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RHYTHMS AND THE MEASUREMENTS OF GEOLOGIC TIME¹

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¹The second of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks." It was presented at the Albany meeting, December 29, 1916, under the title "The Significance of Sedimentary Rhythms." It formed the first and second parts of a paper entitled "The Measurements of Geologic Time," delivered as two addresses in the University of Illinois Public Science Lectures on January 16 and 18, 1912, at Urbana, Illinois. The author feeling that condensation would diminish greatly the value of the paper, the Publication Committee of the Society consented to publish it in full under the title given above.

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INTRODUCTION AND SUMMARY

Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-mark, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of composite rhythms—day and night, calm and storm, summer and winter, birth and death—such as these are sensed in the brief life of man. But the career of the earth recedes into a remoteness against which these lesser cycles are as unavailing for the measurement of that abyss of time as would be for human history the beating of an insect's wing. We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the earth. The larger of these must be measured in terms of the smaller; and the smaller must be measured in terms of years. Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves of change which have pulsed through geologic time.

The doctrine of uniformitarianism has ignored the presence of age-long rhythms, and where they were obtrusive has sought to smooth them out; but in so doing it has minimized the differences between the present and the past, and the constant variations within that past. This doctrine

should be looked on only as supplying a beginning for investigation; the establishment of a datum plane against which may be sought out and measured the amplitudes of oscillations of all factors which have found a direct or indirect record in the crust. This, of course, is not easy, since the causes are often obscure and the degree of variation in period and in amplitude of each factor must be determined and tested by comparison with unrelated factors.

Although, in a later part of this article, a review is given of the evidence furnished by radioactivity, the viewpoint of the paper is geological, the first three parts consisting in a study of the variations to which the rates of geologic processes have been subject. In the assemblage of material and the manner in which the subject is treated here, it is essentially new, although Blytt, Gilbert, F. B. Taylor, E. Huntington, and others have dwelt on one aspect or another of this subject.

In Part I of the paper it is pointed out that erosion is essentially a pulsatory process, as Davis has made most clear and the students of physiography are now well aware. A single rhythm is the erosion cycle; and small partial cycles are superimposed on larger. How much has this pulsatory nature led to variations in the rate of regional and continental denudation in the past, and what is its significance in regard to the sedimentary measures of geologic time? The answer is reached from several points of view in this article that, because of the present great elevation of the continents, because of the magnitude of recent orogenic movements, and because of the pulsatory nature of the Pliocene-Pleistocene uplifts, forming an accelerated series, a concurrence of factors has taken place each of which makes for a high rate of denudation. Their combination must give a rate very much greater than the mean for geologic time.

Passing in Part II to the next step in the argument: in all stratigraphic measures of geologic time, so far as the writer is aware, the rate of deposition of a sedimentary series has been previously regarded as dependent on the type of sediment, whether sandstone, shale, or limestone, combined with the present rate of supply of such sediment to regions of deposition. Here is developed an opposite view: that the deposition of nearly all sediments occurs just below the local baselevel, represented by wave base or river flood level, and is dependent on upward oscillations of baselevel or downward oscillations of the bottom, either of which makes room for sediments below baselevel. According to this control, the rate of vertical thickening is something less than the rate of supply, and the balance is carried farther by the agents of transporta-

tion. The storage of the final excess, except for locally deep water on the lands, is on the abyssal slopes of the continental platforms, constituting deposits lost to observation, since it is a region which has been seldom uplifted and exposed by erosion.

Thus, sedimentation, as well as erosion, is dependent for its rhythmic rejuvenation on changes in baselevel, emergence above baselevel determining erosion, submergence below baselevel giving sedimentation, either of continental or marine deposits. This control of sedimentation by baselevel may be summed up in three principles:

First, the rate of sedimentation is determined usually not by the rate of supply of sediment, but by the rate of the discontinuous depression of the surface of deposition.

Second, subsidence of the sedimentary floor is not initiated by the load of sediment, for depression must precede. When a movement of subsidence has begun, however, the weight of sediment will act in the same direction, but it is a secondary cause. Sedimentation, then, is the effect of depression to a greater degree than it is the cause.

Third, the deposition of a series of beds where the material is carried along the bottom by stirring of currents or oscillations of waves is ordinarily not a continuous process, even during a stage of crustal depression, but represents an irregularly rhythmic alternation of fill and scour with a balance in favor of the fill. There are minor time blanks, consequently, in what appears to be a continuous succession of beds, and larger and larger intervals separate the larger and larger divisions of a series.

Numerous breaks are now known to exist in which the beds above and below lie parallel, and, except for some change in fauna or flora, give little or no indication of the great lapse of time which occurred between their deposition. Such breaks are known as disconformities. The present argument enlarges on this conception, holding that the breaks of smaller time interval are still more numerous and may add up to equally large measures of time unrecorded by sedimentation. Such breaks have generally been too brief to give a clue by means of a faunal or floral change, but must be recognized through the physical features of the beds, often most readily because of a sudden change at the break in the character of the rhythms expressed in sedimentation. It is proposed to recognize the aggregate importance of such minor breaks by giving them a special name. The name selected is diastem. Diastems range of all values from seasonal cessations of sedimentation to those which approach geologic epochs in duration.

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.

Judged in the light of these arguments, 250,000,000 years may be regarded as a moderate estimate, from the geologic data, of the lapse of time since the beginning of the Paleozoic. The indications from radioactivity are in fact that it is more than twice as long as even this figure of 250,000,000 years, and the geologic evidence is seemingly not in conflict. An estimate of 250,000,000 is a return to the order of magnitude of the guesses made by Lyell and Darwin before Sir William Thomson, later Lord Kelvin, began to cut down to a small part of this estimate the capital of years which could be drawn on by geologists from the bank of time. Not recognizing the importance of the principles just stated, and feeling the need, so far as possible, of meeting the demands of the physicists, geologists found it easy to make lower estimates, though difficulty was found in compressing them to the later narrow limitations of 10,000,000 to 20,000,000 or 40,000,000 years for the age of the earth as set by Tait, Kelvin, Ritter, King, and others.

With the opening of the twentieth century the discovery of radioactivity disclosed, however, undreamed of stores of thermal energy. This discovery revealed with startling suddenness the unfounded nature of the assumptions, previously unquestioned, on which rested the restrictions that physicists had placed on geologists. Not only did physicists destroy the conclusions previously built by physicists, but, based on radioactivity, methods were found of measuring the life of uranium minerals and consequently of the rocks which envelop them. Instead of limiting earth history to less than 40,000,000 years, they now granted upwards of 1,500,000,000. Many geologists, adjusted to the previous limitations, shook their heads in sorrow and indignation at the new promulgations of this dictatorial hierarchy of exact scientists. In a way, this skepticism of geologists was a correct mental attitude. The exact formulas of a mathematical science often conceal the uncertain foundations of assumptions on which the reasoning rests and may give a false appearance of precise demonstration to highly erroneous results. No better illustration could be given than that of the case in point. This skepticism was incorrect, however, unless it led to a careful and unprejudiced reexamination of the postulates on which rested the geologic measurements of time.

Looking at the geological side of the problem from the standpoint of the control of sedimentation by baselevel, a subject which had at that time recently engaged the writer's attention, rather than by the present rate of denudation,² he stated in 1906 to Professor Boltwood, the first to seriously develop the evidences of age based on radioactive processes, that no real conflict appeared to exist between the geological facts and the new physical evidence. The conflict was only with one of the several possible interpretations of that evidence, though one which was generally accepted.

This article, as previously stated, is primarily an analysis of the geologic evidence, taking in especially the influence of the fundamental factor of composite rhythms, but it would be incomplete if it discussed only the interpretation of sedimentary processes in terms of rhythms. Such a discussion might fail to carry conviction of the great lengthening which it implies in the vista of geologic time, and at best would be qualitative rather than quantitative. Consequently, in Part III, a review is given of the methods of measurement based, first, on erosion and sedimentation; second, on chemical denudation and the sodium in the sea; and third, on the thermal gradient of the crust. In this review care is taken to examine the postulates which underlie these methods and which have resulted in current estimates of geologic time very much smaller than the estimates reached by the consideration of sedimentary rhythms and the measurements based on radioactive processes.

Another method is that of the detection of rhythms in parts of the sedimentary series, and the correlation of these rhythms with known climatic cycles. The use of the precession cycle has given very long estimates for these small pieces of geologic time. There are suggestions, however, derived from postglacial time, that the rhythm which is prominent is not so long as the precession cycle of 21,000 years, but is probably a rhythm in solar energy several thousand years in length. Such a conclusion comes into accord with the other lines of analysis of this paper, extending geologic time far beyond the generally accepted maximum limit of a hundred million years.

This is followed in Part IV by a presentation of the evidence from radioactivity, as based on the accumulation of helium and lead in radioactive minerals. Such a presentation seems all the more necessary, since no adequate treatment of that subject has been published in American geological literature. It is made easier at the present time by the

² Joseph Barrell: Relative geological importance of continental, littoral, and marine sedimentation. *Journal of Geology*, vol. xiv, part 1, 1906, pp. 316-356.

publication in England in 1915 of an article by Professor Arthur Holmes,³ an investigator who has done much work on this subject.

Becker in 1908 published an article on the "Relations of Radioactivity to Cosmogony and Geology."⁴ On pages 127 to 135 of this article is discussed the subject of "Radioactivity and the earth's age." Becker's argument and conclusions are strongly adverse to the value of the radioactive methods for determining age. This result is based in considerable part on the conflicting testimony derived from the radioactive minerals of the Llano district in Texas. In order to weigh these criticisms, the writer has examined the original data and finds that, instead of being opposed, they strongly support the hypothesis that the ratio of lead to uranium in uranium minerals, serves, when properly used, as an index of age. A hypothesis gains greatly in strength when what appeared to be conflicting evidence is resolved into supporting evidence. For this reason the facts for the Llano region are given in Part V in some detail.

Thus this article seeks to bind the geological and physical arguments into a unity—the geological data giving evidence of highly variable rate and imperfection of record, the physical evidence supporting the assumption of constant rate for radioactive processes and giving the magnitude of the framework into which the geological picture must be set. That framework is given in Part VI, the concluding part, as a new table of geologic time, and is of more generous proportions than geologists would have dared to assume from the data of their field alone; but it appears on testing from various points of view to have been logically constructed and gives room for a bolder and larger treatment of earth history than has been imagined to be held within the past. This table of geologic time is constructed by the dovetailing of two lines of evidence, as follows:

First, the thicknesses and character of the sediments give stratigraphic ratios of the lengths of the several periods. These, for reasons discussed, are subject to considerable uncertainty; yet, when derived with a knowledge of the variables involved, the ratios give some measure of the relative durations. Second, the quantities of helium and lead in radioactive minerals give minimum and maximum measurements of age. These ages are open to some uncertainty because of loss of helium or the presence of original lead, and the stratigraphic positions of the rocks holding the minerals are also in most cases not closely known. Nevertheless, the radioactive minerals give measures of absolute age which are of the right order of magnitude and in proper sequence, as shown by the geologic data.

³ Radioactivity and the measurement of geological time. *Proc. of the Geologists' Association*, vol. xxvi, part 5, 1915, pp. 289-309.

⁴ *Bull. Geol. Soc. Am.*, vol. 19, pp. 113-146.

The adjustment of these two lines of evidence serves as the basis for a table of geologic time stated in years. Such a table is comparable to the first crude measurements of the distances of the stars in space. The progress of research will continually refine the determinations and lead to a higher order of precision. On the present data Cenozoic time is determined as between 55,000,000 and 65,000,000 years long; the Mesozoic as covering between 135,000,000 and 180,000,000 years; Paleozoic time endured between 360,000,000 and 540,000,000 years. The summation of these minimum and maximum figures indicates that the beginning of the Cambrian was between 550,000,000 and 700,000,000 years ago. This may seem to be a wide latitude, but the ratio of the minimum to the maximum is no greater than those estimates now current and based on stratigraphy. The important conclusion is that time since the beginning of the Cambrian is from ten to fifteen times longer than has been generally accepted by geologists.

Surprising as it may seem, the date known with the greatest precision lies far back in pre-Cambrian time. From Norway, Texas, Quebec, and German East Africa uranium minerals associated with granites give an age which approximates to 1,120,000,000 years. In the Scandinavian nomenclature the granite is post-Bottnian. In Quebec it is later than the Laurentian granites and is probably post-Sudburyian (post-Temiscaming).

This is the age, consequently, of the second great granitic invasion of known geologic time. The Laurentian granites, the first great invasion, may have an age as great as 1,400,000,000 years.

These measurements of the length of the several eras give a basis for estimates of the mean rates of erosion and sedimentation. In the pre-Cambrian they point to the existence of long periods of quiet, during which the continents were baseleveled. The profound revolutions, marked by folding, magmatic invasion, and regional metamorphism, were relatively brief periods closing long eras marked by diastrophic quiet and low continental relief.

Another aspect to be considered lies in the relations of organic evolution to this great expansion of time. If it be assumed that the lowest forms of life began shortly after the earth's surface was fitted to support them, then instead of evolution being compressed into less than a hundred million years, it is stretched out over a period of the order of 1,500,000,000 years. A discussion is given of the biologic advantage of this far greater duration for accomplishing the organization of the cell and the establishment of the principles of heredity. Although evolution may advance by saltations and is accomplished through the establishment of new

or the dropping of the old mendelian factors, yet the building up of the organization of the metazoa implies the sifting out of favorable combinations from chance variations by a process of natural selection. Only in this way can organisms become organized and efficiently adjusted to their environment. But this requires numberless generations living in the relatively brief times of changing environment and resulting organic stress.

Finally, the recognition of this larger magnitude of geologic time opens up sharply another problem—the source of solar energy. But the sun is only one of the numberless host of stars, and the source of its energy is a far-reaching cosmic problem. To warm the earth through the vast length of geologic time, gravitational condensation of the solar mass is found to be totally inadequate. The energy supplied by the atomic degeneration of uranium and thorium would have ample endurance in time; but, even if the sun were composed entirely of these elements, their decay could not supply the quantity of energy which is daily expended. Geologic time brings to light, consequently, the evidence of unknown sources of energy, cosmic forces which must constitute a fundamental factor in any satisfactory hypothesis of stellar evolution, a factor which has not as yet been taken into full consideration in its bearings. Even if, as a lesser difficulty, it should be sought to deny the validity of the radioactive measurements of the earth's age, escape can not be had from this conclusion, for various lines of purely geological evidence indicate an age many times greater than that which could be granted if the solar energy were due simply to contraction of the sun's mass. The depths of geologic time leave us face to face with the unknown.

PART I.—RHYTHMS IN DENUDATION

PRESENT RATES OF DENUDATION

Sedimentation rests on the rate of denudation. It can not go forward faster than material is supplied, but it may proceed slower, and the balance of the waste be carried beyond. In studying the time values to be assigned to the components of the stratigraphic column, the first problem, therefore, is to discuss the present rate of denudation. By noting the factors which enter into it we may arrive at a truer conception of the variations of denudation in the past.

The mean rate of denudation—the lowering of the continental surfaces by pluvial and fluvial erosion—has long been sought. The usual method has been to measure the waste which representative rivers carry to the sea in the course of a year. The drainage basin of the Mississippi was thus estimated to be lowered one foot in 6,000 years, or adding the dis-

solved matter, one foot in 4,500 years. These figures have been given considerable weight since the Mississippi has been taken as a representative river.⁵ For the measurement of geologic time the mean rate of erosion has generally been taken, however, as higher than this. Goodchild selected one foot in 3,000 years as the best average. Sollas uses a figure derived from Geikie, of one foot in 2,400 years. A more reliable mean figure is based on solvent denudation. The mineral matter carried in solution in river water, and also the quantity of water, can be accurately determined at suitable intervals. By taking representative streams for various climates and topographic reliefs, a mean result is obtained. Valuable figures for the area of the United States have been contributed especially by Dole and Stabler of the U. S. Geological Survey. On the basis of these data F. W. Clarke finds that, taking the continents as a whole, they are lowered by solvent denudation one foot in 30,000 years. This estimate he regards as probably correct within 10 per cent.⁶ From measurements of the suspended matter collected in the analyzed samples it is found for the United States that the removal of this insoluble material lowers the mean continental surface one foot in 13,800 years. The rate for the combined action is one inch in 760 years,⁷ or one foot in 9,120 years. A number of writers who have used these data have failed to note, however, that the materials transported along the bottom, as sand or gravel, are not reckoned into these results.⁸ In such a stream as the Mississippi near its mouth this would involve but a moderate correction, since the great bulk of its material is there carried in suspension and solution. The silt, however, is carried in greater quantity near the bottom. In applying the method to the rate of erosion in the upper parts of river systems, or at the mouths of streams which carry much sand to the sea, a larger correction for purely bottom transportation would be necessary.

The rate varies greatly from season to season, and the volume of suspended matter may vary 50 per cent from one year to another; but, considering the various factors, Dole and Stabler regard the figures for denudation as generally within 20 per cent of the true value. The rate is highly contrasted, furthermore, in different regions. Measurement of dissolved and suspended matter at Yuma shows the Colorado basin, with an area of 230,000 square miles, to be lowered one foot in 5,300 years. The western Gulf of Mexico drainage, with an area of 315,700 square

⁵ A. Geikie: *Text-book of Geology*, 1903, pp. 589-591.

⁶ A preliminary study of chemical denudation. *Smithsonian Misc. Coll.*, vol. 56, no. 5, 1910.

⁷ Dole and Stabler: *Denudation*. *Water Supply Paper* 234, U. S. Geol. Survey, 1909, p. 83.

⁸ Dole: See methods of collecting samples. The quality of the surface waters in the United States. *Water Supply Paper* 236, U. S. Geol. Survey, 1909, p. 10.

miles, shows the much lower denudation rate of one foot in 21,600 years, but an important correction may be needed in the arid and semi-arid regions for eolian transportation. The amount of denudation increases with high rainfall, but the Mississippi basin shows, nevertheless, a higher rate than the southern Atlantic watershed.

Very high rates have been found in mountain regions in other countries, the Po being estimated to lower its basin one foot in 729 years, the Ganges one foot in 823 years. Geikie devotes a special heading to "The unequal erosion of land."⁹ He calls attention to the dependence of erosion upon slope, and that within each river basin the rate varies greatly in its different parts. It seems likely that over the more rugged portions of the mountains in the Po and Ganges drainage area the rate of erosion may be two or five times the mean for the whole of those areas.

Using Clarke's estimate for chemical denudation for all the continents as one foot in 30,000 years and taking this as 30 per cent of the total denudation gives a mean rate of total denudation at the present time of one foot in 8,600 years. This, although reliable as the present rate, perhaps to within 10 per cent, is seen to depend upon the average of a great range in values, both locally and regionally, from ten to twenty or fifty times the mean as one limit to zero as the other limit, or even beyond it to actual deposition. *Any condition in the past which would change the aspects and areas of the lands in the same direction over various continents would change the mean for such times enormously.* Therefore if such a figure, obtained for the present, is used blindly, it is likely to become an extremely misleading unit for the measurement of geologic time. Harker has recently called attention to the lack of value of mean figures which are based on such widely varying data.¹⁰

RELATIONS OF RATE TO THE CYCLE OF EROSION

Davis in his publications from 1889 to 1892, extending the ideas of baseleveling formulated by Powell and Dutton, showed that the lands had been baseleveled recurrently in former geologic periods. To the resulting topographic form he gave the name of peneplain. Many ancient peneplains are now buried and preserved as surfaces of unconformity; others have been elevated and more or less destroyed by new cycles of erosion as yet uncompleted. In topographic old age the rate of erosion he showed must become indefinitely low.

In 1898 Tarr published a paper in which he brought forward various

⁹ A. Geikie: Text-book of Geology, 1903, pp. 591-593.

¹⁰ A. Harker: Geology in relation to the exact sciences, with an excursus on geological time. Nature, vol. 95, 1915, pp. 105-109.

arguments against the peneplain.¹¹ One of these rested on the fact that no extensive peneplains, not uplifted or dissected, are known to exist at the present time in any part of the earth, although peneplains were said by Davis and his school to have been produced again and again in the past. Therefore, argued Tarr, we need as a fundamental assumption to believe that during a part of the remote past the conditions have been different from these that have prevailed in any part of the known earth during the present and the immediate past.¹²

The following year Davis published a rejoinder,¹³ and, in regard to the contention cited above, he stated that here Tarr and he were in agreement, except that he should prefer to replace "fundamental assumption" by "necessary corollary." Davis notes that it was as a very surprising corollary that he came on the difference between the present and certain parts of the past with respect to peneplanation.¹⁴

Davis's position is now regarded as established, but the significance of this fact of difference between the present and the past is not fully appreciated outside of the field of physiography. The earth has rested time and again in repose; shallow seas have spread far and wide over base-leveled lands: over the greater part of the continental surfaces which remained above the sea erosion must have become reduced to a small part of its present rate. This conclusion, which is fundamental in stratigraphy and in the stratigraphic measures of geologic time, will be developed from other points of view in the following topics.

It is clear that epochs of diastrophism are more or less closely correlated in widely different regions. Changes in sealevel are necessarily felt over the whole earth, increasing or decreasing by relativity the mean height of the lands. But beside this the lands themselves are periodically broadly warped and, more locally, mountain growth takes place. In so far as the relief of the land is simultaneously modified, the stages of erosion cycles in different regions tend to be correlated and the mean rate of denudation for broad regions and even for the whole earth may vary in the same direction.

The rate of denudation increases through the stage of topographic youth, reaching a maximum when all of a drainage basin has become dissected and given a maximum of sloping surface. From this mature stage the rate decreases as the elevation of the interstream areas are lowered, and finally nearly ceases in topographic old age. It is important, however, that this law of variation should be examined in more detail, for

¹¹ R. S. Tarr: The peneplain. *American Geologist*, vol. xxi, 1898, pp. 351-370.

¹² *Loc. cit.*, pp. 353, 354.

¹³ W. M. Davis: The peneplain. *American Geologist*, vol. xxiii, 1899, pp. 207-239.

¹⁴ *Loc. cit.*, p. 221.

much depends on it, especially as the writer has recently heard it stated by an able geologist that in his opinion the angle of slope had but little influence; the rate, on account of various compensating factors, continuing, in his opinion, high until old age was attained. This geologist pointed out as evidence that lowland streams may be silt-laden and show a high rate of denudation, whereas mountain streams are clear. Without denying these facts, the writer would give them a widely different interpretation and holds that denudation *in the same rock formation* varies with the slope, and probably at a somewhat higher rate than the change in the angle of slope. The problem is complicated and the relationship must vary with climate and rock formation. It is not as yet susceptible of precise statement. To the writer it appears probable, however, that the rate of pluvial and fluvial denudation in the same formation and under constant rainfall varies between the first and second power of the angle of slope.

A strong argument that the rate of denudation varies with slope is derived from the nature of the profile of a graded stream and of the cross-section of a mature valley as developed in a single erosion cycle.

FIGURE 1.—Stages in a graded Valley Profile cut in a homogeneous Formation

A valley profile, if a graded slope in a homogeneous rock, is a curved slope, as shown in figure 1. Let A E and A' E' be two successive stages in the erosion of the valley, stages sufficiently close so that the character of the curve does not change in the interval. Then $AA' = BB' = EE'$. Let equal contour intervals A B, B C, etcetera, be taken and the volumes of rock, A A'—B B', removed between each contour interval are equal. But the erosion surface A B for the unit volume of erosion on the steep slope is very much less than for D E on a flat slope. Therefore the rate of erosion on the steep slope per unit of surface area is proportionately greater.

This argument is strictly true for the parallel walls of a valley. For the circumference of a basin, however, there is really a larger volume of rock between the upper contours. For hills situated within the drainage

basin, on the other hand, there is a lesser volume. This and the lesser erosive power of the rain not yet gathered into rills gives such hills a convex profile across the top as the profile of equilibrium.

It is seen further that the main river, with its greater volume of water, comes to flow on a flatter slope than its tributary, and thus there is an adjustment in equilibrium. The erosion of a soft formation on a flatter slope is in adjustment also with the associated hard formation with a much steeper slope.

Another line of evidence on the large influence of angle of slope is seen in the geological speed with which the early stages of a new erosion cycle are completed. On a new pulse of uplift the river becomes entrenched near its mouth and this entrenchment migrates toward the head waters. It advances far up the stream and changes from youth to maturity, while the older part of the valley has changed its character but little. River piracy is another result of the same effect. If a river obtains an advantage in depth it will cut into the basins of other rivers rising from the same watershed. The steeper slopes enable it to remove much more material in the same time interval, and this is a necessary condition for river piracy, although after the capture is effected the added water then gives the river still greater corrasive power.

The pluvial, or stream profile, and the fluvial, or cross-profile, of a valley must show different relations of rate of erosion to angle of slope. The stream profile is not only cut much faster, but is long and flat and in equilibrium with a valley cross-section of far higher slope. The result is seen in the rapid cutting of gorges as the initial effect of uplift, followed by the far slower weathering back of these, accompanied by only a slight further flattening of the stream profile. Flowing water has been theoretically argued to erode as the square of its velocity, and its moving force to increase with the sixth power of the velocity. Gilbert found from experimental work that

"for each combination of discharge, width, and grade of debris there is a slope, called competent slope, which limits transportation. With lower slopes there is no load, or the stream has no capacity for load. With higher slopes capacity exists; and increase of slope gives increase of capacity. The value of capacity is approximately proportional to a power of the excess of slope above competent slope. If S equal the stream's slope and δ equal competent slope, then the stream's capacity varies as $(S-\delta)^n$. This is not a deductive, but an empiric law. The exponent n has not a fixed value, but an indefinite series of values depending on conditions. Its range of values in the experience of the laboratory is from 0.93 to 2.37, the values being greater as the discharges are smaller or the debris is coarser."¹⁵

¹⁵ G. K. Gilbert: The transportation of debris by running water. Prof. Paper 86, U. S. Geol. Survey, 1914, p. 10.

From these considerations it appears that the corrosive power of a stream varies perhaps near the square of the slope.

On the waste slopes leading down to the stream the component of gravity varies with the sine of the angle of slope. For slopes low enough to hold soil it may be said to vary with the angle of slope, as the sine and its arc for small angles are approximately equal. The greater time taken to remove the material from a flat slope is shown by its reduction by weathering to a finer state. In humid regions this soil becomes bound by vegetation which prevents a ready washing away, even though reduced in size of particle. Where the lateral slopes of valleys in humid climates are mantled with clastic material the rate of removal probably varies between the first and second power of the angle of slope. It cannot, however, obey any regular law, but varies with many factors.

The action of ground water must be considered as an important factor. In humid climates it is most important as the preparatory agent in mechanical erosion as well as in solvent denudation, but to be effective it must circulate, not lie stagnant, and for circulation there must be "head." Where the head is high with respect to the length of course, the velocity of underground flow increases. The maximum rate of chemical decay is therefore produced in a well dissected country, but one with slopes flat enough to hold soil and prevent a high ratio of surface run-off to total rainfall. Deeply incised valleys are a factor favoring rock decay, but very thick soil mantles act, on the contrary, as a check to further decay and testify to the efficiency of the natural vegetation to prevent soil waste rather than to a high rate of present chemical denudation. Denudation in such regions is potential rather than actual. In a topography of considerable relief the stimulus of more rapid circulation of ground water causes the zone of oxidation as well as that of hydration to affect a greater volume of rock. Much of this water returns to the surface to swell the volume of the main streams and give them increased carrying power. With very steep slopes, however, there is a lesser proportion of ground water to run-off, but if the intervening hilltops are flat from a previous cycle of erosion, then there is not only abundant ground water, but a more vigorous circulation.

It would appear on reviewing the complex factors that the rate of chemical denudation does not vary with slope to such a high degree as does mechanical denudation. In fact, the steepest slopes are unfavorable. On the other hand, a considerable head promotes chemical denudation.

The conditions for limestone regions are exceptional and quite different from those of compact igneous rocks. In limestones a vigorous circulation and solution by underground waters may go forward with moderate

head, whereas the bare and steep outcrops have superior resistance. In humid climates, consequently, areas of limestone advance to the peneplain stage with great rapidity. In mountainous regions with semi-arid climate, on the contrary, they constitute formations much more resistant than those of shale, standing out above them as more or less prominent ridge-makers.

Let attention be given next to the nature of ground-water action under a peneplain. The conclusion would appear to be opposite to that which has often been advanced. It has been frequently postulated that a peneplain would become mantled with a very deep residual oxidized soil, and that on uplift this disintegrated cover would be rapidly removed and swept into depressions. The red color of the Triassic of the eastern United States has been explained in this way by I. C. Russell and B. Willis and it has been applied to the Potomac deposits resting on a Jurassic peneplain. It seems clear, however, that the very thickness and coarseness of these deposits and the great abundance of fresh feldspar in the Triassic show that erosion went on with uplift and that the material was not greatly weathered. Furthermore, beneath a typical peneplain there should be practically no ground-water circulation. The pore space of the ground will be well filled with water, but there will be no head to give it circulation, and as soon as the water becomes saturated all further solution stops.

Peneplains, then, should possess a relatively thin regolith. The conclusion is of some importance in the explanation of the fresh and clean rock surfaces below unconformities. These planes of separation extend over great areas between the strata of different periods. They represent land intervals, yet when the sea returns the new deposits almost invariably rest on fresh rock. Some reworking of a regolith by marine abrasion doubtless occurs, but the absence of a heavy debris as a bottom sandstone and shale indicates in many cases that this is not important.

All rules have their exceptions, and the truth or error of this general principle, based on the laws of hydraulics, should not be regarded as tested by an individual case. The preceding discussion has assumed a homogeneous rock-floor, and this in many examples not the fact. First, such a formation as the Dakota sandstone leads ground water to great depths below baselevel, and even in advanced stages of the erosion cycle enough head would still exist to give a flow, though feeble than in a stage of higher relief. Second, waters sinking into residual uplands would in places find their way far out under peneplains before rising to the surface. Third, many of the irregular deeper parts of the weathered belt, decomposed during the vigorous circulation of the mature stage of the

erosion cycle, would be preserved as fossil remnants of an older belt of weathering beneath the surface of a peneplain, though no longer serving as zones of underground flow. Facts which appear to require such exceptional interpretations are known, but as long as they are isolated examples they can not be used as arguments against the generality of the principle.

Thus a very flat emerged plain in time would come to have its unconsolidated sediments removed down to baselevel. Below that level cementation rather than solution would go forward, and close below the surface would exist conditions for the indefinite preservation of limestone, fossils, and other soluble materials. Thus on peneplains not only has the mechanical erosion become reduced, but solvent denudation from ground-water action is also reduced to a minimum.

To sum up this discussion, it is seen that no simple law can be given which expresses the relation between rate of denudation and slope. It varies with the absolute magnitude of uplift, and probably, for the average rock and pluvial climate, the exponential factor lies between the first and second power of the angle of the slopes. Thus a region whose surface has an average relief of five degrees probably suffers denudation between two and four times as fast as it will when its average relief is reduced to two and one-half degrees.

Upon the first recognition of the existence of uplifted and dissected peneplains, the date of the older was generally placed as Cretaceous. More recent investigation shows that in regions of moderately soft rocks the oldest recognizable peneplains are hardly older than Tertiary, and may even be late Tertiary, in age. Stages of partial peneplanation of soft rocks and of mature valleys in hard rocks are even younger, belonging to the late Pliocene or early Pleistocene. The Cenozoic is now regarded as an era of general continental elevation; yet from the evidence of the long duration of these partial cycles of erosion the average slope of most parts of the earth's surface due to erosion might be placed as perhaps twice as steep now as during the mean of Tertiary time. The present rate of denudation may therefore be several times the mean rate for the entire Cenozoic.

SIGNIFICANCE OF PRESENT VALLEY FORMS

Over the greater parts of the continents the rivers are now trenched in inner valleys. Rock walls or bluffs more or less narrowly hedge them in. Above the inner valley lies a higher and wider outer valley whose floor represents the level of the stream previous to the last acceleration of erosion. Terraces on this older valley margin or hills with accordant tops give traces of still higher and older levels. The highest level commonly

shows a degree of completion of this oldest erosion cycle which is represented by a peneplain. At any one place the evidence of three successive levels is usually all that can be observed and discriminated; often but two may be detected. The relations are best seen where hard rocks rise to moderate heights, as in plateaus not far from the sea. There, as in the Appalachians, the streams respond quickly to the new upwarps of the land, or possibly what may be equally concerned, new sinking of the sealevel. The hard rocks, because of their resistance, survive for a greater time and record a greater number of pulses of diastrophism. The profile of figure 2 brings out the significance of slopes in a diagrammatic form.

In parts of the Appalachians, particularly in southern New England, where broad terranes of metamorphic rocks occur, successive baselevels are recorded by means of peneplains or valleys at successive elevations which average about 200 feet apart. Successively older ones appear in passing

FIGURE 2.—Diagrammatic Section of Valley

Showing composite slope resulting from pulsatory uplifts in quickening periods

into the mountains. There they become more obscure, and it becomes more difficult to discriminate between them or detect accurately their original differences in elevation. The writer sought the approximate dates of these baselevels by tracing the erosion planes into New Jersey, Pennsylvania, and Maryland, opposite to where the formations of the coastal plain attain a wide exposure. By projecting from opposite directions the slopes of these baselevels recorded by erosion and the slopes of the formations recorded by deposition where they approach nearest, the two series were interrelated; but the formations have their dates fixed by fossils, and this leads in turn to the dating of the erosion forms. Those below 500 feet in elevation are the Columbia group of Pleistocene age. Those beginning with the Lafayette or Appomattox and rising higher are Pliocene. Back of the Pliocene series are more dismantled forms which belong to the older Tertiary and even to the upper Cretaceous.¹⁶ Figure 2 shows the type of valley profiles which pertain to the

¹⁶ Joseph Barrell: Piedmont terraces of the northern Appalachians and their mode of origin. Post-Jurassic history of the northern Appalachians. Bull. Geol. Soc. Am., vol. 24, 1913, pp. 688-696. The burden of other work has prevented up to the present time the elaboration of this subject beyond the first brief publication.

Pleistocene-Pliocene series, but for the upper and outer parts of the river systems which show the older stages the slopes are in general proportionately flatter.

We may turn next to a discussion of these relations of successive stages of valley cutting. On tracing the streams toward their sources, the intrenchment F from the last uplift is found to become shallower and eventually disappear. In the progress of headward erosion the intrenchment from the last uplift has not had time as yet to reach to the upper waters of the river. There the valley section E is higher, narrower, and younger. In long streams, or those rising in the resistant terranes of mountain regions, where the movement has been uplift without warping, several of the latest stages of uplift may not yet have been felt. There one stands in a Tertiary cycle of erosion, still in uninterrupted progress. In order that the successive profiles should be cut, the younger within the older, the oldest cycle, C, must have been the longest; E the next longest, and F the most brief. This kind of a record implies an increasing rapidity of recurrence in diastrophism.

This is a conclusion with far-reaching implication which should be tested carefully. Let us examine, then, some other points of view.

If the present baselevel should endure for a sufficient time, the streams will sink to a flatter grade, the valley slopes flatten down, and profile F change to F', destroying the previous record; but since we can not look into the future, the nature of the series must be decided on the basis of the record of the past. That record is shown in the relations of A, C, and E, and these indicate an increasing rapidity in the recurrence of uplifts.

These uplifts need not, however, have been simple and free from short period minor oscillations. As shown in broken lines in figure 2, a short pause, B, may have existed and yet had the evidence of its existence totally destroyed by a longer pause, C, and another, D, by a longer pause, E. Even the development of peneplains does not require an age-long freedom from movements in baselevel. Minor oscillations may continue, but they do not in that case lead to a progressive rise of the land. In the lower portions of the river systems alternate fill and scour of the valley would take place, but in the upper parts or on the interfluvial slopes erosion would still continue and increase the perfection of the peneplain.

This discussion leads us back to the significance of the quickening series shown by the present valley forms. The quickening is especially in regard to the Pleistocene movements. For certain of those of Pliocene or older date no such hypothesis of acceleration may be necessary, since each new intrenchment below an old peneplain before the previous cycle had

become advanced gives a greater thickness of rock above baselevel, and will require a longer time for the cycle to become completed. If the stages of uplift were equally spaced, the first cycle of rejuvenated erosion would advance farther, there being less rock to be removed. Nevertheless the whole of the younger series, if the erosion due to them is not well advanced, must be embraced in far less time than that which led to the development of the peneplain.

Turning to the shore, the Pleistocene history shows that the aggregate motion of uplift has been not merely discontinuous uplift, but that movements of submergence took place between each emergence, and the land at the present time is in a submergent phase, but not necessarily now in movement. A submergent phase is felt as a stagnation of drainage and marked alluviation on the valley floor for a short distance above the actual drowning of the river mouth. Farther upstream, however, there is but little change in the grade of the stream, and the headward erosion from the previous intrenchments of the rivers continues.

Thus, although the problem involves a number of factors, these do not change the direct and simple interpretation of the significance of the Pleistocene-Pliocene series of valley slopes. There have been aggregate uplifts by movements which on the whole have increased in rapidity, and notably so in the Pleistocene. Over the Atlantic coastal plain of the United States the submergent phases of the Pleistocene movements are represented by deposits more or less eroded, the older showing much greater erosion than the younger. In Maryland, the Lafayette, late Pliocene in age, attains, on the low plateaus facing the sea, a maximum elevation of 500 feet. Up the stream valleys the river grades carry it to higher elevations. The Lafayette Valley forms correspond to C of figure 2. The next younger deposit is known as the Sunderland. It belongs to the older Pleistocene and shows wave-cut terraces reaching to 220 feet in elevation. Farther inland the valley profile corresponds to E of figure 2. The middle or later Pleistocene wave-cut terrace is the Wicomico, reaching to 100 feet in elevation. Its corresponding valley form is F. A number of glacial geologists have estimated the time necessary to cut these valley profiles, and agree that it increases backward in geometrical progression. If F was cut some tens of thousands of years ago, E was cut some hundreds of thousands of years since, and C would appear to date back more than a million years—possibly two million, possibly several million. McGee, in fact, is inclined to estimate post-Lafayette time as from five to ten million years in length.¹⁷

The Pleistocene need not, however, be regarded as unique in showing

¹⁷ W J McGee: Note on the age of the earth. *Science*, vol. xxi, 1893, p. 309.

such an accelerating series of uplifts. Similar series must have occurred in the past, leading up to the crises of diastrophism in periods of revolution, but they must have been followed by retarding series and long periods of quiescence. The uniqueness of the Pliocene-Pleistocene movements lies rather in the great mean heights which the continents have attained.

Having discussed the time relations of the late Pliocene-Pleistocene series of movements, attention should be turned next to the effect of such a quickening series of uplifts on the aggregate rate of erosion.

An uplift steepens the grade near the mouth; headward intrenchment follows up the main stream and its tributaries. As the area of dissected and steepened slopes increases, the quantity of material eroded increases; but as time passes the slopes flatten down, the maximum rate of erosion due to that pulse in that part of the river passes away, and the rate enters on a descending curve which approaches the zero line, but unless disturbed by other factors never reaches it. The second uplift, however, produces another wave of erosion, which follows upstream after the first, but does not catch up to it. It deepens and steepens the valley floor and increases the average slope of the region. In the mountains the erosion in stages due to Pliocene uplift is still at work, and the quicker and younger Pleistocene pulses of uplift have not been felt.

Over wide belts of soft rock and on the plains the present stimulus to erosion is due to the Pleistocene uplifts. The rivers flow in inner valleys bounded by bluffs usually 100 to 200 feet in height. The valley uplands may be several hundred feet higher. These movements have occurred with such geological rapidity that in such regions ground-water action has become greatly favored, because the flat interfluvial tracts serve as catchment areas and the deep intrenchment gives the ground water opportunity for circulation. As the bedrock of many such plains is calcareous the actual rate is very high. Even in regions of low or moderate elevation the rate of erosion may temporarily exceed that of the mountain regions. The average angle of slope may be as high also as in the mountains. The latter owe their bold relief to the continuity of slope for longer distances rather than necessarily to a higher average angle of slope.

Erosion of the lowlands has received still another acceleration in the United States within the past two centuries, and in other lands during a longer period, due to the interference of man with nature. In the United States, especially, the run-off of soil, due to careless agriculture, has become in many sections a national scandal. Deforestation of steep slopes with loose soils, followed by plowing and overgrazing, makes the rivers turbid after each rain and has already impoverished considerable areas.

The high rate of erosion of lowlands is indicated by the figures for denudation obtained by Dole and Stabler. A difference between these and the mountain regions would become apparent in time if the diastrophism were to enter on a slowing pulsation or to cease altogether. With geological rapidity the lowland valleys would widen out, the average slopes become much reduced, and the rate of erosion fall to a fraction of its former rate. In the mountains, on the other hand, erosion would continue with undiminished rate for a time and would only slowly diminish, the mountains remaining mature long after the lowlands had become old.

The conclusion that the Pliocene-Pleistocene movements are members of a quickening series is evident for the Atlantic shores. Around the Pacific the movements are on a more prodigious scale; but there again, especially in the Andes, is seen the evidence of great intrenchment of the rivers flowing through profound gorges. Thousands of feet above is an older mature topography that speaks of a long time of quieter crust and lessened rate of erosion.

The present rate of denudation of the lands may then be twice or thrice the average for the Cenozoic and five or ten times the average for earlier periods. Nevertheless, many ancient sedimentary formations testify to rivers as swift as those of today. The Old Red sandstone consists of deposits analogous to those now forming in Cordilleran or Eurasian intermontane basins. Such formations are, however, relatively local. They are, furthermore, recurrent, not continuous, in time. They emphasize by contrast the low rates and limited areas of denudation characteristic of intervening periods.

The association of glaciation within periods of revolution indicates that one of the ulterior causes of glacial climates lies in diastrophism. The individual advances and retreats of the continental ice can not, however, be correlated with individual crust movements; nevertheless, it is suggestive of the quickening diastrophism that the Glacial epochs appear to have been more quickly recurrent in the later Pleistocene. The relative remoteness of the Glacial epochs is given by Chamberlin and Salisbury as follows:

From the late Wisconsin to the present.....	1
From the early Wisconsin to the present.....	2 to 2½
From the Iowan to the present.....	3 to 5
From the Illinoian to the present.....	7 to 9
From the Kansan to the present.....	15 to 17
From the sub-Aftonian to the present.....	X ¹⁸

¹⁸ Chamberlin and Salisbury: *Geology*, vol. iii, 1906, p. 414.

Long intervening periods of warmer climate seem to show that this is in reality a converging series and not merely an effect of perspective, from a point of view unable to see the full record of the farther past.

Thus from the oscillations of climate, as well as from the signs of unrest in the crust, there is seen to be no evidence that the culmination of the present period of terrestrial revolution is past. The evidence is suggestive, not definitive; but the indications of the quickening series are that, although at the geologic moment the crust is in a minor submergent phase and the climate of interglacial character, yet the crisis may be before us, not behind us. Men have taken hope that the Ice Age is past and have looked on the Quaternary revolution as closed; but the study of the rhythms robs us of that assurance. At several times in the Pleistocene that view, as based upon apparent subsidences of crustal and climatic movements, would have been far better justified by the evidence than it is at the present moment. The high latitudes, unlike their state through the most of geologic time, are still mantled with glaciers. The shorelines are now in a stage of earliest youth. We live, in fact, within the Age of Ice, within an age of crustal unrest and revolution; the geologic morrow may bring forth greater and more compelling changes than the geologic yesterday.

CONTRAST OF CENOZOIC AND PALEOZOIC CONTINENTAL RELIEFS

The present mean elevation of the lands is approximately 2,400 feet, and Murray, in 1912, places their area at 59,870,000 square miles. The waters with a depth of less than 600 feet surrounding the lands cover 10,000,000 square miles. Taking this area of shelf seas as part of the continental platforms, the continents are now six-sevenths emerged. Reckoning in these margins does not, however, give a just comparison with the attitude of the land-masses during the spread of epeiric seas. It is rather the continental interiors which offer the more significant contrast. The floor of the shelf seas forms the continental terrace, which is in considerable part the result of a sedimentary outbuilding. Suppose the sealevel to sink 600 feet. If the movement were moderately slow, the construction of a new but narrower submerged shelf would keep pace with the uplift. The unconsolidated deposits of the present shelf seas, exposed to erosion by uplift, would be planed down with great rapidity by river action and wave action, new waste from the land would also be contributed, and thus a submerged shelf would be maintained.

The present epeiric seas of northwestern Europe and northern North America are not comparable in cause to the Paleozoic seas. The Baltic and North seas and Hudson Bay show a close relation to the lowlands

which were covered in the late Pleistocene by continental ice-sheets. These shallow-water bodies appear to be, consequently, lingering effects of the local depression of the crust under the weight of the ice.

Eliminating these special conditions, let the continents be contrasted with their past states in amount of submergence, and it is seen that not only is there a notable absence of internal floodings, but a very notable elevation of the continents as a whole.

The great contrast between the present broadly elevated lands and the low and flooded condition of the continents during epochs of geologic quiet marks out the later Tertiary and the Quaternary as together constituting a great period of revolution. This, as a general statement, is well appreciated, but certain of the logical consequences have not leavened geologic thought.

The ancient epeiric seas were typically very shallow-water bodies. The evidence is clear and varied. The lime-depositing seas have formerly been regarded as the deepest, yet bottom-growing algae were at times abundant, as seen in the cryptozoan horizons. Sunlight must therefore have freely penetrated to the bottom. But more emphatic testimony is given by interformational conglomerates, which show during the deposition of the beds a vigorous stirring of the bottom by wave action. Still more positive in meaning are the mud-cracks which are abundant in certain horizons. These are not shore phenomena, since they may occur at the same horizon over areas reaching thousands of square miles; neither are they of tidal origin, as shown by their breadth and the absence of tidal channels. With seasonal change of winds, or more probably with slight oscillations in level of longer period, the water came and went.

The wide-spread marine sands and silts of these seas show the effectiveness of wave action in agitating the bottom material and working it by oscillatory action to great distances. Over a broad reach of shallow water the wave action is adjusted to depth, being damped down by the work of stirring the bottom. Furthermore, in times of equable climates, although the circulation of air and water was very effective in distributing the equatorial warmth to high latitudes, yet the intensity of winds was probably less. Winds are due to differences of temperature and pressure and are in general most intense where these conditions rise highest, as in middle temperate latitudes in winter. The wave action in the epeiric seas was then more comparable to that which now exists over broad, shallow lakes or bays in the warmer climates rather than comparable to the waves of the deep and open oceans.

From these lines of evidence depths of 20 and 50 to 100 feet may be regarded as typical. Occasional deeper waters must of course not be ex-

cluded. The fact that these shallow seas were not speedily filled with sediment and converted into river plains shows that erosion was slow. The greater areas of the land were flat and but little above the sea. Mountain axes alone were the regions of pronounced relief. The retreat of the seas from the continents required a falling sealevel of not more than a hundred, or at the most a few hundred, feet. Over broad land areas the elevation was so slight and drainage was so sluggish that when the seas returned they commonly came to rest directly on the uneroded sediments of the previous periods. During the land interval, if it was more than most temporary, the layers of unconsolidated sediment above baselevel were washed off and the evidences of the farther advances of the previous seas were destroyed. Nevertheless this erosion was very limited in depth and speaks of the limited elevation of such lands required to drain the seas. During the Paleozoic and to a lesser degree in the Mesozoic the mean sealevel was evidently notably higher with respect to the continents. Even in the periods of revolution, although mountain systems were made and the epeiric seas withdrawn, yet the continents outside of the mountainous regions still stood low. This is illustrated by the very broad expansion of Ordovician deposits not eroded in the Taconic disturbance, but covered by the Silurian and later sediments. During the Devonian there was intense mountain-making and igneous activity. Basins were filled many thousand feet deep with continental sediments, yet marine waters persisted rather widely over the interior of the American continent. Further orogenic movements in the late Mississippian (Chester) and again in the late Pennsylvanian led to vast deposits of waste, but these were laid down broadly as interbedded marine and continental deposits on the continents, not carried by rivers to the margins. Even the Permian revolution was attended by so little elevation of the continents that, although the seas withdrew, vast areas of sediments of the previous period were preserved with their stores of coal to the age of man. These coal fields are now in considerable part above sealevel, are undergoing extensive dissection, and the completion of the present cycle of erosion would greatly reduce the quantity of Carboniferous coal even without the exploitation by man.

On the other hand, this argument must not be pushed too far. The farthest extensions of the ancient seas left thin deposits which have been stripped back to later and lower baselevels by the erosion of all later time; the lesser extensions, on the contrary, have had their deposits protected by blankets of later sediment. The limitation of present outcrop is consequently no evidence of the original limitation of the formation. That must be determined, in so far as it is possible, mostly by means of the

internal evidence of the sediments themselves and the entombed faunas and floras. Schuchert assigns to the lowest Trenton sea a flooding of 57.2 per cent of the present land area of North America, the widest inundation of geologic time. To the Cretaceous sea he gives a maximum spread of 41.3 per cent.¹⁹ Schuchert's maps are of great value because each represents a limited period of time and the shores are drawn as close to the limiting outcrops as is permissible. As he recognizes, this tends to make the areas of the seas too small, but increase of knowledge will show where and to what extent the boundaries must be extended. These facts must not be forgotten in using the maps. Considering the inevitable cutting back of outlying outcrops in cycle after cycle of erosion, it appears to the writer that the lowest Trenton sea probably covered as much as 65 or 70 per cent of North America and the Cretaceous seas and deltas at their maximum probably 50 per cent.

Another significant feature in interpreting the mean attitude of the continents in the past is found in the fact that the mantle of sedimentary rock, made up by formations of different periods, is wider than the deposits of any one sea, this statement applying to other continents as well as to North America. To what degree is this composite mantle, accumulated through earlier periods, now subject to destruction by a reversal of the balance from deposition to erosion? To answer this we may compare the areas of ancient marine sediments relative to the areas now undergoing marked denudation.

The area of the land is 60,000,000 square miles. Of this it is estimated 20.3 per cent,²⁰ or 12,000,000 square miles, expose Precambrian rocks; 48,000,000 square miles are of sedimentary rocks or of eruptives which mostly overlie sediments. As to elevation, 18,000,000 square miles, or 30 per cent of the land, lies less than 600 feet above the sea and may be taken as the lowland area. It is at the present time subject in part of its area to erosion; in part it is receiving delta and basin deposits. The remainder of 42,000,000 square miles of land is above 600 feet in elevation and is subject to more or less vigorous erosion. If, leaning backward in the argument, all the Precambrian should be assumed as within this upland area, there would still remain 30,000,000 square miles, or one-half of the continental surface, which consists of ancient sedimentary formations, mostly marine, which in the later Tertiary and Pleistocene have been uplifted more than 600 feet, in part to several thousand feet, and subjected to rapid and deep denudation. If the present erosion shall persist into

¹⁹ C. Schuchert: *Paleogeography of North America*. Bull. Geol. Soc. Am., vol. 20, 1910, p. 601.

²⁰ Von Tillo: *Comptes Rendu*, Paris, vol. 114, 1892, pp. 246, 967.

the stage of old age, great areas of Paleozoic and Mesozoic sediments will have become destroyed. But nature reveals while she destroys, and because of this very fact of the contrast of the present to the past the comprehensive study of the stratigraphic record is made very much easier than it would have been in the average condition of the lands, and in this particular century has been further facilitated through the fresh exposures made by man incidental to his development of transportation systems.

The existence of a mantle of sedimentary rocks, mostly marine, covering three-quarters of the land surfaces, proves that since the opening of

FIGURE 3.—Hypsographic Curve of the Continents and its Relation to the Past

- A. Curve of continental relief, showing relations of altitude to area.
- B. Curve giving one-fourth relief, representative of periods of wide epeiric seas.
- C. Limits of periodic oscillations of sealevel to flood two-thirds of continental area with profile B.

the Middle Cambrian these portions of the continents have on the whole received sediment rather than supplied it. Of course, there has been alternating deposition and erosion. Unknown amounts are gone, but the balance was in favor of accumulation of sediments. Marine shales and limestones are the most wide-spread of formations. Through most of geologic time the continents have lain awash with the ocean level and across them the rising ocean floods have flowed. The sediment of these Paleozoic and Mesozoic times came in greatest bulk from the limited

areas of mountain systems, repeatedly worn low. A lesser portion came from the reworking of older sediments from the gently upwarped portions of continental interiors. On these the erosion cycle was carried to such completion during each period that when the waters spread over these lands again the sediment was deposited on level surfaces of unconformity. In these last stages of baseleveling the work of erosion must have become extremely slack.

The evidence of the sedimentary mantle points, then, to the conclusion that the ocean level has stood lower in the Pliocene and Pleistocene and the continents higher, with a more varied relief than they had previously attained since the Precambrian. In figure 3 this conclusion is given graphic expression.

Curve A is the hypsographic curve, or curve of the present continental relief, taken from the statistics given by Penck, as follows:

Continental Relief

Zones of altitude	Relative areas
Below sealevel.....	0.6
0 to 200 meters.....	29.2
200 to 500 meters.....	27.1
500 to 1,000 meters.....	19.0
1,000 to 2,000 meters.....	16.4
2,000 to 3,000 meters.....	3.6
3,000 to 4,000 meters.....	2.1
Above 4,000 meters.....	2.0
	<hr/> 100.0

Our knowledge of the general nature of the hypsographic curve for the Paleozoic periods of recurrent epeiric seas is drawn from the facts previously discussed. During the very widest spread of seas two-thirds of North America is taken as covered and the mean depth of the epeiric seas is assumed as 300 feet, or 90 meters. During the emergent stages between the Paleozoic floods, if the land is assumed to have become drained to the present degree, the slopes of the land would nevertheless be so low that two-thirds of its area is regarded as having been less than 600 feet above sealevel. A hypsographic curve to fit these conditions is obtained by dividing the ordinates of the present curve by four. This is shown as B, figure 3, and it brings out vividly and graphically the great contrast in land relief which the preceding discussion has indicated as existing between the present and certain past periods.

In this diagram the sealevel has been kept for convenience as a constant datum. It is probable, however, that the sealevel has sunk since the

Paleozoic as much as 300 to 500 meters with respect to the continents, and that the present average elevation of the lands, 730 meters, is in large part due to that fact. Such a sinking of the sea, due to increase in the volume of ocean basins, is suggested by the gain in height by every continent and the present approach to isostatic equilibrium for each continent as a whole. In order to represent Paleozoic conditions, B and C should then be elevated 300 to 500 meters with respect to A. This would bring the two curves, A and B, of land relief closer together, and if A represents a fairly close approach to isostasy, would minimize the isostatic strain which is implied by the flatness of the Paleozoic lands and permit more readily the control of their level by sealevel rather than by isostatic rejuvenation. The change from the types of Paleozoic to Cenozoic continental reliefs has, then, been accomplished by an increase in the volume of the ocean basins attended by a warping down of the negative areas of the continents several hundred meters and a warping up of the positive areas to a somewhat greater amount. This tendency to differential warping existed in the Paleozoic, but a marked relief was not attained because erosion of the positive areas led to leveling by sedimentation on the negative areas. The tendency to rise of sealevel during a single cycle of continental erosion—a geologic period—may be due most largely to the displacement of sea-water by sediment; the rise during the Paleozoic era may better be ascribed to the addition of juvenile waters. This latter cause has continued in operation in later time, but has been more than offset by an increase in volume of ocean basins and consequent lowering of the mean sealevel, due presumably to continental fragmentation.

CONTRAST OF PRESENT AND PAST RATES OF DENUDATION

The Precambrian ages were of immense duration and broken up into eras by profound revolutions. Sediments were accumulated in great thickness in geosynclines, but over the continents as a whole recurrent erosion exceeded sedimentation. The result was that at the opening of the Paleozoic metamorphic and igneous rocks of the character of those of the Canadian shield constituted the dominant surface formations. To have exposed such rocks the continents must have been broadly elevated and deeply eroded. During pulsatory uplift the rate of denudation doubtless rose at times to the present high rate, and may even have exceeded it, since vegetation could not then have been an efficient binder for the soil. Following such periods of erosion the lands were low and may have rested in that attitude of old age for vast periods of time. In illustration, it appears that following the last great Precambrian revolution the surface, although of low relief, still lay generally above sealevel, the whole of this

era, marked by the absence of marine sediments on the lands, constituting the Lipalian era of Walcott. Even in the Lower Cambrian deeply warped geosynclines retained the waste, in part as continental deposits, and not until the Upper Cambrian were the broad expanses of the continents covered by the shallow seas.

Although the seas came and went during the Paleozoic era in periodic oscillation, the thickening and spreading mantle of sediments marks the whole Paleozoic in contrast to the Lipalian as an era of higher mean sea-level. Over the greater part of the continents erosion of a crystalline basement had ceased, and over even the Archean shields it was very slight. Erosion was periodically rejuvenated in mountain regions and doubtless, occasionally and locally, attained rates as high as the present. The aggregate rate for the whole world, however, must have been very low as compared to the present.

The long crescendo of orogenic movements which ended in the Permian revolution gave rise to great mountain systems, but did not materially elevate the continents, as shown by the preservation of broad mantles of Pennsylvanian and Permian sediments. Beginning with the Epi-Paleozoic interval, however, epeiric seas played a less conspicuous part and show by this restriction a somewhat lowered mean sealevel. Triassic marine deposits are scanty; the Jurassic seas acquired a wider spread, but in the Cretaceous the conditions resembled again those of the Paleozoic.

At the close of the Cretaceous another great revolution was inaugurated—the Laramide—and the average elevation of the lands may have resembled that of the close of the Paleozoic. But with the opening of the Neocene the earth's internal forces reawoke to great activity and the present grander mountain systems of the earth began to take their form. The Neocene revolution is so close to the Laramide, compared to the length of the older eras, that the latter revolution may be regarded as a preliminary stage leading up to a crescendo, much as the Pennsylvanian movements preceded and led up to the greater Permian movements. The magnitude of the Neocene revolution is seen, however, not only in the breadth and height of the mountain systems, but in the pronounced warping of the continents, giving a steeper hypsographic curve, and the drawing down of the sea, probably through continental fragmentation, giving a more elevated hypsographic curve. This great height of the continents is a most important feature bearing on the aggregate rate of denudation. There appears to be nothing analogous this side of the Precambrian. The Neocene revolution has continued into the Pleistocene and there is no indication that the culmination has yet been passed.

Looking beyond the coming and going of seas which mark off the

periods, to seek out the trends through longer measures of duration, we see an eon-long rise and ebb of sealevel with respect to the continents. It pulsates with the close of eras, falling and then slowly rising again. But from our present elevated continents and lofty mountains, as we look back through geologic time, the eye passes over one system after another, more and more remote, and only dimly on the far horizon do we see in the Precambrian ages a similar relation in elevation of land to sea. This marks the most far-reaching rhythm of geologic time.

But superimposed on this greater rhythm are the crescendoes and diminuendoes of diastrophisms which separate the smaller divisions of time. The Pleistocene represents one of the crescendoes. It has been marked by an acceleration in crustal uplift and oscillation which has raised high the rate of total denudation. Compared to the rate for the whole of the Cenozoic era of revolution, it may be twice the mean. The concurrence of the longer rhythm in sealevel, giving wide and high continents, with the rising diastrophism of a period of revolution may, however, make the present rate of continental denudation ten or fifteen, or even twenty, times the mean for all of earth history, our knowledge of the Precambrian being especially vague. Estimates of geologic time based on measurements of the present rate of denudation and coupled to the assumption that this is the mean for all the past are likely to err correspondingly.

This may seem an abandonment of the principle of uniformitarianism on which the science of geology was founded. Davis, however, saw in the existence of cycles of erosion the necessity of giving a more elastic conception to this basic principle. He has stated the problem well, as follows:

"Uniformitarianism, reasonably understood, is not a rigid limitation of past processes to the rates of present processes, but a rational association of observed effects with competent causes. Events may have progressed both faster and slower in the past than during the brief interval which we call the present, but the past and present events differ in degree and not in kind. This rather elastic understanding of uniformitarianism seems to me comparatively safe from the objections that have been urged against the more rigid conception that some authors regard as necessarily intended in the writings of Hutton, Playfair, and Lyell, especially safe if the very remote hypothetical past of unrecorded time is not considered."²¹

The conclusions reached in this part are so startling that they should be reexamined before acceptance, in order to see if the present can not be regarded as not so exceptional in geologic time. It is clear that the present rate of continental denudation is very high, owing to a concurrence of

²¹ W. M. Davis: Bearing of physiography on uniformitarianism. Bull. Geol. Soc. Am., vol. 7, 1896, pp. 8, 9.

factors, but it may be conceded to have been somewhat higher at recent times in the Pleistocene. Going farther back, it is possible that during epochs of very rapid retreat of seas the wash of sediment may for a brief time have equaled or exceeded the present rate, but such an effect would have been very temporary. It is doubtless true that in other revolutions broad areas of land have been uplifted, the older sediments removed without leaving a trace, and deep denudation cut into the foundations. The rate of denudation must have been locally as high as it is in regions of similar attitude at present.

Nevertheless, although granting such approximations toward the present topographic attitudes, it does seem probable that the present mean rate may be twice the mean for the whole of the Cenozoic and ten or fifteen times the rate for all of geologic time since the opening of the Paleozoic.

To sum up the causes of this contrast of the present with the mean of past time, they are to be found in a notable irregularly progressive increase in volume of the ocean basins, resulting in greater mean continental elevation, in greater isostatic strains brought on the continents as a whole by the deeper erosion, in the existence of a great period of revolution, the Cenozoic, whose culmination in the Pleistocene and Recent is marked by glaciation, and, lastly, the rate has been raised by man through deforestation and agriculture. The mean rate of denudation is a factor which, then, in the very nature of things, is subject to great variation through geologic time and is therefore wholly unsuited to serve as a method of measurement. Qualitatively, however, it is clear that time is far longer than those estimates which have been based on a hypothesis that the present rate is a mean which applies to the geologic past.

PART II.—RHYTHMS IN SEDIMENTATION

GENERALITY OF ACCUMULATION IN SHALLOW WATER

Since the early days of geologic science it has been noted that the greater part of sediments, even where accumulated in a geosyncline, bear the marks of deposition in shallow water. This is conspicuous on noting the significance of the features which are found abundantly in each type of deposit—conglomerates and sandstones, shales and limestones.

Conglomerates and sandstones show transportation by river currents, waves, or undertow. Only rarely, as in torrential deposits poured in lakes, do they exhibit the marks of rolling down a fore-set slope. On the contrary, most conglomerates are stream deposits, a lesser amount being made and deposited by wave action along shores. The marine sands are spread

in even layers and are often ripple- or current-marked, indicating the wide-spread and uniform action of waves on a shallow bottom. Floodplain sands show less continuity and regularity of deposit, indicating a prevalence of shifting currents over deltas and basins.

It may readily be granted that the coarse deposits are of shallow-water origin, but the question of the depth at which the fine-grained sediments are on the average deposited is of more importance. Mud is the most abundant sediment, and shale consequently must be the most abundant rock. A not inconsiderable portion, as is now recognized, has been deposited on river floodplains. Rain-prints, mud-cracks, or other features bear evidences of subaerial exposure and indicate generally this mode of origin. Marine muds where intercalated with layers of sand indicate that they are shallow-water deposits, since the sand can be transported only in limited depths of water. Where the interstratified sands are thin and regular, this feature indicates spreading by wave action and the sediment was deposited at wave-base. In certain formations, on the other hand, in contrast to this interstratified type of mud and sand deposit, both sand and the marks of exposure to the air are absent, the mud consisting of an impalpable material, occurring in thin laminae which may be paper-thin, and varying in color rather than in texture from stratum to stratum. These are presumably lake or sea deposits made in quiet water below wave-base. Such may be classified as deep-water deposits, but among the shales they are the exception rather than the rule.

Limestones are taken as evidence of clear seas. They have often been regarded as deposited in deep water, but, on the contrary, most of the limestones which are exposed on the continental platforms show by their structures that they were deposited in shallow water. In the older geologic periods the contributions of the cryptozoa, bottom-living algæ, indicate that the bottom was effectively lighted by the sun. Mud-cracks and rain-prints at many horizons in limestones prove recurrent exposure to the air, alternating with submergence in shallow waters, usually marine. Intraformational conglomerates are frequent in calcareous and dolomitic formations. They owe their existence, in at least considerable degree, to the drying and cracking of limestone crusts deposited by cryptozoa or deposited as lime silts which were cemented near the water surface at or immediately after accumulation. The fragments have been rounded and further broken by wave action. The chalk which is exposed to observation was formerly regarded as an abyssal ooze, but is now commonly believed to have been deposited mostly in shallow seas. The evidence is found in the stout-shelled mollusks which occur as associated fossils. These thick-shelled types represent adaptations to relatively shallow water.

the mollusks of the deeper waters, by contrast, do not have to withstand the mechanical agitation of waves, are not so vigorously attacked by enemies, and are characterized by more fragile shells. Limestone beds, furthermore, as in the Carboniferous, are often intercalated between shallow-water shales and beds of coal.

The great bulk of sediments which have been uplifted and exposed to observation were deposited in interior continental seas; only as emerged coastal plains on the outer rims of the continents are the records of shelf seas found. These belong especially to the Cretaceous and Tertiary periods, but they also are nearly always of shallow-water origin. Only exceptionally, by profound orogenic movements, have the deposits of the abyssal fore-set slopes of the continents been elevated and exposed by erosion, and still more exceptionally are the bottom-set muds of the ocean depths heaved upward to the light of day.

Thus the sediments whose interpretation form the basis of earth history have been characteristically deposited with respect to a nearly horizontal controlling surface. This surface of control is baselevel, but for continental and marine deposits the baselevel is determined by different agencies and is a word of more inclusive content than the sense in which it has generally been used by physiographers as a level limiting the depth of fluvial erosion. Sedimentation as well as erosion is controlled by baselevel, and baselevel, local or regional, is that surface toward which the external forces strive, the surface at which neither erosion nor sedimentation takes place.

This emphasis on the importance of wave-base, as the surface which controls the deposition of sediment in water bodies, makes it desirable to discuss its depth with respect to the water surface. Wave-base is that depth at which the wave action ceases to be strong enough to transport sediment. If the wave action becomes strong the particles of sediment are moved to and fro, upward and downward, with the oscillation of each passing wave. In each lift from the bottom the sediment is subjected to progressive movement by the undertow in one direction, by currents in various directions, by the dragging effect of waves of translation in a landward direction. With a lesser strength of wave action the particles are lifted less frequently and mostly during the forward pulses of waves of translation. An increase in the strength of wave action leads to a down-scouring of the bottom and removal of material to deeper water, especially the finer material. The coarsest, however, may be shifted toward the shore as sand or shingle. During a following weaker phase a silting up of the bottom will take place to the previous level, but the finer muds are still worked seaward. Thus sand is kept on the con-

tinental platforms, whereas mud tends in larger degree to be deposited below wave-base on the slopes of the submarine continental terrace.

Wave-base is deeper with heavier wind action, with breadth of water surface, with distance from shore, and with fineness of sediment; a gravel or sand would lie below wave-base, because remaining unagitated, in the same locality and depth where silt or mud would be well within wave-base. Conceive a shallow circular basin of water without outlet. The action of waves will tend to shift the bottom sediment and establish a "profile of equilibrium" with steepest slope near shore and flat in the middle. This profile will vary in magnitude from that which is in adjustment with the rollers of the open ocean to that in adjustment with the wind ripples on the surface of a shallow pool, but for these widely different scales it will remain a curve of the same character. For purposes of comparison the following is adopted as an empirical curve for the margin of a wide shelf sea in mid temperate latitudes with a beach of sand and fine gravel. Far offshore the bottom is taken as fine sand and mud.

Profile of Equilibrium for Shelf Sea

Distance from shore in miles.....	1	2	3	5	10	20	100
Depth in fathoms.....	7.5	11	13.5	15.5	18	23	50

For wide lagoons, such as those behind barrier beaches, both ordinates and abscissas of this curve should be divided by about 20. Thus, at a distance of five miles offshore the full depth of about 2.5 fathoms would be attained.

The symmetry of this curve is greatly disturbed by a number of factors which are always present to some degree. The curve is flatter on a shore toward which sediment is driven; undertow sweeps the bottom material in certain directions, giving current effects; variations in storms and in depth of water modify it from one scale to another. In general, the rise of sealevel since late Glacial times, a rise which is generally estimated at as much as 20 fathoms, has overdeepened the ocean profiles and only where there is a great abundance of unconsolidated bottom material has the profile been adjusted to the present higher water level. The lack of recognition of this condition has given a general impression that wave action is effective to a greater depth than is the case. The limit is commonly taken as 100 fathoms. In a few places, as west of the British Isles, this is approximately the case, but an inspection of coast charts in general shows a downward curvature of the bottom profile, indicating the cessation of effective wave action, at about 50 fathoms. Daly, Vaughan, and the writer have come to the conclusion that this would be a better general

figure for the effective wave-base of the ocean.²² This is based on the actual evidence of profiles rather than on the theory of waves, or the ability of exceptional waves to agitate mud in suspension at greater depths.

To gain conceptions as to the depth of ancient interior seas several classes of water bodies must be studied. Stormy epeiric seas are represented by Lake Erie and the North Sea. The full depth of water, so far as wave action is concerned, is attained within 100 miles from the shore. In both of these water bodies there are areas below wave-base which permit an excess of sediment to be swept into such reservoirs, and thus prevent the profile from being shallowed. Quiet epeiric seas are found in tropic waters and are illustrated by the shelf sea east of the Mississippi delta, but more typically by the Persian Gulf.²³ The latter is an epeiric sea which has a central portion unfilled and below wave-base. Large lagoons are represented by Lake Pontchartrain on the Mississippi delta. In addition what may be called playa seas formed recurrently important features in the past. These were annually, or at longer intervals, alternately flooded with shallow marine waters and exposed to the air. Such playa seas are represented at present by the Rann of Cutch, an area of 10,000 square miles east of the Indus delta, flooded from July to November, during the southwest monsoon, to an average depth of five feet, owing to a rise of sealevel due to wind pressure, but constituting a barren and saline mud-flat during the remainder of the year. Over very flat areas facing shallow water bodies the seasonal direction and intensity of winds is thus seen to be an important factor.

A tabulation of the relations of depths to distance from shore for these various types of water bodies is given as follows:

Bottom Profiles established by Wave Action

Depths of water in feet •

Type of water body	Distances from shore in miles				
	5	10	20	80	100
Stormy shelf seas.....	95	110	140	300	300
Stormy epeiric seas.....	55	70	90	110	110
Quiet epeiric seas.....	35	50	70	90	90
Wide lagoons.....	15	15	....	....	....
Playa seas.....	0 to 5	....	....	....	0 to 10

²² Joseph Barrell: Factors in the movements of the strand-line and their results in the Pleistocene and post-Pleistocene. *Am. Jour. Sci.*, vol. xi, 1915, pp. 6, 7.

A good illustration of this limitation in depth is shown in the bathymetric contours of the Boston quadrangle, scale 1 : 1,000,000, U. S. Geological Survey. Sheet North K 19, International Map of the World.

²³ The writer is indebted to Doctor Bowman, director of the American Geographical Society, for data from the British Admiralty charts showing the details of the bottom of the Persian Gulf.

The depths of water given for these examples are probably somewhat above the average for their types, since the ancient examples were commonly shallow throughout and were generally not provided with adjacent reservoirs into which the excess of sediment could be readily swept. In such shallow bodies the wave action is damped down by the energy absorbed in stirring the bottom and can not become progressively greater with breadth of the water body. During storms choppy wave action and sediment churned up with water are the results. Upon the subsidence of the wind the sediment, even if mud, quickly settles in salt waters. Sediment must be slowly worked to the region of exit and escapes chiefly by combined wave and current action in time of storms. If the connections with the outer ocean are restricted, the water of the basin is shallower than for an open water body and a greater degree of bottom stirring will occur during storms. An average depth of several inches of sediment may thus be lifted from the bottom during the exceptional storms, to be quickly deposited during the following calm.

When evaporation exceeds rainfall in a nearly enclosed basin, such as the Mediterranean or Red Sea, the currents in general flow inward instead of outward. In extreme conditions of aridity sodium chloride is deposited, in less extreme conditions gypsum is the chemical precipitate; but even gypsum requires for its precipitation the concentration of present sea-water to 19 per cent of its original volume. Calcium and magnesium carbonates are insoluble, however, in sea-water concentrated one-half, or with lesser concentration where a lime mud has saturated a normal sea-water. In lime-depositing seas any tendency for evaporation to exceed rainfall in partly inclosed water bodies may thus supply more sediment to the bottom than is swept out through the restricted exits. The water body thus grows shallower until a seasonal change in wind may alternately cover and lay bare vast flats of lime muds. The importance of this action is indicated in the past by the abundance of intraformational conglomerates, mud-cracks, and occasionally rain-prints in certain limestones, as, for example, in the Precambrian dolomitic limestones of the Beltian system, in many Cambrian and Ordovician dolomitic limestones, and in the water limes of the Salina epoch in eastern North America. Thus have been developed the playa seas.

Where sediment is poured abundantly into an epeiric sea, the water is somewhat shallowed for a long distance. For example, soft mud is the chief material brought by the Tigris and Euphrates to the Persian Gulf and a depth of ten fathoms is reached only at a distance of 40 to 45 miles from the head of the gulf. The character of sediment on all bottoms tends to vary with depth, the sand being kept in the shallower

water, but by far the most abundant sediment supplied by rivers is mud. Consequently, even shallow waters receiving such sediment show mud bottoms with fine sand as a subordinate constituent. The nature of the bottom of epeiric seas is consequently more dependent upon the breadth of water body, intensity of wind action, and character of sediment than upon the depth of water.

Schuchert, on the basis of the depth of wave action on the exposed shelves facing stormy oceans, has divided the seas into littoral seas and deep water pelitic seas, the littoral seas being less than 150 feet deep, the pelitic seas being from 150 to 600 feet in depth.²⁴ In view of the previous discussion it would seem that this, although applying to the shelf seas of the present, would be an overestimate for the epeiric seas of the previous eras. At times of world-wide equability of climate the temperature gradient between the latitudinal zones was weakened and the mean intensity of winds must apparently have been less, although the atmospheric conditions for the spread of tropic warmth to polar latitudes was at such times more efficient. In the epeiric seas, especially of the Paleozoic, the conditions of wave action should have approached those now found in shallow, partly land-locked bodies of water in the tropics. The prevailing wave bedding of the ancient deposits shows that the water was seldom deeper than wave-base. The general conditions of depth were therefore those shown in the previous tabulation for quiet epeiric seas, lagoons, and playa seas. It may be concluded that the ancient seas were typically not more than 100 feet in depth in their central parts and were often only a fraction of this depth over tens of thousands of square miles. Less frequently a rise of sealevel faster than sediment could fill in a basin would give depths of 200 or even 300 feet, but seldom deeper. Reviewing the prevailing conditions through geological time, it is seen that wave-base is a surface relatively parallel to sealevel and but little below it. During a stage of prolonged crustal quiet the wave-base is a surface below sealevel comparable to the fluvial baselevel of the lands above sealevel, the former being depressed generally not more than 100 to 200 feet below the other, the one passing into the other through a slightly accentuated flexure constituting the shore and near-shore zone.

Thus baselevel may be used as a wide and inclusive term, applying both to land and sea. Nearly all sediment on the continental platforms, either terrestrial or marine, is deposited with respect to it. A further fundamental feature consists in the oscillation in short and long periods of this baselevel surface. On the land, in climates permitting fluvial

²⁴ Pirsson and Schuchert: *Text-book of Geology*, 1915, pp. 490-493.

transportation of land waste, the local baselevel is the slope of the graded stream. This is subject to seasonal fluctuation. The depth and strength of current determines how close to the water surface the surface of sedimentation will approach. In the season of flood there is a deepening of the baselevel within the channel, as marked by the down-scouring. Over the floodplain a rise of baselevel accompanies the flood waters and deposition results. In the season of low water the action is reversed; then a silting up of the channel and a washing of detritus from the floodplain marks the seasonally lower baselevel and slackened current. For the seawaters the factors leading to the oscillation of wave-base have already been discussed.

The sediment deposited at any one point is only a small fraction of that which is carried past. This small proportion which remains represents the rhythmic disturbance of a balanced condition. At a time of sinking baselevel, using this as synonymous with the surface of deposition, scouring will result, which means that a little more passes beyond the point than comes to it. At a time of rising baselevel the disturbance of the balance becomes additive and the geologic response is deposition.

The maintenance of shallow-water conditions during the accumulation of a formation means that there has been nearly always an excess of sediments above what was needed to maintain the surface at baselevel. This excess has been generally swept to the abyssal slopes of the continental platforms, building a continental terrace which has been the storage ground for the excess of waste. The deposits of the terrace have been, however, more commonly hidden from observation by being warped or faulted down toward ocean depths, rather than elevated, and in consequence exposed to erosion and observation.

In the sorting by wave action the coarser materials, as noted, tend to be kept on the landward side of the marine profile and therefore are deposited at wave-base; the suspended matter tends to be deposited in the deeper water farther from shore and partly below wave-base. Where there is an excess of sediment leading to deposition on the fore-set slopes of the continental terrace it must be to a large degree the finer material, giving the red and blue muds, mostly settling within a belt 100 miles wide beyond the outer edge of the shelf seas. A test, then, of the amount of sorting and deposition of sands in shallow water may be found by comparing the ratio of sandstones and shales as they occur in exposed geologic sections with the ratio to be expected from the erosion of the average igneous rock. Leith and Mead have made such a comparison. They find that an average of sections aggregating 520,000 feet, well distributed over North America, contains 46 per cent shale, $32\frac{1}{2}$ per cent sandstone, and $21\frac{1}{2}$

per cent limestone. An average of sections aggregating 188,000 feet, scattered through Eurasia, gives 49 per cent shales; $32\frac{1}{2}$ per cent sandstone, and $18\frac{1}{2}$ per cent limestone. The proportions which they calculate from the average chemical composition of igneous rocks should give 82 per cent shale, 12 per cent sandstone, and 6 per cent limestone.²⁵ Leith and Mead ascribe this discrepancy to the probability that many of the sediments consist of sandstones with undecomposed or unsorted material, including much shale, and further that many limestones are shaly.²⁶ It appears to Professor Schuchert and the writer, however, that this, although it may be a partial reason, can not be an adequate explanation. The chemical analyses of sediments should to a considerable degree include formations of these mixed compositions. An important factor in the explanation is the carrying of mud to the slopes of the ocean basins, because nearly always an excess of sediment has been supplied to the shallow seas beyond that which was required to keep their floors at wave-base. The mud deposits of these slopes are almost never exposed to observation. Thus this discrepancy between the observed and calculated proportions of sediments is in accord with the principles controlling sedimentation which are here emphasized.

The excess of limestones observed to occur on the continents, above their ratio to the total theoretical volume of shale, is also in line with the prevalent deposition of limestone under the control of wave-base. Calcium carbonate is abstracted from sea-water by organisms almost entirely in the zone of surface waters. Of this the part which is permanently lost to the continents is chiefly due to the accumulation of globigerina ooze on many parts of the ocean basins above 3,000 fathoms in depth. This ooze covers 40,000,000 square miles, 29 per cent of the entire ocean surface; but, as Murray and Renard have shown, the per cent of carbonate decreases with depth, so that the bulk of the permanent deposit is on the higher bottoms. The quantity of pelagic life per unit is greater in the waters of the shallow seas than in the central waters of the oceans. Add to this pelagic life the abundance of the lime-secreting bottom life of the sun-lit floors of the shallow seas, and it is seen why the limestones have been chiefly deposited on the continental platforms.

Thus, theory is in accord with observation in indicating that through geologic time deposition of marine sediments on the continental platforms has been in general controlled by wave-base, the terrestrial deposits.

²⁵ Leith and Mead: *Metamorphic Geology*, 1915, p. 60. By a typographical error the per cents stated in the book are in error for the limestones. The corrected figures given above are by Leith in response to an inquiry by the writer.

²⁶ *Loc. cit.*, p. 68.

by current-base. These controls have been subject to rhythmic oscillation in level—complex and superimposed oscillations, of longer and longer periods, years, decades, centuries, millenniums, and geologic periods in duration.

RATE OF SEDIMENTATION DETERMINED BY SUBSIDENCE

During the past century, although the prevalence in the sedimentary rocks of the marks of shallow water was observed, the importance of continental deposition was unappreciated; neither was there recognition of the control of baselevel over both erosion and deposition. It is very easy to transpose cause and effect where the two are essentially simultaneous in action and complex in their nature; and thus the older generations of geologists looked on the marks of shallow water, persistent through thousands of feet of strata, as the result of a delicate balance controlled by deposition, and not by depression. Every foot of sediment was supposed to be the cause, leading, as an effect, to a depression of the basin just one foot, with the result that a sea, always shallow, was supposed to have existed continuously throughout the Paleozoic. Even if such a marvelously delicate relation of subsidence produced by sedimentation were possible, they did not try to explain why the balanced condition should be attained at a level just below the surface of the sea. This necessary corollary is in itself sufficient to indicate that land conditions were in places confused with marine, and that the cause, a downwarping, was mistaken for the effect.

As another line of evidence, the writer has discussed elsewhere the features of the deltas of the Nile and Niger, built out on the slopes of the continental platform into the ocean basins. The extension of the land, as shown by the form of the deltas, into what was previously deep ocean indicates that the crust has there been able to sustain a burden equivalent to the weight of several thousand feet of rock extending over tens of thousands of square miles.²⁷ The stability of the land during baseleveling and the competence of the crust to support volcanoes are further evidence of its degree of stiffness and resistance to yielding under load. Beyond a certain limit, however, isostatic yielding is known to take place.

Although large rivers show a power to maintain their courses across growing mountain ranges, it is nevertheless true that the general drainage of a continent is away from the broadly upwarded areas and toward those which undergo downwarping. A relief map of the North American con-

²⁷ Joseph Barrell: The strength of the earth's crust, part 1. *Journal of Geology*, vol. xxii, 1914, pp. 28-48.

continent shows that the larger relief is determined at the present time by regional uplift and not by the dissection by river systems. The valleys are relatively shallow details carved in this relief, not the cause of it. This convergence of the larger drainage systems toward downwarping areas leads to the building of deltas selectively in regions of subsidence. If the land waste is moderate in amount, an epeiric sea rather than a delta occupies the downward region and is the reservoir of sediments. If, however, the downwarping is very profound, fore-set slopes and bottom-set deposits are built into an unfilled geosyncline or mediterranean deep.

On the surfaces of deltas or the floors of epeiric seas sedimentation records the rate of subsidence, not the rate nor amount of denudation. During stages of no subsidence there is no sedimentary record, except in fore-set or bottom-set beds usually on the margins of the ocean basins. During stages of slow subsidence a few feet of sediment may correspond in the top-set beds to a vast length of time. During stages of rapid subsidence in geosynclines the sediment has generally been supplied still more rapidly. As an illustration familiar to the writer, on the axis of the Appalachian geosyncline in Pennsylvania the floor subsided a maximum of 10,000 feet in the Upper Devonian. This did not result in a deepening of the water; but, on the contrary, the subaerial surface of the Catskill delta was actually built out across the axis of maximum subsidence and by the close of the Devonian had converted this whole section of the geosyncline into a land surface.²⁸ The work was continued in this region into the later Paleozoic periods, but there were times of interrupted record of unknown duration, as marked especially by the unconformity or disconformity at the base of the Pennsylvanian. It may be readily granted that this load of sediment, acting in the same direction as the forces initiating subsidence, would tend to continue it and carry it to greater depths; but without the sediments, deep water would almost surely have resulted, such as exists at present in the southern part of the Gulf of California, a geosyncline filled only at its northern end.

A relation appears to prevail frequently between the rate and height of uplift of a geanticline and rate and depth of depression of an associated geosyncline. When Appalachia supplied coarse and abundant waste it was deposited as thick formations in the parallel geosyncline. In the Ordovician a low rate of erosion is indicated by the dominance of limestones. The rate of supply of sediment was slow, but the water

²⁸ Joseph Barrell: The Upper Devonian delta of the Appalachian geosyncline. *Am. Jour. Sci.*, vol. xxxvi, 1913, pp. 429-472; vol. xxxvii, 1914, pp. 87-109, 225-253.

nevertheless remained shallow. Such a relation between parallel uplift and depression may be due to two general causes. Tangential pressure acting through a great depth of crust, if it bows up an arch on one side will tend to flex down the trough on the other; or the weight of a mountain system will tend isostatically to depress the crust in front of it; for example, the great weight of the Himalaya must tend to depress the rock floor of the geosyncline of the Indo-Gangetic floodplain in front of it over which it tends to be thrust. Whatever the cause, whether from horizontal thrust or from vertical load, there appears to be in times of high relief an accentuation of both uplift and depression. The rate of geanticlinal denudation and the rate of geosynclinal deposition are both at such times accelerated. At times of most pronounced uplift, however, the deposition is apt to be continental, the sediments excluding the sea. Elevation thus dominates over local subsidence, the excess of sediment is carried beyond, and the geosyncline represents a trap which retains only that amount of fill which is necessary in order that the rivers shall maintain their grade and carrying power across it.

Notwithstanding these clear indications pointed out in the preceding paragraphs, nearly all arguments on the measurement of geologic time have rested more or less unconsciously on the assumption that the sediment would be deposited in a limited basin as fast as it was received. It has been conceived to be necessary merely to select the best rate of denudation and the relative areas of erosion fields and catchment basins in order to ascertain the rate of deposition. It is seen that in general the ratio of areas is but one factor of the problem, since usually only a part of the sediment has been deposited in the basin.

There were times, however, especially in the Paleozoic, when arenaceous and argillaceous deposits changed with distance from the shore into limestones. The limestones generally bear the marks of shallow-water origin. The material of the limestones must be looked on as derived from the ocean water and only in part from the same source as the elastic deposits. When the clastic materials change in this transitional manner into organic deposits it appears therefore that, unlike the cases previously discussed, the amount of land waste has been just about sufficient to fill the subsidence without a large balance to be carried farther beyond. Here, in the geosyncline, the rate of supply of sediment approaches the rate of deposition and a continuous record is more nearly approached.

The extreme case in slackness of sedimentation is that even in the geosyncline calcareous material may be the dominant deposit, as in the great Cambro-Ordovician limestones of the eastern United States,

several thousand feet in maximum thickness. These limestones, however, show abundantly and recurrently the marks of shallow water and even exposure to the air, but the poverty of elastic material indicates that either the lands were very low and possibly somewhat distant, or that there was deeper water, with a bottom below wave-base, between the lime deposits and the land—a temporarily unfilled geosynclinal axis east of the present outcrops.

Although, theoretically, deposits of muds below wave-base settling from suspension in geosynclines should be expected to occur, yet they clearly are not a common type of sediments. They are the only deposits, however, from which a continuous record of deposition may be read, and should be sought from this point of view.

The discussion of this topic has thus far turned on the factors controlling the rate of sedimentation. In the light of this discussion, how does the present rate compare with the rates in the past? There are two world-wide features characteristic of the present which determine the answer: One is the present high degree of relief of the earth's surface, as shown by the contrast of the present and past curves of relief as illustrated by figure 3 and discussed in Part I; the other is the direction of the last movement of sealevel.

To take up these in order: The present high relief is a feature which means the rapid downwarping of many catchment areas for sediment during the Neocene and Pleistocene. Very thick formations have been made in a short geological time. A few are upturned and exposed, as in the younger Tertiary formations, which make foothill ranges; for example, the Siwalik formations of India, 14,000 feet in thickness. Other sites of sedimentation, as intermontane basins, are in many cases still somewhat below grade, maintained so by subsidence, and are being rapidly built up. Where no catchment basin is crossed by the rivers flowing from mountains, a large amount of land waste is rapidly supplied to the sea, building out deltas or adding to the continental platforms as a submarine terrace of construction.

To turn to the other factor—the direction of the last movement of the sealevel; the evidence of the shorelines shows that the last stage has for most shores been one of submergence. River mouths are drowned and transformed into harbors and estuaries; the sea is cutting vigorously at the headlands of embayed shores. The motion has been more or less intermittent and there is little evidence that it is now going forward. The evidence around the northwestern shores of Europe indicates, however, that there the last movement of submergence occurred not more than 5,000 or 6,000 years ago. The generality of recent submergence

as the latest phase suggests that it is a movement of sealevel. At a slightly earlier time, the retreat of the great glaciers from the last Pleistocene advance has added between 100 and 200 feet of water to the sea and would appear to be an important factor in the general submergence of coral islands to a depth of 20 to 30 fathoms.

These movements have resulted in the recent depression of the surfaces of sedimentation in deltas and the bordering seas and a corresponding acceleration in upbuilding. Estuaries and tidal bays such as the Persian Gulf, the Adriatic and Yellow seas, are being filled; coral growth has received a great expansion; for the time being the rate of sedimentation approaches the rate of supply of waste. The lack of recognition of the variable nature of these conditions has permitted geologic thought to project them backward through past time as the normal procedure. It is seen, however, that before geologic retrospection can be sound it must recognize in the principles of perspective the markedly cyclic or rhythmic nature of geologic activities, both in denudation and in deposition, and the acceleration of both these processes at the present time, owing to the concurrence of several controlling factors.

*PROGRESSIVE TILTING COMBINED WITH RHYTHMIC OSCILLATION OF
BASELEVEL*

Sediments are deposited either in geosynclines, as prisms thickening toward the axis, or as thinner, lenslike formations in shallow downwarped basins, or on the continental shelves in the form of wedges thickening seaward. In any case room for further sediment is made by downwarping. On the slope of the depressed area this is expressed as a tilting of the floor about an axis. On the landward side there is uplift and erosion; on the seaward side depression and deposition. This tilting of the floor about an axis is, then, a general phenomenon of diastrophic origin connected with sedimentation and is expressed by the thinning down and dropping out of stratigraphic members when followed toward the limits of the formation.

The tilting, like all other crust movements, is discontinuous. Pulses of erosion occur on the landward side. On the seaward side of the axis, by depression of the baselevel, room is made more or less simultaneously for more sediment. These rhythmic pulses, provided that sedimentation is controlled by baselevel, will result in divisions in the stratigraphic series separated by breaks, visible or invisible.

At the same time that the floor is being warped, there are, owing to other causes, rhythmic elevations and depressions in the baselevel without tilting. For example, the rhythm of the seasons causes river action

and wave action to fluctuate in level; the extreme conditions of exceptional years are especially potent in upbuilding or in down-scour. Slow changes in sealevel, hundreds or, more usually, thousands of years in length, form pulsations of a higher order which affect marine and delta deposits. Climatic fluctuations of short and long periods cause variations in the supply of sediment and the carrying power of rivers. These oscillatory rhythms are combined with the discontinuous movements of

FIGURE 4.—Diagram postulating a progressive Tilting of the Crust, combined with a rhythmic Elevation and Depression of Baselevel

This diagram illustrates a variable rate of sedimentation dependent on baselevel and distance from axis of tilting. R = radius of oscillation. 0, 1, 2, 3, etcetera, represent the position of baselevel at equal time intervals.

tilting which are not oscillatory, but irregular and progressive in one direction. In studying the stratigraphic consequences of the combination of the two, the tilting may be regarded as progressive—that is, as continuing longer than the other rhythms—and the latter as producing a parallel rising and falling of the baselevel. In such rise and fall the motion at the turning points is for most kinds of motions very slow, as in the tidal ebb and flow, or may be even arrested until sufficient force has become accumulated. This combination of progressive tilting with

oscillatory rise and fall of baselevel must be very general in its applications and figure 4 is drawn to illustrate its results.

In explanation of this figure it will be noted that the tilting or rotation indicated about the axis through 0 results in sedimentation on the right, in erosion on the left. The oscillatory rise and fall, for the sake of simplicity, are assumed to be of a harmonic nature, as in the rise and fall of a point on a wheel which revolves on a fixed shaft. The successive stages during one cycle are shown at 0 by the levels 1, 2, 3, etcetera. But on the line B B' the progressive rise in baselevel due to tilting is the same during one oscillation as the circumference of the circle of oscillation. The combined motion gives a cycloid, the path of a point on the circumference of a rolling wheel. The successive levels 1, 2, 3, etcetera, at equal time intervals show no scouring, but a marked slowing up of deposition between stages 4 and 0 and a momentary cessation at 6. Farther from the axis, as at C C', there is continuous rise of baselevel and accompanying deposition, but at unequal rates. At a great distance from the axis the rate approaches uniformity.

Between B B' and the axis 0 the curve is a trochoid. In this section there is downscouring and loss of record through a part of the cycle of oscillation. At A A', half way between B B' and the axis 0, there is a sedimentary record of only one-half the time. At 0 deposition and erosion alternate and balance. At M M' erosion dominates, but during one-half of the time at this place there is sedimentation.

To apply this diagram to the geologic record: Most regions of sedimentation have been subject to alternate fill and scour, with a balance in favor of the fill, representing the section of the curve between 0 and B B'. Where formations thin out, only occasional thin beds are preserved. Many beds are missing and the record is very imperfect. On the other hand, on the foreset beds of deltas, on lake bottoms, occasionally on the rapidly subsiding axes of geosynclines, and generally on the slopes of the continental platforms, the conditions approach those shown on C C' and a complete sedimentary record is developed. The diagram is valuable in visualizing the incomplete nature of the sedimentary column in most regions and in emphasizing the large time values of the breaks in deposition, a part of the lost interval being represented by beds which are later removed. Here only one rhythm is shown. In nature the record will ordinarily be more complicated, minor oscillations being superimposed on larger. During the passage of a single rhythm there would be in effect a to and fro migration of the transition line which separates erosion from deposition between B B' and a point equally distant on the other side of 0.

The Atlantic coastal plain of the United States may be cited as an illustration of these principles, valuable furthermore in showing how nature departs from the simplicity of a diagram. In the Jurassic the transition line between erosion and sedimentation was southeast of the present shore and erosion prevailed on all the surface now open to observation. Near the end of the Jurassic or beginning of the Comanche, a pronounced tilting took place, accompanied by a northwesterly migration of the axis inland to somewhat beyond the present edge of the coastal plain. As a consequence, the Patuxent formation, of fluvial origin, was laid down. Then emergence occurred; that is, the axis migrated eastward, and erosion took place to some extent. Then another rhythm again depressed this region, elevated the baselevel, and the Arundel formation was deposited. Here the deposition was brief, as the formation is found within shallow valleys which had been cut in the Patuxent. Following diastrophic rhythms resulted in the Patapsco, the Raritan, and the Magothy. The formations now become marine and the Matawan and Monmouth follow. Between each formation is an unconformity which near their landward margins probably represents much more than half of the total time. Besides the diastrophic oscillation superimposed on the tilting, the stratification of the sediments, as shown in the variegated beds, shows many minor rhythms, doubtless in part climatic. During the Cretaceous the shore migrated inland, uplift slackened, and the resulting waste was less. The sedimentation was now wholly marine and the record for a time is probably more nearly complete than it was during the Comanche, although the thickness of sediment is less. Possibly the greensands of the Cretaceous represent for a time a continuous record, for these are now found to be developed in quiet waters near the limits of wave action on the outer parts of the continental shelf. The Tertiary formations show the continuation of a history of oscillations similar to those shown in the Comanche and Cretaceous, long intervals of sea retreat alternating with advances. Throughout all this time there seems to have been a progression in tilting, doubtless irregular and spasmodic, but irreversible, combined with complex vertical oscillation of the baselevel in longer and shorter rhythms.

Let this record on the shore of a continent be compared with the record as made in a geosyncline within the continent as seen in that of the Appalachian trough. The latter throughout the Paleozoic received sediments from the eastward from the land of Appalachia. The maximum thickness was perhaps 40,000 feet, mostly clastic deposits, but with thick limestone formations intercalated. The sandstones and

shales do not represent continuous deposition where they are thickest, for there was much clastic sediment carried beyond the axis of the geosyncline. The surface was therefore kept near baselevel, and the minor rhythms must have exercised a scouring action during a part of their cycle. The limestones most conspicuously show the absence of a continuous record. They are shallow-water deposits; the successive beds are often in great contrast, and innumerable laminae show, in longer and shorter cycles, oscillation of conditions.

But the southeastern side of this trough of sediments has been uplifted and eroded, with the result that the thickest outcrops of the several formations are commonly the easternmost. If the record was discontinuous in this region of maximum thickness, it was presumably more discontinuous in the portions to the southeastward which are now destroyed. The deposits of a continental shelf, if traced outward far enough, must begin to show a continuous record. Those of a geosyncline, even one containing a maximum depth of 6 to 8 miles of sediments, may be almost throughout a discontinuous record. The thickest formations, although rapidly accumulated, are in most cases of such a nature that a continuous deposition can not by any means be granted. The coarseness of such very thick formations is no criterion of continuity; in fact, it favors the opposite interpretation. The coarseness measures the strength of the streams or waves. Where these are strong, there must, as argued before, be much material carried beyond that point; and, corresponding to rhythmic ebb and flood of carrying force, there must have been alternate fill and scour.

If this interpretation be true, it is seen how unjustified is a procedure which assumes a certain rate of deposition for the thickest formations—a foot per century, as Sollas has taken, and multiplies this by the thickness to determine the time of deposition, making no allowance for the longer and shorter down-scouring phases.

A careful study of the stratigraphic record has brought to light many breaks in deposition within series of similar beds which lie on each other in parallel fashion. These breaks are recognized by noting a sudden change in the fauna or flora at a certain plane, or a sudden change in the nature of the sediments, especially where a coarser layer lies on one of finer grain. The time interval may be great, as where the totally distinct fauna of a later period rests on beds containing the earlier fauna; or the faunal change may be slight, as where in one bed of limestone some species are the same as in the bed below, but others are replaced by new species. Such a plane representing a lost interval has been named

by Grabau a disconformity.²⁹ With the recognition of the importance and number of such planes, the word has become well established in geological literature. Many lost intervals must exist, however, in deposition which are of less duration than those which are detected by marked biotic or physical change. The arguments in the present article point out their large aggregate time value and the generality of their occurrence, owing to the rhythmic character of sedimentation. They must be recognized from the physical conditions of deposition, especially by sharp surfaces separating beds, or by sudden changes in the nature of the sedimentary rhythm.

The term disconformity has come to refer to a well defined hiatus of larger value and essentially due to diastrophism in elevating the land or depressing the ocean level, although for lack of a separate term these minor breaks would also at present be included as minor disconformities. The distinctness of the two classes of lost intervals and the emphasis placed here on the class of smaller pauses, due largely to oscillations in the intensity of climatic factors, seem to justify the erection of a new term and the restriction of the class of disconformities to those breaks which have a large enough value to be recognized by change in fossils or marked contrast in sedimentation. A suitable name appears to be *diastem*, the word meaning a space or interval. It was formerly used in music as signifying an interval. The Latin form, *diastema*, is now used in zoology with the special meaning of a vacant space, or gap, between teeth in a jaw.

A disconformity marks a period of time which is represented in some other region by a deposit of formation value. A diastem is a break represented in other regions, often within the same formation, by a bed or series of beds. A disconformity is theoretically traceable over a broad area. For deposits of epeiric seas it means ordinarily a movement sufficient to more or less completely drain the sea-water from the continent. A diastem does not imply the draining of a shallow sea, but rather a shorter or longer downward oscillation of wave-base. The two classes of breaks, although typically distinct, must grade into each other. The assignment of a break to one or the other category must not depend on a doubtfully assigned cause, but must rest on the observable field evidence. Therefore the discrimination should rest for disconformities on breadth of occurrence and faunal or floral change, for diastems on breaks in continuity of lesser areal importance, of greater number, and not characterized by permanent faunal or floral change. The presence of diastems

²⁹ A. W. Grabau: Principles of Stratigraphy, 1913, pp. 821-826.

makes for a slow rate of accumulation of a formation, associated with a more rapid rate of accumulation of the individual beds.

NATURE OF STRATIGRAPHIC RECORD RESULTING FROM COMPOSITE RHYTHMS

The making of a sedimentary series is conditioned on an oscillating but progressive rise of baselevel. Nature is not so even in her course as to give truly harmonic motion, but in a theoretical discussion that may be assumed as the simplest form, and it will be shown that it does not exaggerate the amount of time which is represented by the intervals. In this type of oscillation the vertical motion slows gradually to nothing at the limits and is most rapid at the middle of the cycle. But nature pulsates with many rhythms, small and large, fast and slow. Their combination gives a varied curve which, if the rhythms are incommensurable in period, may never recur in quite the same combination. How will such composite rhythms affect the stratigraphic record? In figure 4 a diagram was given which compared for various locations the continuity of the record due to a simple rhythm combined with continuous warping. Here another aspect is considered. It is represented by a diagram which will serve to visualize the nature of the stratigraphic record for one place, as dependent on the relations of period and amplitude of the several components of composite rhythms. Figure 5 is drawn for that purpose. In this diagram time is measured from left to right and the rise of baselevel is measured in the vertical direction. The curve A A represents a long term rise of baselevel, beginning slowly, gaining in rate, and then slowly ceasing. This is a portion of a harmonic curve, but for this fundamental curve it could not continue except with respect to a sloping axis of coordinates, as otherwise the following downward sinking would destroy the entire series made during the previous rise.

Such a general rise of baselevel will be accomplished by diastrophic oscillations. In the Paleozoic these larger oscillations are indicated by the coming and going of the epeiric seas or the shifting of their areas. They were usually so slow that erosion and sedimentation kept pace with them and widely extended deposits were laid down, alternating with disconformities.

In the Pleistocene there has been by contrast a general sinking of baselevel, shown by the emergence of the land, but the movement here also has been strongly oscillatory, as shown by the drowned river valleys, and, above the sea level, by the several Pleistocene formations, partly of alluvial and estuarine nature, partly marine, which skirt the margin of the continent. In Maryland the late Pliocene Lafayette deposits were uplifted

and dissected. Then submergence took place to a maximum of 220 feet above present sealevel and the early Pleistocene Sunderland was deposited. Uplift caused dissection as before, and then another submergence to 100 feet led to the deposition of the middle Pleistocene Wicomico. This in turn was uplifted and dissected. Finally, the late Pleistocene Talbot formation was laid down up to 40 feet above present sealevel. In these Pleistocene deposits the aggregate progressive movement of baselevel was

FIGURE 5.—Sedimentary Record made by harmonic Oscillations in Baselevel

A-A. Primary curve of rising baselevel.

B-B. Diastrophic oscillations, giving disconformities D-D.

C-C. Minor oscillations, exaggerated and simplified, due largely to climatic rhythms.

Equation of curve C-C: $y = \sin x - .25 \cos 8x - .05 \cos 64x$.

in a contrary direction to that which leads to the permanent preservation of sediments. They have, furthermore, been geologically rapid, but the nature of the oscillations is nevertheless illustrative of the habit of diastrophism, clear to us because of the recency in time.

In times of slow movements of baselevel the numerous smaller rhythms, some of which are climatic in their origin, are able to take effect in the planation of unconsolidated sediments. These frequent smaller oscillations give a crenulation to that sinusoidal curve which measures the progress of diastrophism. In figure 5 the curve C-C shows the summa-

tion of such effects for three combined rhythms, such as have been discussed, of successively smaller amplitude and shorter period.

On the left is the columnar section of the strata which result from these combined oscillations. The light lines of separation are the bedding planes, or diastems, and in the curve as here drawn represent lost time intervals about equal to that recorded by the beds. The heavy horizontal lines are disconformities due to cessation of sedimentation and down-scouring during the recurrent longer stages of sinking baselevel. On the curve as here drawn they represent considerably longer times than the intervening formations. Lost intervals of more than half the time necessarily occur for harmonic oscillations, if the trough of a secondary rhythm is lower than its preceding crest; in other words, if the slope of the limb of the secondary rhythm in descending phase is steeper than the slope of the primary rhythm in opposite phase. On the other hand, if the minor rhythms have very long period and low amplitude they will not interrupt the continuity of sedimentation on the ascending limb of the next higher rhythm, but will cause only variations of rate. There will be bedding, but no diastems.

The evidence of recent climatic and crustal movements indicates that the changes are relatively rapid, separated by intervals of quiet. The combined curve would differ from the simple harmonic form by showing longer flats and sharper vertical movements. Where sedimentation is closely controlled by baselevel it would mean a necessary discontinuity, or diastem, involved in each rhythm. The assumed harmonic motion, by giving gradual slopes to the curves, is apparently more favorable for giving continuity of record than are the more abrupt changes of nature. In figure 5 the columnar section looks not unlike those found in nature; yet only one-sixth of the time is recorded in it, as shown by the black bars above the curve. The actual material existence of the strata is so much more impressive than the division planes between them that this diagram is necessary to show how for this case the strata give a record for only a small fraction of the time.

The rapidly subsiding center of a geosyncline would correspond to a steepening of the curve A A and a larger proportion of the time would be recorded than on its landward margin. Where the diastrophic oscillations are large as compared to the progressive change of baselevel, as near the margin of sedimentation, or in places of but little progressive submergence, the record is, on the other hand, very discontinuous. Smaller oscillations are in part of a diastrophic nature and are compounded of changes in the level of sea and land. Many small oscillations and some of even larger magnitude are, however, dependent upon climatic change.

The growth of glaciers abstracts water from the sea and locally depresses the land, but a more general effect through geologic time is dependent on changing river grades. In times of lessened water and increased burden, they steepen; under opposite conditions, they flatten. Where the rivers flow 100 miles or more from mountains to the regions of deposition a change of baselevel amounting even to some hundreds of feet may result. This affects especially the continental deposits, but unbalances also the ratio of supply of waste to the carrying and eroding power of the sea.³⁰ Such an oscillation in river grade appears to be an essential factor in the interpretation of the upper Paleozoic formations of the Appalachian geosyncline and must apply to certain other regions also.

The curve, to correspond to nature, should be imagined as less regular and with more orders of rhythms. For regions where the sediment carried past to other localities is large compared to that which comes to rest at that locality, the record becomes very discontinuous. As a result of introducing further rhythms, in those places the black bars in the upper part of the figure which show the time intervals recorded by sedimentation should be in reality broken into gridirons by smaller cycles, cutting out by diastems more and more of the record until the whole comes somewhat to resemble the Fraunhofer lines in the solar spectrum.

A fundamental conception connected with composite rhythms is that a long time interval may be represented by a short columnar section, and yet the individual beds may be deposited rapidly. In coal measures, tree trunks may be preserved in erect attitude, showing burial before decay. In marine deposits, sponges and coral colonies are in certain beds found smothered in mud. Ammonite shells were partially or wholly buried before they could be destroyed. Such burials may have been due to single unusual storms, recurrently scouring sediment from one locality to deposit it in another. At the most, but a few years could have been occupied in the burial. These features show rates of accumulation so rapid that even the advocates of very short geological time would have to admit for such instances recurrent deposition with lost intervals between. But having once admitted the principle, the basis is destroyed for estimating the time of accumulation of the whole formation by means of an assumed rate of continuous denudation and corresponding sedimentation.

ILLUSTRATIONS OF RHYTHMS IN SEDIMENTATION

In advocating a view that sedimentation on the continental platforms in either marine or terrestrial deposits is more often discontinuous than

³⁰ Joseph Barrell: Relations between climate and terrestrial deposits. *Journal of Geology*, vol. xvi, 1908, pp. 159-190, 255-295, 363-384. The Upper Devonian delta of the Appalachian geosyncline. *American Journal of Science*, vol. xxxvii, 1914, pp. 239-243.

continuous, on both a small and large scale, some discussion should be added as to what are conceived to be the stratigraphic marks of such discontinuity.

Leaving aside the significance of angular unconformities as not needing amplification, we may pass to disconformities. These, as previously noted, are not recognized by any structural discordance, but are marked by change of faunas and represent lost intervals of greater or lesser duration; thus they may represent the passage of geologic periods, or they may exist between formations in the same period. Recognition of the large number and importance of disconformities has grown within the past decade, but in their nature, like faults, they must be far more numerous than the evidence can demonstrate. Careful study of the Mesozoic and Cenozoic formations of the Atlantic coastal plain has shown that unconformities lie between nearly every formation. In the Patuxent folio, Maryland, twelve post-Triassic-pre-Pleistocene formations are listed. Of the eleven surfaces of separation between them, nine are given as unconformities. But formations which are not separated by unconformities, as well as the members within a formation, may or may not possess continuity of sedimentation through the large cycle which they represent. If a transition zone exists between two unlike deposits, the suggestion given is one of continuous deposition. This is more probable if the transition is from coarse below to fine above. On the other hand, if there is a sharp contrast, a break in continuity is suggested, and this is more probable if the contrast is from fine below to coarse above.

Passing to the smaller rhythms which characterize beds rather than members of formations, two beds which grade from coarse below to fine above are presumably continuous, but each such pair may be separated from adjacent pairs by a stage of scour or non-deposition, since each coarse bed must lie in turn on one of finer texture. It would be unsafe, however, to use it as an absolute criterion of minor discontinuity, as it is quite possible for sand to be washed over mud-beds without necessarily producing a down-scour. Illustrations of the nature of discontinuity may be given from several types of beds. The first will be for dunes.

Sandstones of terrestrial origin may be produced by wind. The sand travels in the form of dunes. As these slowly march across a tract of accumulation, a region to which more sand is brought than is taken away, the basal part of each dune may be left behind and buried under some following dune. The long sweeping curves of the cross-bedding are planed off and the angular unconformities in cross-bedding indicate a lack of continuity of record with the sand above, giving a diastem. According to shifts in the intensity and directions of the wind, more sand may be

taken away than is brought to the region, down-scour may take the place of upbuilding for shorter or longer periods, and the break, or diastem, between two similar beds represents an unknown time interval. The crescent form of dunes brings in further local complexities, but these may be eliminated in this discussion. The subject lends itself to diagrammatic illustration which brings out impressively the relatively large time value of the lost intervals represented by the division planes between beds.

In figure 6 are illustrated the principles which enter into the building and marching of dunes, but the same reasoning applies in a general manner to all sedimentation where there is alternate fill and scour. The wind is shown blowing from left to right. It rolls and jumps the sand particles up the gentle back slope of the dune and at the crest meets a return eddy. When the wind is strong the sand is seen suspended in the air just to the lee of the crest and the dune is said to smoke. At the top of the lee slope the sand at the crest is kept by the return eddy on a slope of about 30

FIGURE 6.—*Diagrammatic Cross-section to illustrate Time Values of true bedding Surfaces between Beds of false-bedded Dune Sands*

degrees or a little more—the angle of repose. The curvature of the wind currents gives broad sweeping surfaces, passing from the lee slope up the flat back of the next dune to its crest. The dune grows by adding successive beds to the lee side, and these are progressively cut out by the scour on the windward side. Where there is a progressive accumulation the down-scour does not cut on the average quite to the base of the dune.

In the diagram the wave length of the dune is divided into eight stages. A21, B21, C21 are laminae of the same age; but lamina C21 lies above B13 and this in turn above A5. The time value of the breaks represented by the planes of separation is given by the time which is taken for a dune to advance one wave length compared to the thickness of the beds spared by the down-scour. Thus, in a vertical section just back of the left-hand dune, time intervals 3, 4; 11, 12; 19, 20 are represented by sediments; the intervening times are represented by the breaks.

The dunes of the great deserts are often several hundred feet in height. As seen in plan, the typical form is the crescentic barchane, the wings of which slope downward. The wind shifts in direction, and different years are marked by notably different maximum intensities. The great bulk of sand movement is accomplished during relatively brief periods of intense winds. These factors, as previously noted, make the actual struc-

tures in nature far more complex than the simple diagram. Nevertheless, the average or aggregate effect is well represented.

If the sand swept by wind from the source in the stony desert or hamada, or brought by streams from mountains, is accumulating uniformly over a distance of a hundred miles, then over the first mile only 1 per cent will remain and 99 per cent will be carried beyond. As equable deposition can not be postulated, there will be many times when scour rather than deposition takes place in the first mile. The exceptional winds of a single year may scour down to the layers deposited in a previous century and a few following years of slack winds may more than fill in all of the scour. Thus it would be a common feature for C of the diagram to come to lie below B or A, or even below far lower beds. If C should cut down below B, it would bring lamina C₂₁ into contact with A₃, 4; or 5.

It is seen that the average length of the time break, or diastem, between beds depends on the ratio of the volume of material of that kind which is carried beyond to the volume which is deposited in the locality of the bed, but on account of the lack of uniformity which exists in Nature the actual value of an individual break might range from nothing to many times the average. The conclusion of far-reaching importance is that coarse detritus and rapid accumulation of individual beds is no criterion of rapid accumulation of the formation as a whole. This needs to be emphasized because the natural tendency, without analysis of the problem, is for geologists to assume the contrary to be true.

Looking at the farther side of the region of deposition, it is seen that during the maxima of transporting power there is only deposition and no removal of material; but at times when the wind is less intense, there is no transportation of material of this grade of coarseness to such a region. Thus it may be taken as a general proposition that the coarser the waste and the more rapid the accumulation of individual beds, the longer, *relatively*, are the times of non-deposition. Furthermore, it is seen that on the side of the formation toward the source the break, or diastem, is due to an accentuation of the carrying forces. On the side away from the source the lack of deposit is due to the alternating quiescence in transportation. The diastems in one locality are represented by beds in another locality in the same formation. Each section may show a high degree of discontinuity, and yet if various sections could be pieced together a more or less complete record might be attained.

The rate of accumulation of conglomerate and sandstone formations, as well as that of the individual sand beds, may be on the average more rapid than that of argillaceous formations, and these in turn possess a

higher rate than that of limestone formations, but these rates of accumulation are due to the relative rapidity of crust movements generally implied by the coarser waste as compared to the finer, not because the individual beds of sandstone or mudstone are individually more rapidly deposited.

In river deposits the migration of the channel produces scour *into* the floodplain deposits, but the natural levees are laid down *on* them. Thus, in alluvial formations there may be both continuous and discontinuous deposition. Shifts in the regimen of the stream due to variations between the supply of waste and the amount of water are more important. Climatic pulsations thus affect the river grades, and stages of scouring alternate with those of upbuilding. The high plains of the western United States have in this manner suffered alternate dissection and partial rebuilding on a large scale recurrently through the Pleistocene. This oscillation in fluvial transportation is apparently an important factor leading to the division of elastic formations into members, even where the final deposition of the sediment is on the floor of the epeiric sea.

S. H. Knight, in his study of the "Origin and Age of the Red Beds of Southeastern Wyoming,"³¹ has shown that certain beds have been cemented; then eroded, and by a return to aggradation, great residual boulders were reburied *in situ* in younger beds of enveloping sediments of the same formation, thus giving rise to a peculiar type of interformational conglomerate.

Farther from the source of sediments, on the deltas of rivers, or in front of the delta on the floor of the shallow sea, the possibility of deposition depends more closely on subsidence. The river builds up quickly after each stage of down-sinking, and then, after grade is reached, carries its sediment farther out. It must wait for further subsidence before it can make more than thin deposits on the inland portion of the delta.

In limestone formations discontinuity of sedimentation is indicated by recurrent exposure to the air, but also by several other features. The cementation of lime muds is favored by supersaturation of the waters; solution, on the other hand, results from freshening and undersaturation. The wearing down of shells and the transportation of the lime mud elsewhere may retard or even stop the local accumulation. The alternate freshening and saturation of the waters tends to carry away the calcium carbonate and concentrate the less soluble magnesium into beds of dolomitic limestone. Thus there may be continuous or discontinuous accumulation in limestones, but the dominant features of most of these formations suggest that sedimentation was markedly discontinuous from bed to bed.

³¹ Presented orally to the Geological Society of America December 29, 1916.

FIGURE 1.—BEDDING IN SLATE QUARRY, UPPER ORDOVICIAN, SLATEDALE, PENNSYLVANIA.
Photograph by H. S. Palmer, 1913

FIGURE 2.—RIBBONED SLATE, UPPER ORDOVICIAN, SLATEDALE, PENNSYLVANIA
The ribbons have a dual division, consisting of carbonaceous mud below and fine-grained sand above, emphasized by retouching the photograph

UPPER ORDOVICIAN SLATE OF PENNSYLVANIA

Turning to marine mudstones, it would seem that here are the most favorable conditions for a continuous record. They seem well adapted, especially where markedly alternating with beds of lime or silt, to give a basis for the analysis of rhythms.

An instructive illustration of what is probably in some beds a continuous record and in other beds a record not greatly discontinuous is found in the Martinsburg or Hudson River slates. The writer has studied them especially in eastern Pennsylvania, where the commercial value of certain beds has resulted in extensive quarrying and numerous exposures. The formation is here in considerable part a silt rock. This facies, where studied in the neighborhood of the Lehigh River, is divided into beds from several inches to several feet in thickness, constituting a ribboned slate. An illustration showing this feature is given in plate 43, figure 1. In a single exposure the rhythm in bedding tends to great regularity. Through most of the formation the ribbons are reduced to mere parting planes between beds of silty character. In places thicker beds may be almost uniform in texture, but have thin bands of lighter color running through them which appear to be due to a slightly lower content of carbonaceous mud. Such faint color bands may not destroy the value of the slate. In some localities these bands of slightly lighter color alternate with a very regular spacing with bands which vary in the other direction, containing softer and blacker material. All these varieties of divisions in bedding are thus seen to be due to related causes of regular recurrence. Turning to the notably ribboned slates, we may find in them the key to the significance of the bedding. The ribbons often consist of a band of soft black mud-rock overlain by a band of nearly clean sand. The mixture of the two would appear to give the normal composition shown in the intervening beds. This sequence is illustrated in plate 43, figure 2.

The layer of sand is often subdivided into laminæ and occasionally shows ripple-mark. Kindle has shown by experiment that in a silt deposited after stirring up in fresh water the coarser particles are deposited first, whereas in salt water the coagulation into nuclei is such that the slimes are deposited first, and the very fine sand follows.³² These ribboned slates indicate, consequently, that at recurring intervals the bottom of a shallow Ordovician sea was stirred up by waves of unusual intensity. On the dying down of the wave action the sediment which was held in the water at that place settled, making the ribbon of this character. It can not be assumed that the recurrent strong wave action

³² E. M. Kindle: Diagnostic characteristics of marine clastics. Paper presented to the Geological Society of America December 29, 1916.

churned up the sediment without carrying any away. The width of the ribbon represents merely what settled from the water on the subsidence of the storm. During the progress of the storm, sediment was being scoured out and worked to localities of deeper and quieter water. The development of the bedding planes in this slate and their expansion into ribbons represent, then, a region and a depth where waves gently agitated the bottom, sweeping material along and spreading it out in the quieter waters. Rhythmic intensification of this action resulted in an alternation of fill and scour in which the surface of sedimentation was raised and depressed by changing intensity of wave action and maintained throughout a marked parallelism distinctive from current action.

Certain inductions having wide application to beds of marine silts may be drawn from this clear example. The regularity in the succession of the beds and the grouping of these beds into sequences shows a combination of climatic rhythms marked by varying intensity of storms. The sediment was deposited in close accord with wave-base, and the down-scouring probably did not cut out more than half of each deposited bed, since otherwise the remainders would not form such a regular series. After each culmination of intensity continuous deposition, so far as this cycle is concerned, seems to have occurred, giving rise to the following bed with a definite and constant mixture of mud and fine sand. Considering the fine-grained character of the sediment, the wide area of the formation, and the abundance of carbon, the sediment must have been deposited slowly. The thickness of the beds, ranging from several inches to several feet, indicates, then, a rhythm far too long to be regarded as seasonal. It can not be less than decades or centuries in length. The land lay to the eastward and was presumably low. The denudation rate was consequently slow, and therefore, as a maximum limit, the cycle may represent some thousands of years. The amount of variation in wave intensity to give this rhythm was moderate. Thus we reach the conclusion that the climate was more uniform than at present, but was affected by regular oscillations comparable to the Brückner cycle of 35 years, but more probably of longer period. Such a regularity in climatic rhythm suggests as a cause fluctuations in solar energy. In the strata of such ancient formations is locked up, not only a history of the planet, but also the history of the sun as a variable star.

Some further illustrations of the variety of rhythms, especially those showing in disconformities and diastems, should be given. The first of these, taken up in sequence of age, is a view of a series of cryptozoan beds from the Lower Ordovician (see plate 44, figure 1, photograph of an exposure near Allentown, Pennsylvania). The cryptozoan layers show white

FIGURE 1.—CRYITOZOAN LIMESTONE, WEST BANK LEHIGH RIVER, NORTH OF ALLENTOWN, PENNSYLVANIA

Photograph by W. A. Bell, 1914

FIGURE 2.—CONTACT OF LOWVILLE AND BLACK RIVER LIMESTONES, NEWPORT, NEW YORK

Photograph by P. E. Raymond

LIMESTONE EXPOSURES IN PENNSYLVANIA AND NEW YORK

and are interbanded with fine-grained dark gray limestone. Detailed examination brings to light the fact that the cryptozoa were periodically blanketed by a soft lime mud, following which new colonies would start to grow on the layers of mud. The colonies were favored by clear water and became cemented crusts. These crusts, while yet thin, were liable to become broken up by wave action and form intraformational conglomerates. The thicker and stronger colonies had their existence terminated, not by wave action, but by becoming smothered beneath the next heavy invasion of mud. In some localities, however, the life of the colonies was probably terminated by draining away of water and drying, as shown by mud-cracking. Stronger wave action and influx of mud were thus the features determining the dark gray limestones; gentler wave action and clear water permitted the growth of cryptozoa. These conditions alternated in a markedly rhythmic fashion. The nature of the composite rhythm is shown well in the lower portion of the section. Many fine laminations, hardly visible in the photograph, make up a minor rhythm. Four or five repetitions of the minor rhythm led up to a crescendo favoring progressively longer times for the growth of cryptozoa. Then a sudden change took place to that phase favoring the accumulation of lime mud. In the upper third of the section the rhythm is seen to change in character; a lesser thickness is deposited in each cycle, the cryptozoan layers are sharper and thinner, the crescendo seems to have disappeared.

To what degree does this series of beds represent continuous or discontinuous deposition? Each cryptozoan colony doubtless lived a continuous life until it was smothered. The mud appears to have come in suddenly, since all parts of the colony stopped growing at once, both the base and top of the hemispherical turbans. There may thus have been a continuous deposition of alternately organic and inorganic nature, but at a variable rate. On the other hand, alternate fill and scour may have taken place during the deposition of the mud-beds. The rather abrupt change in the character of the rhythm may signify a loss of record during a time when the cryptozoan growth was stopped and before the colony was buried. Such a period of lost record would account for the sudden change in character, but on the whole the evidence suggests for this section the other explanation of sudden death by burial. The regularity and composite nature of the rhythm favors interpretation as a record of climatic oscillations and the whole section may represent a phase of a larger rhythm marked by a slowly subsiding bottom. T. W. Vaughan has shown that such a condition of submergence favors the

growth of coral colonies, and the same was probably true of the cryptozoa. The following illustrations have been called to the writer's attention by Professor Schuchert, although three of the photographs are by P. E. Raymond, R. S. Bassler, and M. Y. Williams, respectively, who have kindly given permission for their publication.

The first, plate 44, figure 2, from the Middle Ordovician, shows the upper regular beds of the Lowville and the nodular lower beds of the Black River limestone. The Lowville, in the older nomenclature, was known as the bird's-eye limestone, from the preservation in it of the casts of vertical stems of marine plants, which seen in cross-section give the bird's-eye effect. The individual laminae were therefore deposited rapidly and in shallow water. The formation consists of blue or dove-colored fine-grained limestones with beds of thin shaly limestone and shows an extraordinary persistence of lithologic characters over an area of 500,000 square miles, mainly east of the Mississippi River. A marked disconformity is pointed out by Ulrich as existing at the base of the Lowville, as it rests in places on the very similar, but far lower, Stones River limestone of the Lower Ordovician. Some of these limestones, probably including the Lowville, exhibit mud-cracks in many beds and in widely separated localities. The writer has also, but more rarely, found rain-printed surfaces. The Lowville is, however, very fossiliferous in certain layers; so that, although the waters were shallow and repeatedly withdrawn, they were typical marine waters. The oscillations must have been very small in amount and were perhaps mostly due to climatic factors, the seas forming marine playas. The overlying, or Black River, limestones are nodular and in places cherty, indicating a different character of deposition and probably much solution of lime in order to concentrate the silica. No large time elapsed, however, between the two formations, as Schuchert states in a personal communication that in the locality shown by the photograph he could not make out a faunal break at the top of the Lowville, but that there was clearly a depositional break, not a disconformity, however, in the generally accepted sense.

Referring to the photograph, the beds which are marked A, B, C constitute the upper Lowville; D, the Black River. There is exhibited here a striking series of rhythms. A major rhythm is represented by B, consisting of three subordinate beds. Each subordinate bed in B is subdivided in turn into three and these in their turn into thin laminae. The weathering brings out a change by a series of steps from A to B to C, the latter consisting of six beds and being apparently equivalent to two rhythms of the value of A and B. The subordinate rhythms of B are almost absent from C. It is not thought that stress should be placed on the precise

FIGURE 1.—BELLEVUE FORMATION RESTING ON THE FAIRMOUNT FORMATION. ERNST HILL, CINCINNATI, OHIO

Photograph by R. S. Bassler

FIGURE 2.—SILURIAN SEQUENCE AT STONY CREEK, SOUTH OF HAMILTON, ONTARIO

Photograph by M. Y. Williams

EXPOSURES OF BELLEVUE AND FAIRMOUNT FORMATIONS, OHIO, AND SILURIAN SEQUENCE, ONTARIO

nature of the rhythms, but it is regarded as very important that a rhythm runs with minor changes a certain distance through the strata and then comes to a full stop. It would be expected that, in a complete record, a rhythm should gradually emerge and disappear. The differences between A, B, and C are expressive, then, of well marked diastems between them. Lesser diastems divide the beds which make A, B, and C. Between C and D is a diastem of such large value that when sedimentation was resumed in D the nature of the rhythm had entirely changed. If this series is interpreted in accordance with the harmonic rhythms shown in figure 5, it is seen that a composite oscillation of baselevel with alternate fill and scour would account for the observed features of the beds. Each of the finest laminae may have been deposited in a year, but the whole may represent only a fifth, tenth, or smaller fraction of the entire time. A long time interval is implied by the diastem between C and D, probably longer than the time represented by the whole of the Lowville formation, though not great enough to produce a notable faunal change on the resumption of the stratigraphic record.

The next illustration, plate 45, figure 1, showing also a change in rhythms, is from the Maysville or Lorraine group, which is the middle group of the Upper Ordovician or Cincinnati. The Lorraine sea, according to Schuchert, was a somewhat limited flood covering most of the area between the Mississippi, the Appalachian land on the east, and the region of the Great Lakes. Winchell and Ulrich make the following statement regarding the section in Ohio:

"At the base of the (Lorraine) division, which at Cincinnati comprises about 200 feet of strata, there are some arenaceous layers that on weathering frequently preserve the fossils as casts. Above these there are numerous layers of crystalline limestone, 3 to 10 inches in thickness, separated by relatively thin bands of shale. In the upper 60 or 70 feet the bedding is more irregular and the limestone layers thinner and generally argillaceous, unfitting them for building purposes. Fossils are well preserved and exceedingly plentiful and among them may be recognized nearly every species that has been described from the equivalent beds in New York."³³

All the stratigraphic features indicate shallow water. The crystalline limestones suggest alternating undersaturation and supersaturation of the water, with alternate solution and precipitation of what was originally organic debris. The abundant fossils suggest periodic rapid burial in wave-stirred muds. A long period of time is represented by a very limited depth of strata. In fact, on a diastrophic basis, the Cincinnati may

³³ B. Willis: Index to the stratigraphy of North America. Prof. Paper No. 71, U. S. Geol. Survey, 1912, p. 166.

come to be given the value of a geologic period. It is to be expected, therefore, that diastems occur here in rhythms of smaller and larger time values. In the photograph, A constitutes the Fairmount, B and C the Bellevue. Ulrich and Bassler consider that there is a well marked break between A and B. Bassler states in a personal communication that:

"Between B and C strata come in, away from Cincinnati, sometimes to a thickness of 50 feet, which are represented around Cincinnati only occasionally by an inch or so. These are the Orthorhynchula beds which are so well developed in central Tennessee. This is only one of the unconformities which have been noted in the Cincinnati section where hitherto the rocks have been supposed to record continuous deposition."

In A there is a very marked rhythm which is not present in B or C. It would seem, therefore, that the disappearance of the rhythm indicates a long time interval and is in accordance with the evidence given by Bassler. The difference between B and C may indicate a lesser diastem. The significance of a sudden change of rhythm is the feature of this section which is most noteworthy.

The next illustration, plate 45, figure 2, is from the lower part of the Silurian. The sequence is given as follows by Williams:

- F. Lockport dolomite, thin bedded.
- E. Rochester shale.
- D. Irondequoit limestone, thick bedded, top of Clinton.
- C. Walcott limestone, thin bedded, Clinton.
- B. Medina sandstone, thin bedded.
- A. Cataract sandstone and shale, Schuchert, thin bedded.

Schuchert states that there is no clear faunal break here. This organic evidence of a disconformity is therefore absent, but the great lapse of time and the many sharp changes in sedimentation may be taken as evidence of the existence of diastems of large time value, approaching the nature of disconformities. The absence of faunal breaks would appear to be a proper basis for classifying the hiatuses as diastems.

In plate 46, figure 1, is shown a section which brings into one view formations of widely differing ages. The formations represented are given by Schuchert as follows:

- E. Chattanooga black shale, Mississippian.
- D. Onondaga limestone, 6 feet, Middle Devonian.
- C. Louisville limestone, Middle Silurian.
- B. Waldron shale, 9-10 feet, Middle Silurian.
- A. Laurel limestone, Middle Silurian.

Willis summarizes the statements of Foerste, Kindle, and Barnett in regard to these Silurian formations of the Niagaran epoch as follows:

FIGURE 1.—SILURIAN, DEVONIAN, AND MISSISSIPPIAN SUCCESSION WEST OF NEWSOM, TENNESSEE

Photograph by C. Schuchert

FIGURE 2.—GYPSUM, WINDSOR FORMATION, MISSISSIPPIAN, NEAR MONCTON, NEW BRUNSWICK, CANADA

Photograph by C. Schuchert

EXPOSURES OF SILURIAN, DEVONIAN, AND MISSISSIPPIAN IN TENNESSEE AND CANADA

"The Laurel limestone is usually hard, white, and evenly bedded. Toward the south it becomes softer and more argillaceous.

"The Waldron shale is a distinct bed overlying the Laurel, and is mainly a clayey shale having the facies of the Osgood shale. It becomes calcareous toward the north.

"The Louisville limestone, which at Louisville is unconformably overlain by Devonian limestone and has a thickness of 55 feet, is described as thinning out toward the north and east.

"The faunas of the several divisions of the Silurian in Indiana are distinguished by Foerste, who recognizes close affinities between those of the Laurel and Louisville on the one hand and between those of the Waldron clay and Osgood clay and limestone (below the Laurel limestone) on the other."³⁴

This section is seen to illustrate a series of disconformities of lesser and greater time value. Without the testimony of the fossils there would be no evidence of the great lapses of time unrepresented by sediments. It is eloquent of the imperfection of the stratigraphic record and of the lack of necessary relation between the thickness of a section and the time represented, in that apparently conformable strata of three periods are shown in one quarry face.

Plate 46, figure 2, is a view of gypsum beds showing the rhythmic crinkled banding in a chemical precipitate. Here the changing concentration of the water may be due to changes in climate or to changes in the freedom of access of sea-water to the lagoons in which precipitation proceeded. The well marked composite rhythm is best seen by looking at the photograph from a distance or with nearly closed eyes, and the regularity of this rhythm suggests that it is a climatic record rather than one owing to the shifts in physical geography. Each lamina represents a stage of warmth and concentrating water; each surface of separation represents a shorter or longer period of undersaturation and consequent absence of record. Gradations may represent continuous deposition, but with changing rates. Such a series of beds is worthy of very careful analytical study as a detailed meteorological record of the past.

PART III.—ESTIMATES OF TIME BASED ON GEOLOGIC PROCESSES

MAGNITUDE OF THE CENOZOIC ERA ON EVIDENCE CHIEFLY FROM EROSION

Time is measured by the recurrence of rhythms or by the aggregate effects which are accumulated during their passage. The two preceding parts of this article have dealt with the importance of rhythms in modifying the rates of erosion and sedimentation; yet it is seen that previous

³⁴ B. Willis: Index to the stratigraphy of North America. Prof. Paper No. 71, U. S. Geol. Survey, 1912, pp. 232, 233.

attempts to sound the depths of geologic time have in nearly all cases assumed a uniformity of processes or have made but slight allowance for their variation. In this part a review will be given of the relations of methods to results and the assumptions on which those methods rest. The trend of the modifications indicated by the recognition of the importance of rhythms may then be perceived. It is not the intention to give a formal review of the many previous estimates which have been made of geologic time, since that has been done by others,³⁵ but merely to present that which seems essential in the present connection.

One of the earliest estimates was based on the evidence of life transformations in successive periods. Lyell divided the geological series into twelve periods and estimated—perhaps guessed would be a better word—that 20,000,000 years were demanded for a complete change in the species of each period, or 240,000,000 years in all. This estimate excluded the Primordial of Barrande and the “antecedent Laurentian formations.”³⁶ Darwin considered that Croll’s estimate of 60,000,000 years since the Cambrian period and the previous 140,000,000 years can hardly be sufficient for organic evolution.

From the physical side, the early geologists saw no indications of infancy or of old age on the face of Nature. Nothing less than interminable time broken into periods by revolutions appeared to be the testimony of the rocks. Lord Kelvin first called attention to the fundamentally erroneous nature of this conception. Of Kelvin’s work A. Geikie states:

“He pointed out that from the high internal temperature of our globe, increasing inwards as it does, and from the rate of loss of its heat, a limit may be fixed to the planet’s antiquity. He showed that so far from there being no sign of a beginning, and no prospect of an end, to the present economy, every lineament of the solar system bears witness to a gradual dissipation of energy from some definite starting point.

“But physical inquiry continued to be pushed forward with regard to the early history and antiquity of the earth. Further consideration of the influence of tidal friction in retarding the earth’s rotation, and of the sun’s rate of cooling, led to sweeping reductions of the time allowable for the evolution of the planet. The geologist found himself in the plight of Lear when his body-guard of 100 knights was cut down. ‘What need you five-and-twenty, ten or five?’ demands the inexorable physicist, as he remorselessly strikes slice after

³⁵ See especially C. D. Walcott: Geologic time as indicated by the sedimentary rocks of North America. *Journal of Geology*, vol. i, 1893, pp. 639-676; *Smithsonian Report for 1893*, pp. 301-334, 1894.

Arthur Holmes: *The age of the earth*. Harper and Bros. London and New York, 1913.

³⁶ *Principles of Geology*, 10th ed., 1867, vol. 1, p. 301. Quoted from C. D. Walcott, *Smithsonian Report for 1893*, p. 303, 1894.

slice from his allowance of geological time. Lord Kelvin is willing, I believe, to grant us some twenty millions of years, but Professor Tait would have us content with less than ten millions."³⁷

Huxley in 1869 had refused to be limited by Kelvin's reasoning, considering that unknown factors may vitiate the results.³⁸ Geikie in 1892 states of it also:

"That there must be some flaw in the physical argument I can, for my own part, hardly doubt, though I do not pretend to be able to say where it is to be found. Some assumption, it seems to me, has been made, or some consideration has been left out of sight, which will eventually be seen to vitiate the conclusions, and which when duly taken into account will allow time enough for any reasonable interpretation of the geological record."³⁹

In 1903 Geikie states:

"Until it can be shown that geologists and paleontologists have misinterpreted the records contained in the earth's crust, they may not unreasonably claim as much time for the history revealed in these records as the vast body of accumulated evidence appears to them to demand. There is a general agreement among the geologists that, so far as the phenomena of sedimentation and tectonic structure are concerned, 100 millions of years would probably suffice for the completion of the geological record. But if on paleontological grounds the allowance of time should be found too small, there appears to be no reason, on at least the geological side, why it should not be enlarged, as far as may be found needful for the satisfactory interpretation of the evolution of organized existence on the globe."⁴⁰

Nevertheless, it is evidently true that, from among the various possible interpretations of the data, geologists were in general inclined to choose those which gave the lower limits to geological time. Such estimates which limited the earth to a duration of 100,000,000 years or less were easy to attain by taking fairly rapid rates of erosion and sedimentation and assuming that these represented the average of geological time. To show how wide are the limits as given by estimates based on geologic processes, the various modes of attack must be enumerated.

First to be taken up are those concerning the duration of the latest periods as determined especially by the erosion history rather than by the record of sedimentation.

Upham, who holds to the view that the Pleistocene consisted of one advance and retreat, concluded that the

³⁷ A. Geikie: Geological change and time. Presidential address, Brit. Asso. Adv. Sci., 1892. Ann. Rept. Smithsonian Institution for 1892, pp. 124, 125.

³⁸ T. H. Huxley: Presidential address, Geol. Soc. London, Quart. Jour, Geol. Soc., vol. xxv, 1869, pp. xxxviii-lxii.

³⁹ A. Geikie: Loc. cit., p. 126.

⁴⁰ A. Geikie: Text-book of Geology, 1903, pp. 77-78.

"probable length of Glacial and post-Glacial time together is 30,000 or 40,000 years, more or less; but an equal or considerably longer preceding time, while the areas that became covered by ice were being uplifted to high altitudes, may perhaps with good reason be also included in the Quaternary era, which then would comprise some 100,000 years."⁴¹

On the other hand, Chamberlin and others, recognizing the complexity of the ice-advances and basing their estimates upon the degree of erosion of the older glacial deposits, obtain a period of 300,000 to 1,020,000 years from the present to the Kansan glacial stage, and an unknown greater time to the beginning of the Pleistocene.⁴² McGee, comparing the relative erosion of river valleys in post-Glacial and post-Columbian (early or middle Pleistocene) time and the work of erosion in the Tertiary, obtains a mean estimate of 200,000 years as the duration of post-Columbian time and 90,000,000 years for the Cenozoic.⁴³

Goodchild takes the time since the close of the Glacial period as 20,000 years. He then makes an estimate of the time needed for the erosion of the Skye volcano. This he takes as beginning to erupt some time in the Oligocene, completed by the close of the Miocene, and as having an initial height of 8,000 feet. Choosing an erosion rate for its gabbroic rocks as one foot in 2,000 years gives an estimate of 16,000,000 years since the close of the Miocene.⁴⁴

Dana obtained ratios of the relative durations of the geologic periods by comparing the volumes of sediment deposited in them. Taking the Quaternary as 1,000,000 years, the length of the Tertiary is 3,000,000. Ward, in the Fifth Annual Report of the United States Geological Survey, gives a time ratio to the Quaternary-Recent as 1, the Miocene-Pliocene as 1, and the Eocene as 1, and Williams adopts these ratios.⁴⁵

These estimates by American geologists are no doubt the basis for a very common statement of the length of the Tertiary as 3,000,000 years. They were probably based originally on a comparison of the rather thin Tertiary deposits of the Atlantic coastal plain, the presence of many unconformities being then unappreciated. At that time the magnitude of Tertiary erosion and sedimentation in the regions of mountain-making was also uncomprehended. Year by year it becomes clearer that, since the opening of the Miocene, uplifts resulting in a greater or less completion of erosion cycles have been repeated several times. Blackwelder

⁴¹ Upham: *Am. Jour. Sci.*, vol. xlv, 1893, pp. 217, 218.

⁴² Chamberlin and Salisbury: *Geology*, vol. III, 1906, p. 420.

⁴³ W J McGee: Note on the age of the earth. *Science*, vol. xxi, 1893, p. 309.

⁴⁴ J. G. Goodchild: Vice-presidential address. Royal Physical Society of Edinburgh. Nov., 1896, pp. 263-265, 1897.

⁴⁵ H. S. Williams: The elements of the geological time scale. *Jour. Geol.*, vol. I, 1893, p. 295.

has discussed these features for the mountains of central Wyoming.⁴⁶ The magnitude of the work of erosion and the number of events since the opening of the Miocene are also illustrated in the Coast ranges of California. The newer interpretations of the structure and erosion history of the Alps testify to the great length and complexity of the geological history of the Miocene and Pliocene as compared to the Pleistocene.

The maximum thicknesses of sediments deposited in the several periods have been made the basis by Sollas of estimates of age. The increase in knowledge concerning the divisions of the Tertiary is represented by the increase in his figures from the year 1900 to 1909. These are as follows:⁴⁷

	A. D. 1900	A. D. 1909
	Feet	Feet
Recent and Pleistocene.....	4,000	4,000
Pliocene	5,000	13,000
Miocene	9,000	14,000
Oligocene	12,000	12,000
Eocene	12,000	20,000
	<hr/> 42,000	<hr/> 63,000

Turning to a reinterpretation of the data, it is to be noted that discontinuities and unconformities occur between many of the formations, and reasons have been discussed in connection with the significance of valley forms for believing that the mean rate of denudation through the Tertiary probably has not equaled more than half of the rate for the Pleistocene and the Recent. From these varied lines of evidence it seems reasonable to regard the total Pleistocene as at least 1,500,000 years in length, and the younger Tertiary, including the Miocene and Pliocene, as perhaps ten times as long as the Pleistocene. But back of the younger Tertiary lies the earlier Tertiary. This was formerly all embraced in the Eocene and lower Miocene, but is now subdivided into Oligocene and Eocene, and the basal Eocene in turn is now set apart by many as the Paleocene. The older Tertiary was probably considerably longer than the younger Tertiary, perhaps twice as long, and the whole of the Cenozoic is as much as twenty and more probably thirty times the length of the Pleistocene.

Another line of attack is found in estimates of the amount of organic evolution accomplished in successive epochs, not forgetting, however, that, as evolution depends largely upon changes in environment, the times of rapid change will also be times of rapid evolution. No one is better quali-

⁴⁶ Elliot Blackwelder: Post-Cretaceous history of the mountains of central western Wyoming. *Jour. Geol.*, vol. xxiii, 1915, pp. 97-117, 193-217, 307-340.

⁴⁷ W. J. Sollas: Presidential address. *Quart. Jour. Geol. Soc.*, vol. 65, 1909, p. cxli.

fied than W. D. Matthew to weigh this evidence for the evolution of the mammals through the Cenozoic. He has discussed this especially for the horses, but finds the results supported by a comparison with the evolution in other mammalian phyla.⁴⁸ On this basis Matthew estimates that the entire Tertiary is about one hundred times as long as the Pleistocene, dating the latter from the first great glacial advance. His impression from the evolution of vertebrates during the Mesozoic is that each of its four periods were comparable in length to the Tertiary. Matthew then raises the question as to what length of time should be adopted for the Pleistocene, the unit of measurement. He takes 100,000 years as representative of the more moderate figures between the 25,500 years of Wright and the 1,500,000 of Penck and other authorities. The resulting estimate of 10,000,000 years for the Tertiary and 40,000,000 for the Mesozoic does not seem to Matthew unreasonable.

Matthew's results show a leaning toward higher estimates than nearly all stratigraphic geologists have admitted, but he has kept them down only by adopting what will seem to most students of the Pleistocene an ultra-conservative estimate of its shortness. With the recognition of the complexity of the Pleistocene and the amount of diastrophism and erosion accomplished in it, 500,000 years has come to be set as a minimum estimate of its length, rather than 100,000 years. As an upper limit, on the other hand, 1,000,000 to 1,500,000 years are not unreasonable figures, and the higher of these is adopted by Penck, one of the foremost authorities on the Pleistocene. Using only 500,000 years as the unit, Matthew's ratios give a length of 50,000,000 years for the Cenozoic and 200,000,000 years for the Mesozoic. These figures for the length of the Cenozoic and Mesozoic the writer believes to be of the right order of magnitude and supported by strong evidence, to be brought out in the later part of this paper.

The foregoing discussion suggests that the early estimate of 3,000,000 years, which has entered so largely into geologic literature, may well be multiplied by twenty. The evidence from radioactivity, to be presented later, suggests that 60,000,000 years may readily be granted to the Cenozoic era, and the geologic evidence as interpreted in this article is in harmony with this magnification, though, being qualitative rather than quantitative, it could, if necessary, be interpreted in terms of half this time. The geologic evidence can not be adjusted, however, to an age as short as 10,000,000 years without ignoring the factors discussed in the earlier parts of this article, and the estimate of 3,000,000 years is clearly an

⁴⁸ W. D. Matthew: Time ratios in the evolution of the mammalian phyla. A contribution to the problem of the age of the earth. *Science*, vol. xl, 1914, pp. 232-235.

inheritance from a time before a proper geological perspective had been attained.

*MAGNITUDE OF THE PALEOZOIC ERA ON EVIDENCE CHIEFLY FROM
SEDIMENTATION*

Estimates of the duration of the Paleozoic era rest especially upon the rate of accumulation of the strata and the valuation of the intercalated disconformities and unconformities. In order to perceive if the data can be equally well or even better interpreted to give greatly longer estimates of time than has been customary, the lines of reasoning of two leading geologists will be examined, Walcott and Sollas, since their work has had great influence on geologic thought in these matters.

Walcott, in his vice-presidential address before Section E of the American Association,⁴⁹ gave the results of a careful study of the deposits of the Cordilleran sea as a basis for estimating the length of Paleozoic time. Giving ratios to the Paleozoic, Mesozoic, and Cenozoic as 12, 5, and 2, he obtained the following results:

Period	Time duration Years
Cenozoic, including Pleistocene.....	2,900,000
Mesozoic	7,240,000
Paleozoic	17,500,000
Algonkian	17,500,000
Archean	10,000,000 (?)

Walcott then states:

"It is easy to vary these results by assuming different values for area and rate of denudation, the rate of deposition of carbonate of lime, etcetera; but there remains, after each attempt I have made that was based on any reliable facts of thickness, extent, and character of strata, a result that does not pass below 25,000,000 to 30,000,000 years as a minimum and 60,000,000 to 70,000,000 years as a maximum for post-Archean geologic time. I have not referred to the rate of development of life, as that is virtually controlled by conditions of environment.

"In conclusion, geologic time is of great but not of indefinite duration. I believe that it can be measured by tens of millions, but not by single millions or hundreds of millions of years."⁵⁰

As a basis for these figures Walcott takes the area of the Cordilleran sea as 400,000 square miles, the area of Cambrian drainage into it as 1,600,000 square miles, a minimum thickness of Cambrian mechanical sediments below the Upper Cambrian as 10,000 feet, a rate of erosion of

⁴⁹ C. D. Walcott: Geologic time, as indicated by the sedimentary rocks of North America. Smithsonian Report for 1893, pp. 301-334, 1894; Jour. Geology, vol. III, 1893 pp. 639-676.

⁵⁰ Jour. Geology, vol. I, pp. 675, 676.

one foot in 200 years and a deposition rate of one foot in 50 years. This rate he regards as more probable than slower ones, "in view of the evidence of rapid accumulation contained in the strata themselves." These basal assumptions give 500,000 years for the 10,000 feet of strata.⁵¹

"In dealing with the post-Middle Cambrian mechanical sediments we have a somewhat different problem, but, as a whole, rapid deposition is indicated. For instance, the Eureka quartzite of the Upper Ordovician is a bed of sandstone, varying from 200 to 400 feet in thickness, distributed over a wide area—perhaps 50,000 square miles. It is made almost entirely of a white, clean sand that was deposited in so short an interval that the Trenton fauna in the limestone beneath it and in the limestones above it is essentially the same. The sand appears to have been swept rapidly into the sea and distributed by strong currents. The same is true of the 3,000 feet of the Lower Carboniferous sand and the 2,000 feet in the upper portion of the Carboniferous, while the shales of the Upper Devonian accumulated more slowly. In this connection we must bear in mind that during the long periods in which the calcareous sediments forming the limestones were being deposited the tributary land areas were in all probability baselevels of erosion, and chemical denudation was preparing a great supply of mechanical material that, on the raising of the land, was rapidly swept into the sea and distributed. In this manner the time period of actual mechanical denudation was materially shortened, yet, on account of the manifestly slower deposition of the Devonian shales, the rate of denudation should be assumed as less than during Cambrian time.

"In post-Cambrian time the area of the land surface was materially reduced by subsidence, which did not, however, greatly extend the Cordilleran sea, and it may fairly be estimated at 600,000 square miles. The depth of mechanical sediments already estimated is 5,000 feet and their volume at two billion mile-feet. Dividing the volume by the area of erosion, we get 3,300 feet as the depth of erosion required.

"Again, applying different rates of erosion, with allowance for slow progress of degradation during Devonian time, we have:

"Post-Cambrian mechanical Sediments

Rate of erosion over land area of 600,000 square miles.	Time required for re- moval of 3,300 feet.	Rate of deposition in sea of 400,000 square miles for 5,000 feet of strata.
1 foot in 3,000 years.....	9,900,000 years.....	1 foot in 1,980 years, or .006 inch per annum.
1 foot in 1,000 years.....	3,300,000 years.....	1 foot in 660 years, or .09 inch per annum.
1 foot in 200 years.....	660,000 years.....	1 foot in 132 years, or .18 inch per annum.

"The rate of one foot in 200 years is assumed as the most probable and 660,000 years as the time required for the removal and deposition of the 5,000 feet of post-Cambrian mechanical sediments."⁵²

⁵¹ Loc. cit., p. 663.

⁵² Loc. cit., pp. 664, 665.

In discussion of Walcott's statements it may be said that, according to his view previously cited, the rate of development of life is controlled by conditions of environment and can not by itself be used very securely as evidence for the shortness or length of time needed for the accumulation of a formation.

The argument has been stated in Part I that a peneplain is not a favorable land surface for the promotion of deep chemical denudation, and can hardly be invoked with safety in aid of a postulated rapid accumulation of sediment. The cleanness of a sand formation, on the other hand, speaks of prolonged sorting and is favored by fill and scour, pronounced wave or current action, and, notwithstanding the rapid accumulation of individual beds, may be accompanied by a slow aggregate rate of accumulation. Thus the principles of rhythms are of peculiar force in such a deposit.

With the conditions of low relief of the land a rate of erosion of one foot in 3,000 years seems more probable than one foot in 200 years. Even this is twice the present rate of erosion for the Mississippi basin, and about three times the rate given by Clarke for the present mean of the continents. It is probable, however, that the retarding effect of land vegetation was not then effective, so that a fairly rapid rate of one foot in 3,000 years for the low lands of the early Paleozoic may be provisionally accepted. But even this low rate gives a length of time fifteen times that regarded by Walcott as the more probable.

On the other side of the question, it may be said that if the mechanical sediments were derived from the unconsolidated deposits of an uplifted coastal plain, the rate of denudation of rock becomes immaterial in the making of the final formation. The unconsolidated deposits may be washed off almost as fast as uplift of the plain occurs, and deposited as fast as subsidence of the sea-floor permits. The time required to develop the original clastic material depended, however, on the rate of rock denudation. The time represented by the final and permanent accumulation of 10,000 feet of clastic sediments may consequently be short or long, according to the rate of crust movements, but with the probabilities in favor of millions, or tens of millions, rather than hundreds of thousands of years.

As a basis for estimating the time needed for the deposition of the Paleozoic limestones of the Cordilleran sea, Walcott takes the quantity as amounting to an average thickness of 2,250 feet over an area of 400,000 square miles. The calcium carbonate can not be regarded as derived only from the tributary land drainage, since the epeiric sea was in communication with the open ocean. The estimate must rest, then,

upon many uncertain factors. Walcott, as the result of his discussion, estimates the area of Paleozoic lands supplying calcium to all the seas as 50,000,000 square miles, approximately the present land area of the globe. The area of ocean now accumulating calcareous oozes he takes as 52,500,000 square miles. The area of the Paleozoic epeiric seas in which lime accumulated he takes as 13,000,000 square miles, giving a total of 66,000,000 square miles as the total area of deposition at that time.⁵³

"The area over which calcareous depositions was going on during Paleozoic time we have estimated at 66,000,000 square miles, which included the areas of the seas over the continental platform and those of the surrounding oceans. As the conditions appear to have been more favorable for the deposition of lime in the Cordilleran and Appalachian seas, we will assume that it was four times that of the open ocean.⁵⁴ With a land area of 50,000,000 square miles (*ante*, page 670) and a rate of chemical denudation of 70 tons per square mile per annum, the total calcium contributed to the ocean per year during Paleozoic time would be 3,500 million tons, or 3.78 times as much as that estimated for per annum at the present time, which is 925,866,500 tons (*ante*, page 668). This would have provided 50.7 tons for deposition per annum per square mile in the 65,000,000 square miles of ocean and seas and 202.8 tons for deposition per annum per square mile in the 400,000 square miles of the Cordilleran and 600,000 square miles of similar seas. On this basis 81,120,000 tons (36.4 mile-feet) were contributed per annum from the ocean water to the deposit in the Cordilleran sea; adding to this the 42,000,000 tons (18.8 mile-feet) contributed per annum by the denudation of the surrounding area to the Cordilleran sea, we have 128,120,000 tons (55.2 mile-feet) as the amount available for deposit per annum in the Cordilleran sea. At this rate it would have required 16,300,000 years to have deposited the 2,007,244,800 million tons (900 million mile-feet) of calcium in the Cordilleran sea; adding to this the 1,200,000 years estimated for the deposition of the mechanical sediments, we have a total of 17,500,000 years as the duration of Paleozoic time.

"In the estimate for the amount of chemical denudation the largest average is taken—70 tons of calcium per square mile per annum—and the assumption made that all calcium derived from the adjoining drainage was deposited within the Cordilleran sea. Again, the total supply provided per annum to ocean waters of Paleozoic time is taken as 3.78 times greater than the amount annually contributed to ocean waters today; of this, four times as much is assumed to have been taken out per annum per square mile as was taken by the remaining area in which calcium was being deposited.

⁵³ Loc. cit., pp. 670, 671.

⁵⁴ Under the reduction of 50 per cent for the interbedded and intermingled mechanical sediments and 25 per cent for other material than calcium deposited from solution, the apparent amount of calcium deposited in the Cordilleran sea was greatly reduced. If this same ratio of reduction is applied to other Paleozoic limestone areas, I doubt if over 1,000,000 square miles will be found to contain as large an average amount of calcium per square mile as the Cordilleran area. On this account 1,000,000 square miles is the area taken for the greater rate of deposition of calcium during Paleozoic time.—C. D. W.

"The area of the Cordilleran sea is given as 400,000 square miles, but it was probably 600,000, if not much more. It may be claimed that the area tributary to the Cordilleran sea was greater than I have estimated. The evidence, such as it is, is against such a view. As a whole, I think the estimate of 17,500,000 years for the duration of Paleozoic time in the Cordilleran area is below the minimum rather than above it."⁵⁵

In discussing Walcott's results it should be noted first that Reade's estimate of 70 tons of calcium salts as the denudation rate per square mile per year for the globe consists of 50 tons calcium carbonate and 20 tons calcium sulphate. Clarke, on the basis of much better data, concludes that these figures are almost twice too large.⁵⁶ Instead of choosing a larger rate of supply to the ocean than the present, it would seem that it would be better to assume it as far lower. In Part I of this article reasons have been advanced for holding that the average relief of the Paleozoic was very low and the land areas suffering erosion were restricted. On this basis Walcott's results might be multiplied by five or ten.

As to the rate of deposition, Walcott makes no allowance for intervals of non-deposition. At the time he wrote it was generally believed that the Paleozoic seas reigned continuously throughout that era, but with somewhat progressively restricted areas. He was in advance of his time in showing that in the Lower Cambrian the continent was largely emerged, but there was not as yet any knowledge of the many discontinuities which represent shorter and longer times of no record. The discontinuity of these Paleozoic water bodies is indicated on Schuchert's paleogeographic maps of successive epochs of the Paleozoic. A total of 36 maps is given for the Paleozoic. On five Schuchert shows no Cordilleran sea whatever. On 11 others it has but slight representation, the region of more permanent water being in Nevada and connecting with the Pacific or southern Atlantic waters.

It is clear that a higher rate of limestone deposition will take place in shallow, warm, and agitated waters; but that is only possible so long as the water is deep enough to prevent bottom-scour. Walcott chose a high rate of deposition of lime for a limited area over the globe, of which he reckoned the Cordilleran sea to be four-tenths, whereas it might perhaps equally well have been taken as not more than two-tenths of the area of the epeiric seas. The actual rate of deposition as controlled by the amount of subsidence was something less than this possible rate.

⁵⁵ Loc. cit., pp. 672, 673.

⁵⁶ F. W. Clarke: A preliminary study of chemical denudation. *Smithsonian Misc. Coll.*, vol. 56, no. 5, 1910, p. 5.

We may conclude consequently that because of times of non-deposition, because of partial limitation of deposition by lack of subsidence, and because of a less ratio of the Cordilleran sea to the total epeiric seas, the time involved may have been five or ten times longer than the time calculated by Walcott. Combining this with the reduction in the estimates of rates previously discussed, the total time is multiplied by the product of these corrections. The 16,300,000 years given by him as the estimate for the time needed for the deposition of limestones is clearly far too short. It might be multiplied by ten, twenty, or thirty to give the duration of the whole Paleozoic. A twenty- or thirty-fold multiplication would accord more closely with the estimates given by the uranium minerals, to be discussed later.

Attention should next be given to the estimates of geologic time made by Sollas, using the method advocated by Haughton—that the proper measure of the length of the successive periods is given by the maximum thickness of strata deposited in them. In 1895 Sollas estimated these thicknesses for the post-Archean to aggregate 164,000 feet, in 1900 he raised the sum to 265,000 feet, and in 1909⁵⁷ to 335,000 feet. The latter figure is distributed among the geological eras as follows: Cenozoic, 63,000; Mesozoic, 69,000; Upper Paleozoic, 63,000; Lower Paleozoic, 58,000; Proterozoic, 82,000; Archeozoic, no estimate.

These maximum thicknesses are deposited in geosynclines which may be taken as deepest in the middle and of a triangular cross-section. He takes a mean rate of denudation for all geological time of one foot in 2,400 years. To get the rate of deposition the drainage into the Gulf of Mexico is used, the drainage area being taken as 1,800,000 square miles and the area of deposition as 100,000 to 180,000 square miles. Sollas assumes consequently the mean deposition area for these thick formations as one-tenth of the erosion area. This gives a mean rate of deposition of one foot in 240 years. But in a triangular section the thickness of the middle is twice the mean thickness. This would give a rate in the region of maximum thickness of one foot in 120 years. But taking the sides of the triangle as somewhat convex upward, Sollas obtains a rate in the region of maximum subsidence of one foot in a hundred years. This gives for the sedimentation of the Paleozoic 12,100,000 years, and for all post-Archean time 33,500,000 years.⁵⁸

In his earlier estimates Sollas made no allowance for the time represented by unconformities, but in his latest work, giving apparently great-

⁵⁷ W. J. Sollas: Anniversary address of the president, Geol. Soc. London. *Quart. Jour. Geol. Soc.*, vol. 65, 1909, pp. lxxxviii-cxxii.

⁵⁸ W. J. Sollas: *The age of the earth and other geological studies*, 1905, pp. 36-38.

est weight to the age of the earth as 80,000,000 years, based on the sodium content of the sea, he grants from 23,000,000 to 29,000,000 years for unconformities. By assuming Precambrian time to have been as long as later time, his total estimate from sedimentation is raised to the desired total of 80,000,000 years.⁵⁹ According to these estimates, the Paleozoic era was about 25,000,000 years in duration.

In discussing Sollas' results, the first point to be noted is the rate of denudation chosen—one foot in 2,400 years. This is more than three times as rapid as the present mean for the whole earth determined by latest measurements, and more than twice as rapid as the rate of denudation for the Mississippi drainage basin, which, except for the Colorado, is given by Dole and Stabler as the highest of the twelve large drainage divisions of the United States. In defense of choosing such a high rate, it may be said that the maximum thicknesses in geosynclines have come especially from bordering uplands or mountains, but on the other hand these mountains were rapidly reduced in slope, long periods of quiet and low relief intervened between uplifts, and the average slope for the Paleozoic was certainly but a fraction of the present high reliefs. Instead of taking a mean rate of denudation as one foot in 2,400 years, the present mean rate might better have been taken, or the present rate might have been even divided by two, giving a denudation rate of one foot in 8,000 to 16,000 years—limits somewhat less than one-third to one-sixth of that which he used.

Sollas speaks of the coarseness of the geosynclinal deposits as proof of rapid deposition; but these coarse beds are only occasional, and the great bulk of the deposits are such as would have been carried by streams of gentle grade.

Turn next to his fundamental assumption of one to ten as the ratio of the deposition area to the denudation area. Instead of making careful estimates from many streams and comparing these to the geographic relations implied by the geosynclines, the Gulf of Mexico drainage is chosen offhand as a sufficient basis. It is doubtful if a poorer illustration could have been found; as is seen when it is noted that now, in a time of abnormal continental relief, the Mississippi and other streams gather together the waters and the waste from the broad interior and high mountainous tracts of a continent and converge it radially into a Mediterranean sea, the Gulf of Mexico, where the deposition is mostly on the slopes of a continental terrace.

The thick formations of the past are not deposits of the continental

⁵⁹ Quart. Jour. Geol. Soc., vol. 65, 1909, pp. cxlii-cxv.

terrace, but are revealed by the erosion of compressed and folded troughs. These lay on the sides of ancient mountain systems facing the continental interiors. These geosynclines were great downwarps which were parallel with and related to great upwarps, the geanticlines. The latter supplied the bulk of the sediments which filled up the troughs. The continental interiors, on the whole, added little or nothing to them, since especially in the Paleozoic they were often the seats of shallow seas which received sediment carried across the geosynclines from the uplands. If waste was sometimes washed back into the geosynclines its ultimate source was nevertheless in greater part the mountainous uplands on the other side. Following the views of Suess, the geosynclines are to be looked on as genetically related to the geanticlines; the mountain ranges depress the forelands or foredeeps and the waste from the mountains is washed into these parallel troughs.

The best present illustrations are found in association with the great Eurasian mountain systems upraised in the Neocene. The valley of the Po with the northern half of the Adriatic show filling by waste from the Alps and Apennines. The plains of Mesopotamia and the Persian Gulf constitute the catchment basin for the associated mountains. The Indo-Gangetic alluvial plains and deltas lie in front of the Himalayas. On examining the maps of such regions it will be found that the area of deposition instead of being one-tenth of the area of drainage, as assumed by Sollas, is approximately equal to it. The sediments of the geosyncline represent a mountain system eroded and inverted.

In times of low relief, however, the proportion of waste brought in from a distance might increase. Assume, then, that the waste of the geosyncline was derived on the average from a land of twice its area. Take the mean rate of denudation as between one foot in 8,000 years and one foot in 16,000 years. Using the other conditions regarding the shape of the geosynclinal prism as postulated by Sollas, the rate of accumulation of the maximum thickness becomes one foot in 1,650 to 3,300 years. Introducing an appropriate ratio for the times of non-deposition, it is seen that Paleozoic time may be anywhere from fifteen to thirty times as long as the estimate given by Sollas.

This rate of accumulation may seem intolerably slow to those used to thinking of sediments as rapidly deposited, as seen by the testimony of their structures. In reconciliation it should be pointed out that the principles developed under composite rhythms in Part II go to show that individual beds may be deposited with great rapidity as determined by the fluctuation of atmospheric and hydrospheric forces, and yet the formation can accumulate no faster than sediment is supplied by the mean

rate of denudation. It will ordinarily accumulate more slowly, as shown by the maintenance of a baselevel surface of deposition, with its implication of the control of sedimentation by the slowness of subsidence.

The mean rate of subsidence in a geosyncline has apparently been such that a fairly large fraction of the mechanical sediment has been caught in it. This is shown by the frequent passage of shales into limestones within or beyond the bounds of the geosynclines. On the other hand, at the times of greatest diastrophism and continental emergence an unknown quantity of waste has been carried to the margins of the continental terrace and lost to observation. We may regard, then, as safe, a conclusion that the Paleozoic era was several hundred million years in length.

Notwithstanding the inexact nature of the total of geologic time as determined by the study of erosion and sedimentation, this line of attack will be valuable for estimating the relative duration of the different periods, the times and the totals being checked by some other and more exact method.

A few geologists have perceived the untenable nature of the assumption that denudation and sedimentation have progressed in the past at the present rate. Some have not published their views specifically. Those who have indicated this opinion in published articles which have come to the writer's attention are E. C. Andrews,⁶⁰ A. Holmes,⁶¹ and A. Harker.⁶²

In conclusion should be mentioned Goodchild's estimate, based on a detailed discussion of the stratigraphic sequence. He obtained 704,000,000 years since the beginning of the Cambrian, 93,000,000 being given to the Tertiary, 236,000,000 to the Mesozoic, 375,000,000 to the Paleozoic.⁶³ He reached these large figures by taking the rate of deposition of sandstone as one foot in 1,500 years; shales, one foot in 3,000 years; limestones, one foot in 25,000 years. He also considered the significance of unconformities. Goodchild, however, did not take into consideration many possible factors, such as the rhythmic nature of sedimentation and its ultimate control by subsidence; so that his estimate doubtless appeared to differ from others by a mere preference for the longer periods of time and in apparent conflict with the clear evidence of the rapid accumulation of individual beds. There is, however, much of value in his detailed discussion, and his results, published before the first estimates based on radioactivity, are in notable accord with those reached in the present study.

⁶⁰ E. C. Andrews: Erosion and its significance. *Journal and Proc. of the Roy. Soc. of New South Wales*, vol. xiv, p. 132; read Aug. 2, 1911.

⁶¹ Arthur Holmes: *The age of the earth*. London and New York, Harper Bros., 1913.

⁶² A. Harker: *Geology in relation to the exact sciences, with an excursus on geological time*. *Nature*, March 25, 1915.

⁶³ J. G. Goodchild: Vice-president's address, Nov., 1896. *Proc. Royal Physical Society of Edinburgh*, vol. xiii, part 3, 1897, pp. 259-308.

The lack of notice given to his paper seems to have been due to a lack of that conclusive demonstration which is needed to force attention to a view not in accord with the times.

ESTIMATES OF TIME BASED ON RHYTHMS IN SEDIMENTATION

Through all of earth history the existence of a solid crust requires that, no matter how effective as a heat retainer is the atmosphere, the maintenance of the atmospheric and hydrospheric envelope in gaseous and fluid form has been due to solar energy, and not in any appreciable degree to heat derived from the earth. The solar heat is now and always must have been delivered in largest quantity to the equatorial zone and in small amount to the polar regions, yet the circulation systems are so efficient that even in this age of polar ice the temperature of the polar night falls only a little way comparatively toward absolute zero. The circulation system which spreads out the heat is kept in motion by the loss of heat in higher latitudes and the latitudinal difference in temperature which results. During most of geologic time the efficiency of the circulation system was so high that relatively small differences of temperature sufficed to maintain it.

But the spread of solar energy by means of the circulation systems from low to high latitudes and from seas to inland regions must always have been rhythmic. This is a very general condition, where speed of flow is limited by the resistances which are set up. In the irregularities of motion the flow seeks that direction where the resistances are temporarily lessened; increasing in speed, the resistances are increased until they in turn overcome the inertia of the motion. As a result, a cyclic damping of the flow is produced in the one place or time with a corresponding acceleration in another. Thus the flow of energy proceeds in pulses. The cyclonic storms of the temperate zones and the blizzards of the polar ice-caps illustrate short-term rhythms of this nature. The shifting of storm tracks and runs of similar weather may represent oscillations in equilibrium of longer term due to such terrestrial conditions. Such pulses may be classified as terrestrial climatic rhythms.

But similar laws of oscillation control the liberation of energy from the sun. To maintain its surface temperature, convective movements must stir its mass, actuated by loss of energy, manifested by cooling and condensation at the surface, renewed by the transformation of other modes of energy into thermal form at depth.

To begin with short-term rhythms and passing to those of longer term, a rhythm has been detected in the change in the frequency of solar prominences in a period of about three years.

The sun-spot cycle with an average length of 11.4 years is well known. Newcomb and others have recognized a slight effect in the mean annual temperatures, and Huntington and Douglass have shown that it finds terrestrial record in certain regions by fluctuations in the growth rate of trees.⁶⁴ The variation in time of culmination of sun-spots is, however, considerable, from 7 to 16 years, and the climatic effects are slight, the geological effects perhaps negligible.

Brückner detected a cycle of 35 years in the variations of glaciers and in the level of the Caspian Sea—a rhythm which has since been found to have its origin in the sun and corresponds nearly to three of the sun-spot cycles.⁶⁵

The work of Douglass has brought to light a 21-year cycle in rainfall and tree-growth in Arizona, and less definitely a larger cycle of about 150 years.⁶⁶

H. W. Clough, from the evidence contained in the catalog of early observations of sun-spots and auroras, compiled by Fritz, holds there is evidence extending back to about 300 A. D. of a solar cycle of about 300 years in length.⁶⁷

As to the existence of long-term changes of climate during historic time, investigators as yet are not agreed. There are those who hold, from the distribution of crops and the dates of harvest, and from the freezing of rivers and harbors, that no appreciable change has taken place. This appears to be nearly true for the past thousand years, in so far as a regular or progressive change of climate is concerned; but the evidence seems to be good that within that time there have been centuries which departed appreciably from the mean. On comparing the conditions previous to the dark ages with later times, however, more notable changes begin to appear. These have been investigated in recent years chiefly by Huntington, and, although there are those who do not accept the results, the evidence in many respects seems to the present writer compulsory in its nature.

Huntington concludes from several methods of attack, but chiefly from the degree of habitability of arid lands, that the climate of such critical regions has varied notably and repeatedly during the historic period. Such changes might pass undetected in the regions of equable rainfall and temperature, except by means of precise scientific observations, but

⁶⁴ E. Huntington: *The climatic factor*. Carnegie Institution of Washington, 1914, Publication No. 192.

⁶⁵ W. J. S. Lockyer: *The solar activity, 1833-1900*. Proc. Royal Soc., vol. 68, 1901, pp. 285-300; *Nature*, vol. 64, 1901, pp. 196, 197.

⁶⁶ Huntington: *Loc. cit.*, p. 117.

⁶⁷ *Astrophysical Journal*, vol. xxii, 1905, pp. 42-75.

in semi-arid to arid regions the oscillations change to a large degree the quantity of life which can exist and compel the rapid migration of faunas. Such changes find geologic record through their effects on the carrying power of streams and the depth of wave action. There have been important fluctuations measured in centuries, and still more important ones which cover several thousand years. They appear, however, to be rather sudden and irregular in their inception. According to Huntington, the climate through the primitive historic era, dating from 3,000 + B. C. to 1,200 B. C. was on the average markedly cold and wet, but still showing oscillations. During the period from 1,000 B. C. to 500 A. D. there was a decrease in these conditions, and from 600 A. D. to the present there has existed a period of general warmth and aridity.⁶⁸

The work of Huntington joins on to that of the glacial geologists. Periods measured in centuries and in some thousands of years should find notable expression in glacial oscillations and result in the building of retreatal moraines. These climatic oscillations during the historic period are geologically of importance, in that they show the existence of such rhythms which are not due to the precessional period of 21,000 years, but which, if found recorded in the strata, might have been mistaken for it.

F. B. Taylor has published a valuable study on the moraines of recession which marked the retreat of the last ice-sheet from the Ohio River to the Great Lakes.⁶⁹ According to Taylor:

"1. Between Cincinnati and Mackinac the Wisconsin drift formation has fifteen terminal moraines which form a consecutive series marking the retreat of the last ice-sheet, and there are three more farther north probably belonging to the same set. The series seems to be complete and is believed to constitute the simplest and most perfect known.

"2. Making due allowance for the influence of topography, it appears that the intervals between the members of the series are remarkably regular, suggesting periodic halts or oscillations of the retreating ice-front, which appear to be attributable only to a periodic change of climate."⁷⁰

Taylor tries to fit the series to the precessional cycle, as the only known cause, but finds 21,000 years too long. He states that a period of between 5,000 and 10,000 years would seem to accord most closely with the phenomena.

In Europe the retreat of the last ice-sheet was marked by three greater halts. These, beginning with the maximum, are as follows:

⁶⁸ E. Huntington: *Palestine and its transformations*, chap. xvi, 1911.

⁶⁹ Moraines of recession and their significance in glacial theory. *Jour. Geol.*, vol. v, 1897, pp. 421-465.

⁷⁰ *Loc. cit.*, p. 464.

Depression of snow-line	Alpine stages	Scandinavian moraines
1,200 meters	Würm	
900 "	Bühl	Baltic
600 "	Geschnitz	Ra
300 "	Daun	Christiania Valley

Time from the Bühl stage has been estimated at from 16,000 to 24,000 years, with the probabilities in favor of the longer period. Time from the outer Ra moraine has been more closely estimated at 17,000 to 18,000 years. Time since the last stage is as much as 7,000 years. Minor retreatal moraines lie between these stages. There seem to be here a combination of two cycles, perhaps both irregular, the cycle discussed by Taylor having a mean period of 2,000 or 3,000 years, the other with a mean period perhaps as large as 10,000 years. In the interior of the North American continent the shorter of these cycles has left a more prominent record; on the northwestern shores of Eurasia the longer is the more conspicuous. Such a difference in emphasis of cycles of different periods in different regions is paralleled by what is known of the expression of the shorter climatic rhythms acting in recent times. The climate of the interior of North America is controlled by continental conditions; that of northwestern Eurasia by oceanic, especially by the nature of the Gulf Stream.

Changes up to this order magnitude are more readily ascribed to cycles in solar radiation than to other causes. Volcanic dust in the terrestrial atmosphere acts as a screen, but it is probably too sporadic and temporary in occurrence to lead to such periodic changes in climate. Furthermore, certain highly volcanic epochs, such as the Eocene and Oligocene, have been marked by warm and equable climates over high latitudes. In addition, the rather regular and pronounced climatic oscillations in the Pleistocene are not known to have been related to rhythmic outbursts of volcanic energy.

Changes in atmospheric composition or in crust movement are too slow and massive to be invoked for such changes as have been discussed, but are the probable causes in determining the character of geologic periods, as is shown by the concurrence of glacial climates at the culmination of periods of continental movement and revolution. The sharp oscillations of decades, centuries, and thousands of years in length may be classified as solar climatic rhythms; the long, slow, and massive movements, rhythmic in their character, as diastrophic climatic changes.

There is another class of recurrent changes most important for the measurement of time. These may be called orbital rhythms, depending on the motions in the solar system. They are familiar as the rhythms

of the tides, of day and night, of the year, of the precession of the equinoxes, and of eccentricity of the earth's orbit.

Of these, the tides act as geological agents on embayed shores and in straits, but are too rapid in occurrence to leave, except rarely, a record of individual ebb and flow.

The alternation of day and night serves as an important geological agent in producing a rapid and marked rhythmic recurrence of temperature changes.

The temperature rhythm of the seasons is now felt in all but a few parts of the earth, and outside of the tropics enters strikingly into the nature of geological processes. Even the year, however, is too brief a space of time to find stratigraphic record except in special cases, the most notable perhaps being in the annual rhythm of clay and silt laid down on the bottoms of lakes, especially those which face glaciers and receive during the melting season an abundant supply of waste. One of the most striking facts of geologic history is, however, the absence of freezing cold through most of geologic times in middle and high latitudes. Celestial mechanics points with certainty to a fixity of the poles and a constancy in their inclination to the orbit of the earth. There must always, therefore, have been seasons of darkness in the polar zones and of diminished solar heat in middle latitudes. But in spite of this the testimony of fossils points to the general absence of severe cold or frost. At times of glaciation, however, evidence is found of marked seasonal changes in such latitudes, as in the banded argillites of Permo-Carboniferous age found by Sayles near Boston, Massachusetts, and in the Precambrian banded argillites found in Ontario and in Sweden. It seems that in periods of glacial climates there is an emergence of winter. Winter, furthermore, must always have been present in continental interiors of higher latitudes as a season of more or less cold, especially whenever the climate was semi-arid or arid. The fur of mammals and the feathers of birds probably find their development in a more prevailing existence of seasonal change over the continents of the Mesozoic era than has been suspected from the biologic record of marine waters and of coal swamps. In sediments of fairly rapid accumulation the record of the seasons may have been somewhat more widely kept than is suspected. In all semi-arid continental deposits the recurrence of waters has probably had a seasonal basis. Generally, however, it is clear that the annual rhythm does not enter into the stratigraphic record, both because it is too rapid and has been too generally submerged. Even in the deposits of semi-arid fluvial basins the strata are the result of far longer and deeper rhythms.

The oscillations of day and night, of summer and winter, have been of fundamental importance, however, not in stratigraphic record, but in the manner in which they have stamped their existence in the life rhythms of organisms. In a little perceived, but even more fundamental way, the diurnal and annual rhythms have been essential to evolution. They have hardened the endurance of plants and animals to changes of temperature and to the dangers of night and winter. From this ever-recurring annealing process organisms have acquired the power of adaptation to the longer rhythms of climatic change, and thus have been able to emerge sifted and improved from the climatic stress of critical periods.

The higher rhythm of precession has a mean period of 21,000 years, from which it may vary by about 10 per cent. It brings in no climatic change except by virtue of the eccentricity of the earth's orbit. Croll has made it familiar by his attempt to apply it as a cause of glaciation, but the lack of accord with the history of the glacial period, as it is now understood, has caused it to be generally discarded. Nevertheless, at times of high eccentricity of orbit it remains true that at one phase of the rhythm the summers in one hemisphere will be somewhat shorter and hotter, the winters somewhat longer and colder. The reverse effects will be felt at the same time in the opposite hemisphere. Every 10,500 years the relations of the hemispheres will shift, and thus a change in the character of the climate will be felt 21,000 years in length. The only question is: Can it rise to visible expression above the various other solar and diastrophic rhythms which are seen to have entered into the climatic oscillations of the Pleistocene and presumably extend backward with various expressions through the earlier periods?

The only rhythms which, because of their certain existence and unchanging length, are adapted to the measurement of geologic time are the regular orbital rhythms. The terrestrial and solar climatic rhythms are apparently too numerous and too irregular in period to serve as safe measures of time. Furthermore, in one region and at one time one rhythm may dominate, as the 21-year cycle in Arizona, and in another place or time another rhythm, such as that of the 35-year cycle in glacial advance and retreat. The oscillations which occur in centuries, in thousands of years, and in tens or hundreds of thousands of years are best adapted to be stratigraphically recorded; but their discrimination, their persistence, their regularity, and their mean period are all open to serious question.

Even if the precessional rhythm can be distinguished it can not bridge unconformities and in most formations surely does not appear; but if from time to time we can detect in the strata under favored conditions

the beating of the precessional clock, valuable clues may be obtained as to the length of time required for the deposition of certain formations. It should be looked for under conditions where seasonal changes might be expected to affect the vegetation, the regimen of rivers, or the intensity of wave action in shallow seas. Such conditions are suggested in middle or higher latitudes, where temperate faunas and floras exist or where the deposits indicate the existence of a semi-arid climate. The evenly bedded fine-grained deposits in lagoons or on the floors of shallow seas would be more favorable than the irregular bedding of river plains. The deposits of lake bottoms or of fore-set slopes, or of sea-floors temporarily below wave-base, are perhaps the most favorable situations. Transition regions between two facies are most favorable, as where sheets of lime and clay sediments are interfingered. In such places a slight shifting of climatic factors is recorded by a more or less wide shifting of the border line between the facies. The shallow limestone seas of the earlier periods should be examined, for they show a marked oscillation in bedding, changing conditions in salinity, and varying turbidity of shallow waters.

To reach a conclusion an exposure should be extensive. The proof would be to find a thin lamination marking an annual rhythm gathered into higher rhythms, and these into still higher but fainter groupings, so that a restoration of the annual layers would aggregate about 20,000 in one of the larger and fainter groupings. This may seem difficult to attain, and a more favorable, but less conclusive, recognition of the precessional cycle may be sought in beds which probably represent each several centuries or some thousands of years, grouped into regularly recurring but faint rhythms, which shall comprise some tens rather than units or hundreds of the lesser beds. There may have been times, however, when the flow of solar energy was so smooth that the precessional rhythm could emerge into control and find stratigraphic expression. It would be marked by great regularity, but other rhythms may, however, rise into recurrent dominance and exhibit for a time a marked regularity, so that caution in identifying rhythms must be ever present.

The possibility of measuring the time of accumulation of strata by means of climatic rhythms has been dealt with rather fully, since notwithstanding the lack of definite results thus far obtained, it seems to contain large possibilities and should lie in the background of the mental vision ready to be invoked.

Many stratigraphic sections show notably regular rhythms in the alternations of beds. A few of the more conspicuous and regular may be cited.

Two remarkable formations, the Sausalito and Ingleside cherts, occur in the Franciscan group of probable Jurassic age.⁷¹ The former is about

⁷¹ See A. C. Lawson: San Francisco Folio, U. S. Geol. Survey, No. 193, 1914.

900 feet thick in the San Francisco region and the latter about 530 feet. They are preceded and succeeded by thick sandstone formations and are separated by the Marin sandstone, 1,000 feet in thickness. The two chert formations consist of sheets of chert alternating with partings of shale. Lawson describes these formations and their conditions of deposition as follows:

"The thickness of the sheets of chert in the typical sections generally ranges from about 1 to 3 or 4 inches, averaging perhaps 2 or 3 inches. Some beds are much thicker, but the sections of the chert nevertheless in general show thin and even bedding. The shaly partings between these sheets usually range from about one-eighth to one-half inch in thickness, but many of them are mere films. As the formations are in some places exposed in sections that are several hundred feet thick, they present the remarkable phenomenon of an alternation of thousands of layers of chert, with as many layers of shale. In the common red phase of the formations the regularity of this thin-sheeted stratification is amazing. In other phases, in which red iron oxide is not so abundant, the regularity is much less marked and the sheets assume lenticular forms."⁷²

"On a smooth surface of almost any specimen of these cherts a lens will reveal minute round or oval dark, hyaline, or whitish dots. These dots, which are scattered through the rock, prove on microscopic examination to be the remains of Radiolaria, the characteristic fossils of these formations. The Radiolaria are minute animals that thrive in sea-water and secrete siliceous skeletons of very complex structure. These skeletons evidently accumulated in great numbers on the floor of the sea while the radiolarian cherts were being deposited and thus contributed to their formation. As a rule, they are sporadically embedded in the siliceous matrix above described, but in some places they are so closely crowded as to constitute the greater part of the chert. Where the Radiolaria are scantily distributed through the chert it is uncertain whether or not the matrix also is derived from these organisms, and the alternative hypothesis that it was formed by the purely chemical precipitation of silica, supplied possibly by submarine springs, is worthy of consideration. If the silica is wholly of organic origin it must have been dissolved and reprecipitated in its present form as an ooze on the sea-bottom.

"As subsidence proceeded the detrital material washed from the receding shore again failed to reach the region and organic agencies once more resumed sway. This time, however, calcareous organisms were replaced by those which secrete silica from the sea-water, so that the sea-bottom was covered with radiolarian ooze, which eventually consolidated as the Sausalito chert. The rhythmical oscillation of conditions which produced the remarkable alternation of layers of chert and shale in this formation has not yet been explained, but was probably due to alternating conditions in the sea-water which affected or interrupted the swarming of radiolarian life. The accumulation of this radiolarian ooze was stopped by a recurrence of the shallowing of the sea and the return of the shore to a line sufficiently near to insure the deposition of

⁷² Loc. cit., pp. 5, 6.

sands upon the siliceous deposits. These sands now form the Marin sandstone. After this sandstone had accumulated to a thickness of about 1,000 feet the subsidence of the sea-bottom, which had been in progress during the period of its deposition, caused the shore again to retreat so far that the conditions became once more favorable to marine life and another deposit of radiolarian ooze was laid down. This ooze formed the Ingleside chert. Again uplift set in, shallow water prevailed, the shore was close at hand, and the sands of the Bonita sandstone were deposited."

These cherts would seem to be deposits made below wave-base, and although the rhythm is probably due to shiftings of currents, this in turn has doubtless a climatic cause. The rhythms are apparently, however, too numerous within a limited geological time to be due to the precessional cycle, even for the long estimates of time given by radioactivity. They suggest, therefore, the presence in the Jurassic of solar rhythms similar to those of the Pleistocene, but in a period of wide-spread equable climates.

Gilbert⁷³ has called attention to a notably regular alternation of strata, recurring four times in the section of the Cretaceous exposed in the basin of the Arkansas River near the Rocky Mountains. This is found in the shales of the Benton, Niobrara, and Pierre groups, totaling 3,900 feet in thickness. The pronounced rhythm is seen, however, in only a small proportion of the total thickness.

The rhythm of shale and limestone is 1.5 feet thick where the principal deposit is limestone, and repeats itself every 2.7 feet where the calcareous material suffices only to modify an otherwise argillaceous shale. Allowing a somewhat more rapid rate of accumulation for the more uniform and non-calcareous portions of the series, Gilbert takes 4 feet as an estimate for the time interval of the rhythm through the whole 3,900 feet. The only regular rhythm of sufficient length known to Gilbert at that time was the precession cycle of 21,000 years, which gives what would generally be regarded as the excessive estimate of 20,000,000 years as the length of this part of Cretaceous time.

The Tertiary rests in this region unconformably on the Pierre, but elsewhere the Fox Hills formation of sandstone and shale, 250 to 500 feet thick in the Black Hills, overlies the Pierre shale, and above the Fox Hills come the Laramie and associated formations, several thousand feet in thickness and containing unconformities. These sediments, however, were probably more rapidly accumulated. They are the record of the Laramie revolution, marked by the upthrust of mountain ranges and the downwarping of associated basins. The Dakota sandstone lies at the base of the Cretaceous, below the shale series, and varies from nothing to

⁷³ G. K. Gilbert: Sedimentary measurement of Cretaceous time. *Jour. Geology*, vol. III, 1895, pp. 121-127.

several hundred feet in thickness. The 3,900 feet of shale may therefore represent two-thirds or one-half of Cretaceous time, excluding the Lower Cretaceous or Comanche as a separate period. This would give 30,000,000 to 40,000,000 years as the length of the Cretaceous; but, as shown later, this accords in order of magnitude with the estimates of the whole of the Mesozoic era based on radioactivity. If the latter should prove to be sound, it appears not improbable, therefore, that Gilbert has fortunately detected running through the Cretaceous the beating of the precessional rhythm.

Professor Schuchert has told the writer that when Gilbert gave this paper he and Dr. Stanton calculated that it would have taken some 6,000 years at this rate for a large *Inoceramus* to have become buried in sediment. As these large fossils are well preserved in many beds, showing but little solution or worm boring, it seemed at the time a strong argument against such an extravagant estimate of the length of the Cretaceous. The answer, as indicated in the preceding parts of this paper, is that the shells of living or recently dead mollusks were buried rapidly, perhaps in a single culminating storm, by a blanket of wave-stirred mud. During times of slow accumulation the successive generations of shells would be completely destroyed by boring animals, by solution, and by the recurrent wear of wave action. Thus it is characteristic of fossiliferous formations that the fossils occur in thin layers between much thicker unfossiliferous beds. Within the layer the shells are commonly well preserved, though often showing a disturbance by wave or current action. The preservation of fossils is, then, following this view, generally due to the recurrence of culminating storms at long intervals, which, stirring the bottom to unusual depths, suddenly bury a layer of organic debris beneath a protecting mantle of argillaceous or calcareous mud.

Such an action seems necessary for the preservation of fossils, even with the current estimates of geologic time. For example, let Cretaceous time be taken as 3,000,000 or 4,000,000 years in length and the burial of a large *Inoceramus* in the muds previously described would, with an even rate of deposition, have required 600 years. This, when tested by their state of preservation, seems to raise difficulties hardly less great than a period of 6,000 years. Generally it would be only the fixed or dead shells which would be entombed by mud blankets deposited by the exceptional storms in the stormy phase of a climatic cycle, but less frequently the deposition of sediment would be so deep and rapid that even the living members of the free bottom fauna would be smothered and buried. As an illustration may be cited the slab of Devonian sandstone

described by J. M. Clarke, which shows starfishes buried while in the act of feeding on bivalve mollusks.⁷⁴

ESTIMATES OF TOTAL TIME BASED ON OCEANIC SALTS

The use of chemical denudation as a measure of geological time began in 1876 with T. Mellard Reade. Joly⁷⁵ has carried forward this method, using the sodium chloride of the ocean, the quantity of which is known with a considerable degree of precision. The chief source of the oceanic sodium is without doubt the lime-soda feldspar of igneous rocks, from which it has been derived by the aggregate weathering and erosion of geologic time.

If the amount of sodium derived annually from igneous rocks and carried to the sea can be determined, and if it be assumed that this rate is a *true mean* for all geologic time, then the age of the ocean is obtained by simply dividing the total sodium by the annual supply. Various corrections have to be applied, however. To obtain the total sodium derived by weathering, the oceanic sodium should have added to it the amount included in the sedimentary rocks, and have subtracted from it the amount derived from juvenile waters, including the original salt, and the amount due to marine denudation. All of these corrections, however, are regarded with considerable assurance as small and would not lead to gross errors if neglected.

The amount contributed by rivers yearly to the sea has been ascertained with reasonable accuracy for representative areas by analysis of their waters. Corrections to this must be made for the amount of sodium chloride which is not derived from igneous rocks, but is borne by the wind or by man from the sea, and also that redissolved from the sedimentary rocks as sodium chloride and originating from the sea. The last correction for chloridized sodium is large and uncertain in amount.

The composition of the average igneous rock is known with fair precision. It contains between 3.4 and 3.9 per cent of soda. In suffering weathering and erosion it retains on the average between 1.3 and 1.4 per cent of its soda, this remaining in the detrital rocks. It loses between 2.10 and 2.5 per cent to the sea.

From the above it is seen that chemical denudation serves to measure the total amount of *igneous* rock which must have been eroded through geological time in order to supply the salt of the sea. Because sediments

⁷⁴ J. M. Clarke: Early adaptation in the feeding habits of starfishes. Jour. Acad. Nat. Sci., Philadelphia, 2d ser., vol. 15, 1912, pp. 113-118.

⁷⁵ Trans. Roy. Soc. Dublin (2), vol. 7, 1899, p. 23; Rept. British Asso. Adv. Sci., 1900, p. 369; Radioactivity and geology, 1909, pp. 233-251.

are uplifted and re-eroded, the total amount of erosion and deposition is, however, much greater than the quantity of igneous rock which has contributed to the salt of the sea. Clarke obtains a volume of igneous rock equivalent to a shell enveloping the earth and ranging from 2,050 to 1,740 feet thick as the quantity necessary to yield the sodium.

It is seen that chemical denudation makes possible valuable estimates of the total erosion of geological time. As a basis for attempting to measure the age of the earth, it is, however, defective only in lesser degree than the methods resting on the measurement of stratigraphic sections. Nevertheless, the method has been used as if it were very exact and conclusive. Consequently a review of the assumptions made by the several investigators on this subject should be given.

Joly assumes that the sodium derived from the sedimentary rocks, mostly as chloride from ancient sea-waters, is equivalent to that derived from similar areas of igneous rocks, so that the rate of annual supply to the sea is the same per unit from sedimentary and igneous terranes. He further assumes a constancy in the supply through all geological time. Both assumptions remove the subject from the realm of exact science to that of vague probability.

Holmes considers, on the contrary, that the evidence points to sodium being supplied by erosion of sedimentary rocks, mostly as chloride, at a higher rate than from equal areas of igneous rocks.⁷⁶ Furthermore, in regard to the rate of denudation, reasons have been shown in this article for holding that it may now be five, ten, or fifteen times higher than the mean for all geologic time. Joly, in one of his later estimates, using Murray's data, obtains an age of less than 150,000,000 years.⁷⁷ Clarke has supplanted Murray's data by more accurate calculations which reduce Joly's estimates to about 90,000,000 years.⁷⁸

Holmes shows how, by varying the mode of using the data, quite different ages may be obtained, still under the assumption of uniform rate. If only river sodium uncombined with chlorine is used as a measure of the annual contributions from igneous rocks to the sea, an age of 180,000,000 years is obtained. Taking the mean rate of denudation as one foot in 8,600 years and the area of igneous rocks, constituting approximately 20 per cent of the drainage areas, as a measure of the new sodium contributed annually, would give an age to the oceans under the hypothesis of uniform rate of 340,000,000 years.⁷⁹ It is seen that the funda-

⁷⁶ A. Holmes: *The age of the earth*, 1913, pp. 68-70.

⁷⁷ *Radioactivity and geology*, 1909, p. 247.

⁷⁸ F. W. Clarke: A preliminary study of chemical denudation. *Smith. Misc. Coll.*, vol. 56, no. 5, 1910, p. 16.

⁷⁹ A. Holmes: *The age of the earth*, 1913, pp. 61-74.

mental difficulties of the method lie, first, in the lack of knowledge as to how much of the present sodium carried to the sea is newly derived from igneous rocks; and, second, as to how the rate of supply compares now with the mean for all geologic time.

The subject should not be dismissed so briefly, however, since the chief publications in American geological literature in the past 10 years on this subject have been those of Becker, and unless the validity of his assumptions is carefully examined, his arguments will appear to possess considerable force. Becker has used Clarke's data as the basis of new calculations,⁸⁰ but introduces two new assumptions into the problem. The amount of sodium in metric tons borne annually to the sea as determined by Clarke forms the basis of Becker's calculations and may be classified as follows:

10.5×10^6 = cyclic sodium, wind borne from the sea.

99.0×10^6 = chloridized sodium of sedimentary rocks.

3.0×10^6 = sodium chloridized by chlorine of igneous rocks.

62.5×10^6 = unchloridized sodium.

175.0×10^6 = total sodium annually borne to sea.

Becker's first assumption is that the *ratio* of total oceanic sodium to total oceanic chlorine, part of which is combined on precipitation with magnesium, potassium, and calcium, though partly ionized in solution, has remained the same throughout geological time. This is contrary to the expressed opinion of others, particularly A. C. Lane, who holds that the ratio of sodium to chlorine was notably less in early geological times, with the consequence that the early ocean waters were relatively rich in calcium chloride. A lesser ratio of sodium chloride to other chlorides is characteristic of the body fluids of marine as well as terrestrial animals and suggests an inheritance of their physiological processes from an early time, when in primitive animals the body fluids more nearly resembled the surrounding medium.

Becker's assumption requires that the annual amount of juvenile chlorine added to the atmosphere from volcanic sources must be equal in number of atoms to the annual supply of new sodium derived from the igneous rocks and dissolved from them mostly as bicarbonate—a postulate which appears to be against the evidence. This permits him to take 32.5×10^6 metric tons away from the 99.0×10^6 tons of chloridized sodium and regard it not as former sea salt, but as new sodium derived from igneous rocks and chloridized in the soil by atmospheric chlorine

⁸⁰ G. F. Becker: The age of the earth. Smith. Misc. Coll., vol. 56, no. 6, 1910.

brought down as rain. As it is the contribution only of new sodium which should enter into the calculation on the age of the ocean, Becker makes up a balance sheet of this annual new sodium as follows:

3.0×10^6 = sodium chloridized by chlorine of igneous rocks.

32.5×10^6 = sodium chloridized by atmospheric chlorine.

62.5×10^6 = unchloridized sodium.

98.0×10^6 = annual contribution of new sodium.

It is seen that his assumption increases the contribution of new sodium by one-half.

Becker's second assumption is that the annual rate of supply of sodium from igneous rocks to the sea has decreased through geological time according to a logarithmic curve. This is made quantitative by various secondary assumptions. He considers that the continents at the beginning had the same area as at present, and then consisted entirely of igneous rocks. The mean area of land throughout past time he takes as 0.8 of the present area and the *present* exposure of igneous rocks to lie between 0.25 and 0.3 of the mean land area. Assume that the annual contribution of sodium has diminished directly with the area of igneous rocks which has lessened in the following manner: In a certain time interval T , it is half the original area, in $2T$ it is one-fourth, in $3T$ it is one-eighth, in $4T$ it is one-sixteenth, and so on, following the same law of decay as the loss of velocity of a body moving in a resisting medium and the decay of radioactivity. On this basis Becker derives an age of the ocean between 70,000,000 and 50,000,000 years. Of these, he prefers the higher figure. These estimates are very close to half the lengths of time obtained by using Joly's assumption of uniform rate of supply. Looking forward to a continuation of Becker's falling rate following a logarithmic curve, there will come a time, he conceives, when the erosion of new igneous rock will be negligible and the sea can never come to have more than 1.43 to 1.33 of its present salt.

In comment on Becker's method it may be said that his assumption regarding decreasing rate seems as unsafe as his other assumption regarding the constancy of composition of oceanic salts. Both Joly and Becker note the present high average elevation of the continents, but regard it as a secondary factor in the matter of rate of supply and one for which allowance need not be made. Reasons have been discussed, however, for holding that it is a major factor, which has multiplied the rate of erosion many times above what it has been during long periods of quiet marked by wide-spread shallow seas. Schuchert's paleogeographic maps show,

according to Becker, that the mean area of North America above water has been eight-tenths of the present area. It may, however, have been more or less. As Schuchert recognizes, his maps minimize the limits of the epeiric seas. At times they probably extended far beyond the ascertainable bounds, since erosion of the following periods would remove the thin outlying deposits; but in the intervening stages, as Schuchert was one of the first to emphasize, the shallow seas were practically withdrawn from the continent.

The rate of erosion, however, does not turn so much on the area of land as on its elevation. During most of the Paleozoic and Mesozoic the continents stood notably low with respect to sealevel. It was particularly the mountain axes and plateaus which suffered erosion. The great Canadian Shield of older rocks stood at a low elevation and suffered but little erosion between the Proterozoic and Cenozoic—a fact first emphasized by Bell.⁸¹ The same relations were true of other continents. Although deep geosynclines were filled with sediments and imply the destruction of great mountain ranges, their volume was small as compared to the broad areas of the continents now well above baselevel and suffering rapid denudation. Erosion could be locally rapid, but the bulk of erosion of igneous rock must have been relatively small.

Since the beginning of the Ordovician, furthermore, the actual area of igneous rocks has not diminished after an exponential law. It appears to have varied considerably with the broad covering and uncovering by sedimentary blankets, and to have been greatly increased at times by igneous extrusions. The Cenozoic has been a period of notable igneous activity, and in North America the erosion of the Cordilleran area is largely from Cenozoic extrusives and Mesozoic intrusives. The Ordovician witnessed a very wide expansion of epeiric seas and the erosion of igneous rocks was reduced to a minimum from that time forward to the Appalachian revolution. In view of these actual geological conditions the refinements of calculation introduced by Becker seem useless and lend only a false security to the results. Joly's assumption of uniform rate of denudation comes nearer to the truth; but, in view of the existence of cycles of erosion through geological time, even Joly's figure may have to be multiplied many times.

ESTIMATES OF TIME BASED ON LOSS OF PRIMAL HEAT

Before the discovery, at the opening of the twentieth century, of the wonderful field of radioactivity, it seemed to physicists that the heat lost

⁸¹ Robert Bell: Pre-Paleozoic decay of crystalline rocks north of Lake Huron. *Bull. Geol. Soc. Am.*, vol. 5, 1894, pp. 357-366.

yearly by the sun and earth was the basis of the soundest methods for determining the limits of duration of those bodies.

It was calculated that if the energy of the sun were derived from gravitational infall of its own mass and had been constant since the beginning, the sun could not be over 18,000,000 years old. Thomson showed, however, that the age could be extended beyond this narrow limit, but his guarded conclusion was that the sun most probably has not illuminated the earth for 100,000,000 years and almost certainly not for 500,000,000 years.

On the assumption that the temperature gradient of the earth was the result of simple cooling through geologic time from a molten beginning, Thomson calculated also the age of the earth. His first estimates were between 20,000,000 and 400,000,000 years; probably within 100,000,000 years. Later, in 1897, he reduced the time limits to between 20,000,000 and 40,000,000 years.

Clarence King, in 1893, argued from the melting curve of diabase and the temperature gradient of the earth that the earth could not possess its known tidal rigidity and be more than 24,000,000 years old. This argument rests, however, on a very nice use of very uncertain quantities. These estimates based on the thermal gradient ignore the great quantities of heat brought up by igneous activity. It is clear that the rise of Archean and later granites must have disturbed profoundly the previous temperature gradients. It has been found, furthermore, that radioactivity gives such an embarrassingly large quantity of heat that it has been necessary to assume the restriction of uranium and thorium with their observed percentage to the outer 40 miles of the earth's crust, since otherwise the earth would be heating up with geological rapidity, instead of being a body slowly cooling or in thermal equilibrium.

The discovery of radioactivity cuts out all solid basis for calculating age from the flow of solar energy or the temperature gradient of the earth. The subject of age as based on temperature gradient must still be discussed, however, because of its inherited influence on geologic thinking.

A recent attempt has been made by Becker to revive the argument from temperature gradient by including the new data of isostasy and radioactivity.⁸² Becker takes the curve of fusion of diabase with respect to pressure as given by Carl Barus, a curve which is quite certainly wrong for high pressures, since Barus assumed that the fusion point increased in a *rectilinear* ratio with all pressures. Furthermore, Barus's measure-

⁸² Age of a cooling globe in which the initial temperature increases directly as the distance from the surface. Science, vol. xxvii, 1908, pp. 227-233; also in later publications.

ment of the initial rate of rise is probably subject to considerable correction.

Becker takes next the depth of complete isostatic compensation for a uniformly distributed compensation, 114 kilometers as given by Hayford for the most probable value determined by deflections of the vertical. He argues from this that the level where the temperature gradient approaches nearest to the fusion curve of diabase is 114 kilometers.

But Hayford later changed this depth to 122 kilometers, and on the basis of measurements of intensity of gravity Bowie has recently reached 96 kilometers as the most probable value. Bowie couples this with the statement that he believes future determinations will fall between 80 and 130 kilometers.⁸³ This great range in the depth, as determined by the method of least squares, applied to a large mass of observational data, is owing to the wide range of the local determinations, the imperfection of isostasy, and also the imperfection of the particular hypothesis of distribution. This hypothesis assumes that the density under every topographic feature is so adjusted that at the depth of complete compensation—for example, at 114 kilometers below sealevel—every column contains the same mass, irrespective of its height. Furthermore, it assumes that the difference of densities between columns are the same at all depths down to the level of complete compensation, at which level the differences abruptly cease.

Such a simple form of hypothesis satisfies the geodetic data, giving the isostatic condition, chiefly between continents and ocean basins, as about nine-tenths complete, but a more natural assumption of variable, regional, irregular, and gradually disappearing compensation satisfies it just as well. Furthermore, a variety of evidence based on the stresses set up in the crust by the loads within it and on it indicates that the shell of greatest strength is less than a hundred kilometers thick, but that the underlying shell of weakness is very thick, with its center apparently as much as 300 to 500 kilometers in depth.⁸⁴ This is the conclusion of the writer, but there are others who hold that the data of isostasy may be so interpreted as to place the compensation even deeper and who see in the data of isostasy no evidence of weakness. It all goes to show on what an insecure and artificial foundation Becker's calculations rest. But this is only one of a series of assumptions of equal unreliability which enter into the result.

⁸³ William Bowie: *Investigations of gravity and isostasy*. U. S. Coast and Geodetic Survey, Special Publication No. 40, 1917, p. 112.

⁸⁴ J. Barrell: *The strength of the earth's crust*. *Journal of Geology*, vols. xxii, xxiii, 1914, 1915.

The next assumption on the list is that the initial temperature gradient of the earth at the time of complete solidification was a straight line with a higher temperature at the surface than the fusion point of diabase, but with a lesser slope, intersecting the diabase curve at some distance below the surface. This primal temperature gradient is next assumed to have been modified by two factors only—some new heat of radioactive origin and a loss by conduction to the surface. Becker thus ignores, as others had done, the evidence of the recurrence on a world-wide scale of the rise of heat, manifested by batholiths and regional metamorphism—a convective overturn which would seem to have completely obscured the original temperature conditions.

By varying the initial surface temperature and the initial temperature gradient he obtains six solutions for the age of the earth and the resulting present gradient as dependent solely on cooling from the initial state. The ages range from 30,000,000 to 100,000,000 years. He chooses the 60,000,000-year earth as being most probable, as indicated by other lines of evidence. This yields a present thermal gradient from primal cooling which amounts to 77 feet for one degree Fahrenheit. As this is not far from the lower figures for the mean temperature gradient, Becker concludes that radioactivity must be a minor factor in the heat of the crust.

Thus, assumption is built on assumption into a many-storied structure and the whole rests on a foundation of quicksand. That it is a castle in the air and can not reflect the conditions of nature is indicated by various well established inferences. For example, the deeper parts of many of the older stratigraphic deposits, such as the Torridonian and Keweenawan formations and the Precambrian series of the Grand Canyon of Arizona, have been buried to a depth of several miles and are now exposed by erosion. They are not metamorphosed and therefore show that a high temperature gradient did not exist in the crust at that time except in regions of metamorphism, where plutonic igneous invasion is often indicated as the cause. Furthermore, measurements of the radium content of the siliceous rocks, and the independence of its disintegration with respect to pressure and heat, so far as laboratory experiments can ascertain, show that to depths of at least some tens of miles radioactivity must be a very important factor in determining the present temperature gradient unless uranium and thorium should have their disintegration arrested by moderate pressure; but of this there is no evidence.

Lane⁸⁵ has shown how Becker could have obtained different results by

⁸⁵ A. C. Lane: Schaeberle, Becker, and the cooling earth. *Science*, vol. xxvii, 1908, pp. 589-592.

varying his postulates and points to the lack of evidence of high temperature gradients in Paleozoic and Proterozoic times.

In contemplating this elaborate and ingenious argument as compared with the uncertain character of the data and the lack of agreement with significant facts, one is reminded of Huxley's well known saying, that—

"Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but nevertheless what you get out depends upon what you put in; and as the finest mill in the world will not extract wheat-flour from peascods, so pages of formulæ will not get a definite result out of loose data."

PART IV.—MEASUREMENTS OF TIME BASED ON RADIOACTIVITY

OUTLINE OF THE THEORY

The detection in 1896 of the Becquerel rays given out by uranium minerals led up to the epoch-making discovery of radium. This was the opening which led to the revelation of the whole series of radioactive elements whose parents, uranium and thorium, have the highest atomic weights of all known elements. Each of these parental elements slowly and regularly breaks down into a descendent series. In so doing they liberate α , β , and γ -rays which enable the process of disintegration to be detected and constitute the radiations discovered by Becquerel. The α -rays are positively charged atoms of helium, shot out of the parent atoms with enormous velocities. The β -rays are negatively charged electrons, having a mass of about $1/1,250$ that of a hydrogen atom, and expelled even more swiftly than the α -particles. γ -rays are not material particles in rapid motion, but appear to be of the same nature as X- or Röntgen-rays.

Confining attention to the uranium series, the evidence indicates that eight successive ejections of helium atoms, separated by other and intermediate β and γ changes, result in the making of lead out of uranium. The atomic weight of helium being 4.0 and uranium 238.2, it follows that the atomic weight of lead derived from uranium should be 206.2.

In the enormous number of atoms which exist in even a chemical trace of a radioactive substance, a few pass each second into a condition of instability and, by ejecting either an α or β particle, pass into another atomic state. The number of atoms is so great that, as in the kinetic theory of gases, the law of averages strictly applies. In the successive products from uranium down to lead various degrees of stability are shown, the more stable atom enduring on the average a longer time before it passes into a configuration of internal instability and as a result breaks

down. From the degrees of radioactivity and the rate of decay of the radioactivity of each substance the relative instabilities may be measured and these may be translated into the length of time when half of the given substance will have been transformed. This is known as the half-value period. For example, let a certain weight of radium be designated as 64 A. In 1,660 years it will have been half transformed into descendent elements and 32 A will remain as radium. In 1,660 years more, or 3,320 years from the beginning, half of this will have been transformed and the quantity of radium will be 16 A. In another 1,660 years 8 A will remain. Thus in 9,960 years an initial quantity of 64 A will be reduced to A. It is clear, then, that the parent element, uranium, exists in the earth's crust only because its half-value period is enormously long—long even in comparison with the geologic eras.

There are at present listed fifteen members and a couple of branch variations in the uranium series, beginning with uranium and ending with lead. Several of these are not chemically separable from certain other elements and are known as isotopes. The half-value periods of representative members in the order of their genesis are given by Rutherford⁸⁶ as follows:

Uranium	6×10^9 years
Ionium	greater than 20,000 years
Radium	2,000 years
Radium emanation.....	3.75 days
Radium D.....	16.5 years
Radium F.....	136 days
Lead	stable

Recent determinations by Ellen Gleditsch of a high order of precision have shown the half-value period of radium to be about 1,660 years.⁸⁷ Professor Boltwood, in whose laboratory this work was done, regards the error of this mean as probably not more than 2 per cent. The half-value period of uranium is decreased correspondingly.

In a uranium mineral all of the descendent elements are present, and after about a million years a state of equilibrium is reached, after which time each decays at the same rate at which it is generated. It follows that after this a constant ratio is maintained between each, the relative amounts being determined by the rates of decay. Thus, in a uranium mineral, radium occurs to the amount of about 1 part to 3,125,000 parts of uranium. These radioactive substances exist consequently in such small amounts that they are insensible in gravimetric analysis, but through

⁸⁶ E. Rutherford: *Radioactive substances and their transformations*, 1913, p. 24.

⁸⁷ Ellen Gleditsch: *The life of radium*. *Am. Jour. Sci.*, vol. 41, 1916, pp. 112-124.

their radioactive properties, the electroscope and the fluorescent screen enable the investigator to identify the substances and even to count the atoms which disintegrate. As a result, the half-value period of radium may be determined by comparison with that of the radium emanation, and uranium by comparison with radium, as well as by other ways. Thus the accuracy with which the rates of decay can be measured, the agreement by different methods, and the great duration of uranium unite to fit the series to serve as a measure of geological time.

The rate of decay is not affected by the nature of chemical combination or physical state. Temperatures up to $2,500^{\circ}$ C. and pressures up to 160 tons per square inch have been found not to influence the rate of decay of the products of radium. It is highly probable but not as yet actually demonstrated that uranium is similarly unaffected. Thus the atoms of uranium break up with a uniform rate whether they are in elemental form or combined in a salt; whether they are in solid, liquid, or gas. Of course there must be conditions under which an element which is now breaking down was built up, but such a physical environment would appear to be so extreme that it must occur under unknown cosmic conditions, and there is no reason to expect the modification of disintegration rates in the outer crust of the earth, a region in which temperatures and pressures are both relatively low.

The uranium minerals are commonly found associated with pegmatite dikes. Since the time of their growth their temperatures have been well below the crystallization temperature of granite and the pressures have diminished with the progress of erosion from an initial maximum of possibly twenty or thirty thousand pounds per square inch to atmospheric pressures as they are exposed at the surface. From the time radioactivity attained equilibrium in the uranium or thorium mineral, the end products have been accumulating within it consequently at a uniform rate. These in a dense crystalline rock are not removed unless the minerals are subjected to passing solvents, which would then surely record their effects by the alteration of the mineral itself. An atom of uranium which breaks up will ultimately give rise as stable products to eight atoms of helium and one atom of lead. If the quantity of these can be measured and compared with the quantity of uranium in the same volume of material, data are obtained for measuring the age of the mineral and with it the age of the rock formation of which it is a part.

Following this introduction, the methods of measuring the earth's age by radioactive processes and the results which have been attained may be considered in more detail. For this purpose the best presentation will be

to quote freely from a recent article by Arthur Holmes,⁸⁸ who by his research has contributed much to this subject. The following three topics are quoted entire, as they give in brief space the essentials of the methods and the original article will be seen by but few American geologists. The importance of the whole subject from a geological standpoint is such that this presentation should be given in an American geological publication.

ACCUMULATION OF HELIUM ⁸⁹

The proof is complete that helium is a stable product of the decay of both uranium and thorium. It is always present in radioactive minerals. In 1903 Ramsay and Soddy demonstrated its genesis directly from radium emanation. In 1910 Strutt went further and measured its rate of formation in pitchblende and thorianite. His results show that one gram of uranium⁹⁰ generates helium at the rate of 1 cc. in 10 million years, and that one gram of thorium⁹⁰ generates helium at the rate 1 cc. in 30 million years. These figures have been verified quite independently by directly *counting* the α -particles—helium atoms—emitted by various members of the radioactive families. Strutt found that the thorianite which he used in his experiments originally contained 280,000,000 times more helium than the amount which the same mineral could generate in a year. The inference is clear. That large volume of helium must have taken 280,000,000 years to accumulate.

Before going a step further and asserting that this is also the *age* of the mineral, two questions must be asked and answered:

(a) Was there any helium present in the mineral at the time of its crystallization, or has it been generated since?

(b) Can we be sure that no helium has escaped from the mineral during the period which has elapsed since its crystallization?

In the first case it is only necessary to notice that ordinary rocks and minerals contain only the slightest traces of helium, and that what little there is can be fully explained by the small quantities of the radioelements which are always present. If any strongly radioactive mineral in an igneous rock did contain a little helium as an original impurity, its amount would soon become negligible in proportion to the large quantities subsequently generated.

The second question is not so easily disposed of. It has been experimentally demonstrated that as soon as a mineral is exposed to the air it

⁸⁸ Radioactivity and the measurement of geological time. *Proc. of the Geologists' Asso.*, vol. xxvi, part 5, 1915, pp. 289-309. The following three topics are quoted from pp. 294-300, 303-309, with some omissions.

⁸⁹ By Arthur Holmes.

⁹⁰ When in equilibrium with all its daughter elements.

begins to lose its helium. When it is powdered for analysis, still more leaks away. Consequently the helium now found in a mineral can only be a part, rarely as much as one-half, of the total amount which has been generated within it during its lifetime. This must be carefully remembered in interpreting the helium contents of minerals.

Returning to our thorianite, it will now be clear that it would be erroneous to suppose that its age is only 280,000,000 years. Its age must be much greater than that. Thorianite occurs in Ceylon in sands and gravels, where it has been exposed to the action of the weather for thousands of years—ever since it was broken away from its original home in

TABLE A

Geological period.	Mineral.	Locality.	Helium ratio. ⁸¹	Millions of years.
Recent.....	Zircon.....	Mount Somma	<0.01	0.1
Pleistocene.....	Zircon.....	Mayen, Eifel	0.09	1.0
Pliocene.....	Zircon.....	Campbell Island, New Zealand.	0.223	2.5
Miocene.....	Zircon.....	Expailly, Auvergne	0.57	6.3
Oligocene.....	Siderite.....	Niederpleis, Rhine Provinces.	0.76	8.4
Post-Eocene.....	Hæmatite....	County Antrim	2.8	30.8
Permian?.....	Zircon.....	Northeast Tasma- nia.	3.88	42.7
Upper Carbonif- erous.	Limonite....	Forest of Dean...	13.3	146 (320) ⁸²
Carboniferous to Cambrian.	Zircon.....	Green River, North Carolina.	13.4	147 (330)
Devonian.....	Zircon.....	Brevig, Norway...	4.94	54 (380)
Devonian.....	Hæmatite....	Caen	13.2	145
Upper Precam- brian.	Zircon.....	Cheyenne Canyon, Colorado.	12.8	141
Upper Precam- brian.	Zircon.....	Miask, Urals.....	19.0	209
Upper Precam- brian.	Zircon.....	Ceylon	26.0	286
Upper Precam- brian.(?)	Thorianite...	Ceylon	27.9	307
Middle Precam- brian.	Sphene.....	Arendal, Norway...	36.8	405 (1,200)
Middle Precam- brian.	Sphene.....	Twedestrand, Nor- way.	40.8	449 (1,200)
Lower Precam- brian.	Zircon.....	Renfrew County, Ontario, Canada.	56.6	623
Lower Precam- brian.	Sphene.....	Renfrew County, Ontario, Canada.	65.0	715 (1,500)

⁸¹ The ratio of helium in cubic centimeters to an amount of uranium (U) equivalent in its rate of helium generation to that of the uranium and thorium present in the mineral. Age = $\text{He}/\text{U} \times 11$ million years.

⁸² The figures in parentheses represent the age in millions of years based on lead ratios for the corresponding periods.

the pegmatite dikes of that island. During all that time its store of helium has been leaking away, and present measurements give only a *minimum* estimate of its age.

In the course of his work Strutt investigated phosphatic nodules and iron ores from sedimentary rocks, and zircons and sphenes from igneous rocks, the two latter being among the most radioactive of the commoner rock-forming minerals. The results for iron ores and zircons are the most valuable and instructive, for they represent widely different periods, and they show that, in spite of the unavoidable leakage, the older minerals contain far more helium than the younger ones.

In Table A some of the highest of the ages based on Strutt's results are given for each of the geological periods represented. It will be seen that with few exceptions they stand in close relation to the geological ages of the minerals. For comparison, the corresponding ages based on the accumulation of lead are given in parentheses in the cases where these have been measured. The figures clearly bring out the limitations of the helium method. All that it can tell us is that the age of a mineral is greater than a certain minimum value.

PLEOCHROIC HALOS⁸⁸

The presence of uranium and thorium in rocks is sometimes revealed in a most beautiful way. When mica and tourmaline and a few other minerals are examined in thin sections under the microscope, small circular spots, known as pleochroic halos, are sometimes seen. At the center a minute crystal of zircon, or of some other radioactive mineral, can usually be detected. In 1907 Joly demonstrated beyond doubt that these intensely pleochroic spots were due to the radioactivity of the tiny inclusions at their centers.

The α -rays, or helium atoms, discharged from the different radioelements have not all the same velocity. Those from uranium can penetrate about an inch of air, and they give up most of their electrical charge just before coming to rest. Since they must be discharged equally in all directions, they come to occupy a spherical surface around the central uranium. The helium atoms from radium travel more rapidly and thus penetrate farther, forming another spherical surface. Those from radium C have the maximum range and form a sphere which incloses all the others. The ranges of the helium atoms from the thorium family are of the same order, but slightly greater than those from the uranium family, and consequently the resultant spheres are of somewhat greater diameter.

The distance to which a helium atom can penetrate depends on the

⁸⁸ By Arthur Holmes.

density of the matter through which it is passing. The ranges in air have been carefully measured, and the corresponding values for biotite can easily be calculated. The largest sphere from the uranium family should have a diameter of $1/30$ mm., and that from the thorium family a diameter of $1/25$ mm. Now the maximum diameters of halos have been carefully measured, and surely enough there are two types of halos with exactly the diameters theoretically to be expected. Clinching the argument by practical demonstration, Rutherford has made artificial halos in glass and in flakes of biotite.

The color of a halo depends on two factors: (a) the radioactivity of the central inclusion, and (b) the age of the mineral in which it occurs. As the helium atoms accumulate in their spherical shells the color gradually deepens. It is interesting and significant to notice that halos are found only in fairly old rocks. Granites of Tertiary age are practically free from perceptible halos, whereas in biotite granites of Permian and Devonian age they are frequently well developed.

Recently Joly and Rutherford have attempted to estimate the age of the biotite halos in the Leinster Granite of County Carlow (Lower Devonian) by means of their color. Artificial halos were made in the same biotite under controlled conditions which made it possible to measure accurately both the *radioactivity* and the *time* for which it acted. Artificial halos are made with a high degree of radioactivity acting for a short time. Natural halos are made with a low degree of radioactivity acting for a long time. Suppose that a natural halo is found with exactly the same depth of color as an artificial one. If, now, the radioactivity of the central inclusion can be estimated, then the *time* for which it must have acted can easily be calculated. The period of time so found would, of course, be a measure of the age of the halo and of the mineral in which it had developed. Once the natural halo has been matched in color with an artificial halo, the only problem that remains is the estimation of the radioactivity of the zircon at the center of the natural halo.

The volume of the inclusion can be determined by working with a high-power microscope. Unfortunately it is impossible to separate the zircons and measure their uranium contents directly. The difficulty is surmounted by an appeal to probable limits. No zircons are known to contain more than 10 per cent of uranium. If this figure is employed throughout for all the halos examined, some of them, the paler ones, will give ages that are obviously too low, while others, the darker ones, will give ages that approach the correct figure, and may perhaps even exceed it. The values actually arrived at by Joly and Rutherford varied between 50 and 470 million years, the larger figure being certainly nearer the

truth than the smaller one. Whether it is too high or too low can not as yet be determined by the method of attack pursued in this investigation.

ACCUMULATION OF LEAD ⁹⁴

Discussion of the evidence.—The suggestion that lead is the final product of the uranium family was made by Boltwood in 1905. All the evidence which has become available since that date convincingly upholds the correctness of his view, which from the first was much more than a mere guess or assumption. Up to the present the generation of lead from a radioactive preparation has not been directly demonstrated, but the reason is not far to seek. Such a preparation, originally free from spectroscopic traces of lead, would require many years to generate within itself a perceptible accumulation of lead. Two or three experiments were begun a few years ago with this end in view, but more time must elapse before there can be any hope of detecting the final product. The following lines of deductive evidence, however, leave no room for doubt that the final product really is chemically identical with lead:

(a) When the radio-elements are arranged in their proper positions in the periodic classification, the final product of uranium naturally falls into the division already occupied by lead.

(b) The atomic weight of ordinary lead is 207.1 (International, 1915), or 207.19 according to Baxter, Thorvaldsen, and Grover (1915). However, according to the data previously given, the atomic weight of the final product should be 206.2, or 206 according to Hönigschmid's measurement of the atomic weight of radium. This was for some years a source of difficulty, but it has now led to the discovery that lead which has accumulated in radioactive minerals, and which is recognized as lead by its chemical and spectroscopic behavior, has actually a lower atomic weight than that of ordinary lead. Richards and Lambert in America, Maurice Curie in France, and Hönigschmid in Austria have investigated lead prepared from pitchblende and other uranium minerals, and the values of the atomic weight found by them range from 206 to 206.5.⁹⁵ The higher values are all from pitchblendes of secondary origin, which are liable to contamination with ordinary lead, owing to their association with galena. The lowest values are from pure uraninite (German East Africa) and from a similar mineral, Bröggerite (Norway), both of which were fresh primary minerals quite free from traces of galena. Atomic weight evidence, therefore, strongly supports the view that the final product of uranium is an isotopic variety of lead.

⁹⁴ By Arthur Holmes.

⁹⁵ For references and a table of results see Holmes and Lawson: *Phil. Mag.*, vol. xxix, 1915, p. 682.

(c) It is found that in fresh, primary, uranium-bearing minerals of the same geological age the amount of lead is closely proportional to that of uranium—that is to say, the ratio Pb/U (referred to as the *lead ratio*) is practically constant. For each gram of uranium in a mineral the amount of lead generated and accumulated is the same as in any other mineral of equal antiquity, always provided that no lead has been lost or gained from external sources during the period concerned.

(d) When series of minerals of different ages are compared it is found that the lead ratios vary in sympathy with those ages. The older the mineral the higher is the lead ratio.

The rate at which lead is generated from uranium can easily be calculated. The rate of production of helium is accurately known, and the mass of lead set free in the same time is roughly 6.5 times that of the helium liberated. In a year one gram of uranium generates 1.25×10^{-10} grams of lead, and at this rate one gram of lead would be produced in 8,000 million years.⁹⁶ If a mineral contains a percentage of accumulated lead of radioactive origin represented by Pb, and a percentage of uranium represented by U, then the *age* of the mineral is given approximately⁹⁷ by the expression:

$$\frac{\text{Pb}}{\text{U}} \times 8,000 \text{ million years (or, using the latter value,}$$

$$\frac{\text{Pb}}{\text{U}} \times 7,500 \text{ million years.—J. B.).}$$

Before applying this method to the actual measurement of geological time, it is necessary to examine closely a number of assumptions which are implied. It is clear that if any lead should have been originally present in a radioactive mineral at the time of its genesis, a serious difficulty will have arisen. In all the ordinary minerals of igneous rocks, lead is a negligible quantity. The difficulty may often be overridden by analyzing only those minerals which are much richer in uranium than the main body of the rock. Within them, lead will steadily accumulate, and any original lead will, as time goes on, become of less and less importance in proportion to the whole. The difficulty is not, however, wholly dispelled in this simple way. If original lead were to be present in trouble-

⁹⁶ NOTE BY J. B.—The newer and more accurate determinations of the half-value period of radium and the ratio between the amounts of radium and uranium reduce this 8,000 million years to 7,500 million, as calculated for the writer by Professor Boltwood. This is the hitherto unpublished mean of various determinations by Boltwood and others. All the calculations by Holmes have been supplemented by the writer, according to this new value, by the addition of a correction in parenthesis which is .9375 of the old value. The results are given, however, to only two or three significant figures.

⁹⁷ See footnote 98.

some quantities the amount is likely to vary from mineral to mineral, and the lead ratios will lack that constancy which is the criterion of their value. Moreover, the lead from such minerals is of two kinds—"ordinary" lead and "uranium" lead—distinguishable by their atomic weights, though not by chemical methods of analysis. If the lead is wholly original its atomic weight should be about 207.1; if generated from uranium the atomic weight should be about 206.2. Values between these figures imply a mixture of the two types. The criteria pointing to the absence of original lead in perceptible quantities are (a) constancy of the lead ratios in a series of fresh, primary minerals of the same geological age, and (b) an atomic weight value of the order 206.2.

In cases where the lead ratios are not constant, or where the atomic weight is too high, the presence of original lead is to be suspected and the ratios become worthless as an index of age. The thorium minerals from Ceylon afford an instructive instance.⁹⁸

We may now proceed to consider a number of analyses of minerals which may fairly be used for the measurement of geological time. In Table E many of the analyses compiled by Boltwood in 1907 are quoted, together with several new ones which have since become available.

I. The uraninite of Glastonbury, Connecticut, United States of America, occurs in pegmatite dikes which are associated with a granite probably of late Carboniferous age. The granite intrudes Lower Carboniferous strata and is certainly pre-Triassic.

III. Unfortunately, uraninite does not occur in the Devonian igneous rocks of the Christiania district of Norway. As has been already shown, analyses of thorite are far from reliable as tests of age, and the writer has felt reluctantly obliged to abandon them from that point of view. The remaining analyses give ratios varying from 0.04 to 0.062, the discrepancies being here due to the difficulty of accurately determining small quantities of lead. The average age given in the table may be too high, and must be regarded as indicating no more than an approximation to the correct figure. It is significant that the somewhat older granites of County Carlow give a maximum age of 470,000,000 years as determined by the pleochroic halo method.

⁹⁸ Since the amount of uranium present is slowly decreasing as the helium and lead accumulate, it is clear that the amount of uranium U_0 originally in the mineral must have been greater than the amount of U now present. For periods of time less than 2,000 million years, the average amount of uranium present in a mineral throughout its history—the time average—is almost exactly $(U_0 + U)/2$. Now U_0 is given by $U + Pb + He$, or by $U + 1.15 Pb$. Consequently $(U_0 + U)/2 = U + 0.575 Pb$, and a more accurate expression of the age of a mineral than that given above is $\frac{Pb}{U + 0.575 Pb} \times 8,000$ million years. $\left(\frac{Pb}{U + 0.575 Pb} \times 7,500 \text{ million years.} - J. B. \right)$

TABLE E

I

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite.....	Glastonbury, Connecticut, U. S. A.....	2.9	70	0.041	Hillebrand. ¹⁰⁰
Uraninite.....	Glastonbury, Connecticut, U. S. A.....	3.0	70	0.043	Hillebrand.
Uraninite.....	Glastonbury, Connecticut, U. S. A.....	2.8	70	0.040	Hillebrand.
Uraninite.....	Glastonbury, Connecticut, U. S. A.....	3.0	72	0.042	Hillebrand.
Uraninite.....	Glastonbury, Connecticut, U. S. A.....	2.9	72	0.040	Hillebrand.

Geological age: Carboniferous.

Average age⁹⁹ from lead ratios: 320,000,000 years. (300,000,000 years.—J. B.)

⁹⁹ Calculated in each case from the formula $\frac{\text{Pb}}{\text{U} + 0.575 \text{ Pb}} \times 8,000,000,000 \text{ years.}$

II

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite.....	Spruce Pine.....	3.9	77	0.051	Hillebrand. ¹⁰⁰
Uraninite.....	North Carolina.....	4.2	77	0.055	Hillebrand.
Uraninite.....	North Carolina.....	3.3	67	0.049	Boltwood. ¹⁰⁰
Uraninite.....	Marietta, South Carolina.....	3.3	71	0.046	Hillebrand.
Zircon.....	North Carolina.....	0.0036	0.076	0.047	Holmes. ¹⁰¹
	North Carolina.....	0.0055	0.130	0.042	Holmes.

Geological age: Cambrian to Carboniferous.

Average age from lead ratios: 370,000,000 years. (345,000,000 years.—J. B.)

(Corrected for primary lead:) 330,000,000 years. (310,000,000 years.—J. B.)

¹⁰⁰ Atomic weight of lead (Richards and Lemberg, 1914), 206.4. This suggests that 20 per cent of the lead may be primary.

¹⁰¹ "The Age of the Earth," p. 160 (1913).

III

Minerals.	Locality.	Lead.	Uranium.	Pb/U	Analyst.
Zircon.....	Brevig, Christiania district, Norway.....	0.037	0.931	0.040	Holmes.
Hornblende.....	Brevig, Christiania district, Norway.....	0.012	0.244	0.050	Holmes.
Zircon.....	Brevig, Christiania district, Norway.....	0.009	0.194	0.046	Holmes.
Pyrochlore.....	Brevig, Christiania district, Norway.....	0.012	0.192	0.062	Holmes.
Pyrochlore.....	Brevig, Christiania district, Norway.....	0.009	0.186	0.048	Holmes.
Biotite.....	Brevig, Christiania district, Norway.....	0.007	0.160	0.044	Holmes.
Zircon.....	Brevig, Christiania district, Norway.....	0.006	0.146	0.041	Holmes.
Tritomite.....	Brevig, Christiania district, Norway.....	0.003	0.063	0.048	Holmes.
Prevalite.....	Brevig, Christiania district, Norway.....	0.003	0.053	0.056	Holmes.
Mosandrite.....	Brevig, Christiania district, Norway.....	0.002	0.043	0.047	Holmes.
Aegirine.....	Brevig, Christiania district, Norway.....	0.0025	0.015	0.060	Holmes.
Eucolite.....	Brevig, Christiania district, Norway.....	0.001	0.017	0.059	Holmes.

Geological age: Devonian (probably Lower or Middle).

Average age from lead ratios: 380,000,000 years. (355,000,000 years.—J. B.)

IV

Minerals.	Locality.	Lead.	Uranium.	Pb/U	Analyst.
Uraninite.....	Annerød, Norway.....	8.4	66	0.13	Hillebrand.
Uraninite.....	Annerød, Norway.....	7.8	68	0.12	Blomstrand.
Annerødite.....	Annerød, Norway.....	2.2	15	0.15	Blomstrand.
Uraninite.....	Elvestad, Norway.....	9.3	66	0.14	Hillebrand.
Uraninite.....	Elvestad, Norway.....	8.0	57	0.14	Hillebrand.
Uraninite.....	Skaartorp, Norway.....	8.8	65	0.135	Hillebrand.
Uraninite.....	Huggenäskillen, Norway.....	8.8	68	0.13	Hillebrand.
Uraninite.....	Huggenäskillen, Norway.....	9.0	76	0.12	Lorenzen.
Thorite.....	Hittero, Norway.....	1.2	8.2	0.15	Lindström.
Bröggerite.....	Norway.....	8.61	67.4	0.13	Hofmann. ¹⁰²
Bröggerite.....	Norway.....	8.49	67	0.13	Hofmann.

Geological age: Middle Precambrian (pre-Jatullian).

Average age from lead ratios: 1,000,000,000 years. (940,000,000 years.—J. B.)

¹⁰² Ber. d. d. Chem. Ges., vol. xxxiv, p. 914 (1901). Atomic weight of lead (Hönigsmid, 1914), 206.06.

V

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite.....	Arendal, Norway.....	9.8	56	0.18	Hillebrand.
Uraninite.....	Arendal, Norway.....	10.2	61	0.17	Hillebrand.
Uraninite.....	Arendal, Norway.....	9.4	56	0.17	Lindström.
Thortite.....	Arendal, Norway.....	1.5	9	0.17	Nordenskiöld.
Orangite.....	Landbo, Norway.....	1.2	7.5	0.16	Hidden.
Xenotime.....	Narseto, Norway.....	0.62	2.9	0.21	Blomstrand.

Geological age: Middle Precambrian (pre-Jatullan).

Average age from lead ratios: 1,200,000,000 years. (1,120,000,000 years.—J. B.)

VI

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Fergusonite.....	Ytterby, Sweden.....	0.18	1.06	0.17	Holmes.
Gadolinite.....	Ytterby, Sweden.....	0.36	2.41	0.15	Holmes.

Geological age: Middle Precambrian (Ser-archean granites).

Average age from lead ratios: 1,100,000,000 years. (1,030,000,000 years.—J. B.)

VII

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite.....	Villeneuve, Quebec, Ontario.....	10.14	60	0.17	Hillebrand.

Geological age: Middle Precambrian.

Age from lead ratio: 1,200,000,000 years. (1,120,000,000 years.—J. B.)

VIII

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite.....	Morogoro, German East Africa.....	6.98	74.54	0.094	Marckwald.*
Uraninite.....	Morogoro, German East Africa.....	6.88	74.72	0.092	Marckwald.

Geological age: Undetermined, but younger than IX and X.

Average age from lead ratios: 700,000,000 years. (655,000,000 years.—J. B.)

* Atomic weight of lead (Hönigschmid, 1915), 206.04.

IX

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Zircon.....	Nrassi Basin, Mozambique.....	0.032	0.193	0.17	Holmes.
Zircon.....	Monapo River, Mozambique.....	0.028	0.171	0.15	Holmes.
Biellite.....	Ligonla, Zambesia.....	0.014	0.097	0.14	Holmes.

Geological age: Undetermined, but younger than X.

Average age from lead ratios: 1,100,000,000 years. (1,030,000,000 years.—J. B.)

X

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Zircon.....	Mozambique.....	0.054	0.257	0.21	Holmes.

Geological age: Undetermined: Oldest gneissose granites.

Age from lead ratio: 1,500,000,000 years. (1,400,000,000 years.—J. B.)

IV. Turning to the Precambrian rocks of Scandinavia, there are three series of igneous intrusions containing radioactive minerals. All are intrusive into the older schists and quartzites of the Precambrian, and all were worn down by the denudation which prepared the platform on which the Jatulian formations were laid down. They all, therefore, belong to the middle division of Precambrian time. The position of these rocks in the Precambrian sequence will be made clear by the following tentative classification:

	Fenno-Scandia	Canada
UPPER PRECAMBRIAN OR EP-ARCHEAN	<i>Rapakivi granite</i> Jotnian	Keweenawan
	Jatulian	Animikie
Ep-Archean interval		
MIDDLE PRECAMBRIAN OR MES-ARCHEAN	<i>Ser-archean and post Kalevian granites</i> Upper Kalevian	<i>Algoman and post Huronian granites</i> Upper Huronian
	Lower Kalevian	Lower Huronian
	<i>Post Bottnian granites</i> Bottnian	<i>Granite intrusions</i> Sudburian
Epi-Laurentian interval		
LOWER PRECAMBRIAN OR PROT-ARCHEAN	<i>Post-Ladogian granite</i> Ladogian	<i>Laurentian granites</i> Grenville series Keewatin series Couchiching series

The first group of minerals—from the Moss district of south Norway—belongs to pegmatites associated with granites of post-Kalevian age. The lead ratios only vary from 0.12 to 0.15 and the atomic weight of lead from Bröggerite (lead ratio = 0.13) was found by Hönigschmid to be 206.06. Here, then, all the criteria of a thoroughly satisfactory series of minerals are fulfilled, and the age assigned to the rocks may be accepted with confidence.

V. A similar suite of minerals is found in the pegmatites of the Arendal district of south Norway. In this case the associated granites may be post-Kalevian or post-Bottnian. The agreement of the lead ratios is good except for the abnormal value given by Xenotime. (It is to be noted, however, that the per cent of lead in this mineral is only 0.62, which indicates that but relatively little weight should be attached to the analysis.—J. B.)

VI. Although many analyses have been made of minerals from the famous pegmatites of Ytterby (Ser-archean granites) no determinations of lead have hitherto been published. Two analyses by the writer indicate that the minerals are of the same order of age as those of the two

preceding groups. Geologically the Ser-archean and post-Kalevian granites can not be distinguished in time, and as far as correlation has been attempted they have been grouped together.

VII. A valuable analysis of a Canadian Middle Precambrian mineral is that of the uraninite from Villeneuve, in Ontario. The writer is indebted to the Canadian Geological Survey for the information (due to the work of Mr. M. E. Wilson) that the pegmatite in which the uraninite occurs is associated with a granite which (*a*) is intrusive into the Grenville series and into the pyroxene granites which penetrate the Grenville series, and (*b*) is intruded by diabase dikes of Keweenawan age. These details make it clear that the pegmatite belongs to one of the periods of granite intrusions contained within the Middle Precambrian of the above classification. This conclusion is completely in harmony with the age deduced from the single analysis available.

*Conclusions on accumulation of lead*¹⁰³—1. The method of determining geological time by the lead ratios of radioactive minerals gives results consistent among themselves and in harmony with geological evidence, wherever this is clear. Rejecting minerals in which alteration, or the presence of primary lead, has vitiated the results in advance, the evidence is conclusive that the ratio Pb/U is nearly constant for minerals of the same age, and that the value of the ratio increases as the geological age of the respective minerals increases.

2. The results are in keeping with those deduced from other radioactive methods.

3. The age of the Carboniferous and Devonian intrusions is of the order of 300 to 400 million years; the age of the granite intrusions of the Middle Precambrian is of the order 1,000 to 1,200 million years.

4. Where geological evidence is obscure, as, for example, in the Appalachians of the Carolinas, the method is capable (when suitable minerals are present) of being applied to the determination of the age of granite and similar intrusive rocks.

5. The method may be used comparatively for the correlation of igneous intrusions in various parts of the world, and in particular for the correlation of the Precambrian rocks.

6. Note added November 8, 1915.—In an address to the Geological Society of America (Bull. 26, p. 171, 1915), G. F. Becker has attempted to correlate recent developments in radiogeology and isostasy. He assumes that Hayford's level of isostatic compensation, at a depth of 121 km., is the depth of easiest fusion—that is, the depth at which the cooling curve most nearly approaches the curve of fusion. On this assumption

¹⁰³ By Arthur Holmes.

he finds that radioactivity maintains only one-seventh of the present gradient, and that the age of the cooling earth is 68,000,000 years. With the data he uses it is calculated that if two-thirds of the gradient is maintained by radioactivity, then the age becomes 1,314,000,000 years, and the depth of easiest fusion becomes 300 km. In a series of papers running through the *Journal of Geology*, 1914 and 1915, J. Barrell has shown that the zone of easiest fusion must be below the level of compensation, and from considerations based on the strength of the earth's crust and on tidal phenomena, he places the source of igneous activity at about the middle of the Asthenosphere—that is, at a depth of 350-500 km. Combining this conclusion with Becker's analysis, it is easily seen that the age of the cooling earth is not 68,000,000 years, but considerably greater than 1,314,000,000 years.—A. H.

PART V.—THE AGE OF THE LLANO SERIES, TEXAS

PREVIOUS OPINIONS

A discussion of the age of the pegmatites which intrude the Llano series of Precambrian sediments would be out of place in an article of this general character if it were merely to settle a disputed point in regard to local geology, but it happens that Becker has used the uranium minerals of the pegmatites in this series in an argument which completely discounts the value of the uranium-lead ratio as a means of determining the age of a uranium mineral.¹⁰⁴ Becker's conclusions are so adverse and apparently so final to one not otherwise familiar with the subject that they may in part account for the lack of further papers treating of the subject in American geological journals since Boltwood's publication in 1907. In England, on the contrary, considerable work has been done. In regard to the radioactive minerals of the Llano series, however, Holmes, relying in part on Becker's statements regarding their age and the variations in the lead-uranium ratios, discusses them as a warning example of the effects of alteration in minerals subsequent to their origin. Holmes takes this position, since, as seen, he holds that for many localities such minerals do give valuable indications of age. The present re-examination of the data goes to show, however, that these minerals of the Llano pegmatites do give definite and accordant measures of age when they are properly interpreted. So many differences arise between the views of Becker and the present writer in the analysis of this subject that, as a basis for discussion, Becker's statements must be quoted as an introduction to the

¹⁰⁴ Relations of radioactivity to cosmogony and geology. *Bull. Geol. Soc. Am.*, vol. 19, 1908, pp. 113-146.

topic. Under the subheading of "Radioactivity and the Earth's Age," Becker states:

"Now from the helium found in an analysis of fergusonite by Messrs. Ram-say and Travers, Mr. Rutherford¹⁰⁵ computes an age of at least 500 million years, and from an uranium mineral at Glastonbury, Connecticut, analyzed by Mr. Hillebrand, a similar antiquity. The Glastonbury granite gneiss is equivalent to the Wilbraham gneiss of Mr. Emerson,¹⁰⁶ who pronounces it unequivocally early Cambrian. Messrs. Rice and Gregory¹⁰⁷ feel some uncertainty as to its age, but do not suggest a new position for it. For the present purpose, it is sufficient to regard it as at the bottom of the Cambrian. Mr. Walcott's estimate of the lapse of time since the beginning of the Cambrian is nearly 28 million years, or about an eighteenth part of that suggested by Mr. Rutherford.

"Mr. Boltwood¹⁰⁸ has computed the age of a large number of uranium minerals from their lead content. He shows that according to theory the age will be given in years to a first approximation, if the ratio of metallic lead to metallic uranium is multiplied by 10 million. In this way he gets for the age of the Glastonbury minerals 410 million years. Now, at Barringer Hill, in Llano County, Texas, there is a very remarkable deposit of rare radioactive minerals, which are so abundant that they have been mined for the use of an electric lighting company. It happens that the age of the granite in which the pegmatite occurs is known. Mr. Walcott¹⁰⁹ discovered in this county his Llano group, which belongs to the Grand Canyon series, not far below the Cambrian. The granites are intrusive in these sediments. The great masses of granite which occur in western Burnet and all through Llano County belong to the same age as the strata, and Mr. Walcott is careful to remark that he did not observe any rocks of undoubted Archean age in the region. A number of analyses¹¹⁰ of the rare minerals of Barringer Hill are available, and by Mr. Boltwood's rule they give the following ages for the Llano beds:

	Million years
Yttrialite, J. B. Mackintosh.....	11,470
Yttrialite, W. F. Hillebrand.....	5,136
Mackintoshite, W. F. Hillebrand.....	3,894
Nivenite, Mackintosh.....	1,671
Fergusonite, Mackintosh.....	10,350
Fergusonite, Mackintosh.....	2,967

"Mr. Boltwood informs me, however, that, with the possible exception of nivenite, none of these minerals is really suitable for throwing any definite light on the question of the uranium-lead ratio for Llano County, since all of the specimens show signs of incipient or advanced alteration; but, according to theory, the state of combination is without influence on radioactivity, so

¹⁰⁵ Radioactive transformations, p. 189.

¹⁰⁶ U. S. Geological Survey, Monograph 29, 1898.

¹⁰⁷ Connecticut Geological and Natural History Survey, Bulletin 6, 1906, p. 116.

¹⁰⁸ American Journal of Science, vol. 23, 1907, p. 87.

¹⁰⁹ American Journal of Science, vol. 28, 1884, p. 431.

¹¹⁰ Hidden & Mackintosh: American Journal of Science, vol. 38, 1889, p. 474.

Hillebrand: American Journal of Science, vol. 46, 1893, p. 99; vol. 13, 1902, p. 145.

that the only alterations which would affect the matter must involve the addition or abstraction of uranium or lead, and mere hydration, for example, should be without effect. The nivenite, interpreted by the rule, indicates an age fifty times as great as seems admissible from a geological standpoint and four times as great as the Glastonbury mineral, which would seem on geological grounds nearly coeval with it.

"I find no convincing evidence that the law of decay is so simple as is assumed. Under the conditions in which uranium compounds are stable, λ must necessarily reduce to zero. It is in the highest degree probable that λ is a discontinuous function, and it is to the same degree probable that the law of decay fails like Boyle's law, or that λ varies with circumstances, such as may have environed a mineral in a pegmatite, even though heat alone or pressure alone may be without effect upon radioactivity.

"It does not seem to me that geologists can possibly accept the ages of minerals as determined from the uranium-helium or the uranium-lead ratios, which do not seem consistent and are far longer than stratigraphers could admit." ¹¹¹

GEOLOGICAL EVIDENCES OF AGE OF URANIUM MINERALS

Upper Paleozoic age of Glastonbury uraninites.—In reviewing Becker's statements the relative ages of the uranium minerals from the Glastonbury and Barringer Hill localities should be given first attention. It will be seen that the age ascribed to each is quite clearly in error and that their relative ages are very different.

In regard to the location and age of the Glastonbury uranium minerals, Hillebrand in 1890 ascribes them to Hale's quarry, but Becker overlooks the statement which Boltwood makes in the article which forms the basis of Becker's discussion. Boltwood states:

"I have been informed by Mr. E. B. Hurlburt, of Glastonbury, Connecticut, who has made a careful study of the mineral occurrences in his locality, that he considers it to be highly improbable that the specimens examined by Hillebrand and described as from Glastonbury were actually found in that place, or even in the neighboring quarries of South Glastonbury. Columbite, monazite, a mineral resembling polycrase, and autunite are found at South Glastonbury; but Mr. Hurlburt, who has looked into the matter quite thoroughly, is of the opinion that the specimens of uraninite credited to Glastonbury must have been found in the feldspar quarries of Portland, a town on the east bank of the Connecticut River between South Glastonbury and Middletown. A number of years ago uraninite in some quantity was found at Portland, and as some of the workmen in the Portland quarries had their homes in South Glastonbury, its occurrence in the latter locality may readily have been assumed by the collectors who afterward obtained the specimens. It is also equally possible that the specimens in many collections labeled as from Middletown are also really from Portland." ¹¹²

¹¹¹ Relations of activity to cosmogony and geology, loc. cit., 1908, pp. 133-135.

¹¹² B. B. Boltwood: On the ultimate disintegration products of the radioactive elements. Part II.—The disintegration products of uranium. *Am. Jour. Sci.*, vol. xxiii, 1907, pp. 77-88; see p. 81.

Now these feldspar dikes of Portland are intruded into the Bolton schist, and so also are nearly all of those in the town of Glastonbury.¹¹³ All the feldspar deposits and their uranium minerals come from pegmatites. As no fossils have been found in the metamorphic rocks of Connecticut, the age relations are in many places obscure. Nevertheless Rice and Gregory consider that the relations to the rocks of eastern Massachusetts suggest a late Paleozoic age for most of the schists east of the Connecticut River, though they do not exclude the possibility of an earlier Paleozoic age. These authors do not express any opinion as to the age of the Glastonbury gneiss, but state that it is "of uncertain origin."¹¹⁴ There is no evidence, however, that it is Cambrian. The placing of the Wilbraham gneiss, the Massachusetts equivalent of it, in the Cambrian goes back to a decade when the banded or mashed granite-gneisses were generally believed by the students of New England geology to be of sedimentary origin. Part of them were regarded as Archean, another part as basal Cambrian. As Van Hise explains, the placing of a great series of granite-gneisses in the basal Cambrian was a natural error, owing to the intricacy of the structure and the fact that the Cambrian has at its base an arkose formation which in places is quite similar in appearance to the granulated granites from which they were in part derived.¹¹⁵ Before 1908, however, Emerson had recognized that much of what was formerly regarded as sedimentary gneiss of Cambrian age in western Massachusetts was in reality an Archean basement of igneous origin. In 1898 Emerson placed the Belchertown tonalite and Williamsburg granite, covering large areas near the Connecticut Valley, in the Carboniferous.¹¹⁶ The map showing these formations did not include, however, the eastern upland. In 1916, in a preliminary geologic map of Massachusetts and Rhode Island,¹¹⁷ Emerson assigns a late Carboniferous or post-Carboniferous age to the Monson granodiorite, which is the Massachusetts extension of the Connecticut Glastonbury gneiss. Thus there has not been at any time a sufficient basis for assigning a Cambrian age to the Glastonbury or Portland uraninites. The evidence of the late or post-Carboniferous age of these granites is derived from a region farther east in Massachusetts, where granites cut schists in which Carboniferous plant fossils have been found. It appears to the writer that all which can at present

¹¹³ E. S. Bastin: Economic geology of the feldspar deposits of the United States. Bull. 420, pl. vi, U. S. Geol. Survey, 1910.

¹¹⁴ ——— Rice and H. E. Gregory: Manual of the Geology of Connecticut, p. 114, Bull. No. 6, Conn. Geol. and Nat. Hist. Survey, 1906.

¹¹⁵ C. R. Van Hise and C. K. Lelth: Precambrian geology of North America. Bull. 360, U. S. Geol. Survey, 1909, pp. 587-592.

¹¹⁶ B. K. Emerson: Holyoke folio, U. S. Geol. Survey, 1898.

¹¹⁷ U. S. Geol. Survey. To be published in 1917.

be positively stated in regard to the Glastonbury uraninites is that they are upper Paleozoic. Granitic intrusions occurred repeatedly in New England and appear to have covered quite a range in time, since Carboniferous formations rest in places upon somewhat older granites as well as being cut by those of younger age.

Middle Precambrian age of the Llano series.—As to the age of the pegmatites in the Llano series in Texas, Becker bases his statement that they are "not far below the Cambrian" on a brief observation by Walcott, made 24 years previously, on what the latter guardedly calls a "hurried reconnaissance of a portion of the Paleozoic area of Central Texas, the chief object in view being the study of the Cambrian section and the collecting of fossils from the Texas Potsdam horizon."¹¹⁸ The rocks which lay unconformably below the Upper Cambrian (Potsdam) Walcott named the Llano group and correlated them with the Grand Canyon group, which at that early time he placed in the Paleozoic, but later removed to the Precambrian. Walcott notes that on Roessler's map of Llano County (1875) all of the Llano group is referred to as "granitic, metamorphic, and igneous" and has been considered as Archean. He, however, states that he did not observe any rocks of undoubted Archean age.

In the Llano-Burnet folio, Texas,¹¹⁹ this region is mapped and its geology discussed in detail. Paige gives the following in regard to the character and age of the Llano series:¹²⁰

"The Llano series has proved to be a completely metamorphosed series of schists, marbles, and gneisses and can be classified as Algonkian in contradistinction to Archean only on the very broadest evidence, such as the preponderance of metamorphic sediments over igneous material. Roessler's description of these rocks as granitic, metamorphic, and igneous was therefore concise and, possibly except for his reference of the series to the Archean, correct."

The granites intrude the Llano series in great volume and the uranium minerals are in pegmatites related to the granites. Thus the age is distinctly Precambrian. The geological relations do not prove more, but the general character is similar to the intrusive granites of the middle Precambrian of Canada, the Huronian or post-Huronian of some authors, the late Archean as defined by Lawson. These are the Lorrain, or Algonman granites, as they have been variously named. Thus there is no such closeness of age as Becker concluded to exist between the Glastonbury (Portland) uraninites and the radioactive minerals of the Llano series.

¹¹⁸ C. D. Walcott: Note on Paleozoic rocks of central Texas. *Am. Jour. Sci.*, vol. xxlii, 1884, pp. 431-433.

¹¹⁹ Sidney Paige: Geologic atlas of the United States, No. 183, U. S. Geol. Survey, 1912.

¹²⁰ Loc. cit., p. 2.

THE LEAD-URANIUM RATIOS OF THE LLANO MINERALS

The original analytical data.—The lead-uranium ratios should be widely different for the Connecticut and Texas regions, but they should be accordant among themselves. Such accordance exists among the Glastonbury analyses, though the force of the accordance is perhaps somewhat weakened by the determinations being all from one species of mineral, uraninite. For the Llano region a variety of analyses and from different mineral species are available, but in the published lists no constancy is shown in the lead-uranium ratio. Becker from the varying ratio obtains ages as cited, ranging from 1,671 million years to 11,470 millions, and takes the variation, the maximum being about seven times the minimum, as evidence of the unreliability of the method for measuring age. Holmes gives a list of values of the lead-uranium ratio ranging from 0.102 to 1.130. He ascribes the variations in ratio to the altered character of the minerals, riddled with secondary products, and speaks of them as eloquent of the uselessness of this series of minerals as an index of geological time.

URANIUM MINERALS OF THE LLANO DISTRICT, TEXAS

Analyses giving Lead-Uranium Ratios

Used by Boltwood (1907)

Arranged in order of increasing ratio; minor constituents omitted

	No. 15. Uraninite. Mackintosh.	No. 14. Uraninite. Hillebrand	No. 16. Mackintoshite. Hillebrand.	No. 17. Yttrocrasite. C. H. Warren.
UO ₂	46.75	44.17	.....	0.64
UO ₃	19.89	20.89	22.40	1.98
ThO ₂	7.57	6.69	45.30	8.75
ZrO ₂ .....	.....	0.34	.88	.....
Rare earths.....	11.22	12.16	1.86	28.59
PbO	10.16	10.08	3.74	0.48
Fe ₂ O ₃	0.58	.....	.....	1.44
FeO .....	.....	.....	1.15	.....
SiO ₂ .....	.....	.....	13.90	.....
TiO ₂ .....	.....	.....	.....	49.72
H ₂ O	2.54	1.48	4.31	4.36
Total.....	99.93	98.74	96.50	100.57
Ref.: Am. Jour. Sci., volume and page..	38.481.	42.391.	46.101.	22.516.
Year	1889	1891	1893	1906
Pb	9.43	9.35	3.47	0.45
U	56.45	55.18	19.75	2.28
Pb/U	.167	.170	.176	.195

URANIUM MINERALS OF THE LLANO DISTRICT, TEXAS

Analyses giving Lead-Uranium Ratios

Used by Becker (1908)

Arranged in order of increasing ratio; minor constituents omitted

	A. Nivenite, (Uraninite), Mackintosh.	B. Mackintoshite, Hillebrand.	C. Fergusonite, (Trihydrated), Mackintosh.	D. Yttrialite, Hillebrand.	E. Fergusonite, (Monohydrated), Mackintosh.	F. Yttrialite, Mackintosh.
UO ₃	46.75	.....	3.12	.....	1.54	0.83
UO ₂	19.89	22.40	3.93	1.64	.....	.....
ThO ₂	7.57	45.30	0.83	10.85	3.38	12.00
ZrO ₂ .....	.....	.88	.....	.....	.....	.....
Rare earths.....	11.22	1.86	31.36	51.70	42.33	51.30
PbO	10.16	3.74	1.94	.80	1.43	0.854
Fe ₂ O ₃	0.58	.....	3.75	.76	0.98	.....
FeO .....	.....	1.15	.....	1.96	.....	2.89
SiO ₂ .....	.....	13.90	.....	29.63	.....	29.17
TiO ₂ .....	.....	.....	.....	.05	.....	.....
Cb ₂ O ₅ .....	.....	.....	42.79	.....	46.27	.....
H ₂ O	2.54	4.31	7.57	.32	1.98	0.79
Total.....	.....	.....	99.80	100.00	98.95	99.754
Ref.: Am. Jour. Sci., volume and page	38.481.	46.101.	38.484.	13.149.	38.483.	38.478.
Year	1889	1893	1889	1902	1889	1889
Pb	9.43	3.47	1.80	0.74	1.33	0.79
U	56.45	19.75	6.06	1.45	1.28	0.69
Pb/U	.167	.176 ¹²³	.297	.513	1.035	1.147

A is the same as No. 15; B is the same as No. 16.

A careful review of the original analyses, however, brings to light unexpected errors and by their elimination results in a good degree of accordance among those minerals whose compositions give indications of a reliable lead-uranium ratio. To demonstrate this statement the following tabulation is given, the percentages of lead and uranium and the value of their ratio being the result of recalculations by the writer from the original publications of the analyses. It is clearly impossible to give proper weight to the value of the ratio unless the percentage occurrences of uranium, lead, thorium, and a number of other constituents are noted. These are assembled and published for this purpose for the first time.

¹²³ Given by Becker as .3894, apparently as the result of an arithmetical error.

Discussion of the value of the analyses.—In comment upon these analyses it should be noted that nivenite of Becker's list is the same analysis as number 15, uraninite, of Boltwood's list.

Number 14 is a different lot of the same material as number 15. The remarks of Hillebrand, therefore, apply to both. Hillebrand states that "a first glance sufficed to show that the specimens were not fresh, and therefore analysis could throw no light on the ultimate composition of the mineral. The cause of the considerable loss shown by the total of 98.74 for the analysis is not known." Notwithstanding Hillebrand's comments on the lack of freshness, it would appear that these analyses are of fair reliability—that is, that no appreciable amount of either lead or uranium has been removed by solution in meteoric waters, since the amount of combined water is not abnormal for a uraninite and the large amount of uranous oxide shows an absence of oxidizing weathering.

Number 16, mackintoshite, shows from the presence of uranous and ferrous oxides in large amount and the complete absence of uranic and ferric oxides a lack of oxidation by descending waters. The material was embedded in massive cyrtolite and associated with fergusonite. It is opaque and black, and alters on the surface to dull yellowish brown thorogummite, a hydrated and oxidized uranium thoro-silicate holding 7.88 per cent of combined water. An analysis is given of thorogummite showing that the change is almost entirely one of oxidation and hydration. In comment Hillebrand states:

"It is in fact remarkable, considering the great molecular alteration that must have taken place, as determined by the totally different appearance of the two minerals, that so little loss of substance has taken place. Almost the sole change has consisted in an oxidation of uranous oxide and an increase in the hydration. These facts render not altogether safe the assumption above made that all uranium and iron in the new mineral exist there in the lower forms of oxidation, and they furthermore indicate that the black mineral itself may have already undergone oxidation and hydration without this being manifest to the eye—a supposition which is strengthened by the loss at 100° C. of half a per cent of water, and in fact by the intimate union which existed between the two minerals when received. Such material alteration without corresponding physical evidence of it seems to be common among uraninites."¹²²

Notwithstanding this possibility of some oxidation and hydration, the smallness of the losses in uranium and lead in the transformation of mackintoshite into thorogummite indicates that no appreciable change in the lead-uranium ratio has taken place in the mackintoshite, the parent mineral. In fact, it is a rather general condition, as Merrill has shown,

¹²² *Am. Jour. Sci.*, vol. 46, 1893, p. 101.

for the chemical changes due to solution in weathering to be only incipient until hydration and mechanical disintegration have become extensive.¹²³

This mineral appears consequently to be well adapted for determining the age of the formation, but in the analysis it is noted that the total is but 96.50 per cent, indicating a loss of 3.5 per cent. This resulted from the limited quantity of the sample and the presence of the rare earths which required it to be divided into three portions. Hillebrand states that "it is probable that the loss should be distributed somewhat unevenly over a number of the constituents, silica and lead excepted, they being without doubt nearly correct." If 1 per cent of this loss should be added to the 19.75 per cent of uranium, the mineral would possess 20.75 per cent uranium and the lead-uranium ratio becomes .167, exactly the same as for analysis number 15, in which the total amounts to 99.93.

In regard to number 17, yttracrasite, Hidden and Warren make the following observations:

"The crystal from which the material for analysis was selected was found in Burdet County, Texas, by Mr. John J. Barringer, who discovered the famous gadolinite mine just across the Colorado River, in Llano County, now known as Barringer Hill.

"The crystal had a thin dull brown coating of amorphous material which was evidently an hydrated alteration product, very similar to the yellowish brown coating observed on the polycrase (?) of North and South Carolina. The fresh underlying material is black in appearance and has a bright, pitchy to resinous luster, and closely resembles that of polycrase and euxenite, and like these has an uneven and small conchoidal fracture. Its hardness is between 5.5 and 6.

"The mineral when examined between crossed nicols is seen to consist of a mixture of isotropic and a feebly double refracting material. In several instances a distinctly spherulitic structure was observed with high powers; otherwise nothing of a definite nature could be made out regarding the optically active portion. The mineral is not now, therefore, of a strictly homogeneous structure. The fact, taken into consideration with its content of water and carbon dioxide, 0.68 per cent, suggests that the mineral is a hydrated alteration of an originally anhydrous species. It may be mentioned here that a very similar heterogeneous structure has been also noticed as characteristic of specimens of polycrase (?) from North and South Carolina."¹²⁴

In this connection should be discussed the significance of the hydration. If it is due to the leaching of descending ground waters it would indicate a geologically recent alteration, which would raise doubt as to the value of the lead-uranium ratio. The rather well crystallized nature of certain of the uranium and thorium hydrates and the lack of accompanying oxida-

¹²³ G. P. Merrill: Rocks, rock weathering, and soils.

¹²⁴ Am. Jour. Sci., vol. 22, 1906, p. 515.

tion suggest, however, that the hydration was accomplished in a decadent stage of the pegmatitic crystallization. Such deep-seated hydration by *ascending* hydrothermal waters tends to be pervasive, owing to the high internal pressures and temperatures of the solutions, favoring diffusion. Hydration due to the *descending* waters connected with weathering is, on the contrary, characteristically not pervasive until admission to all parts of a rock is prepared by an intimate crackling. Now a hydration dating back to a decadent stage of the pegmatization might change the content of uranium at that time, but would not affect the present lead-uranium ratio. In view of these and other considerations, it would appear that Holmes has been misled in speaking of the altered character of these minerals as eloquent of their uselessness as an index of geological time. The material on the market has all come from shallow pits, weathering has altered the surface, but this recent action is distinct from what appear to be primordial alterations. Furthermore, these occurrences fortunately are within the inner valley of the Colorado River, just above the flood-plain level, are 500 feet below the old upland of the surrounding country, and have consequently been exposed to erosion during only the last cycle of valley-cutting. It is found in general that, in rock outcrops exposed only to this last cycle of erosion, comparatively little chemical alteration of the bedrock has been accomplished by weathering. Under the higher uplands ground water has been active for very much longer periods of time, but in the bottoms of the inner valleys, on the contrary, the rocks are much fresher closer to the surface, indicating that the valley erosion has been more by mechanical breakage accompanied by superficial alteration.

Although in this yttracrasite the uranium is small in amount, yet so far as the analytical errors are concerned the analysis is of a high order. Boltwood states:

"The writer (Boltwood) had the good fortune to meet Professor Warren at the time this analysis was in progress and the latter kindly consented to take especial precautions in the determination of the lead and uranium."¹²⁵

Experience seems to show, according to Holmes, that thorium minerals give unreliable indices of age because some original lead is apt to be found in such minerals with the lead originating from uranium. The degree of admixture of original lead doubtless varies with the region and also the mineral. Its quantity may be estimated by a careful determination of the atomic weights, since the original lead appears to be mostly not derived from the uranium series. The uraninite of the Llano region is

¹²⁵ Am. Jour. Sci., vol. 23, 1907, p. 82.

sufficiently abundant, so that this test should be applied. The analyses which have been given, however, carry internal evidence that in the Llano region such original lead must be very small in quantity. In the minerals where the percentage of uranium lead is small and thorium is large the original lead should notably modify the lead-uranium ratio. Now, in analysis number 17, U is only 2.28 per cent, Pb is 0.45, and ThO_2 is 8.75. The Pb/U ratio is nevertheless only .195, which is but one-sixth greater than the most probable value. The presence of .08 per cent of original lead would account for this increase in the ratio, which is but one-one-hundredth of the ThO_2 present. On the other hand, analytical errors which come in with the determination of small quantities may be more important than original lead. Furthermore, the agreement of the ratio, as derived from four analyses and three different minerals which show great ranges in the amounts of uranium and thorium, is another indication of the reliability of the ratio and the smallness of the amount of original lead.

On assigning weights to the several determinations, the greater weight should be given to the minerals high in uranium, since this decreases the errors due to original lead and to analysis. Some slight and variable amount of original lead may be granted in all of these minerals. Therefore the best value of the ratio for the Llano region may be taken as .165. This corresponds to an age of 1,125,000,000 years.

Explanation of previous discordant results.—Having reached this conclusion as to the value of the ratio in the uraninite of the Llano region, attention must be turned to an explanation of the entirely different conclusion reached by Becker and quoted on a previous page. In the six analyses used by Becker no two give similar ratios and these range in value from .167 to 1.147. As Becker does not state that Boltwood had used four analyses giving accordant ratios from this region, the reader, unless intimately familiar with Boltwood's article, would assume that no analyses from the Llano County minerals give accordant results. How different this is from the facts has been shown on the previous pages. Becker, for some unknown reason, avoided using two ratios of Boltwood's list and apparently made an arithmetical blunder in recomputing the lead-uranium ratio from a third. Instead of getting .18, as Boltwood did, or .176, as computed by the writer to another significant figure, Becker derives a ratio of .3894. Thus, if Becker had included correctly all of Boltwood's list, there would have been four highly accordant ratios in a total of eight—a very different result from no two similar ratios among six analyses.

Let attention be given next to the four analyses used by Becker which Boltwood did not use. On page 864 the six analyses which are the basis of Becker's conclusions are listed, not in the order given by Becker, but in the order of decreasing uranium content. It appears also that this is the order of the *increase* in the lead-uranium ratio. As the uranium in the four additional analyses is but 6.06 per cent in the first and ranges in the remaining three from 1.45 down to the small quantity of 0.79 per cent, the relations clearly indicate the worthlessness of these analyses as tests, compared to minerals as high in uranium as are uraninite and mackintoshite; yet, as Becker does not give in his article the per cents of lead and uranium, but only their ratio, this conclusion could not be suspected from his paper. The thorium in the last three analyses greatly exceeds the content of uranium. Some original lead is suggested by the regular increase of ratio with decrease in uranium. The amount of original lead implied, provided the analytical work is very accurate, would be from approximately 0.5 to 1.0 per cent. Small errors in the analyses would, however, greatly change the ratios between quantities so small, and seems to the writer to be probably the more important factor. The small changes which are likely to have resulted from the incipient alteration so common in these minerals would also greatly affect the results. That we may have to look to analytical errors and incipient alterations more than to original lead for the explanation is suggested by the fact that gadolinite, a silicate of the rare earths from the same region, shows in its analysis by Mackintosh neither uranium nor lead. No thorium is present either, but Ce_2O_3 occurs to the extent of 2.66 per cent. As cerium is very similar to thorium in its chemical properties, original lead might be expected to accompany it if it accompanies thorium. The same is true of rowlandite.¹²⁶ Hess gives a complete list of the minerals found at this locality.¹²⁷ Although chalcopyrite, pyrite, spalerite, and molybderite are listed, galena does not appear. It appears, then, that original lead must have been very rare in the solutions which gave rise to these minerals.

From this examination of the evidence it is seen that the four analyses rejected by Boltwood but used by Becker are, as Boltwood stated, not suitable for throwing any definite light on the lead-uranium ratio for Llano County.

Attention must next be given to the explanation of the discordant ratios for the same region reached by Holmes, whose list is as follows:¹²⁸

¹²⁶ Bull. 419, U. S. Geol. Survey, 1910, p. 276.

¹²⁷ F. L. Hess: Minerals of the rare-earth metals at Barringer Hill, Llano County, Texas. Bull. 340 D, U. S. Geol. Survey, 1908, pp. 63-65.

¹²⁸ A. Holmes: Radioactivity and the measurement of geological time. Proc. Geologists Asso., vol. xxvi, part 5, 1915, p. 303.

TABLE D

*Radioactive Minerals from Llano County, Texas, United States of America*¹²⁹

Analyst.	Mineral.	Lead.	Uranium	Pb/Ur.
1. Mackintosh.....	Yttrialite	0.8	0.71	1.13
2. Mackintosh.....	Yttrialite	0.8	0.75	1.07
3. Mackintosh.....	Fergusonite	1.3	1.28	1.01
4. Hillebrand.....	Yttrialite	0.76	1.5	0.51
5. Mackintosh.....	Fergusonite	1.8	6.14	0.29
6. Hillebrand.....	Mackintoshite	3.65	19.6	0.186
7. Mackintosh.....	Cleveite	10.25	55.2	0.186
8. Hillebrand.....	Mackintoshite	3.47	19.7	0.176
9. Hillebrand.....	Uraninite	9.4	55.0	0.170
10. Mackintosh.....	Nivenite	9.45	56.1	0.168
11. Mackintosh.....	Bröggerite	7.82	67.2	0.116
12. Mackintosh.....	Thorogummite	2.01	19.7	0.102

Number 1 appears to be F of Becker's list.

Number 2 the writer has not been able to identify.

Number 3 is E of Becker's list.

Number 4 is D of Becker's list.

Number 5 is C of Becker's list.

Number 6 appears to be from an incomplete analysis by Hillebrand: *American Journal of Science*, volume 46, page 101, analysis *b*. The thorium and rare earths were lost, and Hillebrand states that the percentage of UO_2 would be slightly increased by uranium which was not separated from the earths. The analysis therefore has no value as compared with number 8.

Number 7 is not from Llano County, but apparently from Norway. It is given on page 482, *American Journal of Science*, volume 38, 1889, for purposes of comparison with nivenite. The analyst was Lindström, as given in Dana's *System of Mineralogy*, edition of 1911, pages 890, 891. The responsibility for the error rests in greater part on Mackintosh, as it is only by reading the text that one discovers that this is not the analysis of a local mineral. Dana also was misled and incorrectly lists it as coming from Texas.

Number 8 is B, Becker's list, and number 16 of Boltwood's list.

Number 9 is number 14 of Boltwood's list.

Number 10 is A, Becker's list, and number 15 of Boltwood's list.

Number 11 is another Norwegian mineral given by Mackintosh for comparison with nivenite. The analyst was Blomstrand. The same errors have been made as in number 7.

Number 12, thorogummite, occurs as a yellowish brown alteration product of mackintoshite. It is thoroughly oxidized and hydrated. It seems to be a product of recent oxidizing waters, and although it retains a chemical resemblance to the original mineral it has lost over 1 per cent of its lead. According to the calculations of the writer, the uranium is 18.76 per cent, not 19.7, as Holmes has it. This is due to the lesser proportion of uranium in the higher oxide. The uranium has therefore also decreased about 1 per cent, but an

¹²⁹ *Am. Jour. Sci.*, vol. xxviii, 1884, pp. 431-433; vol. xxxviii, 1889, p. 480; vol. xlv, 1893, p. 98.

equal elimination of both lead and uranium will make a large difference in the ratio. From the nature of the mineral, apart from the chemical analysis, it is clearly unsuited for the present purpose.

Eliminating nine of the twelve analyses from Holmes' list for reasons given above, leaves numbers 14, 15, 16 of Boltwood's list and gives for this remainder a highly accordant ratio. These appear to serve, therefore, as a reliable means of measuring the age of the Llano series and add their weight to the value of the method.

PART VI.—CONVERGENCE OF EVIDENCE ON GEOLOGIC TIME AND ITS BEARINGS

METHODS OF TESTING THE AGES GIVEN BY RADIOACTIVITY

In the last third of the nineteenth century physics, in the embodiment of its leaders, Kelvin, Helmholtz, Tait, and others, spoke with assurance on the limits of geologic time. Geologists sought to meet their demands, in so far as they could, but such men as Huxley, Geikie, Goodchild, and others, giving greater weight to the geologic evidence, refused to accept the restrictions which were set. We have lived to see unsuspected sources of energy discovered, stupendous in amount, which wholly remove the former limitations on the age of the earth and set new boundaries far beyond what, to most geologists, has seemed the testimony of the evidence.

After the one experience in the fallibility of physical argument notwithstanding its mathematical character, it would certainly be unwise for geologists to accept unreservedly the new and larger measurements of time given by radioactivity. There may be here, also, factors undetected and unsuspected which vitiate the results. The radioactive measurements, however, can and should be tested by the degree of concordance or discordance of the several results when compared with each other, and also with independent lines of evidence, especially geological.

In the preceding parts of this paper a reexamination has been made of these various lines of evidence. This concluding part will bring these results together and point out what seem promising fields for future investigation. The first conclusion of importance is the essential lack of uniform rate of erosion and sedimentation through geologic time. The introduction of the idea of rhythm as ever-present in geological processes in here made fundamental. It is seen on applying this to the present condition of the earth, as compared to past geologic time, that there exists at present a very unusual rate of aggregate erosion. Joly, overlooking the significance of composite rhythms, holding to the essential uniformity of geologic processes, and, furthermore, regarding the present rates as

representative of all time, concluded that it was impossible to accept the results based on the hypothesis of the uniformity of radioactive disintegration. He pointed out that this would imply that the present rate of supply of sodium to the sea was from ten to fourteen times the mean rate throughout past time. This seemed to him so impossible that to his mind it was easier to think of some unknown factor modifying the rate of atomic disintegration and resulting in a marked slowing of atomic decay with increasing age of the uranium mineral. It has been shown, however, on geologic grounds that there is good evidence for holding that the present rate of denudation is ten or fifteen times the mean rate which has existed since the opening of the Paleozoic. There is thus brought about a general accordance between independent lines of evidence.

There is seen to be even less justification for Becker's assumption that the contribution of sodium from igneous rocks to the sea has been regularly decreasing with the passage of time. So far as the stratigraphic evidence goes, it may or may not have had a higher mean rate in the Precambrian. Areas of Archean rock were then, it is true, more widely exposed, but the repeated baseleveling implies long periods when the lands had been worn low and erosion was very sluggish. Through much of the Paleozoic and Mesozoic, however, the evidence is clear that the continents were widely covered with seas or their deposits, and that the relatively small areas which supplied the waste were generally of low relief. This paleogeographic interpretation is distinctly against the postulate of a regular decrease of new sodium through geologic time, especially a decrease following a logarithmic curve.

The question of the uniformity of rate of atomic disintegration, which is the basis of all calculations on the age of radioactive minerals, has been discussed and, although in the nature of things, a uniformity of disintegration of uranium through geological time can not be directly demonstrated, the evidence from the measured rates of decay of its products points strongly to a similar uniform rate for the parent element. Nothing is known to support a hypothesis that there is an increase in stability of unstable atoms by a process of aging. The temperature and pressure limits, through which the uranium minerals have existed since their formation, are not greater than those within which its more unstable products have been studied in the laboratory. The effects of the profound temperatures and pressures of the earth's interior are, as yet, wholly unknown, but the conditions which exist within the outer crust have been duplicated by experiment.

But may not these moderate ranges affect the rate of disintegration of the more stable parent? That can be tested by geological evidence. If

uranium minerals well adapted for age determination and of a well determined stratigraphic position, such as the Devonian, are found in different regions to give notably different ages, it may be an indication of inhibition of disintegration beyond certain limits of temperature and pressure which have existed in these formations through a part of their existence. Unfortunately the data are as yet too meager for this test to be so precisely applied. Most of the uranium minerals come from formations whose stratigraphic positions are not closely known, and they represent a wide range of geologic occurrence. There is another test, however, which can be reasonably well applied. That is the test of proper sequence. If the rate of disintegration of uranium is altered by physical conditions within a few miles of the surface, then, in a considerable number of instances, some range in the lead-uranium ratio might be expected within the minerals of a single district; but the more searching test is found when the measurements of the age of minerals of widely different regions and stratigraphic positions are assembled according to sequence of age as determined by the radioactive transformations. It would be expected that, if variable rates of disintegration prevailed, the geologically younger mineral would in some instances show a greater amount of disintegration products and indicate an apparently greater age. With a wide range in age, with many points determined, and a large list of minerals, this argument begins to assume great force, notwithstanding considerable indefiniteness in the geological evidence regarding the exact stratigraphic position of many of the minerals.

This test could be, and was, applied to the first paper on the subject, published by Boltwood in 1907. It showed that his work bore internal evidence of the essential correctness and importance of the hypothesis of the lead-uranium ratio as a means of determining age, though a number of subordinate and modifying questions remained to be settled, especially in regard to the presence of various kinds of lead. This internal evidence was stated by Boltwood, in 1907, as follows:

"The actual value of the ratio varies considerably for the primary minerals from different localities, the maximum value being about six times the minimum. It is beyond the writer's province to discuss the data bearing on the geological ages of the different deposits; but he is indebted to Professor Joseph Barrell, of Yale University, for the statement that, so far as the knowledge of the latter extends, the relative values of the ratios are not contradictory to the order of the ages attributed by geologists to the formations in which the different minerals occur.

"From the data which have been presented in the preceding tables, it is apparent that the requirements for a disintegration product of uranium are fulfilled by lead within the limits of probably experimental error. On the basis

of this evidence the assumption would appear to be justified that lead is the final product of uranium."¹³⁰

As has been noted, Becker argued that the sequence of geological age was in certain examples directly opposed to Boltwood's conclusions, but in a preceding section it has been shown that Becker's conclusions were based on a series of errors.

With an increasing recognition of the importance of the radioactive methods, it is to be hoped that the problem will be directly attacked, and from the standpoint of geologic science, rather than left almost wholly as incidental investigations of the radio-chemist. Minerals high in uranium are, however, rare. Those with only accessory uranium are seen to be relatively unreliable because of the small amount of uranium, the still smaller amount of uranium lead, and the large changes in the ratio which may result from analytical errors, original lead, temporary thorium lead, or other causes.

It would seem, however, that the ratio of helium to uranium and thorium might be made of high supplemental value in a manner which, so far as the writer is aware, has not been used. Holmes has pointed out that the helium content of uranium and thorium minerals is always less than the amount of helium which has been generated, because of the leakage of the gas. Nevertheless, in fresh rocks which contain such minerals, no matter what their age may be, there is reason to believe that the helium is mostly present, though in part outside of the parent mineral. It is known that fresh unbroken rock is practically impermeable, as is shown by the storage of carbon dioxide under high pressure in microscopic vesicles. The very freshness of the rock proves, furthermore, the lack of permeation of surface waters. The helium generated in the small minerals, such as zircon, will be in part ejected by the initial velocity of the atom; in part it will slowly diffuse into the adjacent minerals, owing to the accumulating excess of vapor pressure within the mineral. In an uncleaved rock it will, however, practically all remain within a very limited distance. In those parts of a rock-mass where uranium and thorium are concentrated in appreciable quantity, the amount of new helium would be large in comparison with original helium. In a rock containing zircon, biotite, minerals of the rare earths, or other minerals holding uranium or thorium, if a cube several centimeters in diameter were cut from the fresh rock and the whole subjected to analysis, the amounts of uranium, thorium, helium, and lead might be ascertained by

¹³⁰ B. B. Boltwood: On the ultimate disintegration products of the radioactive elements. Part II.—The disintegration products of uranium. *Am. Jour. Sci.*, vol. xxiii, 1907, pp. 83, 84.

virtue of the large volume of material, and the quantity of helium should approach more nearly the theoretic amount.

AGE POINTS GIVEN BY URANIUM MINERALS

By diligent search the evidence of age based on uranium minerals can, without doubt, be greatly increased. With that which is at present available it is desirable, however, to construct a tentative table of geologic time.

In regard to the table of ages given on page 846 by the helium ratio and quoted from Holmes after Strutt, it should be noted that certain of the ages are open to question. In the Eifel, New Zealand, and Auvergne occurrences the zircons may have been derived from older rocks.¹³¹ The Pliocene age of the Campbell Island, New Zealand, formation is, furthermore, open to question. The hematite from County Antrim, Ireland, offers a maximum age, 30,800,000 years, for a Tertiary occurrence of a helium mineral, and, furthermore, occurs associated with leaf beds which serve to fix the age within comparatively narrow limits. Heer originally classified these beds as Miocene. With the separation of the lower Miocene as Oligocene they become Oligocene. Gardner, however, maintained later that they were lower Eocene. In order to obtain the latest opinion the writer submitted the question of their age to Professor E. W. Berry, who kindly replied as follows:

"Regarding the age of the Antrim basalts with the intercalated leaf beds—Heer's Miocene was of course 'old Miocene'—that is, Oligocene. I am quite sure that their age is not Lower Eocene, as J. Stanley Gardner held, and it is my opinion that they are either Upper Eocene or Lower Oligocene, and by that I mean either Bartonien (as restricted to the Upper Bartonien after segregating the Auversien below) or Sannoisien (Latterfien). It is increasingly difficult to paleobotanically differentiate the *temperate floras* of late Eocene and early Oligocene times, although it is easy enough in lower latitudes, as, for example, in southern Europe or southeastern North America.

"I think the evidence is rather good for considering all of the far northern basaltic sheets associated with the plant beds of the 'Arctic Miocene flora' (Mull, Iceland, West Greenland, etcetera) as essentially synchronous and as contemporaneous with the most tropical floras and marine faunas of lower latitudes, as, for example, those of the Jackson and Vicksburg of our Southern States. Correlation by old-fashioned methods is not possible for a variety of reasons, chiefly since Heer, who was the original describer of most of the Arctic floras, brought to that study a profound acquaintance with the Miocene floras of central Europe, and in subsequently dealing with these more fragmentary northern floras he often saw resemblances that did not exist. Both

¹³¹ R. J. Strutt: The accumulation of helium in geological time. III. Proc. Royal Soc. London, vol. 83, ser. A, 1910, p. 301.

in America and in Europe we commence to get a northward spread of plants from the equatorial regions in the Lower Eocene (for example, in the Wilcox). This is emphasized in the Middle Eocene (Claiborne and the corresponding Upper Lutetian and Auversien) and culminates in the Upper Eocene and Lower Oligocene. Several of the Lower and Middle Eocene types of our Gulf States appear in the flora of west Greenland and in the Kenai flora of Alaska, etcetera, and, granting the time necessary for dispersal and considering the forested condition of the country north to latitude 75°, it seems to me that this should make these northern floras correspond to the time when the most tropical floras and faunas flourished farther south."

Let it be assumed that the beds are Lower Oligocene and that but little helium has been lost, or that they are Upper Eocene and somewhat more helium has been lost. The length of the whole of Cenozoic time may then be regarded as 50 per cent longer, giving 55,000,000 to 65,000,000 years. This is obtained by considering from stratigraphic evidence that the Eocene constitutes at least one-third of the Tertiary period. The mean figure of 60,000,000 years is twenty times as long as the conventional estimate of 3,000,000 years, but a discussion has been given in a preceding section which goes to show that the geologic evidence demands that this figure of 3,000,000 should be increased to the order of magnitude set by the helium measurement. The two independent lines of investigation and the nature of the helium measurement are in sufficient accord to warrant accepting the round figure of 60,000,000 years as a provisional estimate for the length of Cenozoic time.

We come next to a group of Upper Paleozoic occurrences in which the precise geologic position, or the possible presence of some original lead, is in most cases undetermined.

First come the Glastonbury uraninites, previously discussed in this article. Emerson regards the age of the associated igneous rocks as late or post-Carboniferous. They are clearly Upper Paleozoic, but the granitic intrusions in New England and the Maritime Provinces are known to range from the Devonian onward, and some of them may be dated from the Taconic disturbance at the close of the Ordovician. So far as the writer is aware, the schists cut by the Glastonbury pegmatites might possibly be as early as sub-Carboniferous, the Mississippian period of present American nomenclature, but there is no real evidence for Holmes' positive statement that the granite intrudes Lower Carboniferous strata. Caution and latitude are desirable in this regard. The lead content averages about 3 per cent, giving reliable determinations, and the lead-uranium ratio is .041, giving an age of 300,000,000 years. No determinations of the atomic weight of the lead have been made, but the lead-uranium ratio is very constant in the several analyses, suggesting that

but little is present. The geological age can not be later than the close of the Permian. Uraninites from the Carolinas gave Richards and Lemberg an atomic weight of 206.4. This suggests that some of the lead of those uraninites may be primary, as this is higher than the lowest atomic weights which have been found for uranium lead. The 300,000,000 years for the Connecticut uraninites should therefore be a maximum. In the table as given on a following page for the column of maximum ages it is seen that for any probable correction in age due to original lead the minerals would still fall within the Carboniferous, including Pennsylvanian and Permian. In the column of minimum ages the Glastonbury uraninites fall into the close of the Devonian. Although this does not seem so probable, it is not positively excluded by the evidence. The column of minimum ages is based for the Paleozoic on the Middle Devonian age of the uranium minerals from Brevig, Norway. The two determinations, although in the proper sequence of age, do not agree closely with each other in the amount of time which elapsed between them. Another possibility is that the Glastonbury uraninites are in reality late Carboniferous, with an age of about 200,000,000 years, but with one-third of the lead original, giving an age about 50 per cent too great. More probably the truth lies in some adjustment between several of these factors. On the whole, the column of minimum ages should for the present be regarded as probably nearer to the truth. Nevertheless, uraninites, from the Carolinas, with an estimated correction for primary lead made by means of the atomic weights, give an age between 310,000,000 and 345,000,000 years. Their geologic age is, however, unknown, further than that they are now regarded as Paleozoic and probably Upper Paleozoic. Their most probable position is Carboniferous, either Pennsylvanian or Permian.

The next older determination is of Devonian minerals from Brevig, Christiania district, Norway. It is seen from the tables previously given, page 853, that the per cent of lead is very small, ranging in twelve determinations from .001 to .037 per cent. The lead-uranium ratio, ranging from .040 to .062 in different minerals, nearly constant to the second decimal place, considering the small amounts of lead, may be taken as evidence of the accuracy of the analytical work by Holmes, and also of the absence of more than a trace of original lead. Holmes and Lawson give an elaborate discussion of this question in a recent paper,¹³² showing that thorium-lead is not present. Holmes gives the mean age as 370,000,000 to 380,000,000 years, which should be corrected to 345,000,000

¹³² Lead and the end product of thorium. *Philosophical Mag.*, 6 ser., vol. 28, 1914, pp. 823-840.

to 355,000,000 years. If, however, the anomalous pyrochlore with Pb/U ratio of .062 is omitted for reasons stated by Holmes¹³³ and the analyses with less than 0.14 per cent of uranium are rejected because of lessened analytical reliability, a lesser age is obtained. By weighting the remaining six analyses according to the content of uranium a mean lead-uranium ratio of .043 is obtained by the writer, or from the whole list of analyses thus weighted .045. These ratios correspond to ages from 315,000,000 to 330,000,000 years. It would seem safer to take the age as no higher than the latter of these figures.

Regarding the geological position, Holmes makes the following statement:

"In this area there is a nearly complete sequence of early Paleozoic rocks. Above these strata there are a few beds of red sandstone of Lower Devonian age. Over these beds and intercalated with them are lava flows; and, finally, penetrating the whole mass, representing a later phase of this period of igneous activity, are great intrusions of plutonic rocks. Among the earliest of the intrusions is a series of thorite-bearing nepheline syenites. Brögger believes them to be of Middle or Lower Devonian age, most probably the latter. The minerals occurring in them are, in many instances, notably radioactive, and thus they afford an admirable series in which to investigate the consanguinity of lead and uranium. Several of these minerals were obtained from Brevig, and estimations of these elements in each case were made."¹³⁴

Arthur Holmes adds later:

"A recent discovery of *Osteolepis* proves that the sediments upon which the igneous rocks are intruded belong to the Middle rather than the Lower Devonian, and the age assigned to the nepheline syenites from which our minerals were taken is not far removed from this, being almost certainly Middle Devonian."¹³⁵

It should be said, however, that *Osteolepis* is not clearly Middle Devonian, but belongs more precisely to the Middle Old Red or Orcadian deposits. These are probably somewhat older than the marine division of Middle Devonian, the greater break, corresponding to Middle Devonian time, occurring between the Middle and Upper Old Red formations. The minimum table of geologic time, on page 885 of this article, is arranged so that 330,000,000 years falls early in the Middle Devonian; 315,000,000 years falls early in the Upper Devonian. In the column of maximum ages this age of 315,000,000 to 330,000,000 years falls into the first half of the Pennsylvanian, a period of great diastrophism. This shift in age brings to attention a discrepancy in the evidence noted also in the discus-

¹³³ Proc. Royal Soc. London, vol. 85, ser. A, 1911, p. 254.

¹³⁴ Proc. Royal Soc. London, vol. 85, ser. A, 1911, p. 251.

¹³⁵ Philosophical Mag., 6 ser., vol. 28, 1914, p. 831.

sion of the Glastonbury, Connecticut, uraninites. The Brevig, Norway, rocks are indicated as only 15,000,000 to 30,000,000 years older than the Glastonbury uraninites; but according to the geological positions which have been assigned to the one by Brögger and to the other by Emerson, all of the Pennsylvanian and Mississippian periods and parts of the Permian and Devonian lie between the two. Taking the ratios of ages of these periods to the whole length of time as given by stratigraphical studies, there should be from 100,000,000 to 150,000,000 years between them. This discrepancy may be reconciled by finding that some original lead is in the Glastonbury uraninites, or the stratigraphic ratios may be seriously in error, or, what is more probable, the geological position of one or both is in considerable error. As has been pointed out, but little is positively known regarding the age of the Glastonbury uraninites, further than that they are Upper Paleozoic. In regard to the geological position of the Brevig, Norway, uranium minerals, they belong to the second series of igneous rocks in a total of six series. The first series is interbedded as extrusives in the Middle Old Red sandstones, and Brögger regards the second series as related and but slightly younger. The actual age of the younger series is, however, not fully proven.¹³⁶ It appears, nevertheless, that greater weight should be attached to the Brevig than to the Glastonbury occurrences. The column of minimum ages may be regarded as having greater weight than the column of maximum ages.

Of course, the question might also be raised here if the discrepancy does not throw doubt on the fundamental assumption of the uniform rate of decay of radioactive substances through geological time. The whole body of evidence is, however, sufficiently in accordance to indicate that this is the more improbable explanation.

The next older series of minerals comes from Branchville, Connecticut, and consists of uraninites giving in four analyses a lead-uranium ratio of .053 to .054,¹³⁷ the mean corresponding to an age of 390,000,000 years. The atomic weight of the lead is not known, but the ratio is highly accordant in the several analyses, suggesting that adventitious lead is probably low. The associated granites can not be older than the end of the Ordovician nor younger than the close of the Permian. By assigning them to the Taconic disturbance at the end of the Ordovician, a diastrophic movement which is known to have greatly disturbed the rocks immediately to the west, in the Hudson Valley, they are brought into this place in the column of maximum ages. In the column of minimum ages the Branchville uraninites fall in the early Devonian. If the presence of

¹³⁶ W. C. Brögger: *Die Mineralien der Syenitpegmatitgänge der Sudnordwegischen. Augitund Nephelin-syenite.* Leipzig, 1890, pp. 43-81.

¹³⁷ B. B. Boltwood: *Am. Jour. Sci.*, vol. xxiii, 1907, p. 79.

original lead should reduce the age to 360,000,000 or 370,000,000 years, the intrusion of the associated granites would fall into the Middle or Upper Devonian, times when granitic intrusions are known to have occurred in Nova Scotia and which were marked by notable diastrophism in the northern Appalachians, as reflected by the greatly stimulated sedimentation.

The next older granite whose age is accurately measured by the lead-uranium ratio is that of Morogoro, German East Africa, giving a ratio of .093 and an age of 660,000,000 years. The atomic weight of the lead is 206.04, showing it to be wholly uranium lead. The age relations are, unfortunately, not definitely known.

The next determination in the sequence of age is that from a series of analyses from the Moss district of south Norway. The lead is wholly uranium lead, as proved by its atomic weight, and the large per cent of uranium gives high reliability to the result. The weighted lead-uranium ratio is .132, corresponding to an age of 925,000,000 years, the age of the post-Kalevian granites.

At a period still more remote in time occurs the most distinctive group of Precambrian granites. The percentages of lead and uranium from an analysis of a uraninite from Villeneuve, Ontario, have been recomputed by the writer, allowing for the two states of oxidation of the uranium. The result is somewhat different from that given by Holmes, the following figures being obtained:

$$\text{Pb} = 10.46, \text{U} = 64.74, \text{Pb/U} = 0.162$$

in contrast to the ratio of 0.17 given by Holmes. From the Llano district in Texas a lead-uranium ratio of 0.167 to 0.170 was obtained as the most reliable. From the Arendal district in Norway a mean ratio of 0.168 to 0.169 has been derived by the writer by a reinspection of the original data. Holmes gives ratios for two other regions, but they depend on much smaller amounts of uranium. From Ytterby, Sweden, two ratios of 0.17 and 0.15 were obtained and two ratios of the same values were found for two localities in Mozambique.

These constitute the oldest reliable group of determinations and they show a remarkable concordance among themselves. A ratio of .165, corresponding to an age of between 1,100,000,000 and 1,200,000,000 years—more exactly, 1,125,000,000 years—satisfies the data from Canada, Texas, Norway, Sweden, and Africa. The geological relations show in Canada that the intrusions at Villeneuve belong to one of the Middle Precambrian granites—post-Sudburyan or post-Huronian. In the Arendal district the indications are similar, the granites being either post-Bottnian or post-

Kalevian. At Ytterby the intrusions are given as Ser-archean and equivalent in age to the post-Kalevian, but the Moss granites, with a well determined age of 925,000,000 years, are also post-Kalevian. The data for the Ytterby region are thus discordant, but they rest on two analyses in which the lead is given by Holmes as only 0.18 and 0.36 per cent, respectively, a lesser lead-uranium ratio and consequent lesser age being given by the higher and more reliable percentage. The Ytterby granites may then be provisionally regarded as not properly belonging to the group whose age is 1,125,000,000 years.

The number of determinations is not yet large enough to make it clear if the Precambrian granites over the world fall into a series of sharply defined groups. If they do, the decay of uranium minerals will give the most valuable method of Precambrian correlation. At present it appears that the group of granites whose geological position is designated as post-Kalevian, post-Huronian, or pre-Animikean is approximately 925,000,000 to 950,000,000 years old, and that the group variously designated as post-Bottnian, post-Sudburyan, or post-Temiskaming has an antiquity of 1,125,000,000 to 1,150,000,000 years.

Back of these lie still older granite-gneisses—the Laurentian system of Canada, the post-Ladogian of Fenno-Scandia—and these in turn were intruded into older sedimentary and effusive igneous series. It seems probable, then, that the oldest known rocks are as much as 1,400,000,000 years of age.

Beyond these most ancient milestones lies the Primordial era, whose stratigraphic record has been destroyed by engulfment in magmas from below and by repeated cycles of erosion from above. As to its length, there is no indication other than that the oldest known rocks which mark the beginning of the following era contain sediments which testify to an earth surface on which air and water played their parts, much as in later times. Crust, ocean, and atmosphere had by the opening of the Archeozoic already attained a condition of stability.

ADJUSTMENT WITH GEOLOGIC EVIDENCE

With these various control points more or less definitely established by means of the age of uranium minerals, a time table may be constructed for the eras of fossiliferous rocks, using the evidences of the quantity of erosion and of sedimentation to assist in establishing the relative lengths of the periods. The periods of a single era may be thus measured, but it has been argued that the mean rate of erosion and sedimentation for the several eras was quite different. In the stratigraphic records of the older eras there is, furthermore, a larger proportion of lost intervals.

Another line of control is given by the recurrences of crust movements which separate the periods. These pulse through earth history, apparently with some degree of regularity, and constitute the diastrophic basis for the division of the eras into periods.

The application of this principle may be seen in the Lower Paleozoic. From the basis of stratigraphy, the Cambrian and Ordovician are concluded, on the whole, to have been times characterized by widely flooded continents. The lands were restricted in area and low in relief, yet wide and thick limestone formations accumulated, indicating the passage of geologically long intervals of time. A better appreciation of the extreme length of these two periods is given by a close study of the diastrophic record. Schuchert and Ulrich, tracing out disconformities as revealing the coming and going of the epeiric seas, and delimiting the periods on this basis, have found that both Ordovician and Cambrian consist of several periods. On this basis Schuchert has recently subdivided the Ordovician into four new periods and the Cambrian into three.¹³⁸ This explains the unusual length, as given by stratigraphic evaluation.

Thus, adjusting the evidence regarding land area, relief, rate of deposition of sandstone, shale, and limestone, valuation of disconformities and unconformities, and fitting these to the ages determined by uranium minerals, there may be constructed a geologic chronology. This evidence is brought together in the following time table, the ratios for the periods being obtained from a series of papers by various geologists in which these have been individually estimated. A discussion of these ratios is next in order.

Dana, seeking the maximum thicknesses, taking each foot of limestone to be the equivalent of five feet of sandstone and shale, and assuming a uniform rate of accumulation throughout geologic time, obtained certain ratios for the successive periods. H. S. Williams, in 1893, taking into consideration the newer knowledge regarding the magnitude of Cambrian and Ordovician sedimentation, slightly modified these ratios,¹³⁹ his results being given in the following table, page 884. Walcott made at this time a careful study of the Paleozoic deposits of the Cordilleran sea and obtained a somewhat different set of figures,¹⁴⁰ the basis for which has been discussed in another section of this article. He did not attempt to give an estimate for each period, but dealt with the eras only. He considered

¹³⁸ C. Schuchert: Correlation and chronology on the basis of paleogeography. *Bull. Geol. Soc. Am.*, vol. 27, 1916, p. 496.

¹³⁹ H. S. Williams: The elements of the geological time scale. *Jour. Geol.*, vol. 1, 1893, pp. 283-295.

¹⁴⁰ C. D. Walcott: Geologic time as indicated by the sedimentary rocks of North America. *Jour. Geol.*, vol. 1, 1893, pp. 639-676.

that the relative lengths and the order of magnitude were satisfied by the following:

Era	Time duration Years
Cenozoic, including Pleistocene.....	2,900,000
Mesozoic	7,240,000
Paleozoic	17,500,000
Algonkian	17,500,000
Archean	10,000,000 (?)

Schuchert, following Walcott's results for the length of the eras, published in 1910 an estimate of the proportionate time to be given to each period from the beginning of the Paleozoic.¹⁴¹ These figures are listed in the following table, page 884. Lately, however, in a still unpublished manuscript,¹⁴² he has revised his ratios and concedes a far longer duration for geologic time.

Sollas, in 1909, revised upward his previous estimates, giving 80,000,000 years as the most probable value of the age of the earth, as determined by the salt of the sea. He still estimated the duration of each period by means of the maximum thicknesses of sediments known in each, taking one foot as equivalent to a century and making up the balance of the 80,000,000 years by means of the time value assumed for unconformities. Following his method of measuring time by means of the maximum known thicknesses of sediments accumulated in each period, Sollas would with present data presumably raise the Jurassic to 2,000,000 years, since in northwestern Alaska the Cape Lisburne section shows about 20,000 feet of sediments, of which 15,000 bears plant fossils showing Jurassic age.¹⁴³ It would appear on this basis that the estimate for the Triassic might also be raised, since the very thick Newark deposits are restricted to Upper Triassic time.

The estimates by these geologists may be greatly magnified, but the ratios are nevertheless of value as expressing their judgment as to the *relative* lengths of the periods by those who have made special studies of stratigraphy. They have been made on a uniformitarian basis, with a knowledge of the limitations set by Lord Kelvin, and without reckoning in the significance of rhythms, but they must form a starting point for any revision of the duration of the several periods. These authors place more reliance on the relative length of the periods as expressed by ratios,

¹⁴¹ C. Schuchert: Paleogeography of North America. Bull. Geol. Soc. Am., vol. 20, 1910, plate 101.

¹⁴² C. Schuchert: The earth's changing surface and climate. Chapter II of The evolution of the earth and its inhabitants. Yale Sigma Xi lectures for 1916-1917; to be published.

¹⁴³ A. J. Collier: Bull. U. S. Geol. Survey, Nos. 218, 259, 278, 1903, 1906.

NEW TABLE OF GEOLOGIC TIME

The following table shows the ratios for the geologic periods:

1.0 = 1,000,000 years

	Williams, 1893.	Schuchert, 1910.	Sollas, 1909.	Matthew, 1914.	Goodchild, 1896.	Barrell, 1917.			
						Minimum.		Maximum.	
						Each.	Total.	Each.	Total.
Recent.....	1	1.5	0.4	0.1	16.0	1	1	1.5	1.5
Pleistocene.....							1		
Pliocene.....	1	1.5	1.3	1.0		6	7	7.5	9
Miocene.....			1.4	3.0		12	19	14	23
Oligocene.....	1	1.5	1.2	2.0	77.4	16	35	16	39
Eocene.....			2.0	3.5		20	55	26	65
Cenozoic.....	3.00	3.00	6.30	9.60	93.40	55		65	
Cretaceous.....		2.7	2.4	.....	31.4	40	95	50	115
Comanche.....	4	1.8	2.0		72.6	25	120	35	150
Jurassic.....	3	2.25	.8			35	155	45	195
Triassic.....	2	2.25	1.7	.....	87.5	35	190	45	240
Mesozoic.....	9.00	9.00	6.9	40.0	191.5	135		180	

Permian.....		1.62	1.2	.....	45.0	25	215	40	280
Pennsylvanian.....	} 6	2.16	} 2.9	.....	31.8	35	250	50	330
Mississippian.....		2.70		.....	62.5	50	300	40	370
Devonian.....	5	1.98	2.2	.....	125.0	50	350	50	420
Silurian.....	4	1.80	1.5	.....	56.0	40	390	40	460
Ordovician.....	15	4.14	1.7	.....	57.0	90	480	130	590
Cambrian.....	15	3.60	2.6	.....	42.0	70	550	110	700
Paleozoic.....	45.00	18.00	12.10	.....	419.3	360		540	
Sum.....	57	30.00	25.3	.....	704.2	550		700	
Unconformities.....	.....	.....	14.7	.....	700	550			
Round number.....	60	30	40	.....				700	

rather than on an absolute length as stated in years. Their results have been brought together in the following table and the ratios are given a numerical value such that unity represents 1,000,000 years as their best judgment. Their results have been carried out to fractions of a million years in order that the sums should be consistent, but the fractions have no other significance, since these authors have disclaimed a belief in the reliability of any such exact estimates of time.

The data from the various lines of evidence are assembled in the table, the conclusions being expressed in the right-hand columns. That designated the minimum is regarded as the more probable, but it is desirable to give maximum and minimum estimates in order to prevent a single column of figures conveying the idea of a precision or certainty which is not yet attained. The date of the opening of the Paleozoic is the most uncertain feature of this table because of the lack of uranium minerals of early Paleozoic age. Certain Precambrian dates are much better determined. These may be listed as follows:

Intrusion of post-Kalevian granites 925,000,000 years ago.
Intrusion of post-Bottnian granites 1,125,000,000 years ago.
Intrusion of post-Ladogian granites 1,400,000,000 years ago.

The oldest of these rests as yet, however, on very meager data.

The ratios of the length of the three fossil-bearing eras to each other approach more nearly to the ratios given by Walcott in 1893, followed by Schuchert in 1910, than to those given by others, but the absolute lengths which are assigned are from 18 to 22 times greater. These absolute lengths approach nearest to the estimates of Goodchild.

In regard to the Precambrian, a difficulty is encountered in giving appropriate divisions. It seems probable that on the same basis of crustal revolutions attended by notable granitic intrusion on which the later eras have been established, there may be as many as four Precambrian eras following the unknown Primordial time. As no settled opinion prevails, either as to the number of these eras, the best division points, or their names, and as the proper correlation of widely separated regions is still open to doubt, there is given here merely a list of the dates and consequent time intervals between points determined by granitic intrusion. The Fenno-Scandian nomenclature is used because the radioactive measurements have been somewhat more fully determined with reference to it.

As to the degree of accuracy of the table: First, the absolute ages depend fundamentally on the determination of the radioactive constants. It does not seem likely that future research will change the half-value period of uranium more than 2 per cent. They depend, secondly, on the

presence of original lead or later alteration in the minerals by passing solvents or on analytical errors. The errors in these matters for some minerals have been shown to be small, under 5 per cent. For other minerals they may be several times as large. Third, the precise stratigraphic position is in many cases open to considerable doubt. This may introduce errors as high as 15 per cent of the total time. Fourth, the use of the stratigraphic ratios to supplement the radioactive evidence introduces another error affecting the ages of periods for which as yet no uranium minerals have been found. This may be rated as high as 15 or 25 per cent, but does not affect the determined points.

These several classes of errors are independent, so that to some extent they tend to offset each other. The divergence of the two columns marked minimum and maximum is intended to show about the latitude which the summation of the probable errors gives to the results, but, as stated before, the column of minimum figures should probably be given the greater weight.

CRESCENDOES IN DIASTROPHISM DUE TO COMPOSITE RHYTHMS

The distribution of time given in this new table brings out a notable regularity in the length of the periods, considering the Eocene and Oligocene to have the value of a single older period and the Cambrian and Ordovician as being equivalent to several of the later periods. The value of this rhythm of the periods ranges in general from 35,000,000 to 45,000,000 years, but the extreme limits are quite uncertain. The Comanche, for example, given a minimum length of 25,000,000 years, was a time of but moderate diastrophism. The rate of denudation may have been lower for it than for the adjacent periods, and if such were true the stratigraphic measurement of its length would give an underestimate unless the lower rate were considered. On the other hand, if the Mississippian, given here a length of from 40,000,000 to 50,000,000 years, should be subdivided into two periods, as Schuchert and Ulrich are inclined to hold, the length of these would appear to be not much greater than 25,000,000 years each.

The periods, 35,000,000 to 45,000,000 years in length, are delimited by epochs of notable diastrophism of an order of magnitude which Schuchert has named "disturbances." But the periods are subdivided by minor movements leading to "breaks" in the stratigraphic record, and are combined into larger groups constituting eras. The eras are terminated by periods in which the diastrophism is recurrent and reaches the proportions of a "revolution." The personal equation enters to a considerable extent in classifying the magnitude of these division lines, and a tendency

exists to restrict, in thought, the crust movements to the end of a division, be it epoch, period, or era; whereas in reality the movements pulse through a division, the larger oscillations subsiding in the stage of quiet, rising in increasing pulses to that culmination which marks the close of one division of time, then subsiding through the initial portion of the following division.

The stages of crust movements, according to the nature of composite rhythms, are grouped into diastrophic crescendoes and diminuendoes. Thus in the great clastic formations of the lower Cambrian, laid down chiefly in geosynclines, we see recorded the decadence of a great period of revolution which terminated the Precambrian. The mudstones and sandstones of the upper Ordovician show a reawakening of internal forces which led to the Taconic disturbance or revolution. The Silurian was a period of quiet as compared to the Devonian, and the Mississippian was quiet in comparison with the Pennsylvanian and Permian. The comparative quiet of Triassic and Jurassic times led up in the close of the Jurassic to a diastrophic movement of marked proportions in the Cordillera which subdivides the Mesozoic era into an older and a younger division; but this was followed by the still greater diastrophism of the Cenozoic, awakening as the Laramide revolution, and rising to even greater magnitude in the Neocene.

Thus, there appears to run through geologic time a recurrence of greater crescendoes which in their average period approach in round numbers to 200,000,000 years. This is seen in the Precambrian, in that the post-Bottnian-pre-Kalevian era is found, apparently with accuracy, by means of uranium minerals, to comprise 200,000,000 years. The following post-Kalevian-pre-Paleozoic time, covering about 400,000,000 years, has important granite intrusions within it, and is marked in its earlier and later halves by contrast, in the nature of sedimentation, which serve to subdivide it. The Paleozoic, whose length is not well known, but which may comprise about 400,000,000 years, has been similarly subdivided, though the place and number of the division lines have not been chosen alike by all geologists. Dana used the end of the Ordovician as the place of separation, calling the earlier section the Eopaleozoic, the later section the Neopaleozoic. These sub-eras are broken into either two or three well marked groups of periods.

In so far as diastrophism serves as a basis for correlation, the Laramide revolution includes the Paleocene, Eocene, and Oligocene epochs and constitutes one period—the Paleogene or Eogene of Schuchert. It corresponds to the Pennsylvanian in the sequence of the Neopaleozoic periods. The Miocene, the beginning of the Neogene, witnessed the birth of the

great Himalayan-Alpine mountain system from the geosynclines of ancient Tethys. Great movements took place also in western North and South America. The continents have been warped and the sealevel depressed in the Pliocene and Pleistocene to a degree not known to have occurred before since the earlier eras of earth history. Far-spreading glaciation and aridity have oscillated and rendered large areas of the lands almost or entirely uninhabitable. These conditions have by no means disappeared and the recent retreat of glaciation to high altitudes and latitudes must not be mistaken for the end of the period. In fact the upper Pleistocene appears to have shown a greater persistence of glaciation than was true of the middle or earlier parts of the epoch.

The Neogene should be used consequently as a term to include the Pleistocene and Recent, as proposed by Ulrich in 1911,¹⁴⁴ but its course should be looked upon as only one-half run. It is seen that the Appalachian revolution began with the opening of the Pennsylvanian period and pulsed through this and the Permian. The Laramide revolution began in the closing epochs of the Cretaceous, but it is only a part of a greater cycle of revolution whose convulsive phases have recurred with increasing magnitude through the Cenozoic, consisting of two periods, and whose end lies still hidden in the future, rather than revealed in the past. Comparing the march of diastrophism in the Cenozoic with that through the Carboniferous, beginning with the Pennsylvanian, it is seen that the present epoch, which the turning wheel of time will probably reveal to be but an interglacial stage of the Pleistocene, corresponds to about the middle of the Permian.

The Upper Cenozoic stands so close to us that we see it in detail, and conspicuously subdivided into epochs, emphasized by the rapid evolution of mammals; but the Permian was similarly subdivided, and if the Neogene were as remote from us in geologic time it would doubtless be seen in more accurate perspective in the whole history of the earth, as the period of revolution closing a great era which began with the Triassic. Taking the length of the Mesozoic from the minimum column of geologic time as 135,000,000 years, adding 55,000,000 years for the length of the Cenozoic and 10,000,000 years as yet to be fulfilled, gives to this whole Mesozoic-Cenozoic era a length of 200,000,000 years.

There is a human tendency, however, to seek for over-much regularity in nature and it is doubtful if much weight should be attached to this cycle of approximately 200,000,000 years. Although extremely suggestive

¹⁴⁴ E. O. Ulrich: Revision of the Paleozoic systems. Bull. Geol. Soc. Am., vol. 23, 1911, pp. 281-680; see pl. 26, p. 376.

of a new perspective, there are not enough terms, nor are they sharply enough defined, above those of lesser magnitude to give this indication more than such suggestive value. In regard to the lesser rhythms, consisting of the geologic periods and leading up to crescendoes of two or three geologic periods in span, the evidence is more clear. It is made apparent in this new time-table through the time-spacing which is necessary in order to bring adjustment between the radioactive and stratigraphic evidences. In such crescendoes, marking the liberation of forces pent up in the rigid body of the earth, we should not expect too much regularity of recurrence, nor similarity of expression, and yet such rhythms, the heart-beats of the earth-mother, running through her lifetime, must serve as the great division points determining the crises in the evolution of the protoplasmic life which she has born.

A graphic representation of these composite rhythms in diastrophism, showing their rise into crescendoes, is to be published by Professor Lull, to which he adds the graph of the pulse of life.¹⁴⁵

There are seen to be grounds for maintaining that, from the standpoint of diastrophism as a basis of correlation, the Recent is a part of the Pleistocene, and the Pleistocene an epoch of the Neogene period. The older Tertiary, or Paleogene, is a separate period, and both are divisions of the same order of magnitude as the four periods of the Mesozoic. They stand in somewhat the same relation to these earlier periods as the Permian and Pennsylvanian do to the preceding periods of the Neopaleozoic.

This brings out the difference between a classification founded on a diastrophic basis which begins an era with the *close* of a period of revolution and that founded on an organic basis. From the latter standpoint the Cenozoic, the Age of Mammals, is a separate era from the Mesozoic, the Age of Reptiles. But, for that matter, the reptiles date back into the Pennsylvanian. They seem there to occupy a place subordinate to the amphibians, but this is largely due to the fact that the coal swamps were the natural habitat of the amphibians; the drier uplands that of the reptiles. The sedimentation in the habitat of the amphibians accounts largely for the more abundant record of these lower forms. The aridity of the upper Mississippian must have been a stimulating cause, acting on ancestral amphibians, dependent on a life in water in embryonic and adolescent stages, which urged their transition into a class of vertebrates whose eggs were incubated in air and whose young dropped from

¹⁴⁵ R. S. Lull: The pulse of life. Chapter IV of the evolution of the earth and its inhabitants. Yale Sigma Xi lectures for 1916-1917.

their life cycle the gill-breathing of their ancestors.¹⁴⁶ During the Permian the reptiles clearly dominate over the amphibians and were differentiating into those orders which ruled the later periods. Thus, from the standpoint of vertebrate evolution the Age of Reptiles began in the Pennsylvanian, was established in the Permian, and ended with the Cretaceous. This is in fact the classification proposed by Ulrich¹⁴⁷ on the basis of diastrophism. The diastrophic and organic classification can then be brought into adjustment by placing the periods which mark crescendoes of diastrophism as the beginnings of new eras, not the ends of old ones. This is more logical and accords with the system of human history in which revolutions and their changed political conditions are placed as the opening events of new eras. It is doubtful, however, if this logical view will prevail in geology, since the older classification is solidly entrenched in the literature of a century.

On this new basis the Mesozoic, beginning with the Pennsylvanian and ending with the Cretaceous, would include 205,000,000 years on the minimum estimate of time, 270,000,000 years on the maximum estimate. The Neopaleozoic, embracing the Silurian-Mississippian periods, would include 140,000,000 or 130,000,000 years, thus falling short of the normal measure of an era. But the Eopaleozoic would include the revolution preceding the Cambrian. The Torridonian, Keweenaw, Beltian, and Grand Canyon systems, constituting the Lipalian era of Walcott, should apparently go into the Eopaleozoic. If the Morogoro granites of Africa, with an age of 660,000,000 years, mark a time in this Lipalian period of revolution characterized by continental uplift and continental deposits, then the Eopaleozoic also is delimited by a duration of 200,000,000 to 270,000,000 years, according to which scale of time is used.

MEAN RATES OF EROSION AND SEDIMENTATION

This table of geologic time carries several corollaries. The first to be noted is the mean rate of sedimentation for the several eras which would be required if the maximum thicknesses represented continuous sedimentation, as postulated by Sollas in his work previous to 1909 and by most geologists writing previous to the present decade. It has been argued in the present paper that this postulate is very far from being true, the very nature of sedimentation implying the presence of breaks of all orders of magnitude, the proportion of lost intervals increasing with the more distant eras. In the axes of maximum thickness, however, the disconti-

¹⁴⁶ Joseph Barrell: Origin and significance of the Mauch Chunk shale. *Bull. Geol. Soc. Am.*, vol. 18, 1907, pp. 449-476; see pp. 469-474.

¹⁴⁷ *Loc. cit.*, plate 26.

nuities are reduced to a minimum. Recognizing that they still exist, it will be of value for comparison of the present conditions with the past to take the maximum known thickness for each era and divide it by the length of the era in years in order to get the comparative times represented by one foot of sediment. For this purpose the minimum ages given by uranium minerals will be used, as more probably of the proper magnitude. The tabulation follows:

Geologic interval	Time interval	Maximum thickness	Time for one foot
	Years	Feet	Years
Pleistocene	1,500,000	4,000	375
Cenozoic	55,000,000	63,000	875
Mesozoic	135,000,000	84,000	1,600
Neopaleozoic	200,000,000	78,000	2,600
Eopaleozoic	160,000,000	43,000	3,700

It is seen that the rate of accumulation of the geosynclinal deposits appears to grow progressively slower with remoteness in time. There are several factors contributing to this effect in addition to the discontinuity which has been emphasized.

First. It has been shown that the Pleistocene has been a period marked by great orogenic movements and by high continental uplift, accomplished in a pulsatory manner. The Pleistocene, including the Recent, constitutes the culmination of a period of revolution, and the rates of erosion and sedimentation are both in consequence abnormally high.

Second. The stratigraphic record of the Cenozoic is fairly complete, since various deposits, largely continental, made above sealevel and geologically temporary, fill in the gaps represented by unconformities in other localities. Such a complete record could not be expected for an older era.

Third. As to the relative rates for the several eras, although the mean rate of erosion and sedimentation of the Tertiary should show less than the Pleistocene, the Tertiary, nevertheless, consists of two periods of revolution and its rate is naturally higher than that of the Mesozoic as a whole. There were long times of quiet and spreading seas in the Mesozoic when the surface processes must have sunk to a low rate. The blanks left by unconformities, furthermore, begin to play a larger part.

Fourth. In the Neopaleozoic the continents stood lower, as shown by a more prevailing spread of epeiric seas as compared to the Mesozoic. A low attitude of the continents reduces the area which is subjected to erosion and, even if the rate for the remaining land areas is high, the total volume of sediments per year for the whole continent is low. The sediments derived from a small land area are spread over a wide shallow sea

and the rate of accumulation even in the geosyncline tends to be reduced, though the rate in the geosynclines depends more largely on the rate of subsidence.

Fifth. The relation of high sealevel to the vertical forces tending to maintain isostasy. When a continent is leveled with respect to a higher sealevel, the erosion of the smaller areas involves less isostatic strain toward rejuvenating uplift than if the whole continent were worn down to a lower level. Longer times of quiet may elapse and the movements toward equilibrium need not be so wide-spread nor violent as they must be for a greater depth between the isostatic level and the continental baselevel.

Sixth. The stages of lost record due to breaks of various magnitudes during sedimentation have already been mentioned. In addition to this, for the more distant times the record tends to become more imperfect, owing to the later events of geologic history. Some parts are uplifted and destroyed; others are mantled over with later sediments.

Seventh. It is possible that beside these factors which make for a low apparent rate in the Paleozoic, a real change may have taken place in the nature of the earth's internal forces. The later revolutions have been less profound than the great convulsions of the Archean, but diastrophism may make up for this by becoming more recurrent, tending to stimulate in post-Paleozoic eras the mean rate of erosion and sedimentation.

The stratigraphic record of the Precambrian is so fragmentary and imperfect that the preceding method of calculation is quite inapplicable. To gain some idea as to the mean rates of erosion and sedimentation which prevailed, recourse may be had to another line of argument. The Precambrian portion of geologic history shows regional metamorphism acting more than once on a world-wide scale. Molten rock welled up from the depths; part of it poured over the surface; other and greater parts did not reach the surface, but as abyssal magmas melted in, broke up, and engulfed the overlying crust. By aid of the escaping gases the cover rocks were crystallized. Compressive forces contorted and mashed them and led to recrystallizations, transforming both older and younger rocks into an intricate structure—the basement complex. Erosion planed sufficiently deep to expose these structures of the zone of rock flowage as the dominant type of Precambrian structures. In later ages such internal activities have been restricted to the belts of mountain systems. This contrast would seem to suggest that the Precambrian was characterized as a whole by more rapid, wide-spread, profound, and violent geologic activities, associated with the youth of the earth; but other lines of evi-

dence to be discussed indicate that these revolutions were temporary conditions separated by long periods of quiet which have left almost no record.

The first line of evidence bearing on this conclusion is derived from the quantity of salt in the sea. It has been seen that the sodium would be derived from the weathering and erosion of a shell of average igneous rock about 2,300 feet thick, if enveloping the whole earth, or about 6,800 feet thick if derived from an area equal to the present continental platforms. It does not appear possible to materially modify these estimates. The greater part of present erosion consists in the reworking of sedimentary material, but since the opening of the Paleozoic it would appear from the large volume of the strata deposited that at least a third of this mile and a half shell of igneous rock must have yielded up its sodium. The implication is that Precambrian erosion was not by any means so profound, on the average, as the broad exposure at the surface of rocks originating in the zone of flow would suggest. It would seem that at times of great batholithic invasions regional metamorphism must have gone forward freely under a load of a mile or two of cover, the recrystallization being due to the great quantities of gas at high temperatures penetrating upward from underlying magmas. It has been found, in fact, for a number of far later batholithic invasions that they have approached so near to the surface as to be covered only by a slightly older mantle of tuffs and lavas of their own genesis; yet their texture is granitic and the cover rocks show extensive contact metamorphism.

If Precambrian erosion took place over an area greater than the present continental platforms, the mean depth of erosion of the igneous rock over this larger area was less than 6,800 feet. If the early erosive processes were less effective in weathering than in later times, then it would take a slightly thicker mantle to give rise to the oceanic salt. This factor tends to offset the one due to larger area of Precambrian lands, but is probably of much less importance. We may conclude, therefore, that the mean depth of erosion of average igneous rocks through all geological time has been less rather than over 6,800 feet. Let us grant the maximum available for Precambrian time, as this is leaning backward from the direction of the argument. Allow only one-fifth for later geological time, and the mean depth for the Precambrian erosion of igneous rock is still not more than a mile as a maximum figure.

The second line of evidence bearing on the problem is found in the peneplanation which occurred repeatedly, so that each Precambrian system was laid down on an almost level floor of older crystalline rocks. As compared to the scale of the initial relief following each revolution, the peneplain, even if hummocky, represents erosion to practical complete-

ness. The development of such peneplains implies that the crust was stable and the earth rigid through long periods of time. Cooling, following each period of magmatic invasion, must have gone on to a very considerable depth, giving a temperature gradient perhaps lower than the present, and the deeper body of the earth may then, as now, have had throughout its present rigidity. These features alone show that Precambrian time was very long. The degree of evolution and differentiation of all the invertebrate phyla by the opening of the Paleozoic suggests also that the preceding time was as long as, or longer than, all subsequent time. The evidence from the uranium minerals comes now to support that view.

We are confronted, then, by several controlling conditions as to the nature of the Precambrian; the enormous duration of those ages, at least 700,000,000 years, perhaps 1,000,000,000 years; the wide-spread and recurrent igneous activity and regional metamorphism; the *average* depth for the erosion of *igneous* rock needed to reveal the Basement Complex over the continents not over a mile, and the existence of long periods of quiet and peneplanation. The long periods of quiet were comparable to the Cambro-Ordovician save that the continents in the earlier time tended to stand just above, rather than just below, sealevel. Instead of sheet after sheet of sediments being thinly spread, successive thin layers of rock were planed from the land—now here, now there—in addition to the removal of more limited tracts of higher plateaus and mountains.

The difference in geologic history between the Precambrian and the following eras was, consequently, largely due to the change in the mean sealevel; a slow change through a wider sweep of time than even those age-long tides which divide earth history into periods; a sweep so wide that all of geologic time has brought to pass only one completed rhythm, the continents now emerged from the Paleozoic seas suffering dominant erosion as in the remote Precambrian. But in other aspects the change is not rhythmic, but progressive; for the present conditions are, in many respects, not comparable: the ocean water has progressively increased in volume, but the continents have broken down into ocean basins in larger ratio. These causes are progressive and do not represent a return to primordial conditions, but the effects on the level of the sea have exhibited such a returning phase.

During the periods of plutonic overturn of the crust through the rise of **magmas** the rate of erosion for the uplifted areas may have exceeded the present rates for mountain regions, but during the long periods of **quiet** and peneplanation erosion must have sunk to a negligible amount. **Slight** oscillations downward would have stopped it altogether and have

led to wide-spread and possibly long-enduring epeiric seas which have left no record, because a somewhat later sinking of the sealevel would have resulted in a washing of the previous deposits from the land.

The conclusion is so important that for better visualization it may be subjected to a quantitative statement in so far as the inexact nature of the data lends itself to such statement. The total volume of average igneous rock needed to supply the oceanic sodium is 84,300,000 cubic miles. This allows for the incomplete leaching of the igneous rock during erosion and sedimentation.¹⁴⁸ Take, as the extreme assumption, four-fifths of this as eroded in Precambrian time. This gives 67,000,000 cubic miles, the maximum which can be granted. Take the length of the Precambrian as 670,000,000 years, a minimum figure as given by uranium minerals. The result is an average of 0.1 cubic mile of igneous rock eroded per year—a maximum estimate.

To compare this average for the Precambrian with the present rate of supply of new salt to the sea, take the present area of igneous rocks as 20 per cent of the land area, or 11,000,000 square miles, as measured by Von Tillo. Take the present mean rate of erosion as one foot in 8,600 years, as given by the measurements of chemical denudation, and consider it to apply to the regions of igneous rock. This gives an erosion of .24 cubic mile per year of igneous rock.

A check calculation is given by taking the sodium uncombined with chlorine which is carried by the rivers to the sea each year. This is 69,000,000 tons. Let this be taken as a measure of the new sodium derived annually from the erosion of igneous rocks. In so far as new chlorine from volcanic action is combined with new sodium in the soil, this figure may be below the truth and tends to be a minimum. Now one cubic mile of average igneous rock will, by being subjected to erosion, yield 200,000,000 to 210,000,000 tons of sodium. The 69,000,000 tons of unchloridized sodium represents, then, the erosion of 0.33 cubic mile of average igneous rock. Thus we may take the mean of the two estimates and conclude that not less than 0.3 cubic mile is eroded per year now as compared to not more than 0.1 cubic mile as the average for Precambrian time.

But the present supply of new sodium is from only 20 per cent of the land area. In the Precambrian the average area of igneous rocks exposed was much greater, though at times considerable portions of the continents were covered in part by shallow sea and mantles of sediment. If the mean area of exposure of igneous rocks was then four times the present area,

¹⁴⁸ F. W. Clarke: *Data of geochemistry*, p. 30, Bull. 616, U. S. Geol. Survey, 1916.

the mean rate of erosion of the Precambrian continents *per unit of area* was not more than one-twelfth of the present rate.

But it seems probable, first, that the Precambrian continents extended beyond the limits of the present continental platforms; second, that more than one-fifth of the erosion of igneous rocks has been accomplished since the Precambrian; third, that Precambrian time was somewhat longer than 670,000,000 years. The mean rate of continental denudation of Precambrian time was consequently not more than one-twelfth of the present rate and was perhaps not more than one-twentieth of that for the Pleistocene. This is a lower rate than was derived for the Eopaleozoic by means of the maximum thicknesses of sediments.

If at times of Precambrian revolution the rate of continental denudation occasionally reached its present amount and an area of three-fifths of the present continents consisted then of exposed igneous rocks, the annual destruction of igneous rock would have amounted at such times to about seven-tenths of a cubic mile. The total igneous rock destroyed in Precambrian times has been taken as 67,000,000 cubic miles. If the assumed maximum rate had continued, this total erosion would have been accomplished in 100,000,000 years, leaving nothing for all the remainder of the Precambrian ages. It seems clear, therefore, that the times of general continental rejuvenating uplift and denudation were very limited, occupying not more than a tenth of the time. Between these must have stretched long periods of quiescence, during which peneplains lay near baselevel and erosion subsided to a negligible minimum.

A low average rate of denudation for a continent may exist simultaneously with a far higher rate for the areas supplying the waste. Such a very low continental rate must have existed in the Eopaleozoic, since obviously when seas spread over the land the erosion rate for the flooded areas became even negative and must have been very small for the slightly emerged portions. For the Precambrian, however, the result is unexpected, since erosion proceeded over the continents at one time or another deeply enough to expose nearly everywhere a crystallized rock-floor. The low mean rate for these earlier periods brings into startling contrast two opposite aspects of Precambrian paleogeography—the almost interminable periods of quiet and peneplanation; the profound revolutions which separated them.

Such a period of revolution connected with broadly uplifted lands, diversified by mountain ranges and geosynclines, coursed by rapid rivers in a wide-spread network, occurred in the late Precambrian. Its formations are the continental deposits of the Keweenawan, the Torridonian, the Beltian, the Grand Canyon, and other systems—river deposits of semi-

arid climates. But in the following era a new factor entered—a rising oscillating sealevel produced wide recurrent floodings of the lands and led to the deposition of the Eopaleozoic formations. But before that last Precambrian revolution occurred, an era passed away during most of which the lands must have been so flat that the deposits such as those of the Animikie were widely spread, and the streams must have meandered with stagnant flow over the low and restricted regions of erosion. Thus the Lipalian or Grand Canyon revolution looms forth in mountainous grandeur between a preceding and a succeeding world of low restricted plains and still more restricted uplands.

Lull has seized upon this contrast of physiographic conditions as a factor in the initiation of vertebrate evolution. During the period of peneplanation the sluggish currents which marked the physical environment would not have required sustained movement in floating animals of either the seas or rivers in order than they should remain within their habitat. With the opening, however, of a period of revolution the continents were uplifted, the domain of the fresh waters would expand and they would take on a rapid flow. The freely moving animals of these waters would now have to become vigorous swimmers if they were to stem the currents and survive within their fluviatile environment. Lull regards this environmental stimulus as apparently essential for the development of the initial fishlike forms of the early chordates, adjusted thus to the flowing fresh waters and leading to the establishment of their dynamic superiority over other phyla. From first to last the chordates have thus found their central field of evolution on the surface of the continents—at first within the flowing waters, later as true terrestrial vertebrates.

Thus, through the recognition of these wide variations in environmental conditions leading from age to age out of the remote geologic past, supplanting a picture of monotonous uniformity, the progress of evolution is perceived to have been attained by pulses. Tracing this surge of cause through geologic time and detecting its effects in the progress of organic evolution, Lull has written “the pulse of life.”¹⁴⁹

By far the greater portion of the Precambrian consisted of periods of comparative quiet. These, as shown, must have been more than ten times longer than the periods of revolution, but we see them represented chiefly by surfaces of unconformity, whereas the revolution thrusts its existence before the imagination through the evidence of igneous activity and

¹⁴⁹ R. S. Lull: The pulse of life. Chapter IV of *The evolution of the earth and its inhabitants*. Yale Sigma Xi lectures for 1916-1917; to be published.

R. S. Lull: *Organic evolution*, 1917, section 3. *Paleontology*, pp. 409-691.

metamorphism—of mountain structures and consequent rapid erosion and deposition. These periods of wide and profound disturbance, lying in the background of earth history, because of their very remoteness are projected into one sphere of vision. Perception of distance and perspective are lost—as in the stars which spangle the firmament, showing by their radiance their fiery activities, but giving no suggestion of the vast spaces of empty cold which lie between.

RELATIONS BETWEEN LAPSE OF TIME AND ORGANIC EVOLUTION

Closely connected with this expanded view of terrestrial duration is another problem which in conclusion should be touched upon—the relationship of geologic time to the progress of organic evolution.

If life originated at an early period on this earth and was not derived from germs driven by the pressure of light from other worlds, protoplasm must have existed at first as mere molecules of very complex nature. Possessing a power of assimilation, such molecules became colloidal aggregates by virtue of adding to their substance, at first totally without structure or differentiation. In our ignorance of the ultra-microscopic stages of organization which lie between the protoplasmic molecule and the visible structures, we are prone to slight the necessity for the evolution of these stages which led up to the organization of the cell; yet in these the foundations of all later progress were laid. Protoplasm had to become differentiated and organized, chemically and physically. There had to arise nucleus, cytoplasm, and cell wall; powers of photosynthesis, of digestion and excretion, of irritability and contractility. This chemical organization represents an adaptation to environment which must have resulted from the selection of efficient variations out of numberless chance chemical combinations. The initial preservation of the successful protoplasmic combination was owing to the fact that the world was as yet without predatory organisms.

Most remarkable of all, perhaps, in this basal evolution was the establishment of the principles of inheritance, residing in a marvelous mechanism, by virtue of which the descendants start life with the capital of efficiency acquired by their ancestors and sifted by selection through all previous time. Without inheritance there could be no progress, but powers of inheritance mean an incomprehensible complexity in the ultra-microscopic structure of the cell. The chromatin threads in the single, undifferentiated metazoan egg-cell determine the differentiation and assemblage of the billions of daughter cells which build the adult body. Considering the stages which have to be passed through, the child is

marvelously like the parent; the wonder is not that there is so much variation, but that there is so little. Yet this development of the meta-zoan is only a higher expression of powers already evolved in the proto-zoan. The evolution of the habits of conjugation, of the exchange and combination of Mendelian factors, of the habits of precisely similar growth generation after generation, are all parts of a protoplasmic machinery which had to become established before even protozoan progress was possible. This machinery could not rapidly evolve. Like all later advances, it must have been the result of numberless variations, the efficient sifted out by the elimination of the unfit. It would seem that the vast length of the early Precambrian ages was none too long for the accomplishment of this half of evolution of which we know so little.

Turning to a better known side of the subject, the evolution of the vertebrates; the geologic record shows that the great advances coincide with changes in environment. The advances represent modifications of older structures and their combination to new ends and with increased efficiency. The variations must come from within by modifications of the germ plasm, and these, once established, are carried forward and perpetuated through the stability of inheritance. But the efficient variations, representing improved adaptations to a changing environment, must be sifted out from inefficient and degenerative variations by natural selection leading to the survival of the fittest. The same principles doubtless led to the long upward journey in the organization of the protozoa.

If evolution were due only to internal changes, to the mere sloughing off of inhibiting Mendelian factors, it might proceed with rapid pace; but if, as the geologic record testifies, it waits on environmental change and requires a transformation of unrelated organs with mutual support and efficiency, as seen in the organization of lungs, circulation, and limbs—needed to transform the fish into the amphibian—then evolution must proceed with surpassing slowness. Millions of generations must cross the stage of life to furnish again and again the chance combinations which are seized on by nature at times when the environment exerts a critical and selective pressure. These forces which make for evolution work intermittently, not continuously. Degeneration rather than evolution is the result where nature ceases to drive and organisms are left to procreate freely.

Viewed in this light, it seems impossible to compress the evolution and deployment of Cenozoic mammals, gained through the march of many successive faunas, into any such limited time as 3,000,000 years. Ten times this seems none too long. In fact, fifty or sixty million years, giv-

ing perhaps from ten to twenty million generations, may have been needed for the transformation of the generalized mammal of the basal Eocene through the many successive faunas into the varied life of the living age.

Lyell regarded 20,000,000 years as a probable length of a geologic period required for the transformation of species. Darwin thought 200,000,000 years too short for the accomplishment of organic evolution. It would appear that they were conservative in these expressions of opinion and that this expansion of geologic time should be welcomed by the biologist as well as by the geologist.

BEARINGS OF GEOLOGIC TIME ON THE PROBLEM OF STELLAR ENERGY

The length of geologic time has a highly significant bearing on the nature of the supply of the solar radiant energy, and, as the sun is but one of the host of stars, it has a wider bearing on the whole problem of the sources of stellar energy and the course of stellar evolution.

Until the discovery of radioactivity, there seemed to be no conceivable adequate source for the enormous expenditure of solar energy save in the contraction of the sun's mass, transforming the energy derived from gravitational infall into radiant energy. A present shrinkage in radius amounting to 200 feet per year would be sufficient to liberate enough energy to balance the expenditure. On this basis Helmholtz calculated in 1856 that if the sun had in past time delivered heat at its present rate that it could not be more than about 20,000,000 years old. Kelvin, by introducing the condition that the sun is probably very much denser in its interior, considered that the age might be somewhat greater. Ritter, Tait, and certain other physicists held, however, that the earth's organic history could not have extended beyond 10,000,000 or 12,000,000 years.

In view of these very restricted limits, attempts have been made by various men to draw on the internal heat of the earth as a supplemental supply. It has been argued that such a source would account in earlier times for the equable climates and the absence of marked zones. A thick atmosphere, moist and rich in carbon dioxide, is a further postulate, serving as a blanket to hold in more effectively the internal heat and maintain a higher temperature of the surface.

There are several serious obstacles to the acceptance of such a hypothesis as an important factor in paleoclimatology.

First, the amount of radioactivity known to exist in the crust appears adequate, or more than adequate, to account for the whole emanation of heat. There is no evidence, therefore, that the earth is cooling and that the crust gave forth more heat in earlier times.

Second, the deeper parts of many Precambrian formations, such as the Unkar and Chuar exposed in the depths of the Grand Canyon of Arizona, have been buried to a depth of several miles in the late Precambrian, and again in the Paleozoic, and yet show no regional metamorphism, comparing in this respect with Paleozoic and Mesozoic formations. The temperature gradient since the late Precambrian could not, therefore, have been notably higher than the present.

Third, the quantity of heat which the earth delivers to the atmosphere is now and must always have been inconsequential in comparison with that derived at present from the sun. For instance, to have conducted five times the heat, the temperature gradient would have to be five times as steep, giving a temperature of molten rocks at a depth of five miles.

Fourth, the presence of banding in certain argillites of early Precambrian times in Norway and Canada, associated with ancient glacial deposits, is directly comparable with the annual banding in stratification in Pleistocene clays in those same regions, and testifies to the dependence of temperature in those times on solar radiation with an atmospheric condition which permitted the existence of winter.

Fifth, the abundance of carbon in the clays of early Precambrian time suggests the presence of sunlight sufficient to carry forward photosynthesis in plants and therefore the absence of an extremely dense cloud envelope.

Sixth, glacial conditions are found to be associated with times of terrestrial revolutions closing the eras and to have recurred at times since the Middle Precambrian. Similarly, periods of wide-spread aridity have recurred at intervals since the Upper Precambrian. The composition of the atmosphere and ranges of temperature have, therefore, been subject to fluctuation through all geological time and have not shown a steady decline, formerly suggested as a cause for Pleistocene glaciation. The normal existence of warm temperate climates in high latitudes and the Permian glaciation in low latitudes must therefore rest on some other explanation.

Consequently, we must return to the conclusion that the sun through all geological time has been the only effective source of terrestrial warmth. But life began to evolve in the earliest known times, and since then the temperature limits compatible with the continued existence of the various classes of organisms have never been exceeded. When it is considered how narrow these limits are, as compared with the absolute cold of space on the one hand and the temperature of the sun on the other, it is seen that not only has the sun radiated energy through all geological time, but that the flow of energy, although subject to rhythmic fluctuations,

has been nearly constant. This constancy suggests that the sun was already past the formative period in the earliest times for which there is a geological record and has not yet entered into the declining stages of its history. In view of these facts, it is seen that even for an age of 50,000,000 years the hypothesis of solar energy due to gravitational infall seems hopelessly inadequate. What, then, shall be said of an age as great as 1,500,000,000 years? It is of the order of one hundred times too great. The issue is sharply drawn and indicates that either geological time has been overestimated a hundred fold or the hypothesis of self-contraction as the source of solar energy does not account for more than perhaps 1 per cent of the expenditure.

This problem has been discussed also by Holmes.¹⁵⁰ Rutherford and Soddy in 1903 pointed out the possible importance of radio-thermal action in the sun, but Wilson in the same year showed that, if the sun were wholly composed of uranium and thorium in equilibrium with their disintegration products, the radioactive disintegration, although ample in duration, would give rise to only a fraction of the daily expenditure of solar energy. Holmes finds, on account of the slowness of these transformations, that by no possibility could more than one-third of the sun's heat be accounted for by the radioactivity of uranium and thorium. Either, then, there are further atomic disintegrations which supply more heat or, as Arrhenius has suggested in more general form, there are higher stores of energy which may be liberated by changes in physical states at high temperatures and great pressures, latent heat being given out as thermal energy by their transformations.¹⁵¹ Of course, such suppositions only emphasize our ignorance of the cosmic process, for before this energy can be liberated it must in some manner have been stored. For example, the enormous energy liberated by the stepping down of uranium, with molecular weight 232.2, into lead of molecular weight 206.2 must previously have been absorbed in the building up of uranium. The lead in its origin has presumably still stored within its atom much more energy than is liberated by its generation from uranium.

Such intra-atomic energies may be inferred for the elements which are not radioactive from analogy with those that are and also from the higher incompressibilities of the elements of small atomic volume. An external load only slightly condenses the sphere of influence which may be regarded as the volume of the atom, and the work of condensation is ab-

¹⁵⁰ Arthur Holmes: *The age of the earth*, 1913. Chapter VIII, the thermal energy of the sun.

¹⁵¹ Svante Arrhenius: *The life of the universe*, vol. II, chap. VIII. The energy conception in cosmogony, 1909.

sorbed as an added store of energy. The coefficient of expansion is also small and indicates that the energy of the absorbed heat only slightly expands the sphere of the atom's influence. The internal fixed energy of the atom is therefore enormous as compared with that which can be added or taken away by processes under human control.

In some manner the elements must have had their evolution, and according to the law of the conservation of energy that which the stars are now liberating must first have been absorbed. The apparent running down of the visible universe must be but one phase of a recurrent cosmic cycle philosophically necessary in infinite time, or else the running down would have been completed in previous eternity. The nature of this cyclic process is still far beyond the bounds of scientific investigation. It was thought that in gravitational infall an adequate explanation had been found for one phase of the cycle, that of the liberation of the radiant energy of the stars; but the quantities dissipated by the sun through the vast length of geologic time indicate that the contraction of the solar mass can not be more than a minor factor in the conversion of its energy.

The scheme of the universe is more profound and the unknown is a little nearer than it was recently thought to be. But such has been the progress of knowledge since man, in the days before the advent of science, naively regarded the earth, his home, as the center of the universe and the heavenly bodies as lights in a near-by firmament, created a few thousand years previously especially for his benefit.

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Rhythms and the measurements of geologic time

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