the earth, the method of multiple working hypothesis must be assiduously cultivated, and although the present analysis favors one group of hypotheses, it should not be regarded as ruling others out of further consideration."

Finally, Barrell wrote "On Continental Fragmentation and the Geologic Bearing of the Moon's Surficial Features." This paper, published in 1927, includes his ideas of how land bridges like western Gondwana across the Atlantic may be dragged into the depths of the oceans. "The outer crust of the earth," he says, "granitic in its upper part and somewhat more basic at depth, is held to have a thickness of from 50 to 75 miles. It is very strong, and is marked by broad variations in density amounting to as much as 5 per cent, and by more local variations up to 10 per cent, these differences corresponding to the broader relief of the earth's surface. Below this lies a thick, hot, basic, rigid yet weak shell, the asthenosphere, or sphere of weakness. The problem of the origin of the ocean basins and the continental platforms consequently resolves itself into one of the origin of the density differences in the lithosphere and the maintenance of the heated and weak condition in the asthenosphere."

"The small content of radioactive elements in the basaltic shell or asthenosphere below the granitic crust of the continents would then supply that slow increment of heat which is necessary to generate new molten rocks. The granitic shell loses its excess heat by conduction to the atmosphere, but the asthenosphere is so deeply buried that its heat can not escape, but must slowly transform some of the solid rock into liquid form. Reservoirs of molten rock gather until their mass, combined with their decreased density in the fluid form, enables them to work their way into and through the lithosphere and demonstrate their existence in igneous activity at the surface of the earth. The magma which thus comes from the greatest depth and in greatest volume would, because of the initial density stratification, produce a notable increase in the density of the outer crust. In order to reëstablish isostatic equilibrium, such a region must subside."

"Most American geologists hold strictly to Dana's theory of the permanency of the continents and ocean basins, whereas European workers in general stand by the older view that ocean basins are broken-down portions of the granitic shell. We may also include this grander process of crustal change under the term of continental fragmentation. Great intercontinental troughs, such as the Red Sea and the Caspian, are thought to have been made in later geologic times by fracture of their margins and subsidence of their floors. The writer accepts the European view, since, in spite of its difficulties, it yet accounts for many geological relationships. If continental fragmentation is real, it has a strong bearing upon the general problem of the origin of ocean basins, for the progress of fragmentation is in reality a continuation of the formative process. Through fragmentation the margins of the continents break down into the oceanic depths and enlarge them, and at the same time diminish the areas of the land."

Finally: "Smoothing out the crustal oscillations connected with periods and eras, it appears that a great cycle of progress has run through earth history. High and wide lands marked the Archeozoic and Proterozoic revolutions; fragmentation was apparently widening the earliest ocean basins and lowering the ocean levels, but the juvenile waters from the accompanying igneous intrusions reëlevated them. Then came a long time, from the early Paleozoic to the close of the Devonian, during which the oceans rose and repeatedly spread over the lands. Since the later Paleozoic, however, the ocean level has tended to sink, and fragmentation appears to have gained on the accessions of juvenile water. . . . But the lands have been kept high above the increasing waters only by the breaking down of portions of their areas into ocean basins. . . ."

Barrell then takes up a study of the moon's surface as known to astronomers and ends the paper of 1927 as follows: "Thus the study of the earth's small sister planet supports the general hypothesis that the ocean waters as well as the ocean basins have arisen through igneous activity, and that fragmentation of the original crust has dominated the moon as well as the earth throughout geological time."

In the Sigma Xi lecture mentioned above, Barrell modified the Chamberlin hypothesis of slow growth resulting in a cold earth to one of quick growth through planetoids the size of asteroids, a postulate which necessitates a molten earth.

PALEONTOLOGY AND EVOLUTION

As Barrell also taught Biology at Lehigh and Historical Geology at Yale, it was but natural that he should be interested in Paleontology. This side of his activity is little known away from Yale, but his colleagues there were often made aware of his deep interest and knowledge along this line. He never was concerned with species and genera, nor with classification, but to him the bony structures of vertebrates were mechanisms and he tried to see in them the effects of the operation of the laws of mechanics. And through his insight into Paleoclimatology, he tried to discern the effects of changing environment as the most important cause of organic evolution.

While studying the nature of the Old Red Sandstones, and what they show as to their climatic environment, Barrell became deeply interested in Chamberlin's ideas regarding the probable habitats that gave rise to the fish-form, and to lungs. His ideas on these subjects culminated in 1916 in a paper entitled "Influence of Silurian-Devonian Climates on the Rise of Air-breathing Vertebrates." The problems he seeks to answer are two: "first, as to the environment in which fishes developed; second, the changes in the environment and the associated organic responses which brought forth amphibians from fishes. It is the solution of the second problem which is here especially sought."

"It is shown to be probable that fishes arose in land waters. As such they constituted primarily a river fauna." It is in the Middle Devonian that the fishes "first really begin to conquer the ocean and its former rulers." On the other hand, in the fresh waters of this time fishes abounded in greater variety than in the seas. In the Upper Devonian, crossopterygian fishes had risen to a dominant place, and they were adapted to living in warm climates marked by alternation of wet and dry seasons, the kind of environment that gave rise to the amphibians. "The warm and stagnant waters of the dry season compelled those fishes which should survive to make larger and larger use of air."

"The evidence is regarded as strong that the air-bladder was originally developed as a supplemental breathing organ, although in modern fishes it has been mostly diverted to other uses." Barrell also quotes this significant passage from W. D. Matthew: "The evolution of land life in adaptation to recurrent periods of aridity supplies a satisfactory background of cause for the whole evolution of the higher vertebrates," to which he adds, "Climatic oscillation is a major ulterior factor in evolution."

The study of the natural environment as recorded in the sediments that also entombed the fossils led naturally to the work entitled "Probable Relations of Climatic Change to the Origin of the Tertiary Ape-Man." Here we again read that climatic variation is the most fundamental evolutionary factor for terrestrial life. This was especially true for the Pleistocene, when the land biotas "have come and gone at the command of climatic change. Those animals which were trapped on the northern sides of mountain ranges or water barriers were remorselessly exterminated by the waves of advancing cold; those which could escape to the south returned with milder climates, but changed in assemblage." Barrell held that man was brought to his present high physical and mental state not as the "mere product of time and life," but that he is "peculiarly a child of the earth and is born of her vicissitudes." "The progress of life on the earth has been highly favored, consequently, by the rhythmic pulses of diastrophic and climatic changes which have remorselessly urged forward the troop of living creatures. The progress of organic evolution has depended upon a series of fortunate physical events, conditioned in the internal nature of sun and earth, rather than the byproduct of mere life activities as expressed in orthogenesis through long periods of time. Evolution is in no sense an inevitable consequence of life, and the compulsion of climatic change has been more than once a fundamental factor in the age-long ascent from protozoan to man."

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