Testing the compressibility of actual rock specimens at high pressures has shown that the velocities of elastic waves in the upper layer are consistent with its being granite ; geologists seem to be coming to regard the upper layer as more like a granodiorite than a normal granite, but this is a minor change. The lower layer fits olivine or dunite in elasticity as well as in density ; it is definitely too dense and too stiff to be basalt, which, if it forms any extended layer at all, can only be the deepest and least clearly recognisable of the intermediate ones.

A strong curvature near 20° of the curves representing times of transmission against distance was first noticed by Byerly, and work by I. Lehmann, K. E. Bullen and myself has shown that there is a sharp change in the slope there. This appears to correspond to an increase of the velocity by about 10 per cent at a depth of about 350 km. The nature of this change is not yet understood. Apart from the upper layers, this discontinuity, and the boundary of the core, there are no other sudden changes in properties with depth. Search has been made for a sulphide layer, which has been expected to form the outermost part of the core, but it is necessary to do some violence to the observations to fit one in at all, and there seems to be no room for one more than a few kilometres thick at the most.

The study of gravity made a great advance in 1912 with the publication of Hayford's work in the United States, which showed that the larger mountain ranges of the United States are associated with such a defect of density below that the whole produces little disturbance of gravity. Unfortunately this work, and the later work of Bowie, have suffered greatly from exaggeration and misinterpretation. The general result was to assume that this compensation made a great reduction in the differences between observed and calculated gravity ; but it did not abolish them. It was inferred by many that the approximate compensation was exact, and elaborate theories have been constructed upon it, assuming that it showed not only the lower layer, but even the upper ones, to be completely devoid of strength, in direct opposition to the plain fact that the surface of the earth is not perfectly flat. Others, unwilling to accept the conclusion, have gone to the opposite extreme and denied that the observations imply any compensation at all. It still does not seem to be generally recognised that a theory that reduces the average residual in a mountainous region from twenty times to six times the probable error of a single observation, is on a different footing both from a theory that reduces it to the mean error of a single observation and from one that does not reduce it at all. On the other hand, the generality of the American results is not complete ; they seem to apply to all the great mountain regions where they have been tested, but they break down in India and in the East Indies, as De Graaff Hunter and Vening Meinesz have shown.

Meinesz's introduction of a method of determining gravity at sea by observing in a submarine is perhaps the greatest advance towards determining the figure of the earth accurately that has been made recently. Stokes showed how a complete knowledge of gravity over the earth's surface could give a determination of the external field ; but so long as observations were available only over the land, and very limited proportions of that, we were in the position of trying to locate one end of a rod of unknown and variable curvature by observing a lot of points near the other. Now lines of observed values of gravity are available right across the main oceans, though there is still a great need for more in the southern hemisphere.

The Measurement of Geological Time

By PROF. ARTHUR HOLMES, Professor of Geology, University of Durham

TWENTY-FIVE years ago, opinions as to the scale of geological time were still in a chaotic state. The earlier controversy between Kelvin and the geologists had come to a dramatic end in 1906 with the discovery by Strutt (the present Lord Rayleigh) of the widespread distribution of radioactive elements through the rocks of the earth's crust. The earth could no longer be regarded as a spendthrift living on a limited capital of ancestral heat. An independent source of income had been disclosed in the energy liberated during radioactive disintegration, and henceforth no thermal argument could set a limit to the age of the earth. Already, however, helium and lead had been recognised as the end-products of the uranium family, and Rutherford had suggested (1905 and 1906) that the accumulation of these elements in radioactive minerals might provide a measure of the age of such minerals.

In 1907 Boltwood made the first attempt to calculate the ages of minerals which had been analysed for uranium and lead. During the next three years, Strutt carried out his far-reaching researches on the accumulation of helium during geological time and on its rate of production in uranium and thorium minerals. Thus, by 1910 the foundations were being actively laid on which our present knowledge of the subject has been built. It was evident from the preliminary results that the earth might well be fifty times as old as Kelvin had thought. Geological evidence, based on a statistical comparison of rates of denudation with accumulated sediments on one hand, and with the salinity of the sea on the other, had suggested a period of about 100 million years for the age of the earth. The possibility that 1,000–2,000 million years might be available seemed to many geologists to be as embarrassing as the former limitation to 20–40 million years. Interest in the validity of the rival methods was thus re-awakened, and most of the discussion of the last quarter of a century has rightly been focused on this fundamental aspect of the subject.

For reliable measurements of geological time we require to know : (*a*) the rate at which some suitable process is going on at the present day ; (*b*) the law of its variation during the interval to be measured ; and (*c*) the cumulative change effected by the selected process during that interval.

Except in their application to relatively short intervals, none of the geological methods fulfils these requirements. Present rates of denudation are fairly well known over a wide range of environments, but there are many reasons for regarding their average as abnormally high compared with that of the geological past. River gradients are steeper than usual, because of recent mountain building ; groundwater circulation is more active for the same reason ; easily eroded blankets of glacial and fluvio-glacial sediments are widespread ; and human activities—agricultural, engineering and chemical—have introduced a unique source of acceleration. Evidently no law of past variation can be formulated.

The total accumulation of sediments is difficult to estimate even approximately, since exposed sediments are worked over afresh by denudation, and deeply buried sediments may be metamorphosed beyond recognition by transfusion and granitisation. Measures of maximum thicknesses provide comparable figures for the individual systems, but no corresponding rate of deposition is available, since the maximum thicknesses are really measures of crustal depression. If the sodium method of estimating the age of the oceans is apparently simpler in form and superior in quality, it is only delusively so, and not only because present rates of chemical denudation are high. The geochemistry of sodium is still insufficiently explored in two directions. Sodium is probably returned to sediments by base exchange on the sea floor, and it is certainly added to them from plutonic sources by processes of albitisation and granitisation. The metamorphic cycle introduces incalculable sources of variation, but their effects are all in the same direction, so far as our problem is concerned. All we can conclude is that the actual age of the oceans must be many times higher than the estimate calculated from present conditions.

The radioactive methods are based on the generation of helium and of isotopes of lead from uranium, actino-uranium and thorium, and on the accumulation of these stable end-products in minerals, rocks and meteorites which have retained them. The original uncertainties, which Becker and Joly never allowed to be overlooked, have now been completely dispelled. Unless the contemporary state of scientific knowledge is as misleading in our day as it was in Kelvin's, we can now claim to be in possession of data that are securely founded in principle, and stable in the sense that continued research only increases their accuracy and extends their range*.

The present rates of production of helium and lead from uranium are well established ($\mathrm{U\,I} \rightarrow \mathrm{Pb}^{206} + 8\mathrm{He}$). To a first approximation, the age of a uranium mineral is given by the ratio of lead to uranium, (Pb/U), $\times 7600$ million years. But the investigations of von Grosse on the actinium series, and those of Aston and of Piggot and Allison, in recognising and disentangling the isotopes of lead leave no room for doubt that the actinium series springs from an isotope of uranium, AcU, and terminates in Pb^{207} ($\mathrm{AcU} \rightarrow \mathrm{Pb}^{207} + 6\mathrm{He}$). Thus, a slight error is introduced into the above formula, and this must be allowed for, especially in the case of old minerals. At present, the ratio of AcU to U I is about 4 to 96, and the former disintegrates about ten times as fast as the latter. Clearly the older the mineral the higher should be the ratio $\mathrm{Pb}^{207}/\mathrm{Pb}^{206}$, and hence this ratio itself constitutes an index of age.

The chief defect in Boltwood's original use of lead-ratios only became apparent with the recognition that the thorium series also terminates in an isotope of lead ($\mathrm{Th} \rightarrow \mathrm{Pb}^{208} + 6\mathrm{He}$). For a thorium mineral, the corresponding lead-ratio can be expressed as $\mathrm{Pb}/k\mathrm{Th}$, where k depends on the rate of lead production by thorium relative to that by uranium. Strutt's early work showed that k was not far from 1/3. Later estimates have varied between 0·38 (Lawson) and 0·25 (Kirsch). In Bulletin 80 of the National Research Council, Washington, D.C., referred to above, the value

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* A complete résumé of the subject up to 1931 appears in "The Age of the Earth", Bulletin 80 of the U.S. National Research Council, Washington, D.C. Since then a remarkable amount of new work has been accomplished, largely as a result of the direct influence and co-ordinating activity of the National Research Council Committee on the Measurement of Geological Time. The annual reports of the Committee, prepared by its energetic chairman, Prof. A. C. Lane, not only record the rapid progress which is being made, but also enable individual workers in various parts of the world to keep in close touch with each others' results and ideas.

0·36 was adopted by Kovarik and the writer, and more recent investigations by Kovarik, Ruark and Fesefeldt on the period of thorium have confirmed this value. For minerals containing both uranium and thorium, as many of the suitable minerals do, the simple lead-ratio (uncorrected for the actinium complication and the wearing out of the parent elements) thus becomes Pb/(U + 0·36Th). The corresponding helium-ratio is He/(U + 0·27Th). If helium is stated in cubic centimetres per 100 grams of material, the age of the latter in millions of years (provided there has been no loss of helium) is given approximately by multiplying the ratio by 8·8.

The question whether the rate of generation of lead isotopes and helium has varied during geological time has now been satisfactorily answered. None of the physical or chemical conditions appropriate to the terrestrial environment of radioactive minerals has been found to disturb in any way the normal rates of spontaneous disintegration. But this is not all. Positive evidence of the inferred constancy of rate is provided by pleochroic haloes, the rings of which correspond in radii to the ranges of the respective α-particles responsible for their development. The range of each α-particle is connected in turn with the rate of disintegration of its emitter by a simple law. Hence, if the ranges measured from pleochroic haloes in old Pre-Cambrian minerals are identical with those from Tertiary haloes and experimentally produced haloes, the chain of evidence is complete. In 1923, Joly claimed that the uranium ring showed a progressive increase of radius with increasing age. However, more accurate measurements by Kerr-Lawson in 1927 failed to reveal the alleged increase, and indicated that Joly's identification of the rings had been at fault. A recent study of haloes by Henderson, Bateson and Turnbull, in which a highly sensitive recording photometer was devised to measure the halo features, shows that there has been no variation of range, and therefore no change of rate of disintegration, over a period of a thousand million years. Henderson has also identified a ring due to actinium C and indicated how its development can be used in comparison with that of the radium C′ ring to yield estimates of age. Preliminary results are clearly of the right order.

The third condition of validity implies knowledge of the total accumulation of lead isotopes or helium in the radioactive material under investigation. To consider first the lead method: the presence of initial lead, if any, must be recognised and allowed for, and evidence is required that the mineral has remained uncontaminated by external influences since the time of its crystallisation. Field occurrence, microscopic examination, chemical composition, atomic weight determinations of lead, and isotopic analysis of the lead all contribute data bearing on these important points. After rejecting those numerous minerals which fail to satisfy the requirements, there still remain many for which the evidence of reliability is good. Assurance is confirmed when it is found: (*a*) that minerals of the same geological age, but with varying values of U/Th, give concordant lead-ratios; and (*b*) that suites of minerals of varying geological age fall into an internally consistent time-scale. A good example of (*a*) is given by uraninite and monazite from a Pre-Cambrian pegmatite in Manitoba. Ellsworth obtained a lead-ratio of 0·260 from the first (a uranium mineral), while Miss Kroupa found 0·259 for the second (a thorium mineral), the corresponding ages being approximately 1,745 and 1,725 million years. To illustrate (*b*) the data set forth in the accompanying table will suffice.

AGE DETERMINATIONS BY THE LEAD AND HELIUM METHODS.

Geological Age	Material	Locality	Millions of years from	
			Lead-ratios	Helium-ratios
Miocene	Uraninite	Mexico	35	
	Brannerite	Idaho	38	
Tertiary	Tholeiite	Cleveland Dyke, Durham		28
Eocene	Basalt	Deccan, India		37
Late Cretaceous	Kimberlite	Transvaal		58
	Pitchblende	Colorado	60	
Late Jurassic	Ishikawaite	Japan	128	
Triassic	Dolerite	Connecticut		170
Early Permian	Pitchblende	Bavaria	205	
Close of Carboniferous	Dolerite	Whin Sill, Westmorland		196
Upper Devonian	Uraninite	Portland, Connecticut	283	
	Monazite		278	
Late Ordovician	Uraninite	Fitchburg, Mass.	370	
	Cyrtolite	Bedford, N.Y.	380	
	Uraninite	Connecticut	380	
Upper Cambrian	Kolm	Sweden	455	
Late Pre-Cambrian	Basalt	Gwalior, India		500
	Basalt	Keweenawan, Lake Superior		580
	Pitchblende	Katanga	600	

The early applications of the helium method led to the conclusion that only minimum age determinations were possible on account of the leakage of helium from radioactive materials. Such loss is inevitable when the internal pressure of generated helium becomes high. In recent years, however, certain feebly radioactive substances, such as native metals and iron meteorites, have been found to retain helium completely, and fine-grained basaltic rocks also seem to be satisfactorily retentive. The technique for the determination of minute quantities of helium has been developed by Paneth to such a degree of precision that the amounts accumulated in iron meteorites and in basaltic rocks can now be accurately measured. In 1929 the writer pointed out that "since igneous rocks suitable for the helium method are far more abundant and far better distributed in time than are radioactive minerals suitable for the lead method, there is now available a practical means of effecting long-distance correlations and of building up a geological time scale which, checked by a few reliable lead-ratios here and there, should become far more detailed than could ever be realised by means of the lead method alone". In the accompanying table some of the results which have since been obtained by Paneth, Dubey and Urry are listed.

The oldest minerals so far reliably dated by the lead method are those of Manitoba, to which reference has already been made. A similar age of more than 1,700 million years has recently been found for zircons from a South Dakota granite, which itself is older than the South Dakota uraninite analysed by Davis (1,465 million years). At least one cycle of sedimentation preceded the intrusion of these oldest known granites of North America, and by analogy with other such cycles, this would seem to indicate that the age of the earth cannot be less than 1,900 million years. No approach to a closer estimate is practicable at present. It is not improbable that a maximum limit may be set by the age determinations of meteorites made by Paneth and his colleagues. The results range up to 2,800 million years, but while the origin of meteorites remains in doubt the significance of these figures remains speculative. It appears possible, however, that the earth, the solar system and the present organisation of the stellar universe may all be of the same order of age, namely, 2,000–3,000 million years.

To geologists, the exact age of the earth is of less importance than the application of age measurements to dating igneous rocks, correlating Pre-Cambrian formations in various parts of the world, and building up a reliable time-scale. With the aid of the latter it is becoming possible to estimate the rates at which various geological processes have operated in the past. It is already clear that, at least during the later part of geological time, there has been a remarkable acceleration of activity, and that during the Tertiary period, in particular, the earth was more vigorous in its behaviour than at any other time since the late Pre-Cambrian.

Atomic Physics

By THE RIGHT HON. LORD RUTHERFORD, O.M., F.R.S., Cavendish Professor of Physics, University of Cambridge

THE past twenty-five years has been a period of unexampled activity in physical science, and has witnessed a series of important discoveries which have widely extended our knowledge of the nature of the atoms and the interaction between matter and radiation. On looking back, we can see that the direction of advance was greatly influenced by three fundamental discoveries made at the end of last century—the discovery of X-rays, of radioactivity and of the electron. The proof of the wave-nature of the X-rays in 1913 led to the development of simple methods for studying the X-ray spectra of the elements, and thus gave us important information on the arrangement of the electrons deep in the atom and their frequency of vibration. The study of the radioactive bodies had disclosed that they were undergoing spontaneous transformation and gave us for the first time an idea of the enormous forces which must exist within the structure of the atom. Sir J. J. Thomson early recognised that the electron must be a fundamental constituent in the structure of all atoms, and had devised methods for estimating the number of electrons present in each atom.

The nuclear theory of the atoms, based on experimental evidence of the scattering of α-particles by matter, belongs to the beginning of the period under review. The proof by Moseley that the properties of an atom are defined, not by its atomic weight, but by its atomic or ordinal number, was an outstanding step in advance. It was shown that the atomic number was a measure of the number of units of resultant charge carried by the nucleus and also a measure of the number of electrons surrounding the nucleus. A relation of extraordinary simplicity was thus seen to connect all the elements—a relation which has governed all subsequent advances in our knowledge of the elements.

The proof that the chemical elements are complex and in general consist of a number of isotopes of different masses was an important advance. This conception, which we owe to Soddy, had its origin in the study of the chemical properties of the radioactive elements. In the nuclear theory, isotopes represent atoms of identical nuclear charge but different masses. They should have the same chemical properties, apart from mass, and