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# THE AGE OF THE EARTH[1]

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BEFORE inaugurating my lectures on this generous foundation established by Mr. George Fisher Baker, I would first of all express my pleasure at having this opportunity to spend a term with my colleagues and the students of this department, which has reached such a high degree of perfection under the able, far-seeing guidance and efficient administration of your genial director, Professor L. M. Dennis. The actuality far exceeds what I had come to expect from the glowing accounts given by my predecessors.

For my introductory lecture I have chosen the problem of the age of the earth. Our earth was born from our sun. The sun, while in the giant-star stage, is supposed to have been broken up by tidal actions induced by a passing star several times more massive than itself. Originally formed in the gaseous state, the earth passed to the liquid state through loss of heat by radiation from its surface, and later into the solid state. The earth's crust and some of its individuals were formed simultaneously, followed at a much later era by the formation of biological individuals. When did the earth's crust solidify? How many years then elapsed before "life" began to develop? These questions are of interest for both the physical and the biological sciences, and an answer will be sought in the following discussion.

Astronomy teaches that the various members of the solar system have originated from the same material. This conclusion is supported by the chemical analysis of meteorites, which not only contain the same elements in approximately the same proportions as in the material of the earth, but also show them in the same isotropic combination. The two nickels of atomic weights 58 and 60 are present in exactly the same ratio in iron meteorites as in terrestrial nickel. The silicon of the stone meteorites contains the three isotopes of atomic weights 28, 29 and 30 in exactly the

[1] Introductory public lecture.

same ratio as does terrestrial silicon. There can be no doubt that the material of the earth separated from the sun's mass and the cooling of the gaseous material led to solidification and the formation of minerals.

The sand-filled hour-glass is the simplest clock. If at any spot on the earth's surface sand were deposited at a fixed rate since the solidification of the earth, then the total amount of sand deposited by this geological hour-glass would indicate the age of the earth, if we could measure the rate of deposition and the volume of the sand. Such geological hour-glasses actually exist. Rivers carry salts to the sea and, knowing the annual volume of salts carried down and the total salt content of the oceans, we can deduce the length of time this process has been in action. This interval of time corresponds to the age of the earth's crust. Even accumulations of sand itself are actually found in nature where rivers have brought sand, mud and sludge down to the sea and deposited them at the river mouth. A knowledge of the total thickness of the sediment and of the annual deposit therefore leads to a knowledge of the date of the beginning of the process. Professor Arthur Holmes, of Durham, to whom we are indebted for numerous important contributions to the determination of the earth's age, makes the following estimates for the maximum thicknesses of the sedimentary strata:

| | Meters |
|---|---|
| Cenozoic Era (modern life forms) | 24,000 |
| Mesozoic Era (medieval life forms) | 30,000 |
| Paleozoic Era (ancient life forms) | 61,000 |
| Precambrian Era at least | 60,000 |
| Total | 175,000 |

We can form a general idea of the rate at which these sediments have been deposited. To take an illustration used by Sir James Jeans in his very stimulating volume "The Universe around Us," since Rameses II reigned in Egypt, over 3,000 years ago, sediment has been deposited at Memphis at the rate of one meter every 1,200 to 1,500 years. With geological strata deposited at an average rate of one meter per 3,000 years, the total 175,000 meters of strata listed above would require over 500 million years for their deposition. At the much slower rate of one foot in 4,000 years,[2] the time would be about 2,100 million years.

As early as 1715 it occurred to the famous astronomer Edmund Halley that from its salt content one might calculate the age of the ocean and hence the age of the earth's crust. In that year he published a paper entitled "A Short Account of the Cause of the Saltness of the Ocean, and of Several Lakes that Emit no Rivers; with a Proposal by Help thereof to Discover the Age of the World." He showed that since the water removed from lakes by evaporation is perfectly fresh, "the saline particles brought in by the rivers remain behind, while the fresh evaporate; and hence it is evident that the salt in the lakes will be continually augmented and the water grow salter and salter." Applying the same principle to the oceans, he wrote: "It is not improbable but that the ocean itself is become salt from the same cause, and we are thereby furnished with an argument for estimating the duration of all things."

In Halley's time the necessary figures for such a calculation were lacking, but 184 years later when the same suggestion was made by Professor Joly, of Dublin, accurate data on the mass of the oceans, their sodium content and its yearly increase were at hand. The oceans contain 1,180,000 billion ($=10^{12}$) tons of water. The sodium content is 1.08 per cent. by weight, so that altogether there are 12,600 billion tons of sodium. Rivers annually contribute 35 million tons of sodium to the sea, and a simple calculation gives the age of the sea = (12,600 billion/35 million) = 360 million years. The salts which the condensing vapors of the magma directly led to the sea by volcanic processes, the amount of salt removed by wind-borne spray, and similar factors are neglected in these calculations. These factors can hardly influence the results to any very appreciable extent; but grave errors may ensue from our tacit assumption that the rate of our geological clock is the same now as it always has been. We assume that the salt additions to the sea and sedimentation proceed to-day at the same rate as yesterday and as ever. These assumptions are not necessarily true; there is definite evidence, indeed, that these regulating processes proceed now more rapidly than the average rate in the past geological ages.

We are now approaching the end of a geological period which is characterized by the formation of hills and rising continents. These conditions are favorable for the transportation of matter to the sea since the river gradients are steeper and the circulation of ground water more thorough. In the long geological ages of the past when the sea flooded the present lands and mountain elevations were consequently appreciably lower, exactly opposite considerations applied. This natural geological change is not the only reason for rejecting the assumption of a regularly running clock. Human activities tend to accelerate these time-keeping processes upon which our calculations depend. Man cultivates the land, cuts off and uproots the forests, and his industry brings large quantities of soil into the rivers. Many

[2] The present rate of subaerial denudation over North America is estimated at 15 cm, or about 6 inches, in 4,000 years.

of the largest and geologically most active rivers such as the Ohio and the Mississippi flow through cultivated and thickly populated districts where formerly forests protected the land from erosion. The sodium gained by the sea in the past must, therefore, have been less than at present, and the age of the sea as estimated from its sodium content must be set correspondingly higher. Similarly, the age as estimated from the sediments must be also increased. The late Professor Barrell even succeeded in showing a definite rhythm in geological processes. He showed conclusively that most regions of sedimentation have been subject to alternate scour and fill, and that the actual thickness ultimately preserved is merely the balance left by these two processes.

Geological methods for determining the age of the earth as thus sketched evidently do not satisfy the most important assumption that the time-indicating processes proceed now at the same rate as they have always done in the past.

The astronomer as well as the geologist is interested in the age of the earth and has also applied his principles towards the solution of the problem.

The fate of the earth is bound up with the fate of the sun. If it were possible to determine the present age and the term of the life of the sun, then the same period is simultaneously the maximum possible life of the earth. The sun loses energy at the rate of $3.3 \times 10^{33}$ ergs per second, and if we knew the source of this energy, it would be possible to calculate the time required for the sun to reach its present state. Helmholtz and Kelvin believed—in agreement with the state of physical learning in their day—that the contraction of the sun provided its energy. A contraction indicates a segregation of material toward the center and a consequent liberation of potential energy which would be converted into heat. Lord Kelvin calculated that the shrinkage of the sun to its present size could have provided energy for hardly more than about 50 million years of radiation in the past.

If these calculations are applied to the calculation of the age of other stars, it soon becomes apparent that the results obtained are untenable. $\delta$ Cephei, one of the variable stars, radiates 700 times as much heat as our sun. According to the above theories, this star should have decreased in radius by 1/300 since 1788 when it was first carefully observed, but the actual contraction is not more than 0.5 per cent. of the calculated value.[3]

In addition to these and other astronomical contradictions, numerous geological arguments oppose so low an age as 50 million years for the sun and the earth. Thus the contraction hypothesis must be rejected. Stellar energy must have some other source.

To-day we know that colossal energy is stored in the nuclei of the atoms, and this knowledge is one of the most important results of our modern study of the transmutation of the elements. It is most natural to assume that this large amount of energy is the source of the radiation from the sun and stars. As the amount of stored-up energy of a star determines its length of life, modern astronomical theories through this nuclear energy just referred to arrive at a possible life-span for the sun several hundredfold that estimated by Kelvin.

The energy stored in the atomic nuclei can be set free in many ways. Radioactive decay, the dissociation of heavier into lighter atoms, sets free a comparatively small quantity of heat, although even this is many times greater than the heat developed by a normal chemical reaction. For example, the heat obtained from the decay of one gram of radium, which requires about 20,000 years for its practical completion, is $3.7 \times 10^9$ calories, which is equal to the heat of combustion of 500 kg of coal. Other processes, involving the atomic nuclei, supply yet larger quantities of energy, namely, syntheses of the elements from the hydrogen atom.

The nucleus of the helium atom contains four protons, and consequently the nucleus of the helium atom should be four times as heavy as the hydrogen atom. This is not the case, however, for the helium atom mass is 0.8 per cent. less than that of four hydrogen atoms. The difference is due to the fact that during the formation of the helium nucleus from 4 protons and 2 electrons an enormous quantity of energy is set free and radiated. Now according to the theory of relativity a loss in mass corresponds to a loss of energy, although this is never noticed, as a rule, in ordinary chemical reactions on account of the extremely small mass which corresponds to one erg of energy. One gram of mass corresponds to the absolutely prodigious amount of energy of $10^{20}$ ergs.[4] The extreme ratio between the units of mass and energy will be more readily understood from the following example.

If 100 carloads of coal were burned to carbon dioxide, then the combustion of this million kilograms of coal would set free a large amount of energy, but the loss of mass due to the release of this huge amount of energy would be equivalent to only about 1 gram. In the processes of the atomic nuclei, however, the

[3] So large a change in its radius should have caused a change in the rate of oscillation of $\delta$ Cephei, but this has not been observed. This point is discussed by Sir Arthur Eddington in his illuminating book "Stars and Atoms."

[4] According to the special theory of relativity, the relation between mass and energy is given by $E = c^2m$, where $c$ is the velocity of light.

quantities of energy involved are so colossal that the resulting changes in mass are no longer negligible.

The difference in mass between one helium atom and four hydrogen atoms together with a number of similar values, thanks to Aston's marvelous experiments, are now known with great precision, and these enable us to calculate the energy set free by the formation of a helium atom from the four protons and in similar atomic reactions. Such syntheses are the sources of extraordinarily huge amounts of energy.[5]

Radioactive disintegration is the transformation of heavier elements into lighter ones, and is a well-studied phenomenon, but very little is known about synthesis, the reverse process.

In the Cavendish Laboratory at Cambridge and in other research institutions like Professor Harkins' Laboratory in Chicago the disruptions of the nuclei of light atoms under bombardment by alpha-particles have been studied. It was found that a minute proportion of the alpha-particles was successful in disrupting the nuclei, and some of the successful particles remained in the nucleus of the bombarded nitrogen atom. The latter lost a proton (mass 1) and gained an alpha-particle (mass 4), the actual increase in mass being 3. The nitrogen atom was thus converted into an isotope of oxygen (atomic number $7-1+2=8$). It is to be presumed that a building up or synthesis of heavier elements from lighter ones takes place on a large scale in some unknown part of the universe.

Radioactive decays and the synthesis of the elements from hydrogen constitute two sources of enormous energy that were unknown to Kelvin and his contemporaries. Furthermore, the sources of energy are not yet exhausted. The mass can even completely disappear and be converted entirely into energy. When a helium nucleus is synthesized from protons and electrons $3 \times 10^{18}$ ergs of energy are released by the annihilation of only 0.8 per cent. of the mass of hydrogen involved; but if the *total* mass of hydrogen be destroyed the energy set free is 125 times as great.

Thus we recognize three sources of energy which may be responsible for the radiation of the sun and other heavenly bodies, viz., in order of magnitude: radioactive decay of the heavy elements; synthesis of the elements from hydrogen; complete transformation of matter into radiation. The ratio of the wealth of these sources is roughly 1:1,000:100,000. A uranium sun decaying to uranium lead thus can provide only a thousandth part of the energy supplied by a hydrogen sun transforming itself to helium, and only a hundred thousandth part as much as a sun whose mass is completely transformed to energy. In this way we arrive at very different values for the upper limit of the age of the earth, according to which of these possibilities is employed in our calculations. A uranium sun would have a life-period of only 100 million years; a hydrogen-helium sun would have a life of $10^{11}$ years, and a mass-energy sun (the third type) of $10^{13}$ years. The first value is certainly too small, for the earth must be younger than its parent the sun and we shall see that the earth is certainly older than 100 million years. Astrophysics also entirely supports this conclusion. Radioactive change can not be the sole source of the sun's radiation.

There are definite astrophysical arguments against the assumption that the sun's center or the material of the stars contain more than 10 per cent. of hydrogen, and these have been discussed by Eddington in his book on "Stars and Atoms." In the event that the source of the sun's energy is the synthesis of higher elements from hydrogen, the above value for its age must be reduced to $10^{10}$ or 10,000 million years.

The leading astrophysicists regard the assumption of atomic synthesis from hydrogen as insufficient to explain the astronomical phenomena, and they are inclined to the view that the aging of a star consists, to a large extent, in the annihilation of its original mass and its transformation into energy. The simultaneous destruction of $10^3$ protons and electrons per gram of the sun's material per second would suffice to account for the loss of energy by radiation and would secure a continuation of the sun's radiation for 10,000 million years.

It is, perhaps, essential to point out here that just as Kelvin's calculations were vitiated by the less complete state of scientific knowledge at that time, so the same fate can overtake our present calculations. Science is compelled, however, to base its concepts on the contemporary state of knowledge, and nothing makes greater demands on the intuitive and critical faculties of the scientist than the estimation of how far the possible explanations of a phenomenon are exhausted, even when possible future developments are considered.

Nevertheless, and bearing this possible fate fully in mind, we now consider that the knowledge acquired from the study of atomic transformations not only constitutes one of the greatest advances of science but also very probably exhausts the possible sources of the sun's energy.

Geological methods give a lower limit to the possible age of the earth, while astrophysical methods supply an upper limit. The geological clock runs too slowly and the astrophysical too fast. One of the many beautiful achievements of radioactivity is that

[5] The accurate value, as determined by Aston, for the loss of weight when helium is synthesized from hydrogen is 0.00724 per gram of hydrogen.

it has provided us with the necessary magic clock whose accuracy and reliability leave nothing to be desired, and—for us the most important specification—whose rate has remained constant since the solidification of the earth's crust.

Single atoms of uranium and other radioactive substances explode. The number of particles exploding and decaying in unit time is strictly proportional to the number present. For instance, from $10^{15}$ uranium atoms ($4 \times 10^{-7}$ gm), 1,000 atoms decompose in 5 days; and from $10^{14}$ atoms there decompose 100 in the same time.

Uranium decay is the desired strictly uniform process whose velocity has remained unchanged throughout geological time, for it is the nucleus which is involved in the decay, and nuclear processes proceed independent of temperature, pressure and other external conditions. Therefore, there is absolutely no reason to believe that the process has gone forward at any different rate than at present at any period in the earth's history. The study of radioactivity with its inexhaustible applications has provided further proof that uranium and other radioactive substances have always decomposed in the past with the same velocity as at present. The decay of a uranium atom is always accompanied by the radiation of an alpha-particle. These alpha-particles, which leave the atom with a velocity of 8,800 miles per second (or about one twentieth of the velocity of light), can travel a certain distance or work on a photographic plate, color mica, glass and other substances within a certain fixed limit from their place of origin.

Beyond this distance, called the range, which in air is about 2.8 cm and in mica about 0.013 mm, the velocity is so small that the alpha-particles are powerless. In nature certain micas such as biotite and muscovite inclose minute uranium-containing crystals. The alpha-particles from these inclosed uranium atoms, in the course of geological ages, have evidently colored the mica over a quite definite area. Some decomposition products of uranium also emit alpha-particles, but these have a different velocity and a correspondingly different range so as to form a ring of different diameter in the mica. The sections of these colored circular areas exhibit the property of pleochroism under polarized light and for this reason were called "pleochroic halos." The diameters of these halos are closely related to the velocity of the decomposition of the radioactive atom from which the alpha-particles originate, as has been experimentally demonstrated; therefore, a change in the rate of decomposition of the radioactive substances during geological time would correspond to an alteration in the diameters of the halos. The halos corresponding to the various radioactive substances have in every case the same diameter, from which it can be concluded that the rate of decay has remained the same throughout the ages. Hence the decay of uranium provides us with a process going on at a strictly uniform rate. To use this rate of uranium decay as a measure of time, however, it is necessary to know two facts: (1) the total quantity of uranium that has decayed in some mineral since the solidification of the earth, and (2) the rate of that decay.

(1) One helium atom originates from the decay of each uranium atom. This helium collects in the uranium-containing rocks and its volume gives the number of uranium atoms that have decomposed since the formation of the rock. (2) The production of 1 cubic centimeter of helium from 1 gram of uranium requires 9 million years. A knowledge of the uranium and the helium content of a rock gives, therefore, its age. According to this method the age of the rocks has been computed to be 570 million years. Although the rocks store a large part of the helium which is produced in them, a small portion gradually escapes in course of time so that the values obtained by this method give only a lower limit for the age of the earth. Fortunately in addition to the helium accumulated in the rocks we may also measure another and this time a solid product which can not escape, namely, lead. Uranium decay leads also to the production of lead, and we need only determine the lead content of the uranium minerals in order to be able to calculate what proportion of the uranium has decomposed since the mineral was formed. The following table shows the rate at which uranium decays and uranium lead is formed:

| Initially: | | 1 gm uranium | No lead |
|---|---|---|---|
| After | 100 million years | 0.985 " | 0.013 gm lead |
| " | 1,000 " " | 0.865 " | 0.118 " " |
| " | 2,000 " " | 0.747 " | 0.219 " " |
| " | 3,000 " " | 0.646 " | 0.306 " " |

These figures refer solely to the chief quantity of uranium, namely, uranium I, which amounts approximately to 97 per cent. The lead which has originated from uranium need not be confused with any accessory lead because uranium-lead has a lower atomic weight (206) than either ordinary lead (208) or actinium-lead (207).

When this lead method is applied to a great number of uranium-containing minerals we obtain the following ages of the geological eras:[6]

[6] Holmes and Lawson calculated these ages from the uranium, thorium and lead content of minerals using their approximate formula:

| Geological age | Age in years |
|---|---|
| Late Oligocene | 37 million years |
| Permo-carboniferous | 204 " " |
| Late Precambrian | 587 " " |
| Middle Precambrian | 987–1087 " " |
| Lower Precambrian | 1257 " " |

The lead method leads therefore to the result that the Precambrian minerals were in existence even 1,260 million years ago, and therefore the solidification of the earth's crust must have already taken place, perhaps about 1,400 million years ago.

The lead method has proved to be of great importance because its application enables us to determine not only the age of the oldest minerals but also the lower limit of the age of the earth's material and consequently of the chemical elements. The transformation of uranium into lead had already progressed to a certain point while the earth's material was still gaseous. The lead (206) so produced did not remain isolated as such, however; it had opportunity at that stage to mix with the thorium lead (208) from thorium decay and as a result common lead (atomic weight 207) was produced. Hence approximately half of our common lead was formed from uranium before the earth's materials had solidified. The ratio of all the uranium to about half of the common lead (plus the uranium lead) present in the whole earth's material must give the age of the earth's material. To a certain extent we can regard the whole earth as a colossal uranium- and lead-containing mineral. From this standpoint we consider not only the lead now existing as pure uranium lead or thorium lead, but also that other lead which *was* produced as uranium, thorium or actinium lead but has ceased to exist as such on account of mixture with thorium lead in the gas-liquid earth. Such a mixing of practically chemically identical elements, the so-called isotopes, was a common occurrence and must be the explanation for the fact that, for example, chlorine always has the same atomic weight. In whatever form chlorine occurs in nature there is always the same ratio between its two isotopes Cl (35) and Cl (37). The lead which has been produced in uranium minerals has had no such opportunity to mix with thorium lead, and consequently it has remained fixed as uranium-lead. H. N. Russell first drew attention to the fact that by such a method as the above the upper limit of the age of the earth could be calculated, but at that time it had not been proved that ordinary lead is a mixture of uranium-lead and thorium-lead. Since then Aston has succeeded by means of his mass spectrograph in showing that normal lead is chiefly such a mixture. These outlined considerations give about 3,000 million years as the upper limit of the age of the minerals and the lower limit of the age of the earth's *material*. During this huge period, it is only the few radioactive elements, decaying according to accurately known laws, that have altered; the other elements which build up the earth's constituents have undergone no change.

Formerly one was inclined to make no distinction between the radioactive and non-radioactive elements, and to believe that elements of the latter class were also transformed, although extremely slowly. Aston's beautiful experiments have shown, however, that this is not so. The heavy radioactive elements decay with an energy loss, whereas in the synthesis of the lighter elements from protons or alpha-particles energy is set free. Thus there is a basic difference between the radioactive and the non-radioactive lighter elements.

All the minerals and rocks which have been subjected to tests by the helium and lead methods have been taken from the earth's crust, since samples from the center of the earth are not obtainable. When the geochemist desires to know details of the composition of the interior of the earth, he turns to the meteorites and makes the assumption that iron meteorites correspond to the iron core of the earth and the stone meteorites to the more or less silicate layer. On account of experimental difficulties, only the helium method has hitherto been applied to the determination of the age of meteorites. The disadvantage of this method, that the helium can escape from the sample in course of time, is here without significance since the iron meteorites even when heated to a red heat lose no trace of helium. In recent years my predecessor in this lectureship, Professor Paneth, has developed the methods for helium determination to such an extent that one can measure $10^{-7}$ cubic centimeters of helium, and he has carried out determinations of the ages of meteorites. He has found for the iron meteorites a maximum age of 2,600 million years. This result lends additional appreciable support to the theory that the meteorites and the earth were formed from the same stellar material.

We can follow the fate of the earth's materials back for about 3,000 million years and show that, except for the few radioactive substances, the elements have undergone no change in the course of these years. How and to what extent the individual elements have appeared and disappeared in the span of about 8 million million years between the creation

$$\text{Age} = \frac{z}{x + 0.38\,y} \times 7{,}400 \times 10^6 \text{ years.}$$

They denoted by $z$ the grams of lead present in the mineral, by $x$ those of uranium and by $y$ the grams of thorium. As thorium is usually associated with uranium, the thorium present must be, in practically every case, taken into account.

of the sun and the creation of the earth remains, however, hidden from us. Astronomers estimate the sun's age as about 8 million million years.

The study of radioactivity has led us to the above conclusions. Scientific research attempts to discover and to explain the connections of the natural phenomena. The most fascinating feature of such research is that the experimenter never knows whither the developments may lead. When Bequerel discovered radioactive rays, he had no idea that his discovery would lead to an efficient method for determining the age of the earth. The action of X-rays caused a green fluorescence of the glass walls of his tubes and Bequerel wished to determine whether all fluorescing substances sent out X-rays. Thus he discovered the action of uranium on a photographic plate and hence the radioactive rays. Continuing Becquerel's work, Pierre and Marie Curie were led to study the activity of uranium-containing minerals and discovered in pitchblende the presence of an element radiating much more strongly than uranium, namely, radium. The radioactive rays and radium were indeed epoch-making discoveries; but the most important contribution to the science of radioactivity was made by Rutherford and Soddy when they recognized that radioactive radiation was merely a subsidiary phenomenon accompanying the transformation of uranium and the other radioactive elements, and that it indicated a *disintegration of the atom.* They pointed out that the disintegration products must be present in uranium minerals and accumulate in the mineral in the course of time. Boltwood, who did so much for the early development of radiochemistry, studied a series of uranium minerals, and the constant ratio of uranium to lead struck him as remarkable. He concluded that lead was the end-product of the uranium disintegration and was the first to suggest that the uranium-lead ratio could be employed for the determination of the age of the earth. Simultaneously, the present Lord Rayleigh showed how the accumulation of helium in the uranium minerals furnished a method of determining their age. Experimental and theoretical researches by many workers were necessary in order to extend especially the lead method and to lead to the well-established numerical values here given.

The age of the earth according to ordinary time standards is enormous, but when compared with the age of some stars our earth is extraordinarily young. Three different astronomical methods can be applied to the calculation of the age of the stars, and all three astronomical clocks show the same time, 5 to 10 million million years. If the age of a human being is 1 second, of the human race 6 hours, then the lower limit of the age of the earth is one year, and the age of the stars is 5,000 years.

# THE ORIGIN OF SOUTH AFRICAN ALLUVIAL DIAMONDS[1]

By Dr. GEORGE FREDERICK KUNZ

NEW YORK

ONE of the most important contributions of recent years to the technical literature on the diamond was the comprehensive and masterly treatise on "Diamond-Bearing Alluvial Gravels of the Union of South Africa," presented before the Empire Mining and Metallurgical Congress in Johannesburg in March, 1930. The author, Alpheus F. Williams, a graduate of the University of California and Lehigh University and general manager of the De Beers Consolidated Mines, is the son of the late Gardner F. Williams, the great organizing engineer who, after Cecil Rhodes had unified the mines, did much to bring about the establishment of the methods of control of the native labor that prevented the great amount of pilfering that had previously not only absorbed much of the profits of the mines, but had also damaged the market for the legitimate stones by the sale of the illicit stones. Mr. Williams's paper includes in its 169 pages some 52,000 words of text, 6 maps of the districts under discussion, 38 illustrations and an appendix listing the weight, name of finder and the location and date of discovery of 66 diamonds of 100 carats or more that have been found in the South African alluvial gravels. These 66 stones range in weight from 100 carats to 416 carats, and total 11,324 carats.

Ever since their discovery, the origin of the alluvial diamonds and the methods by which they were transported from their source to their final location have been subjects for speculation and debate. The first alluvial diamond in South Africa was found in the early spring of 1867 near the junction of the Orange and the Vaal Rivers among the bright pebbles picked up by a farmer's children. How many others had been picked up in this way and then lost or discarded no one will ever know, but fortunately this particular pebble caught the mother's eye, because of its bright-

[1] A review and discussion of the paper of Alpheus F. Williams on "Diamond-bearing Alluvial Gravels of South Africa."