HOW OLD IS THE EARTH?

BY CHESTER A. REEDS

GUIDE LEAFLET SERIES, No. 75

THE AMERICAN MUSEUM OF NATURAL HISTORY

NEW YORK, N. Y.

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THE INNER GORGE OF THE GRAND CAÑON OF THE COLORADO RIVER

From a Painting by Gunar Wildforss, 1930

LINCOLN ELLSWORTH COLLECTION

VIEW looking west-northwest across the mouth of Bright Angel Cañon from near the Kaibab Suspension Bridge. The Colorado River is in the left center, and flows here at an elevation of 2450 feet above sea level. The varied rocks of the north wall of the inner gorge appear in the foreground and in the mid-distance, with the isolated Tower of Set, 5997 feet, appearing in the background, left center. In the right center the towering mass of the Cheops Pyramid, 5350 feet, crowns the slope to the inner gorge. The twin peaks of Isis Temple form the highest elevation 7028 feet, in the right background. To the south of the river in the left margin appears a portion of the rocks in the south wall of the inner gorge with the isolated peak of Dana Butte, 5025 feet, prominently in the background.

The geological section, which is of special interest, is explained more fully in the article "How Old Is the Earth ?"

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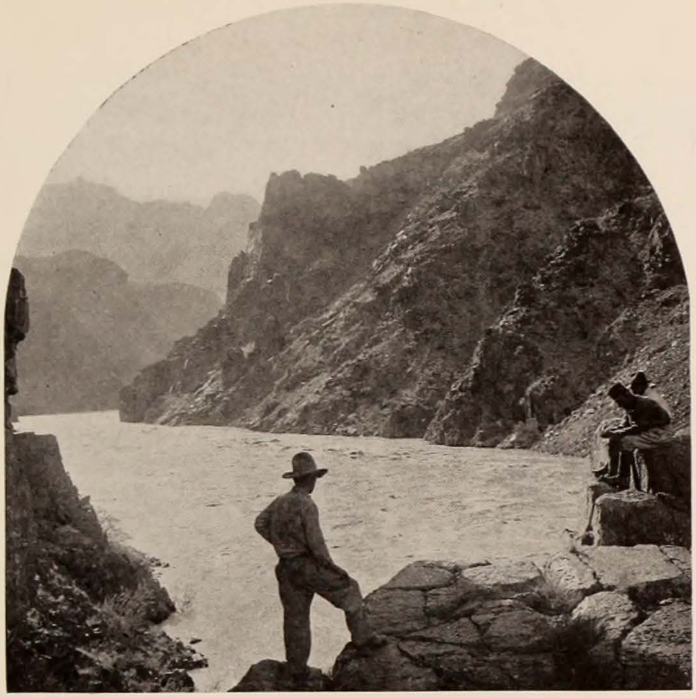


The Colorado River at the Bottom of the Grand Cañon of Arizona

HOW OLD IS THE EARTH?

The Earth Reveals Its Age By Hour-glass Deposition of Sodium and Sediments, and the Atomic Disintegration of Radioactive Elements

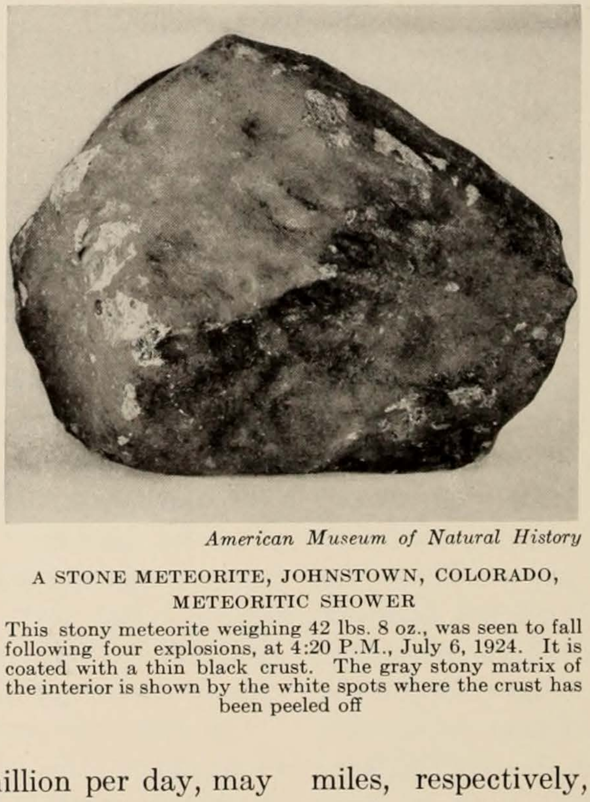
By CHESTER A. REEDS
Curator of Geology and Invertebrate Palæontology, American Museum

IT may be stated at the outset that nobody knows just how old the earth is. There are certain criteria available, however, which indicate that the oldest rocks are of the order of 2000 million years. There are data which imply that the upper limit of the age of the minerals is about 3000 million years. This may be considered the lower limit of the age of the earth's material. Iron meteorites have been analyzed which yield a maximum age of 2600 million years. These are stupendous figures. The lower figure of two billion years as a minimum age for the earth implies that it has encircled the sun as many times, and that during this period it has turned on its axis 730,500,000,000 times to afford as many days of light and darkness.

The presence of ripple marks, sun-crack impressions in muds, water-worn pebbles, rounded sand grains, seasonally banded clays, limestone deposits, and vestiges of primitive forms of life in rocks of very ancient origin, all point to physical conditions on the surface of the earth that are similar in every respect to those enduring today. Various folded gneisses and schists, without vestiges of life, much distorted and frequently impregnated with volcanic injections, constitute the oldest rocks exposed on the earth's surface. The earth, although very old, has a remarkable history. The various steps in its development are in some instances still obscure, but they are becoming more apparent with the growth of knowledge concerning the earth.

Spectroscopic analyses reveal that 49 of the 90 chemical elements found on the earth have been recognized in the sun. In fact, astronomy teaches that the 1091 members of the solar system have originated from the same material. Various theories as to the origin of the earth postulate that the earth and the other planetary bodies in our solar system were born of our sun when it was in a giant-star stage. This transformation of the sun is supposed to have been induced by the close approach of a passing star several times more massive than the sun itself. The resulting effect of such a close approach was the setting up of great tidal stresses in the sun and the drawing out of two long filaments of gaseous matter from opposite sides of the sun's surface. After the large star passed on, the filament on the far side of the sun as well as a portion of that on the near side may have been drawn back into the sun; however, a considerable portion of the filament remained in space subject to the influence of the sun. In the course of time the matter in this filament was gathered together about certain nuclei to form the nine planets and their satellites. The material was originally in a gaseous state. Later it passed to a liquid state through loss of heat by radiation from its surface, and finally, as in the case of the earth, into a solid state, at least for the outer crustal portion which may be 40 miles in thickness or about 1/200 of the radius of the earth.

The meteors, which enter the upper levels of the earth's atmosphere in great numbers, estimated to be 20 million per day, may be remnants of the original filaments, or of like matter from outer space. Most of these meteors are small, one to two-tenths of an inch in diameter. Upon entering the earth's atmosphere they travel at planetary velocities varying from 9 to 47 miles per second. Due to the great resistance offered to their passage by the earth's atmosphere, which is estimated to be 90 to 100 miles in thickness, the solid portions of most meteors burn up before reaching the earth. In addition to the ash of burnt-out meteors a minimum of one meteorite per day reaches the earth's surface.



American Museum of Natural History

A STONE METEORITE, JOHNSTOWN, COLORADO, METEORITIC SHOWER

This stony meteorite weighing 42 lbs. 8 oz., was seen to fall following four explosions, at 4:20 P.M., July 6, 1924. It is coated with a thin black crust. The gray stony matrix of the interior is shown by the white spots where the crust has been peeled off

The portions of 700 meteoritic falls exhibited in various museums are composed primarily of either nickel-iron, or of stone specimens, or, of combinations of these two kinds of matter. The stony meteorites resemble the light colored felsitic lavas of the earth. There are differences in texture in each, however, which the skilled observer readily detects. The iron meteorites with nickel, troilite, carbon, and other inclusions are not found duplicated on the earth. Some 29 elements found on the earth have been detected in meteorites. On the other hand, six mineral compounds have been noted in meteorites, which have not been found on the earth.

It may be stated thus that the earth, the meteorites, the sun, the moon, and the stars are distantly related. The earth and its moon with diameters of 7918 and 2162 miles, respectively, are intimately related to the sun, which is 866,400 miles in diameter. Although their densities, as compared with equal volumes of water, vary, the density of the earth being 5.52, the moon 3.40, the sun 1.39, these differ-

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THE MYSTIC POWER OF THE COLORADO RIVER IN ARIZONA

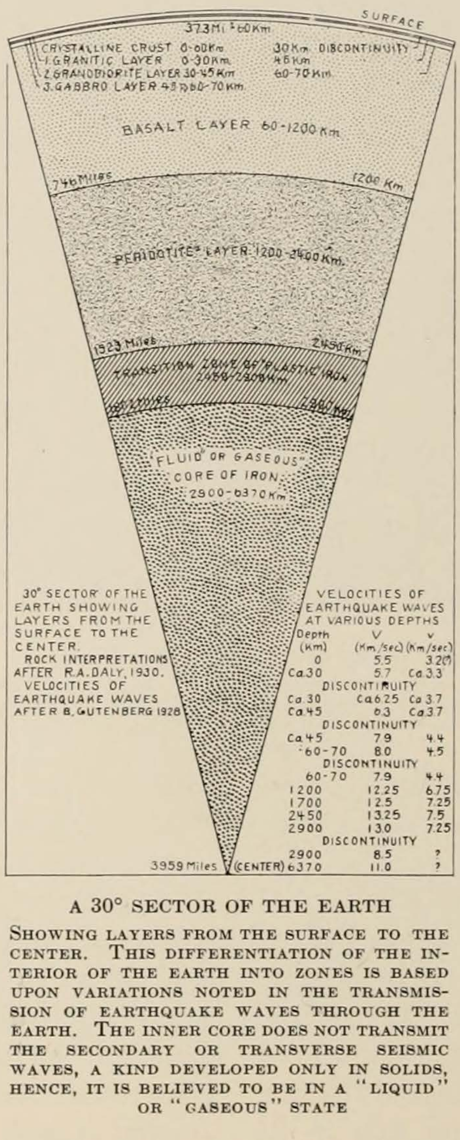
A view from the upwarped plateau rim, 7000–8000 feet above the sea, into the outer and inner gorges of the Grand Cañon where the river flows at a level of 2400 feet. This cañon is 217 miles long, from 8 to 20 miles wide, and more than a mile deep. It was eroded by the river during the last one million years

ences are explained by the different states of like matter, the earth and moon being solid and the sun gaseous The fact that the earth rotates on its axis at a rate of 18.5 miles per second, and about the sun at a rate of 66,000 miles per hour, also implies that the mass of the earth, which weighs 6590 million million million tons, is controlled by the larger mass of the sun, which revolves once on its axis in 25 days, and weighs 1.983×10^{33} grams.

The various stages involved in the upbuilding of the earth are of interest in discussing its age. No two theories agree, however, on the number of steps involved, nor in the way in which it was accomplished, yet most of them assume that in the beginning the materials of which the earth is composed were in a gaseous state. The number of years required for a planet having the size and density of the earth to pass from a gaseous to a solid state is of course problematical.

According to the Planetesimal Hypothesis proposed by the late T. C. Chamberlain and F. A. Moulton of the University of Chicago in 1905, all but the central core of the earth, which is 4346 miles in diameter, has been built up by the infall of planetesimal matter. Since but a small amount of such planetesimal, or meteoric matter, is now added daily to the earth, the hypothesis implies a great age for the earth. Chamberlain held that at the present rate of fall it would require 1,000,000,000 years to form a layer of meteoritic material one inch in thickness on the earth. J. Barrell (1923) took exception to Chamberlain's views and argued for a molten condition of the earth at the completion of its growth. He assumed that the earth developed rapidly by the infall of planetoid-like bodies rather than by the slow accumulation of dustlike particles. He was of the opinion that all of the near-by planetoids, even those several hundred miles in diameter, except the moon, had been gathered in by the time the earth attained a condition of stability and completed growth.

Present knowledge of the earth indicates that it has a shell-structure. The past thirty years of seismological research have led to this definite conclusion. Besides the solid crust which is composed of a somewhat heterogeneous mixture of sedimentary, igneous, and metamorphic rocks, there are successive zones of material and a central core which differ from one another in density, in chemical composition, and in elasticity. The earth as a whole is more rigid than steel. Earthquake waves are transmitted through it. Each earthquake records three principal kinds of waves on a seismograph, namely: primary, secondary, and main waves. The primary or longitudinal waves pass through all portions of the earth. The secondary or transverse waves, a kind developed only in solids, pass through only the outer portion of the earth; they do not pass below a depth of 2900 km. It is at this depth, 0.45 of the radius of the earth, that the inner core begins. Since this type of wave is not transmitted through the inner core, this portion of the earth is believed to be in a liquid or gaseous state. The main waves which are the largest and last to be recorded, are confined to the crust of the earth.



A 30° SECTOR OF THE EARTH

Showing layers from the surface to the center. This differentiation of the interior of the earth into zones is based upon variations noted in the transmission of earthquake waves through the earth. The inner core does not transmit the secondary or transverse seismic waves, a kind developed only in solids, hence, it is believed to be in a "liquid" or "gaseous" state

The velocity of the primary and secondary waves at various depths, V and v respectively, as determined by B. Gutenberg, 1928, and the nature of the rock in the respective zones, as interpreted by R. A. Daly, 1930, are given in the accompanying sketch of a 30 degree sector of the earth. The density of the various zones is noted in the text below.

It may be noted that the crystalline crust is 60-70 km. in thickness. In addition to the outer sedimentary layer, which varies in thickness from 0-5 km. with density 2.7, the crust is composed of three zones of rock each separated by planes of discontinuity as follows:

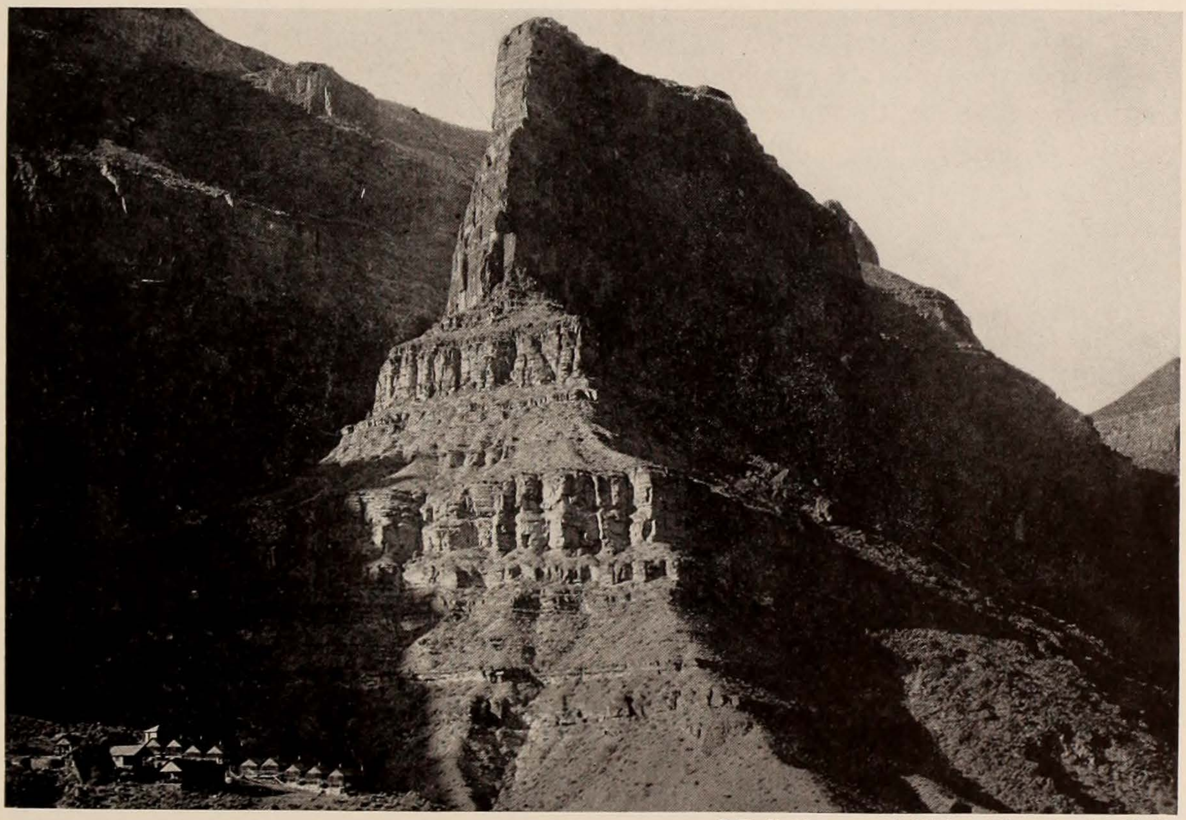
(1) granitic layer 0-30 km. in thickness, density 2.7

(2) granodiorite layer 30–45 km. in thickness, density 2.7+

(3) gabbro layer 45 to 60-70 km., density 2.9.

Below the crust lies a hot, vitreous, basaltic layer 60-1200 km. in thickness, density 3.3. This is followed by a layer 1200–2450 km. in thickness, which Daly believes may partake of the nature of peridotite, while H. Jeffries (1929) refers to it as the dunite layer, density 5.0. At a depth of 2450–2900 km. there occurs a zone composed perhaps of plastic iron, density 9, where seismographic waves slow down. This would indicate that it is transitional in character from the more or less silicate layers above to the great inner core of the earth below. The inner core with great pressures and temperatures resulting from its superimposed load is believed by H. Jeffries (1929) to be liquid iron, by Daly (1930) to be in a "fluid" or "gaseous" state. Its average density is 11.5. It is probable that the inner core of the earth was originally composed of material resembling that found in iron meteorites. Iron meteorites have a specific gravity of 7 or higher. The idea of a liquid inner core is supported by present-day seismology, for the secondary or transverse wave of an earthquake, a kind appearing only in solids, is not transmitted through the inner core.

The methods of palæogeography afford theoretically a splendid insight into the successive geologic stages involved in the upbuilding of the earth. If one could visualize, even in the crudest fashion the changes in geography that have taken place at regular intervals, say 100,000 years, the sequential history of the earth would be in large measure solved. In accordance with the normal sequence of events such a series of pictures should begin with the birth of the earth, from the parent body, the sun. One hundred thousand years later a sufficient change would have taken place in the earth to depict the second scene. A large number of pictures would have to be sketched, 30,000 in fact, if the earth is three billion years old, before the present day is reached, with its magnificent panorama of continents, oceans, irregular coast lines, mountains, plateaus, plains, rivers, lakes, seas, snow fields, glaciers, deserts, and various forms of plant and animal life,



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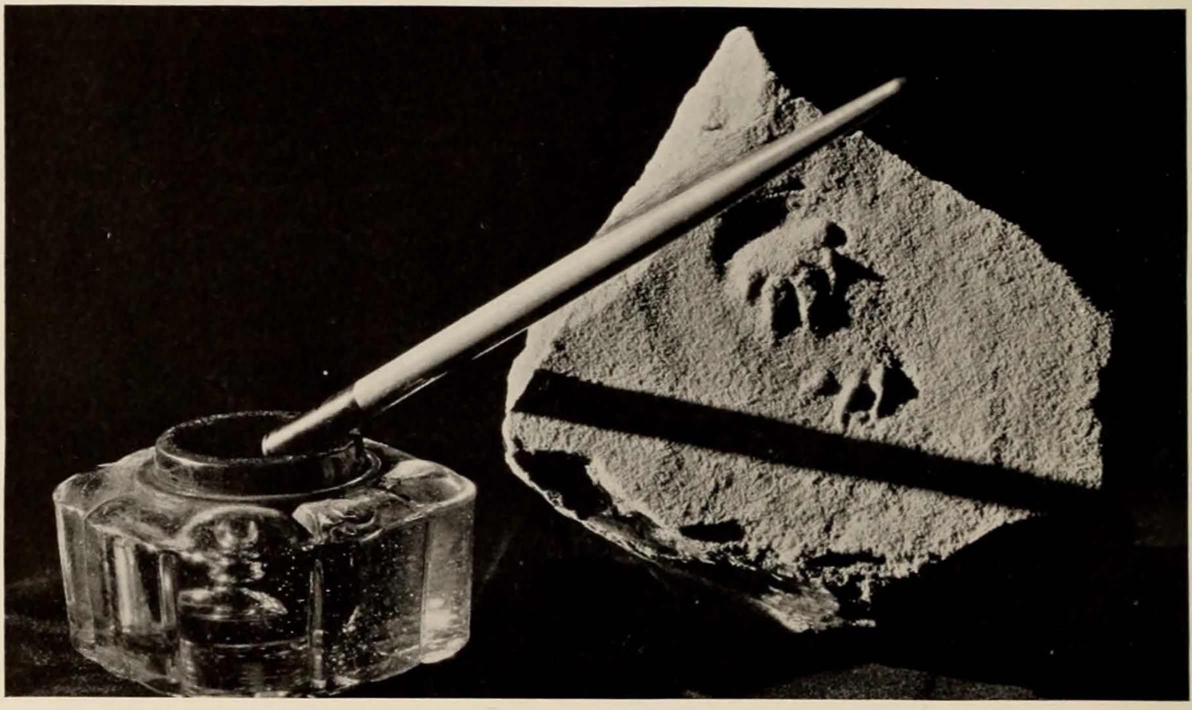
HERMIT CAMP AT THE END OF THE HERMIT TRAIL, GRAND CAÑON

This tourist camp, 3700 feet below the south rim, is a half mile east of Columbus Point, the imposing central rock tower. This towering spur is composed of horizontal sediments that are green, mauve, red, and gray in color. The camp overlooks the inner gorge of the Colorado River, 700 feet deep



FOOTPRINTS OF A LABYRINTHODONT, COCONINO SANDSTONE, GRAND CAÑON

Footprints made by an amphibian of Permian age as the sands of the Coconino formation were being deposited 210 millions of years ago. The sands were moist when the impressions were made. The weight of the animal compacted them and the footprints were covered and preserved

not to mention the cities and other works of man.

No fault is to be found with the idea, for geologic processes are continuous and they have been so throughout the immensity of geologic time. The difficulty in preparing such a series of pictures arises from the fact that the records of past events, which are preserved in the earth itself, are somewhat fragmentary and, furthermore, they are not dated in terms of years, as man dates his present chronology.

The data most frequently used in estimating the age of the earth are those based on geologic processes such as erosion, sedimentation, and deformation. These processes are in evidence on the surface of the lands. For epochs, other than the present, these data are to be found in the stratigraphic record as preserved in the crust of the earth.

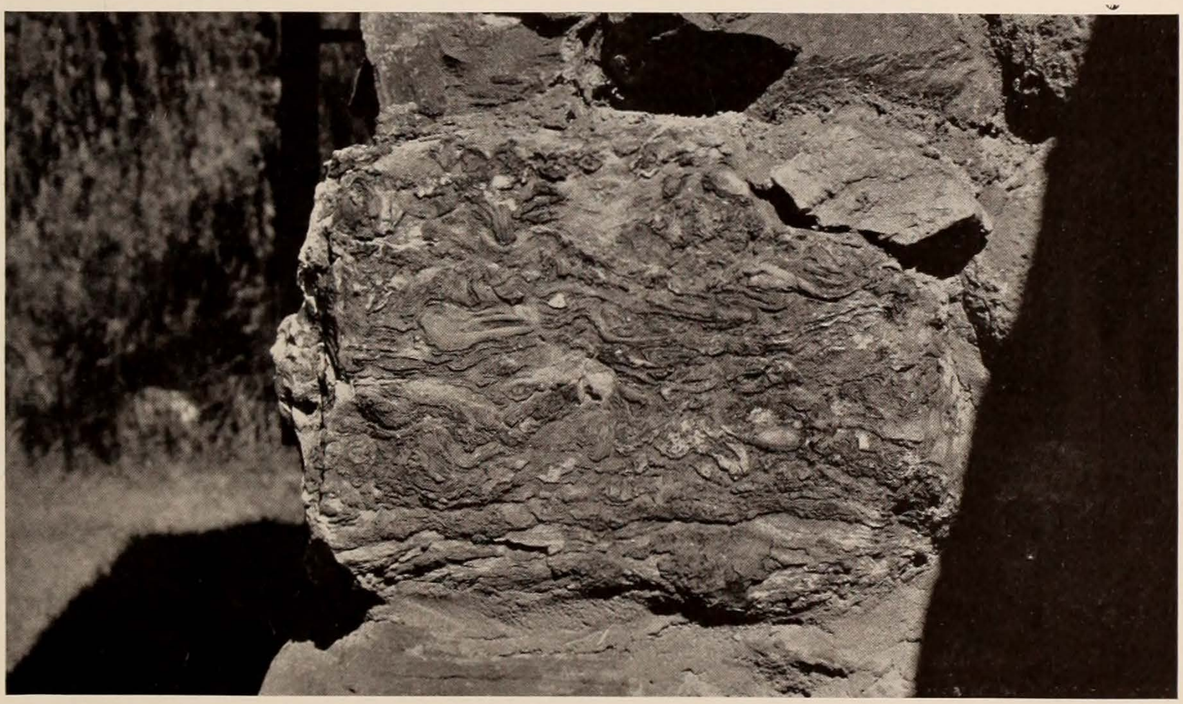
The rate of erosion of the lands is of value as a criterion. Samples of water from representative streams for various climates and topographic reliefs have been taken and analyzed. From more than 8000 analyses F. W. Clarke in his *Data on Geochemistry*, 1924, observes that taking the continents as a whole they are lowered by solvent denudation one foot in 30,000 years. From measurements of the suspended matter collected in the analyzed samples he concludes that the chemical denudation represents but 30 per cent of the total denudation. This gives a mean rate of total denudation at the present time of one foot in 8600 years.

The average height of all lands above sea level has been computed to be approximately 2300 feet. The average depth of the oceans is about 13,000 feet. If the land surface is lowered one foot in 8600 years and the average height of land above the sea is 2300 feet then it would take 19,780,000 years to erode the lands to sea level, assuming that the rate continued uniform to the end, which is not likely. Granting that the oldest rocks on the surface of the earth are approximately 2,000,000,000 years old, that the rate of erosion continued to be one foot in 8500 years throughout all this time, and that the lands were uplifted at the close of each complete erosion period, then the lands would have to have been uplifted 101 times to afford continuous erosion.

The American geologists, Powell, Dutton, and Davis, have shown that the lands have been base-leveled frequently during geologic time. To this level surface Davis applied the term peneplain. Each peneplain was developed as the result of a cycle of erosion. Many ancient peneplains lie buried and preserved as unconformities between different beds of sedimentary rock; others have been elevated and more or less destroyed by later cycles of erosion. These later cycles are uncompleted, since before any one of them could be finished the lands were uplifted and a new cycle inaugurated. In fact no extensive peneplains, not uplifted or dissected, are known to exist at the present time.

Nevertheless, it is apparent to geologists that the earth has been in repose repeatedly, as far as denudation is concerned; at such times shallow seas have spread far and wide over base-leveled lands; new areas of deposition have thus arisen; sedimentation accompanied by slow subsidence in well defined troughs followed; then folding, crumpling and overthrusting of the horizontal strata appeared as the result of lateral compression; this was followed by a general uplift of the folded rocks into high mountains by forces acting from beneath the crust. Such uplifts were frequently accompanied by the intrusion of igneous and volcanic rocks into the distorted mass. With the uplift of the region a new cycle of erosion was inaugurated, the agents of erosion again renewed their efforts to reduce the new landscape to a peneplain. This in brief is the history of various regions of the earth's crust, particularly where numerous old and young mountains exist.

While the rate of denudation in the various cycles of erosion has not been preserved, the sediments that were deposited in the shallow seas lying upon and about the margins of the continents and



FOSSIL ALGÆ IN A ROCK WALL, PHANTOM RANCH MESS HOUSE, BRIGHT ANGEL CAÑON, ARIZONA
The algæ in this isolated block of Bass limestone from the Unkar group, middle Proterozoic, led to the discovery, 1927–1930, by Dr. David White and Mr. Lincoln Ellsworth, of additional specimens of these ancient lime-secreting plants

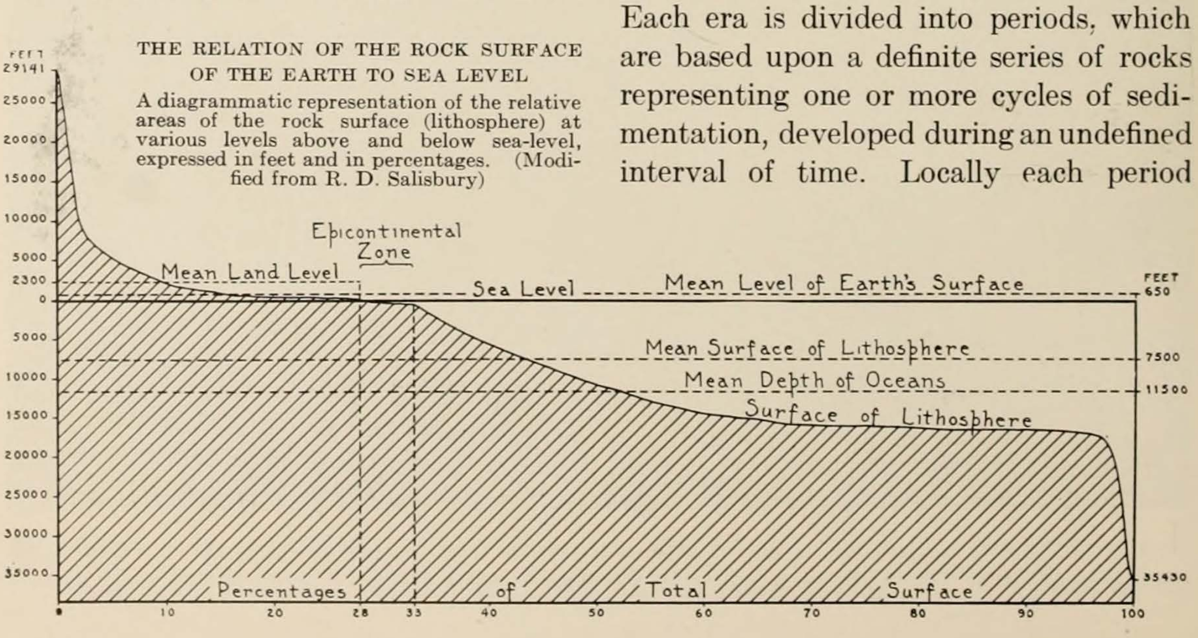
in the depressed troughs have been preserved, except where erosion removed all or a part of the uplifted beds. Due to the shifting of the areas of deposition for different epochs the entire series of these sedimentary strata, which total some 529,000 feet or 100 miles in thickness, are not all to be found at any one place, but in different places upon the face of the earth.

Where the erosion of the lands by rivers proceeded in cyclical manner, the deposition of the transported land derived sediments in marine basins followed in accordance with cycles of sedimentation. Conglomerates and sandstones were laid down near shore and at the base of the series; shales and limestones were deposited farther out, or on top of the more coarsely bedded sediments as the rivers became longer or less active, with gentler grades and greater sorting powers.

The various forms of animal and plant life which lived in the sea at the time the deposits were laid down were entombed, as they died, by the incoming sediments. Their remains constitute the fossils of the sedimentary rocks. Different species and different forms of life are found in rocks, not only where they were deposited in regular sequence, but in areas where a more recent formation extended over older rocks and a gap in time and in sedimentation was recorded thereby. Fossils are invaluable to the stratigrapher, for where a regular sequence of beds occurs the changes in the species, from bed to bed, permit the establishment of a faunal scale and this may be used elsewhere in deciphering the relations of beds where the sequence may be different or where the character of the rocks may have changed.

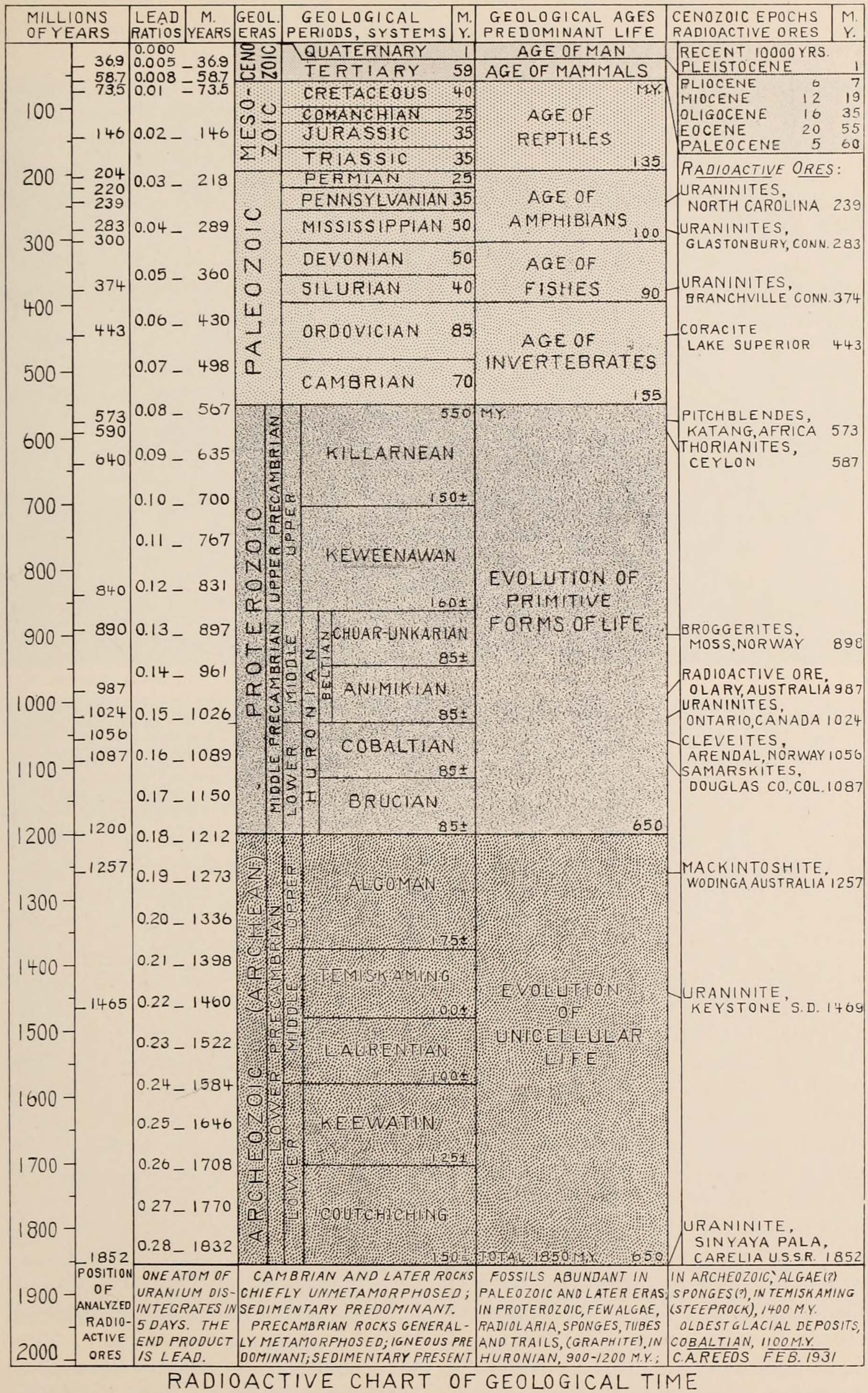
Beginning with William Smith in England in 1796, geologists have built up a geological time scale, the major features of which are applicable to the known rocks of the world. Smith, as a local surveyor, came to recognize beds of rock from place to place by the fossils which they contain. By continued observation over a number of years and much traveling, he was able in 1815 to publish a geological map of England and Wales on which he showed the distribution and succession of rocks of different ages. The local names which he applied to the beds have remained in use to this day.

The geological time scale, as now recognized, is the work of many geologists. It is a kind of chronological chart with various subdivisions, the oldest rocks appearing at the bottom, the youngest at the top. It is the geologists' alphabet. The terms ending in *zoic* refer to eras of life, which constitute major divisions. Each era is divided into periods, which are based upon a definite series of rocks representing one or more cycles of sedimentation, developed during an undefined interval of time. Locally each period



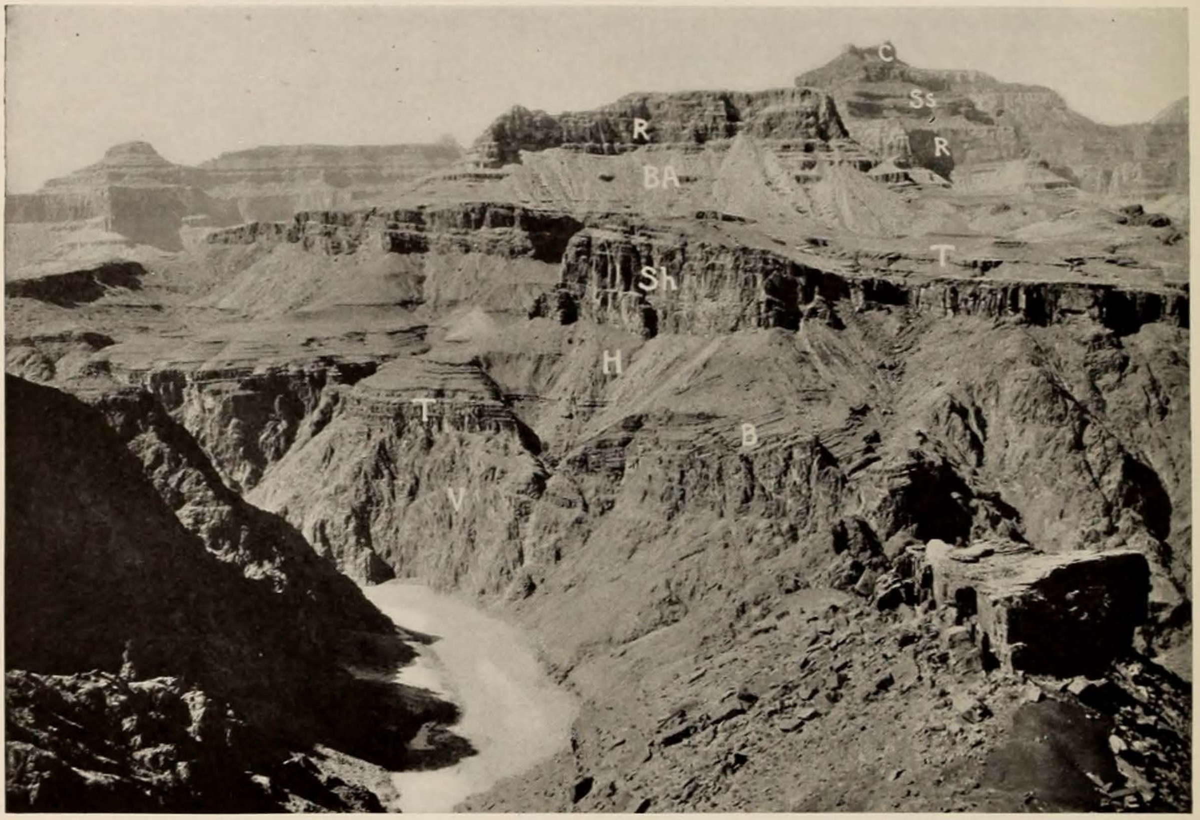
THE RELATION OF THE ROCK SURFACE OF THE EARTH TO SEA LEVEL

A diagrammatic representation of the relative areas of the rock surface (lithosphere) at various levels above and below sea-level, expressed in feet and in percentages. (Modified from R. D. Salisbury)



RADIOACTIVE CHART OF GEOLOGICAL TIME

Note: For every 1,000,000,000,000 uranium atoms (or a mass weighing 1/40,000,000,000 of a gram) one atom explodes every five days. Five eras are shown on this chart; see page 146 for radioactive clock of geological time, showing seven eras.



Ewing Galloway, N. Y.

INNER GORGE OF THE GRAND CAÑON, ARIZONA

View as in frontispiece. Looking down the Colorado River from the Kaibab suspension bridge. Rock section from river bed to top of Isis Temple: *Archeozoic:* V. Vishnu schist; *Proterozoic:* B. Bass limestone; H. Hakatai shale, Sh. Shinumo quartzite; *Palaeozoic:* (Cambrian) T. Tapeats sandstone, BA. Bright Angel shale; (*Mississippian*) R. Redwall limestone, (Permian) Ss. Supai sandstone and shale, C. Coconino sandstone

and system of rocks is further divided into epochs and formations of rocks. These local designations, which are numerous and variable from place to place, have not been included in this general chart.

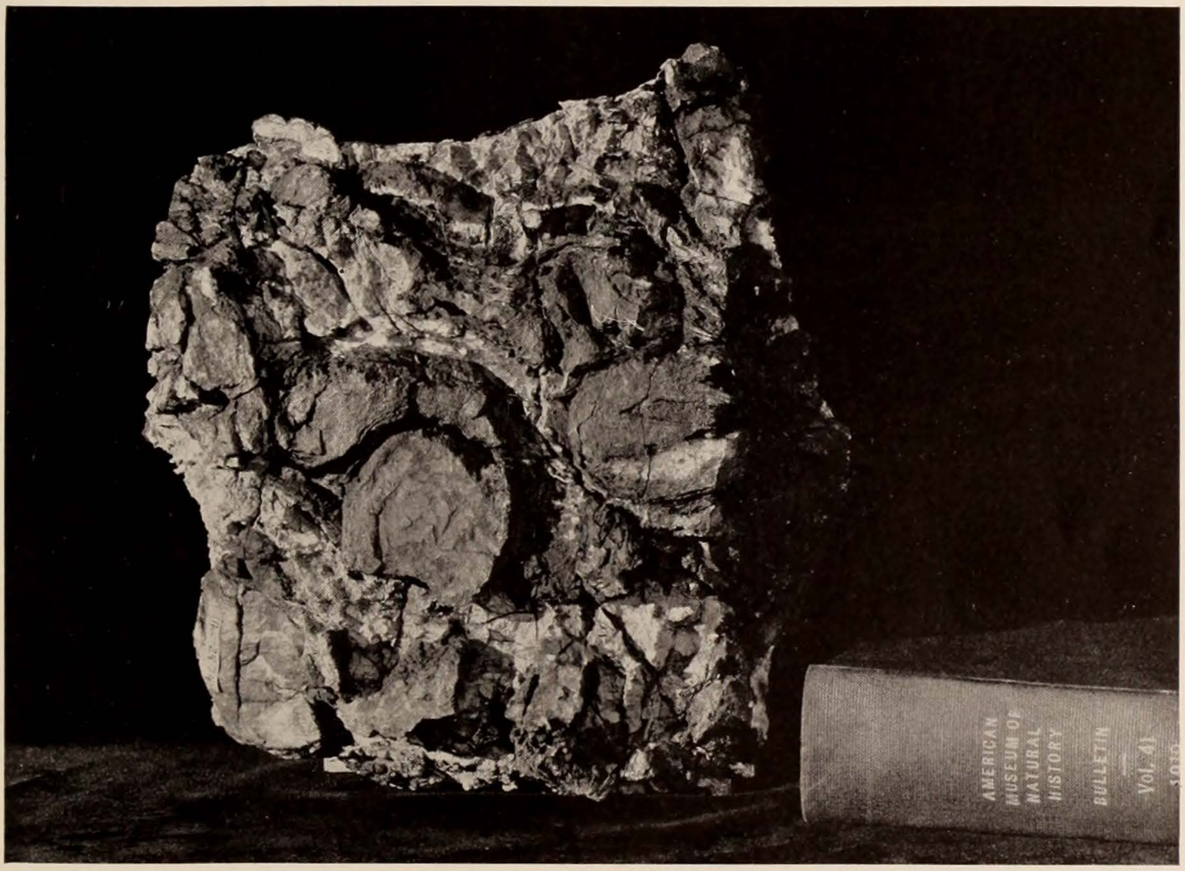
To illustrate the meaning of portions of this chart the wonderful section of rocks exposed in the Grand Cañon of the Colorado River in Arizona may be cited. Across a plateau, the upper surface of which rises from 7000 to 8000 feet above sea level, the Colorado River has eroded a trench about 217 miles long and a mile deep at the western end. This trench consists of two conspicuous features, one, an outer cañon, which is 4600 feet deep from the north rim and from 8 to 20 miles across, the other, an inner gorge which is another 1000 feet deep, narrow, and V-shaped in cross section. The buttressed walls of the outer cañon are composed of a succession of horizontally stratified sedimentary rocks; limestones, sandstones, and shales representing the Permian, Mississippian, and Cambrian periods of the Palaeozoic era. Below these level strata the river has cut its inner gorge through tilted sedimentary rocks; quartzite, limestone, and shale, some two miles thick, which are of Middle Proterozoic age. Below this series the river has cut its way into a crystalline basement rock, without stratification, which belongs to the earliest era, the Archæozoic. While this great section is wonderfully impressive to those who visit the Cañon, the story has been but partly told.

The ancient basement rocks are separated from the overlying Proterozoic series by a great erosion interval. This interval is represented in the section by an uneven surface known as an unconformity. Prior to occupying their present position, these basement rocks in the bed of the river which are 3000 feet above sea level, were deeply buried, crushed, smashed, and recrystallized by the processes of diastrophism as they lay at a lower level beneath a thick cover of rock. This cover was removed slowly by surface weathering, wind, and running water, acting throughout a complete cycle of erosion. The present erosion of the Grand Cañon is but a small beginning as compared with the great erosion period under consideration which was completed perhaps 1,200,000,000 years ago.

On top of the gently subsiding peneplain thus established, sediments of the Proterozoic Chuar and Unkar series were slowly deposited. It was a long enduring period, for the deposits are more than 11,000 feet in thickness. The sediments were at least partly of marine origin, for Dr. David White and Mr. Lincoln Ellsworth have collected primitive forms of plants known as fossil algæ, from the Bass limestone, which appears just above the base of the Unkar series. These are the oldest fossils in the Grand Cañon.

Following the long period of deposition, diastrophism renewed its activities. The Proterozoic series was faulted and tilted, in fact, great block mountains thousands of feet in height were uplifted.

This epoch of mountain uplift was followed by a second long period of erosion, during which time the region was again worn to a smooth plain, except for a few low lying hills. In many places the thick Proterozoic series was entirely removed and the basement rocks again exposed except where a few downfaulted blocks of the Proterozoic rocks were preserved. These downfaulted blocks of sediments are all that remain of the great Proterozoic era in



SILICIFIED FORMS OF FOSSIL ALGÆ IN THE BASS LIMESTONE

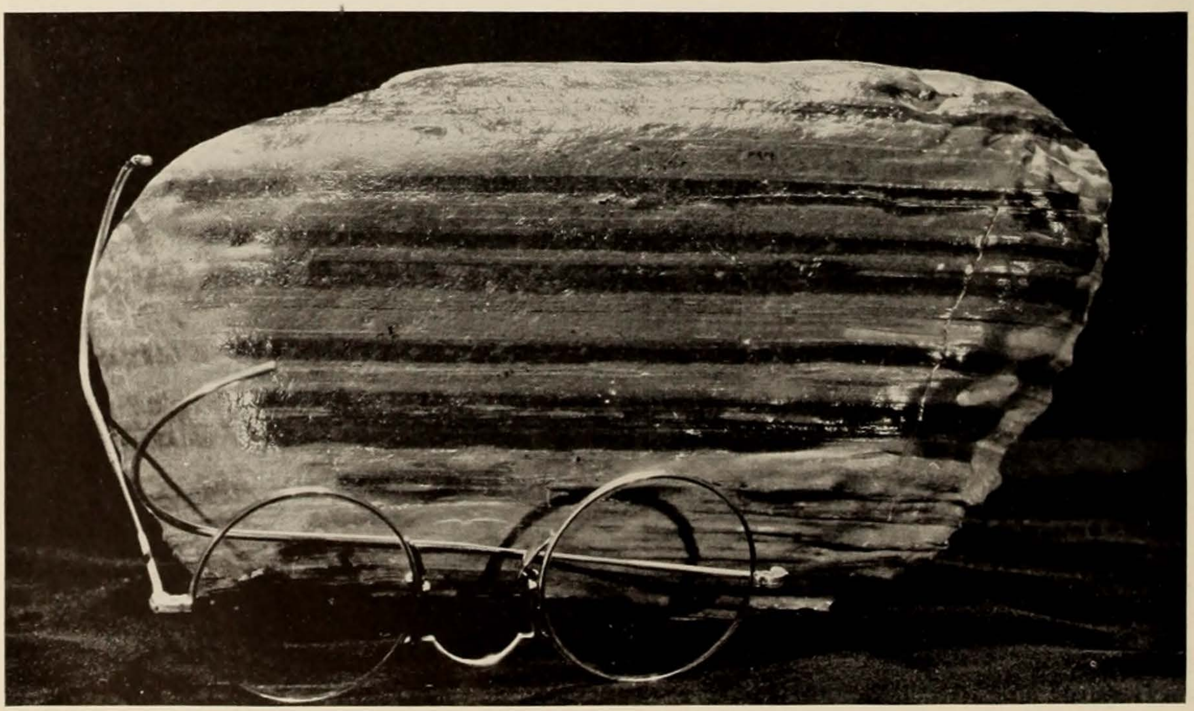
Collected by Mr. Lincoln Ellsworth from the middle Proterozoic rocks, near the mouth of Bright Angel Cañon, Arizona. This specimen is of exceptional interest to students of the early remains of life. The Radioactive Chart of Geological Time indicates that it is about 940 million years old this region. A second great line of unconformity separates the Proterozoic rocks from those of Palæozoic age.

As the land again sank, the seas of Cambrian time rolled in over the smoothed plain to inaugurate another great era of deposition in this region, the Palæozoic. Horizontally disposed sandstones, shales, and limestones were deposited. Amongst them may be found the fossil shells of various invertebrates, the tracks and remains of trilobites, et cetera. In the wonderfully impressive Palæozoic series of beds, the Orodovician, Silurian, and Devonian periods are missing. They are represented by an unconformity. We shall know more about what happened to them when the Grand Cañon is more fully explored.

As one views the Grand Cañon from the rim at El Tovar, it is difficult to realize that the rim rock, the Kaibab limestone, of Permian age, is not the top of the series of sediments. The great cliffs on the north and east that overlook the region are the higher strata that once extended over the whole district of the Grand Cañon. The distant strata represent deposits of Permian, Mesozoic, and Tertiary age. They are about a mile in thickness. Two major cycles of erosion are preserved in these rocks, one at the end of the Permian, the other at the close of the Mesozoic era. Each denotes prolonged erosion and a great interval of time. This Grand Cañon section, although extremely interesting and impressive, represents but portions of the geological time scale.

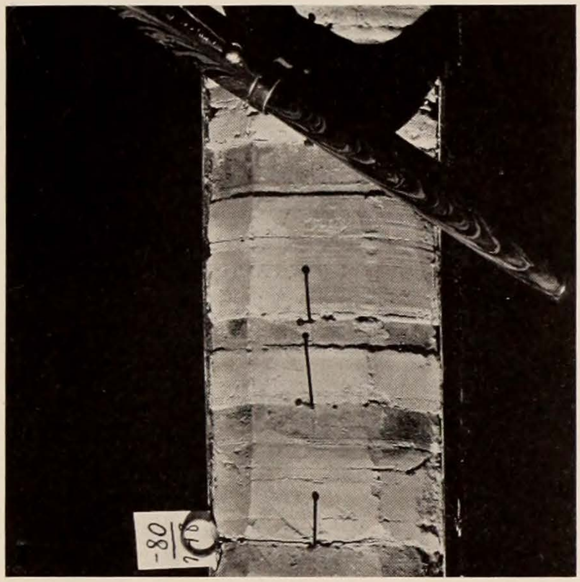
We have now suggested briefly the part played by the great geologic processes during the upbuilding of the earth. The question arises how long have these forces been acting? While various criteria have been used in the investigation of this problem, the data most frequently consulted are the sodium salts of the oceans, the thickness of the sedimentary rocks, and the radioactivity of the igneous rocks.

The sodium in the oceans has been derived from the land by the weathering of igneous rocks. It has been transported



GLACIAL BOWLDER OF VARVED CLAY OF MIDDLE PROTEROZOIC AGE

The seasonal layers of this compact rock were deposited in a glacial lake of Cobaltian time, 1100 million years ago, in Ontario Province, Canada. This specimen of the oldest known glacial period was carried by the ice of the last Pleistocene glaciation to Battle Creek, Michigan. E. M. Brigham collector from the land to the sea by rivers carrying it in solution. As noted by J. Joly of Dublin in 1899, the mass of the ocean waters is 1,180,000 million million tons. The percentage of sodium in the oceans was calculated by him to be 1.08 per cent by weight, so that there are 12,600 million million tons of sodium in the oceans. The amount of sodium contributed by the rivers to the sea annually has been variously estimated. After applying certain corrections, A. Holmes, 1927, calculated that the yearly increment amounts to 35 million tons. The amount of sodium in the sea divided by this annual rate gives 360,000,000 years as the age of the oceans.



VARVED CLAY OF LATE PLEISTOCENE AGE
HAVERSTRAW, N. Y.
This partial section of Haverstraw brick clay, 30,000 years old, was deposited seasonally in fresh water as the ice of the last glaciation retreated northward. The space between pins represents a year. The lighter colored layers of fine sand are the summer deposits; the dark bands of clay are the winter layers

This calculation is based upon the present rate of denudation and delivery. It is most probable that the rate is much higher now than during many of the former geologic ages when the lands were less high, less extensive, and the seas more widespread. To account for these differences, J. W. Gregory (1921) recommends that the present estimates based upon sodium should be multiplied by five giving a total of 1,800,000,000 years as the age of the oceans.

The age of the earth based upon the thickness of the stratified formations is more difficult to apply since the average annual rate of deposition of sediments is not definitely known for the present or for past epochs of geologic time. A. Holmes, 1927, estimates the thickness of the sedimentary deposits of various ages as 529,000 feet or 100 miles. J. H. Bretz, 1926, on the basis of several estimates obtains an average rate of accumulation of one foot in 880 years. These figures give a total of 465,520,000 years as the amount of time required for the deposition of the sedimentary record.

This estimate does not include, however, the beds which were deposited in epicontinental seas, uplifted and subsequently removed by erosion, leaving only an erosion plane as a record of the events. Neither does it take into consideration those great gaps separating the five eras of geologic time when sedimentation was presumably confined to the margins of the continental platforms. Ocean waters now cover the margins of the continental platforms to a depth of 600 feet and embrace continental areas totaling 10,000,000 square miles. J. Barrell, 1917, notes that geologic processes, embracing erosion, sedimentation, and deformation recur in composite rhythms in which landscapes alternate with seascapes and geosynclinal areas of sedimentation with high mountains. The processes of sedimentation are complex and variable, defying rates of deposition. Areas of sedimentation alternate with scour and fill, the resulting product represents merely the balance between these two processes. In some areas sediments may not always have reached so far, in others they may have been carried away to more distant spots, leaving small or large gaps in the horizontally disposed sediments known as disconformities. On the basis of these numerous deficiencies in the stratigraphic record it would seem that the above estimate of 465,520,000 years should be multiplied by a small figure such as 4, to account for the total time involved since sedimentation began, namely, 1,862,080,000 years ago.

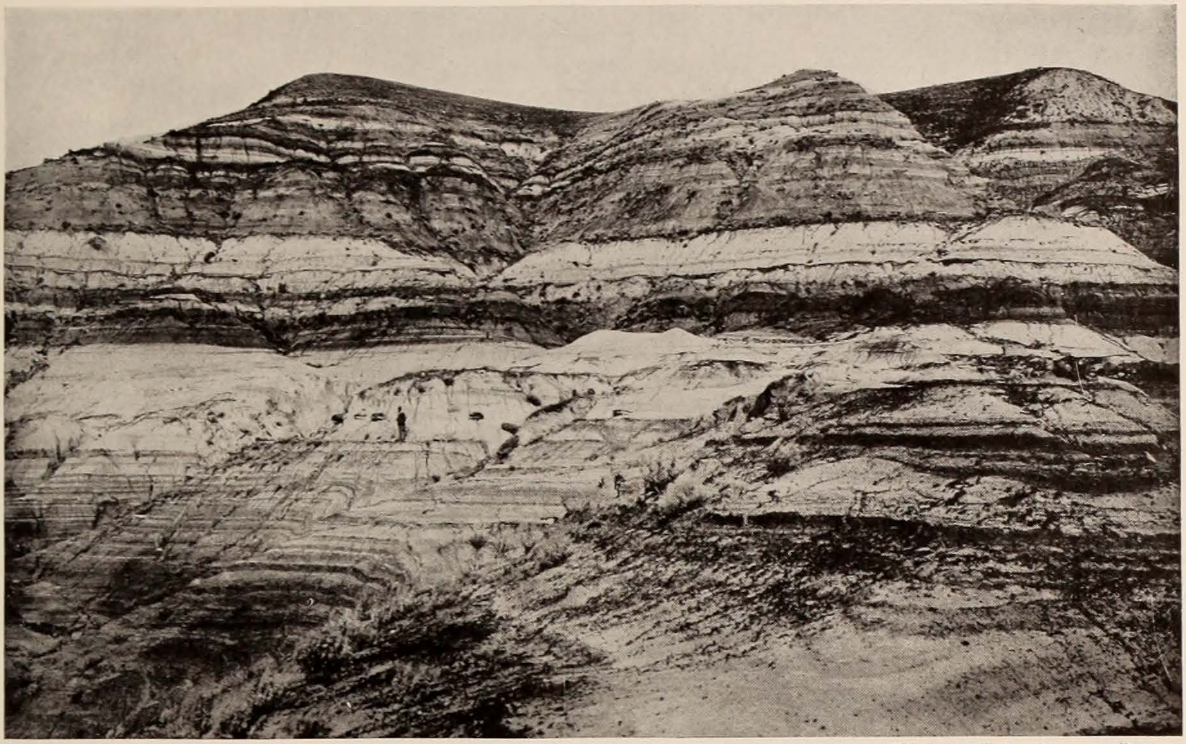
Another line of evidence, which has yielded remarkable results as to the age of the earth is the radio-active method. It was first used in this connection by Boltwood of Yale in 1907. It is based upon the invariable rate of disintegration of the radioactive substances, such as uranium, thorium, radium and actinium, which possess high atomic weights and disintegrate with the continuous emanation of helium into substances of lower and lower atomic weights, terminating in lead. While chemists and physicists have analyzed but a comparatively small number of rocks of different ages containing radioactive minerals, the determinations so far made yield results which are in accord with the sequence of rocks as determined by geologists. The radioactive method affords age determinations which are more accurate than that produced by any other known method.

According to G. von Hevesy in *Science*, Nov. 21, 1930, single atoms of uranium and other radioactive substances explode. The number of particles exploding and decaying in unit time is strictly proportional to the number present. Thus where one atom of uranium out of 1,000,000,000,000 atoms, (or a mass weighing 1/40,000,000,000 of a gram) explodes and disintegrates every 5 days, 73.05 atoms disintegrate in like manner in the course of a year. If the mass and the number of atoms be 10 times as large, 10 atoms will decompose in five days. If the mass be 100 or 1000 times as large, 100 or 1000 atoms will decompose in the same time. Hence, whether the mass be 10, 100, or 1000 times larger, it disintegrates at the same rate.

Uranium disintegration is thus a strictly uniform process whose velocity has remained unchanged throughout geological time. Von Hevesy says that it is the nucleus which is involved in the decay, and nuclear processes proceed independently of temperature, pressure, and other external conditions. Hence, he asserts there is absolutely no reason to believe that the process has gone forward at any different rate than at present at any period in the earth's history.

To students of this subject it is a well-known fact that the disruption of a uranium atom is always accompanied by the radiation of an alpha-particle, which is a charged helium atom, or by the loss of a beta-particle, which is a free electron. The alpha-particles leave the atom with a velocity of 8800 miles per second and travel a distance of about 2.8 cm. in air and about 0.013 mm. in mica before they become powerless. The beautifully colored "pleochroic halos" seen in mica (biotite) under polarized light are produced by these alpha particles as they are emitted by the contained uranium and the decomposed products of uranium. The fact that the halos, corresponding to the various radioactive substances, have the same diameter, indicates that the rate of decay has remained the same throughout the ages. To apply the rate of uranium decay as a measure of time it is necessary as von Hevesy says to obtain (1) the total quantity of uranium that has decayed in some mineral since the solidification of the earth, and (2) the rate of that decay.

Accompanying the radiation of alpha-particles from uranium it is known that one atom of helium, an inert gas, rises from the decay of each atom of uranium. Although a small portion of this helium escapes, most of it collects in the uranium bearing rock, where its volume gives a



Photograph by Barnum Brown

STRATIFIED CRETACEOUS DINOSAUR BEDS, ALBERTA PROVINCE, CANADA

The man near the center of the picture stands on the contact between the marine Pierre beds below and the fresh-water Belly River dinosaur beds above. The contact denotes not only a change in the character of the sediments, but a lost interval of time occurring about 65 million years ago

measure of the age of the rock. Lord Rayleigh noted that one cubic centimeter of helium may be produced from one gram of uranium in 9,000,000 years. Since a small portion of the helium gradually escapes, this method gives but a minimum age. On this basis, age determinations of ancient rocks have been made to the amount of 570,000,000 years.

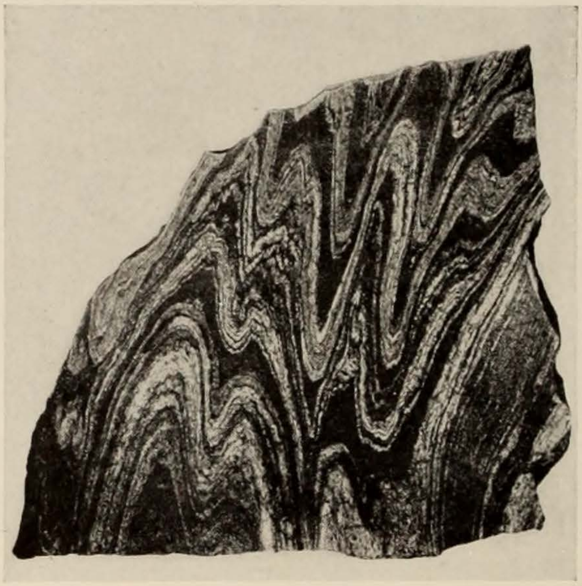
Uranium has an atomic weight of 238, helium 4. Hence, as the decay proceeds and helium is liberated, the products of the decay have atomic weights, 234, 230, 226, 222, 218, 214, 210 and 206. The atomic weight of a beta-particle is 1/1800, hence, when it is lost, the atomic weight is decreased by an insignificant amount.

The atomic weight 206, which is lead derived from uranium, is of special interest in radioactive determinations, since it is a solid product and does not disintegrate. It may be observed that 238 parts of uranium produce 206 parts of lead as 32 parts of helium are developed. Hence, from the known rate of the production of helium from uranium, A. Holmes, 1927, calculates that a million grams of uranium give rise to 1/7400 of a gram of lead every year. Holmes also presents formulæ for making age determinations from the various radioactive minerals. Thus after determinating the lead content of the uranium minerals it is possible to calculate what proportion of the uranium has decomposed since the mineral was formed.

In the *American Journal of Science* for March, 1927, A. Holmes and R. W. Lawson reviewed the methods of determining the radioactive disintegration of 18 samples and presented 22 determinations, the results of which have been incorporated in the left margin of the geological time scale on page 137. In the same journal, Aug., 1930, A. F. Kovarik described two additional analyses of ancient rocks, one for 1,465,000,000 years, the other for 1,852, 000,000 years. These have also been added to the chart.

The radioactive method, which is based upon the natural disintegration of uranium to lead, is of great importance for it enables us to determine the following interesting things about the earth:

1. The age of the oldest igneous rocks containing radioactive minerals, that is, the minimum age of the earth.
2. The date of various events in the later history of the earth.
3. The nature perhaps of various transformations in the gaseous and liquid stages of the earth's history.
4. The maximum age of the earth.



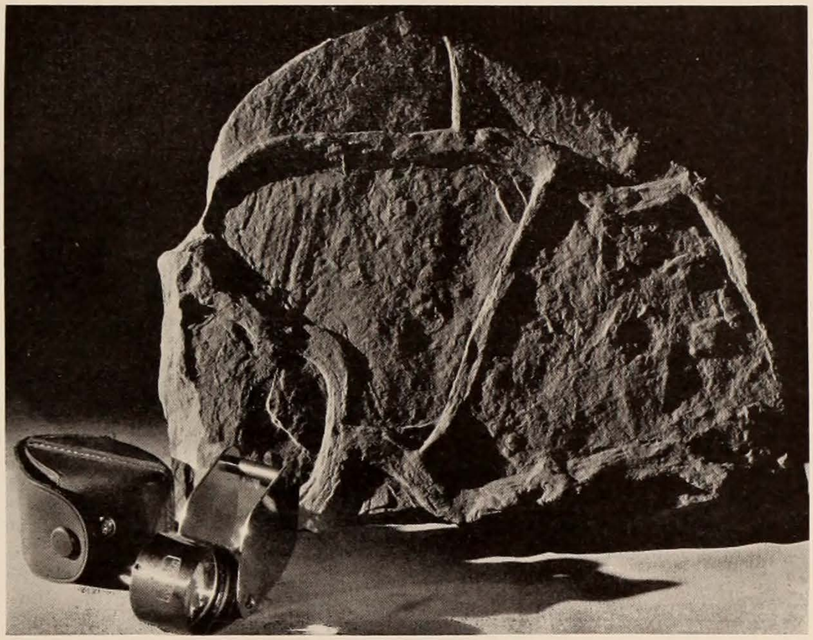
SECTION OF FORDHAM GNEISS, ARCHÆOZOIC AGE NEW YORK, N. Y.

The folded and contorted bands of light and dark colored minerals represent lines of segregation of the mineral matter, and folding when in a plastic state. It is typical of many Archæozoic rocks. Specimen from excavation, eastern abutment of Fort Washington bridge over Harlem River. Age problematical, perhaps 1800 million years

As to these various points it may be said that the oldest radioactive mineral so far determined is a specimen of Uraninite from Sinya Pala, Carelia, in northwestern U.S.S.R., and that its age is 1,852,000,000 years as determined by A. F. Kovarik, Sloane Laboratory, Yale University, August, 1930. Another specimen of the same mineral from Keystone, South Dakota, as determined by Prof. Kovarik, gave 1,465,000,000 years. It is probable that other specimens yielding an even greater age may be found and that the minimum age of the earth, that is, the formation of the crust, may be considered to have begun approximately 2,000,000,000 years ago.

The age determinations of various events in the later history of the earth have been entered in the geological time scale on page 137.

The third and fourth points are of special interest, since the early history of the earth is still obscure. According to von Hevesy, 1930, the uranium-lead method is not only of value in determining the lower limit of the age of the earth's materials, but of the chemical elements. As a chemist he considers that the transformation of uranium into lead had already progressed to a certain point while the earth's material was still gaseous. He asserts that this lead with atomic weight 206 did not remain isolated, but mixed with lead (208) formed by the decay of thorium and as a result common lead (207) was produced. He goes on to say that approximately half of our common lead was formed from uranium before the earth's materials had solidified. He cites F. W. Aston as having proved recently that ordinary lead is a mixture of uranium-lead and thorium lead. He considers that lead formed in uranium minerals has had no opportunity to mix with thorium lead and consequently it has remained fixed as uranium-lead. Thus the ratio of all the uranium to about half the common lead (plus the uranium-lead) present in the whole earth must give the age of the earth's material. His considerations give about 3000 million years as the upper limit of the age of the minerals; it is also the lower limit of the age of the earth's material. He draws a distinction between the few radioactive elements, which have altered according to accurately known laws during this long time, and the other elements which built up the earth's constituents and have undergone no change.



MUD FILLINGS OF "SUN CRACKS," SUPAI FORMATION

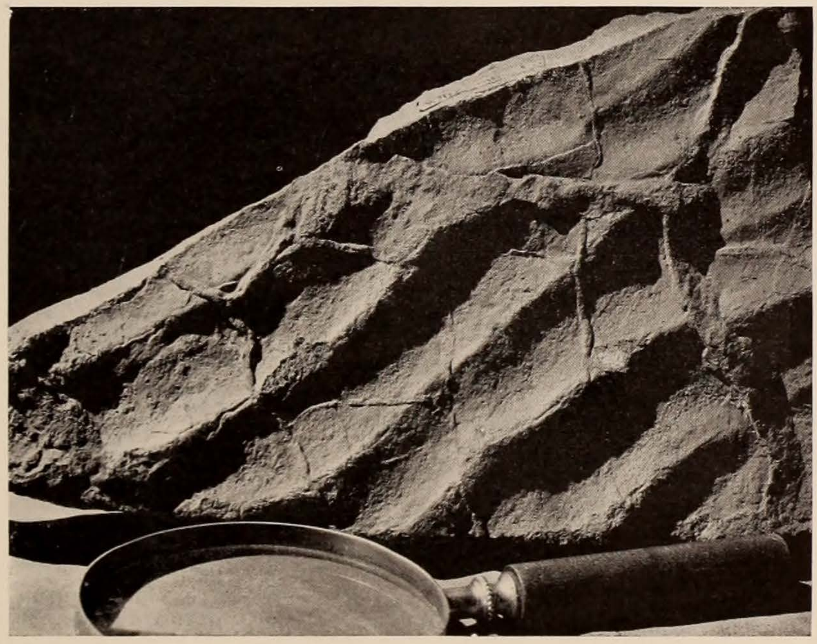
A specimen of lower Permian age that is some 215 million years old. It exhibits the same physical phenomenon as is found in the Hakatai shale specimen 935 million years old of middle Proterozoic age. From the Grand Cañon of Arizona. Lincoln Ellsworth Collection, 1930

The foregoing determinations have had to do with the crust of the earth. Since the earth's interior is inaccessible, the geochemist turns to the meteorites and assumes that the iron meteorites correspond to the core of the earth, and the stony meteorites to the more or less silicate-like material lying between the core and the crust.

F. Paneth of Berlin developed in 1926 the methods for determining the helium content of meteorites. He notes that the iron meteorites when heated to a red heat loose no trace of helium. According to von Hevesy, 1930, Paneth has found for the iron meteorites a maximum age of 2600 million years.

These data are significant. It lends support to the theory that the original materials of the earth and of meteorites may have come from a common celestial source. It also implies that the youthful earth, which grew presumably from the inner core outward by the addition of layers of planetoid and planetesimal matter, began its development 2,600,000,000 years ago. The oldest surface rock so far analyzed yields an age of 1,852,000,000 years. The difference in age between the oldest rock and the oldest meteorite is 748,000,000 years. May not this difference, or some 600,000,000 years, represent the time consumed in the upbuilding of the primeval earth?

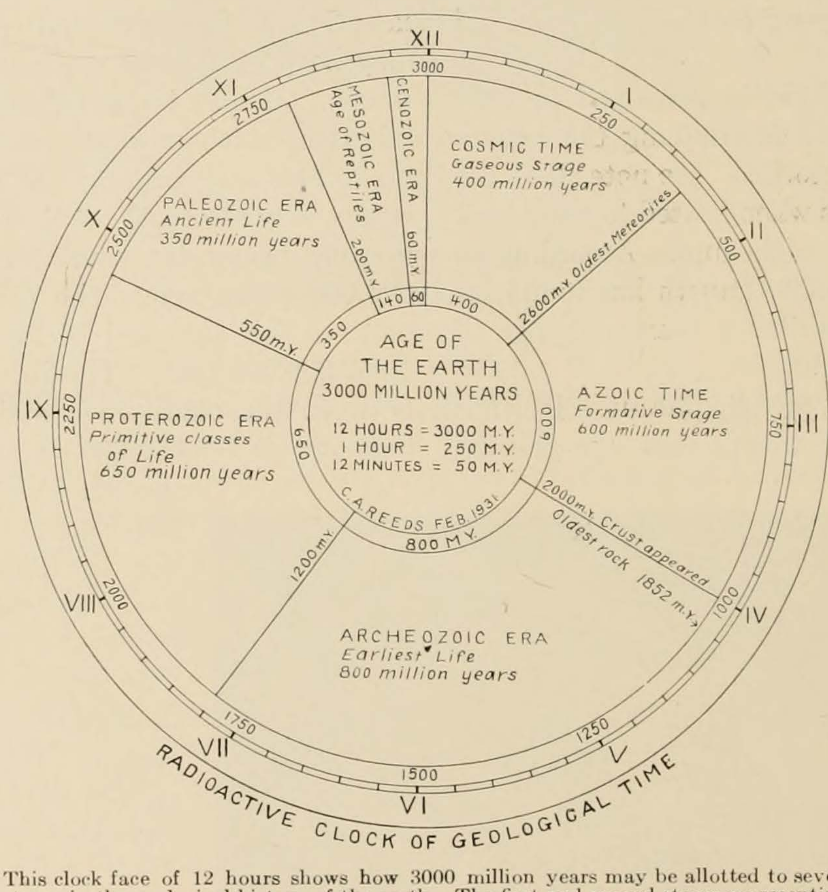
In conclusion it may be stated that these radioactive determinations are not only astounding, but remarkable. Al-



PROTEROZOIC RIPPLE MARKS AND "SUN CRACK" IMPRESSIONS

This slab of red Hakatai shale of middle Proterozoic age is some 935 million years old. It shows that the same physical phenomena were in force during the early eras of the earth's history as are in evidence today. Specimen from the Grand Cañon of Arizona. Lincoln Ellsworth Collection, 1931 though the method is still young the results are dependable. The method is based upon the natural rate of disintegration of the atoms of the few radioactive elements. This rate cannot be changed by any known human or physical agency. It is thus a reliable and thoroughly scientific method. When its application has been extended to numerous samples of radioactive rocks and minerals from all parts of the world, embracing rocks of all ages, then we shall know, in all probability, how old the earth is.

Upon the basis of knowledge for 1931, we may consider the crust of the earth to be 1,852,000,000 or about 2,000,000,000 years old; the inner core, 2,600,000,000 years old; and the upper limit of the minerals, or materials of the earth, as 3,000,000,000 years old, as noted below in the radioactive clock of geological time. The radioactive determinations and the oldest fossils indicate that primitive life was present on the earth one and one-half billion years ago; stone implements and human remains in Pliocene deposits imply that the human race was on the earth about one and one-half million years ago.



This clock face of 12 hours shows how 3000 million years may be allotted to seven stages in the geological history of the earth. The first and second stages representing the gaseous and formative eras respectively, are not shown on the preceding more detailed radioactive chart of geological time, page 137.