

81. MEASUREMENT OF GEOLOGICAL TIME IN INDIA: THE AGE OF ROCKS AND MINERALS

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ABSTRACT

In this paper, the various physical methods for finding out the age of rocks are reviewed and methods in use in the Palit Laboratory of Physics are described. Plea is made for setting up a committee on the Age of Rocks by the Council of Scientific and Industrial Research.

The age of the Earth, i.e. the time elapsed since the Earth has been created, has formed a favourite subject of speculation for theologians and astrologers. The Jews say that the Earth was created 3,751 years before the Birth of Christ on the day of the autumnal equinox. God is supposed to have commenced the labours of creation on the first Week Day and finished it in six days, and then took rest on the seventh day which according to Jews was Saturday. Archbishop Usher nearly two hundred years ago calculated the date of creation of the Earth from the age of Patriarchs as narrated in the Bible and came to the conclusion that Jehovah finished the labours of creating the Earth 4,400 years before the Birth of Christ. The Hindus had an ampler sense of time-scale. They consider that creation and destruction of the world was a periodic phenomenon, the periods running to as much as $4,320 \times 10^6$ years. Based on these calculations, the Hindu calendars give out that 1,972,949,046 years have elapsed since the present cycle began. But after all, this was probably idle speculation based upon certain magic properties of numbers as they could not find sufficient events or evidence to fill up such enormous epochs of time and filled them with legendary heroes having incredibly long lives. Scientific study into the question of age of rocks started with the discovery of fossils of animals and plants of past ages by William Smith in the 1780's. It is not our intention here to describe the methods by means of which the geologists estimate the time which have elapsed since rocks of a certain type have been formed. The geological methods though rough give correct indications but for more precise work they have been supplanted by physical methods based on the study of radio-activity.

PRACTICAL IMPORTANCE

The physical methods, as applied in geological investigations, are not only of academic and scientific interest,

but have a great bearing on the all-important question of location of valuable metallic and non-metallic economic minerals, as well as on the question of location of underground deposits of oil. Geophysical methods are also used for detecting hidden or deeply buried geological structures such as folds, faults, dykes of heavy basic rocks, etc., by methods of Torsion Balance Survey or Seismic or Magnetic Survey, etc. A general knowledge both of the lithology of rocks and their structure is essential in the prospecting of valuable mineral occurrences. But to the question of the age of rocks, geological methods alone do not always give an unambiguous answer. To take our own example, India with its enormously thick unfossiliferous pre-Cambrian formations offers a rather puzzling problem for geologists. Her geological history appears to have been rather peculiar and different from the other parts of the world. The Deccan Peninsula appears to have been a solid mass of dry land almost through the whole duration of geological time, and has not been subjected to those periodic marine transgressions, e.g. alternate submersion under the sea and subsequent upheaval, which most areas of our Earth have passed through. On the other hand, Northern India has been subjected to numerous such transgressions of the sea and other violent geological changes. Some parts of the Deccan, as for example, the tract measuring about 200,000 square miles between Bombay and Nagpur, has been flooded by lava flows, thousands of feet in thickness, that have completely obliterated the previous land-surface and all traces of plant or animal life then existing.

Indian geologists have therefore to coin a peculiar nomenclature to designate the totally unfossiliferous rock-systems found in Peninsular India. For instance, the great thickness of sedimentary strata, designated as the *Purana* Group, contains the *Cuddappah* and *Vindhya* systems, while the overlying zone of strata, designated as the *Dravidian* Group, comprises a few fossiliferous systems of Cambrian and younger ages. A vast thickness of land deposits, composed

GEOLOGICAL AGE CORRELATION TABLE FOR INDIA

GEOLOGIC ERA	GEOLOGIC SYSTEM	MAX. STRATA THICKNESS IN THOUSAND, FT.	INDIAN FORMATIONS				APPROX. AGE IN MILLION YEARS	DISTINCTIVE OR TYPICAL LIFE	TYPICAL FORMATIONS
			PENINSULA	HIMALAYA	SALT RANGE	OTHER AREAS			
KAINOZOIC	Holocene (Recent)		New raised Beaches & Coral Banks	Dry Deltas & recent River Deposits	Blown sand and loess		Modern man		
	Pleistocene (Glacial)	4	Nurbuda alluvium, Porbander Sand-stone	Glacial moraine of Kashmir, Sutlej Deposits	Loess Deposits	Indo-Gangetic Alluvium	Paleolithic man Pithecanthropus Javaman etc.		
	Pliocene	13	Peninsular Laterite	Upper Siwalik	Siwalik	Irawaddy system Manchar system of Sind	15	Modern Mammals Rhinoceros, Mastodons, Apes.	Formation of the Indo-Gangetic Plains
	Miocene	21	Iron ore deposits of Baiyapada in Mayurbhanj	Kasauli series	Middle Siwalik	Surma Valley	35	Early Mammals and early Flowering Plants	Himalayan Elevation
	Oligocene	15	Dwarka beds by Kathiar	Intrusive granite core of Himalayas	Upper Murree (Eastern part)	Lower Pegu	50		
	Eocene	14	Laki series of Bikaner	Indus, Jammu, Kohat & Ranikot series	Ranikot series	Intrusive granite of Baluchistan	70		
	Mesozoic	Cretaceous	64	Deccan Trap	Plutonic Volcanic rocks of Sikkim	Trans. Indus Salt Range	Cretaceous series of Assam & Intrusive Granites of Burma	120	Reptiles (Saurians)
Jurassic		20	Upper Gondwana series & Rajmahal Tracts	Tals of Garhwal Banihal in Kashmir	Jurassic Trans. Indus Salt Range	Lime stones of Baluchistan	150		
Triassic		25	Middle Gondwana & Mahadev Series	Trias sandstone of Central Himalayas	Napeng beds of Burma		190	Amphibians	Limestone & Sand Stone of Baluchistan & Central Himalayas

GEOLOGICAL AGE CORRELATION TABLE FOR INDIA—Continued

GEOLOGIC ERA	GEOLOGIC SYSTEM	MAX. STRATA THICKNESS IN THOUSAND FT.	INDIAN FORMATIONS			APPROX. AGE IN MILLION YEARS	DISTINCTIVE OR TYPICAL LIFE	TYPICAL FORMATIONS	
			PENINSULA	HIMALAYA	SALT RANGE				OTHER AREAS
Paleozoic	Permian	13	Lower Gondwana Ranigunj-Barakar system	Shale & Limestone of Central Himalayas	Limestone of Salt Range	Limestone of Shan States	Amphibians Plants, Fossils, (Ferns etc.)	Formation of Gondwana Coal seams and the recession of the Sea	
	Carboniferous	40	Talchir, Lower Gondwana coal measures	Pir Panjals		Subansiri Beds of Assam	Early fishes and first Vertebrates		
	Devonian	37		Chitral series of N.W.F.P.					
	Silurian	15		Spiti Valley in Kangra of Kashmir				Gastropods Crustacea Cephalopods and other Invertebrates	Vindhyan elevation movements
	Ordovician	40		Kashmir Ordovician			Shales & Limestone of Northern Shan States		
Archaean	Cambrian	40	Upper Vindhyan (?)	Haimanta System of Central Himalayas	Cambrian of Salt-range (?)			Corals and Low forms of Marine fossils, like Trilobites etc.	Cuddappah formation and extensive earth movements
	Proterozoic	Thickness very great actual figures unknown	Dharwar and Lower Vindhyan (?)			Shillong system		Very early forms of life rarely found	Dharwar and Aravalli formations (Oldest sedimentary formations)
	Archeozoic Eozoic		Chotanagpur Gneiss				Fundamental Intrusive Granites of Burma, Assam and Baluchistan	Very Rare or No Fossil Remains	Fundamental Gneiss and Intrusive Granites of Assam, Chhottanagpur & Burma

←— ORIGIN OF EARTH ABOUT 2000 MILLION YEARS —→

Fig. 1

of river-borne sediments, which carry our principal coal deposits, has been designated as the *Gondwana* system and so on. These have been correlated, on such evidence as is available on purely lithological grounds, to the standard systems of the European geological scale. A vast system of crystalline metamorphic rocks, known as the *Dharwar* system, has been assigned to the *Archean* age, while the upper *Vindhyan* system, formerly classified as *Purana*, is now with some justification correlated to the Cambrian. But most of these assignments, in the absence of reliable fossil evidence, lack solid confirmation; and accurate correlation with well-established systems has still to be worked out by other means. In the great extra-Peninsular mountain-zone which bounds Deccan to the west, north and north-east, we stand on quite different ground. Here, wherever fossil evidence is found in the various rock formations, it has enabled a more or less precise correlation to be established with the accepted standard systems of European and American geology. But here also, when fossil evidence is lacking or obscure, the same uncertainty occurs. A striking example of this is the recent controversy regarding the age of the Salt-series in the Salt Range mountains of the Punjab. This important mountain range lies in the Doab between the Jhelum and the Indus and carries rock-salt deposits of considerable magnitude that has supported important salt mines for centuries. One school of geologists holds this formation to be of the Cambrian age, while another school, on equally plausible grounds, hold them to be of the Tertiary age. This controversy has lasted for nearly five decades. The Cambrian system of rocks is held to be nearly 500 million years old, while the oldest Tertiary system is not more than 50 million years. To the non-geologists, these widely divergent views seem anomalous. Recently, Professor Birbal Sahni of the Lucknow University, by using a new technique, has detected minute plant fossils *in situ* in the saline-series, which go to prove a lower Tertiary age for the series. The *in situ* nature of these fossils (which are microscopic in size) is doubted by the Geological Survey of India and geologists of various Oil Companies. (*Nature*, 1944, p. 462, Vol. 153; *Nature*, 1945, p. 258, Vol. 155).

MODERN TECHNIQUE OF GEOLOGICAL AGE DETERMINATION IN THE U.S.A.

A somewhat similar condition prevailed in the U.S.A. Systems of rocks lacking in indubitable fossil testimony were found difficult to correlate with those of Europe, and names such as *Mississippian*, *Pensylvanian* and *Laurentian* have been coined by American geologists. In order to collect more precise scientific evidence regarding the age of rocks in the U.S.A., a National Committee under the Chairmanship of Dr. A. C. Lane, Professor of Geology in the Harvard University, was set up by the National

Research Council of the U.S.A. in 1932. The work of the Committee has resulted in the development of more accurate physical methods in the age determination of rocks and minerals, employing the mass-spectrograph, the interference spectroscope, determination of radio-activity by electronic methods, lead-helium ratio, micro-volume measurements, etc. Such geophysical methods have not yet been used in India, except some stray measurements by N. C. Nag, Swaminathan, Mahadevan, Dube and one or two others.

The Time Scale of Geology.—The time scale of the geologists is derived by painstaking study of the surface rock formations. The fossil remains of past epochs that get embedded in sedimentary rocks are the hour-marks on the face of his geologic clock, for fossil remains have been found to show the successive stages of evolutionary development through the ages. There are, moreover, periods of prolific development of particular species over a large part of the face of the Earth during certain geologic eras. The Carboniferous era of geologists, so called because of the sudden development of types of conifers and other exuberant vegetation over large tracts of the world's surface, is the time during which the principal coal-seams of the world were formed. Limestones and chalk are also attributed to a sudden proliferation of several species of small foraminifera, corals, crustacea and shell-like creatures. The oldest fossil remains are attributed to the Cambrian age. The actual time elapsed since the Cambrian age cannot be estimated accurately, but it is supposed to be somewhere about 500 million years. Geologists have estimated the duration of an epoch by the thickness of the sedimentary layers corresponding to that epoch and by other means. The estimates vary greatly as the thickness of sedimentary deposits of the same epoch are not of equal thickness, nor is the rate of deposition of sediment anywhere near constant.

Pre-Cambrian Age.—All rocks older than the Cambrian age, that is, all rocks formed before the advent of life on the globe, are lumped together into one group usually called 'Archaen' meaning old or pre-Cambrian. The Archaen rocks according to current estimates of geologists cover a period of time nearly four to six times as long as the total time from the Cambrian rocks down to the present time. Since there are no fossil remains in these old rocks it is difficult to attach much importance to the estimation of age of these old formations. There are also frequent cases when the fossil remains in a particular rock are entirely unsatisfactory and cannot be used to determine the era to one's satisfaction. There are other cases where an independent check may be desired due to conflict of evidence. In addition, the question of absolute age of rocks on geological evidence alone will ever remain unsatisfactorily answered in all parts of the world.

Physical Methods.—Physicists have long attempted to

find a solution to this vexed problem in terms of a physical process whose time rate of variation can be correctly determined. One of the earliest attempts was by Lord Kelvin who tried to calculate the age of the Earth from its rate of cooling. He assumed that the Earth was originally at the temperature of the surface of the sun, i.e. about 6000°C ., and that it has cooled down through the ages at a uniform rate depending on the internal and surface temperatures. He calculated the thermal conductivity of the Earth from several samples of rock and obtained a mean value. The results that he obtained were, however, unacceptable to the geologists as they were very much lower than the estimates of geologists. In fact his estimate of a few lacs of years were not even enough to account for the long span of evolution of life on Earth. This contradiction proved fatal to the conductivity method of measuring ages and showed that Kelvin had neglected some very important factor.

Radio-activity.—The discovery of Radio-activity of Uranium and Thorium late in the nineteenth century brought this factor to light and gave a veritable physical time-clock for estimating ages of rocks. As is well known, a few heavy atoms like uranium, thorium and actinium atoms are found to disintegrate at a constant rate breaking up into simpler atoms. This rate is a characteristic of the type of disintegrating heavy atoms and is entirely unaffected by temperature, pressure or the state of chemical combination of the radio-active element. Uranium for example breaks up by emitting successively eight doubly charged helium atoms or α -particles and ends up finally as lead of isotopic weight 206 (Pb 206). The rate of disintegration is expressed in half-lives which simply means the time in which half of the total number of radio-active atoms of a particular element will disintegrate. Uranium which is at the head of the uranium-series of disintegrations has a half-life of 4,400 million years. The successive elements of the uranium series disintegrate very much faster and do not have any geological significance due to the shortness of their lives. Radium is the longest lived of the daughter elements of uranium and has a half-life of 1,600 years which is quite small compared to the duration of the geological epochs.

Thorium behaves very similarly to uranium giving rise to another chain of disintegrations of which again thorium has the largest half-life of 18,000 million years. The final end product in this case is also an isotope of lead of isotopic weight 208.

The third chain of disintegration, the actinium series can now preferably be called the Actino-uranium series, since the parent of the actinium series is not actinium but an isotope of uranium of mass 235 whose half-life has been recently estimated by Nier at 700 million years. Uranium of the mass 235 is present in a ratio of 1:139 with the ordinary uranium isotope of mass 238 and disintegrates

finally to lead 207. All these three radio-active elements can be used as geological time-clocks as their rates of disintegrations are known.

Besides the isotopes 206, 207 and 208, lead contains another isotope of mass number 204 in very small proportion which appears to be unconnected with any radio-active disintegration, though the opinion has been expressed that it may be the result of α -ray disintegration of Pb^{208} followed by two successive β -ray disintegrations, But this theory has not been proved, and we may take Pb^{204} as a stable isotope, unconnected with any radio-active process.

When lead is found to occur in a rock, either containing radio-active matter like U, or Th, or entirely free from these, the first task is to estimate accurately the proportion of uranium, lead and thorium. This is a comparatively easy task in analytical chemistry. The second task will be to estimate the chemical weight of lead. This has been found to vary widely from 206 to 208, the first figure being found in rocks containing high proportion of U, e.g. in Curite, Uraninite, the last in rocks containing high proportion of Th, e.g. in Thorianite, but in rocks containing no *radio-active matter*, the atomic weight of lead is generally found to be 207.23. What is the cause of this wide variation in the atomic weight of lead?

It is obvious that in the rocks where the atomic weight of its lead is about 208, e.g. in Thorianite from Ceylon, most of the lead has been derived from the disintegration of thorium and in those minerals where the atomic weight is nearly 206; e.g. the Curite from Katanga in Belgian Congo, it is derived mostly from the disintegration of uranium. But such rocks are few and in most minerals the atomic weight varies all the way between 206 and 208. To explain these wide variations we may start with the plausible assumption that when rocks were formed, they not only contained U^{238} , U^{235} , Th^{232} in different proportions, but also contained some lead from the primeval matter. After the rock has aged sufficiently additional amounts of lead were formed from the decomposition of U and Th and were added to the lead already present, thus changing its atomic weight, and the relative proportions of the different isotopes of lead. We can generally take that the lead in a rock is composed of two types of lead: (i) non-radiogenic lead which was deposited in the rock from the primeval matter when the rock was formed, and (ii) radiogenic lead, which grew subsequently out of the disintegration of uranium and thorium.

To test this hypothesis, our next task is to estimate the proportions of the different isotopes in this non-radiogenic and the radiogenic lead. The isotopes cannot be separated chemically, but complete separation by physical methods have been devised lately (method of thermal diffusion). Here we are concerned only with the estimation of relative proportions of the isotopes, and this can be done either (1) by the method of hyperfine structure analysis or (2)

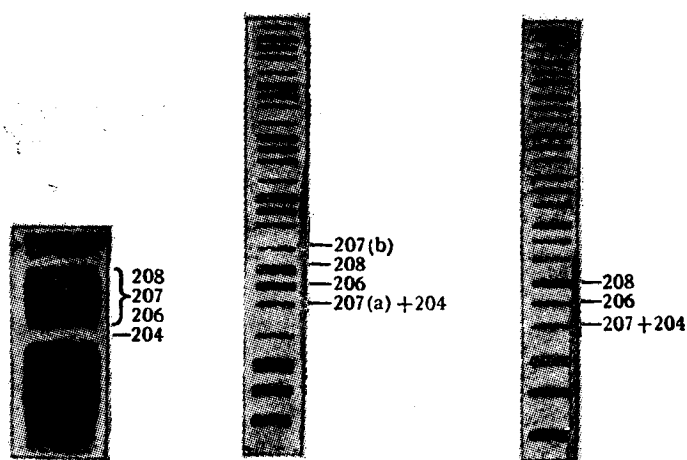


Fig. 2

by the mass-spectrograph; the first method depends on the fact that spectral lines due to the four isotopes slightly differ in wavelength and structure and if apparatus of extremely high dispersion be used, they can be separated.

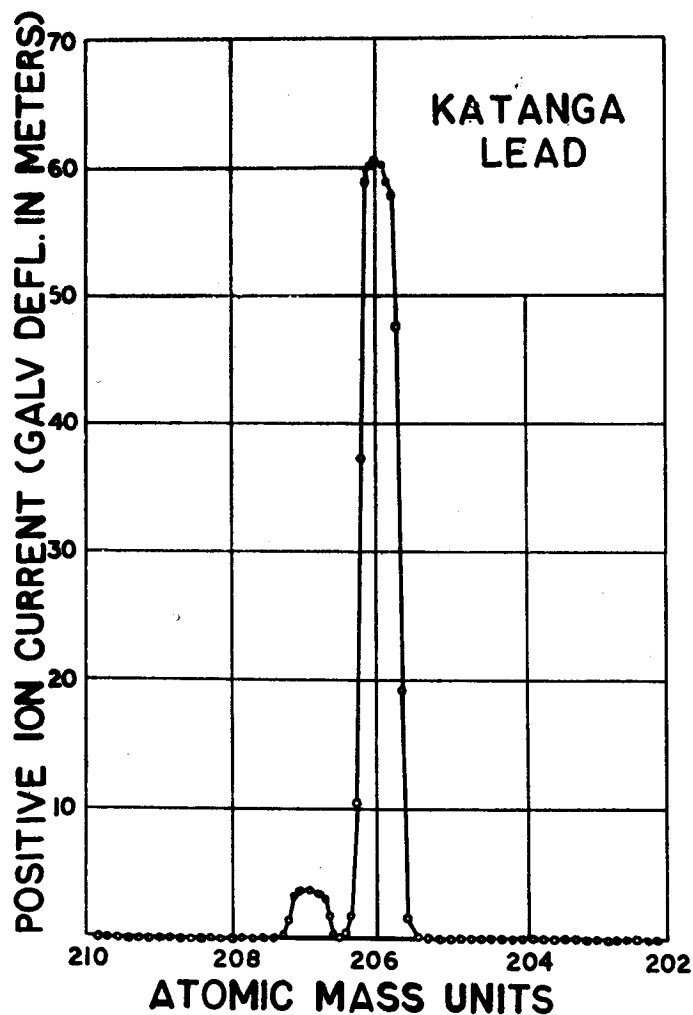


Fig. 3

The relative intensities of the components ascribed to the isotopes give us their relative proportions.

The mass-spectrograph is, however, a far more powerful and accurate apparatus for this purpose, and in the hands of Nier and others, it has received so many improvements that relative proportions of the isotopes in a sample can be estimated quickly and quite accurately.

Nier and others have analysed isotopic ratios in different samples of lead with the help of the mass-spectrograph from rocks and minerals completely free from radio-activity. They find that in the main, the isotope ratios for non-radiogenic lead is fairly constant and their average values are: (Nier: P.R. 55, 194)

Pb ²⁰⁴	Pb ²⁰⁶	Pb ²⁰⁷	Pb ²⁰⁸
1	18.8	15.7	38.9

with the mean atomic weight as 207.23. There are, however, slight differences in isotope ratios from sample to sample quite outside the range of error claimed by Nier. These variations are slight and, for practical purposes of age determination, can be neglected. For more complete analyses the extreme values of isotope ratios should be taken into account.

One can picture that the primeval magma out of which the rocks have been formed contains lead in which the isotopes are in the constant proportion approximately given by Nier's analysis. Supposing a rock in some distant geological epoch has trapped in it radio-active elements together with the primeval lead. Through the ages the radio-active elements will now disintegrate to give certain isotopes of lead. The proportions of these isotopes in lead will then increase while lead isotope (204) will remain the same and if the original proportion is assumed as given above the amount of increase of each lead isotope can easily be estimated.

The following table (fig. 4) gives an idea of the proportion of isotopes of lead occurring in some of the representative minerals of North America. Three selected non-radiogenic lead minerals are also analysed for comparison and to show the natural range of variation of the proportions of the isotopes. It is clear from these figures that the total percentage of lead in a mineral alone is no indication of the age of the mineral. Colorado Pitchblende and the Connecticut Samarskite contain the same percentage of lead although it is obvious from the isotope analysis that the Pitchblende contains about six times the quantity of non-radiogenic lead compared to the Samarskite. An exact analysis yields an age of about 50×10^6 years for the Pitchblende compared to 280×10^6 years for the Samarskite.

Geologists and geochemists like Keevil and Urry have used a rough modification of this method which avoids the complicated and difficult isotope ratio analysis of lead.

PHYSICAL & CHEMICAL ANALYSIS OF TYPICAL MINERALS

NAME	CLASS	LOCATION	%U	%Th	%Pb	Pb ²⁰⁸	Pb ²⁰⁷	Pb ²⁰⁶	Pb ²⁰⁴	MEAN At wt
1. URANINITE	URANEUS MINERALS	PARRY SOUND, CANADA	6.9	2.9	10.8	1.52	7.40	100	.006	
2. PITCHBLENDE		WOODS MINE, COLORADO	72.3	.11	.314	38.0	19.4	100	1.01	
3. CURITE		KATANGA, BELG. CONGO	65	.04	.96	.178	6.18	100	×	
4. MONAZITE	THOREOUS MINERALS	HURON CLAIM, CANADA	.28	15.6	1.5	100	2.11	11.6	.011	
5. MONAZITE		LASVEGAS, NEW MEXICO	.12	9.39	.372	100	1.25	10.1	.028	
6. THUCHOLITE	MIXED MINERALS	PARRY SOUND, CANADA	4.63	.90	.187	6.9	5.88	100	.024	
7. SAMARSKITE		GLASTONBURY, CONNECTICUT	6.9	3.1	.314	21.3	7.6	100	.167	
8. GALENA	NON-RADIOGENIC LEAD MINERALS	DURANGO, MEXICO	NIL	NIL	×	38.5	15.7	18.7	1.00	207.227
9. GALENA		FRANKLIN, NEW JERSEY	NIL	NIL	×	36.5	15.5	17.2	1.00	207.233
10. GALENA		TETREAUULT, CANADA	NIL	NIL	×	35.6	15.2	16.3	1.00	207.239

Fig. 4

There are a number of well-known uranium and thorium minerals which normally occur with little lead, e.g. Uraninite, Curite, Gumite, etc. Geochemists make the plausible assumption that all the lead occurring in these minerals is wholly of radiogenic origin. The chemically determined proportion of lead in the mineral is then determined and attributed wholly to the disintegration of uranium or thorium or both as determined from the radio-active content of the mineral. The expression which is used is

$$T \text{ (in million years)} = \frac{7,600 \times \text{Lead (gms.)}}{U + .36 \text{ Th}}$$

and is applicable for minerals of less than 500 million years without appreciable error. It must be emphasised, however, that the result, although sometimes quite concordant with the earlier and more rigorous method of isotopic analysis, is at other times in grievous error. We cite as an example the Curite from Belgian Congo which yields an age of 125 million years by this method yields an age of 115 million years by the more accurate analysis of the lead isotopes. The results are quite concordant. In the case of the Connecticut Samarskite obtained in a very good condition, the same method yields a value of 380 million years which is somewhat in excess of the value of 250 to 280 million years obtained by isotopic analysis methods. This excessive value is due to the presence of a small amount of non-radiogenic lead in the mineral. Larger amounts of non-radiogenic lead in the mineral might give even larger discrepancies.

Estimation of Uranium and Thorium.—The estimation of relative proportions of Th and U is a very important task in all these problems. So far they have been estimated by chemical methods alone which are rather tedious and time-exhausting. Recently physical methods for quick estimation of thorium and uranium have been evolved. They depend on the radio-active properties of these elements.

These three methods may be tabulated as:—

- (1) Method of Finney and Evans by α -counting.
- (2) Method of β -ray ionisation chamber and foils.
- (3) Method of β -ray counters and foils.

	Uranium Content	Thorium Content	References
Method of Finney and Evans	20.08 ± 1.42%	60.94 ± 2.2%	Nag, Das and Das Gupta, <i>Proc. Nat. Inst. Sc.</i>
β -ionisation method	21.16 ± 1.1%	60.24 ± 2.0%	Mousuf (in preparation for press), M.Sc. thesis, 1944.
β -Counter method	20.5 ± 1.7%	61.3 ± 2.5%	Nag (private communication).
Chemical Analysis	21%	61%	P. B. Sarkar, <i>Science and Culture, Bull. Nat. Res. Council.</i>

These methods are all essentially the same in principle and the results of a sample of Thorianite measured by the three different methods are compared here with the results of direct chemical analysis. The Thorianite was a gift from Prof. D. N. Wadia, for some time Geological Adviser to the Government of Ceylon.

Within the errors involved in the experiment all the methods give approximately the same result and are about equally reliable. The β -ray ionisation current method which has been developed in the Palit Laboratory gives the quickest and simplest quantitative analysis of all the methods including chemical analysis but is applicable only for quantities of radio-active elements of 1 per cent or greater in the mineral. It is now in use as a standard method for finding proportions of uranium and thorium in minerals regularly in this laboratory. The chemical method suffers from the defect that losses on ignition may be large where small amounts of U or Th is involved. The method of Finney and Evans has been very extensively used and consists in counting the alpha particles emitted from a

given sample and noting the number of counts with various thicknesses of thin absorbing foils. This method is limited by the difficulties of counting kicks of a galvanometer over long periods of time and the impossibility of counting more than 100 per second. If the radio-active contents of a mineral sample is large, i.e. greater than 20 per cent of the total weight of the mineral, large errors may be introduced.

The Lead 206/Lead 207 Ratio Method.—Nier has recently proposed an ingenious method which does away with measurements of uranium and thorium content as well as the chemical estimation of lead in the mineral. He determines the isotope ratio of the lead by the mass-spectrographic method and calculates the geological age from these data alone. Uranium has two isotopes, U^{235} and U^{238} , both of which disintegrate finally to lead but to two different isotopes, 207 and 206, and at two different rates. The half-life U^{235} is 700 million years and this isotope thus disintegrates at a rate nearly four times faster than U^{238} . Suppose initially both the uranums start to disintegrate and no lead is present in the mineral, then Pb^{207} will accumulate at a rate nearly four times as fast as Pb^{206} . The isotope ratio of Pb^{207}/Pb^{206} will increase with the age of the mineral. This straight forward idea has to be modified to take three factors into account. Firstly, the initial quantities of U^{235} and U^{238} or their ratio has to be known. Their present ratio has been measured accurately from various sources and yields a more or less constant ratio of $U^{235}/U^{238} = 1/139$. Knowing their rates of disintegration the ratio at any geological time can be calculated very simply. Secondly, the mineral may contain an unknown quantity of non-radiogenic lead. The lead 204 isotope is then used as an index of the presence of non-radiogenic lead and corrections are made in the lead (206/207) ratio by subtracting a certain fraction of lead 206 and 207 isotopes from the respective quantities to eliminate the effect of non-radiogenic lead. For example, take the Pitchblende from Colorado in our table, the apparent Pb^{207}/Pb^{206} ratio = 19.4/100, but since Pb^{204} occurs, non-radiogenic lead is present in the sample. The average ratios of isotopes in non-radiogenic lead have been given earlier and are subtracted from the lead ratios of the lead from Pitchblende,

207	206	204
19.4	100	1.01
15.84	18.98	1.01
3.6	81	

and the ratio of Pb^{207}/Pb^{206} to be used is 3.6/81. Thirdly, corrections have to be made to take into account the fact that the U^{235} is being depleted much faster than U^{238} and hence, even, though the rate of disintegration of U^{235}

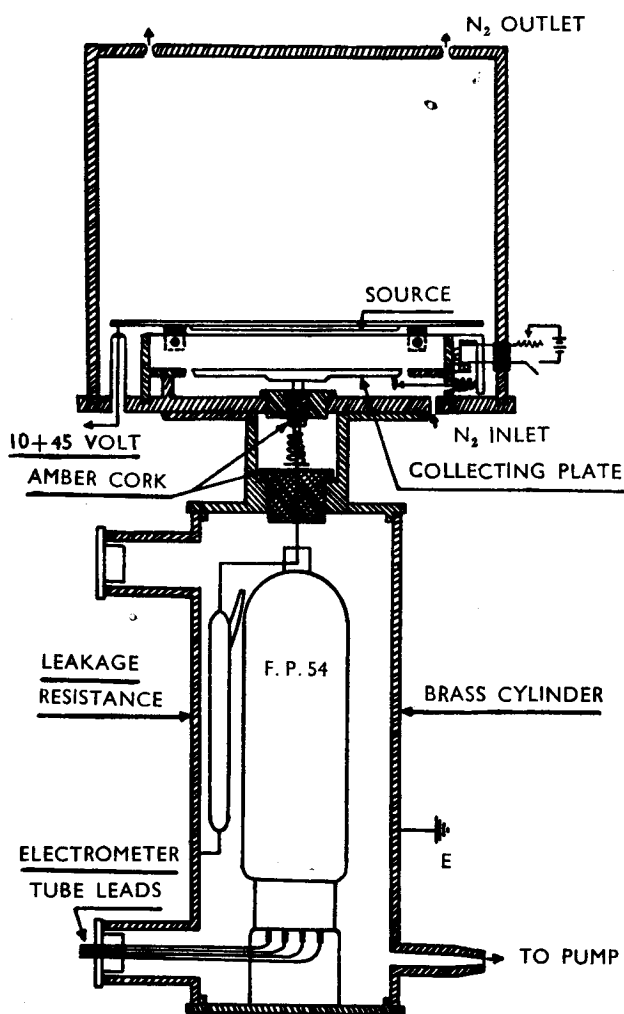


Fig. 5

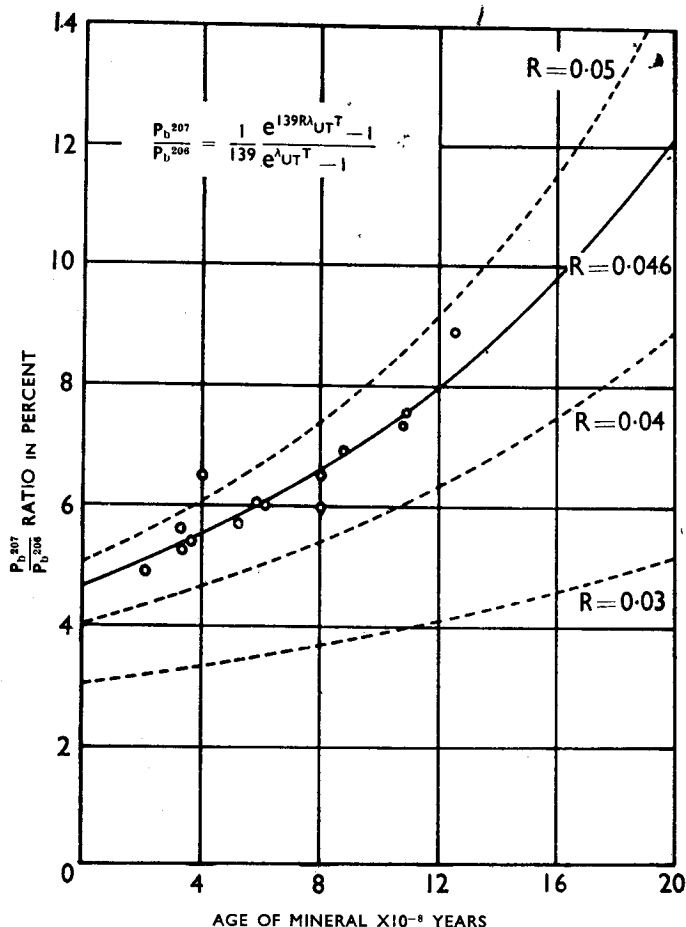


Fig. 6

is three and a half times faster, the accumulation of lead is not exactly in proportion but somewhat smaller. Nier has drawn a curve which we show in fig. 1 giving the actual calculated age taking the first and third factors into account against the ordinate of Pb^{207}/Pb^{206} ratio after correction for the presence of non-radiogenic lead. The age of this mineral is 90 million years from Nier's Curve in accordance with values by other methods.

Nier has developed a mass-spectrograph for routine studies of lead isotopes and has examined several minerals from all parts of the world for determining their ages by this method. The lead is usually used as a halide and the lead ions are obtained by electron bombardment. The mass ratios are measured in terms of ion currents, by an electrometer arrangement.

Measurement of Helium in Rocks.—Another method of measuring the amount of decay of uranium and thorium is to measure the amount of helium that has accumulated from the disintegration of uranium and thorium. For every uranium atom that disintegrates to lead, eight helium atomic nuclei are given out in the process. With thorium there are six helium atomic nuclei emitted for every atom of thorium. Helium accumulates six or eight

times faster than lead and can be estimated by methods of micro gas analysis. Helium estimations, however, suffer from a very serious defect. Helium is a very light gas and can pass through a lot of solid substances including glass and hence quite a large fraction of helium may have been lost from the mineral through the ages. Such loss of helium is very common and frequently give quite erroneous results when estimating geological ages. The helium method, however, leads to a minimum estimate which is sometimes useful, if care is taken to select minerals which are unweathered and show very little crystallisation. Paneth has pointed out certain minerals that contain natural helium which may give an over-estimate. Samarskite can be cited as an example of a mineral which, if obtained in unweathered condition, is likely to yield fairly consistent results if the mineral is not from a very old formation. The formula for young rocks is

$$T \text{ (in million years)} = \frac{8.8 \text{ He (in gms.)}}{\text{Uranium (in gms.)}} \text{ which yields}$$

for the Samarskite an age of 180 million years.

Keovil, Larsen, Evans and others have worked with extreme care on the helium ratio method and have made large number of measurements. They claim that with proper choice of minerals and due care, the error in age estimation may be reduced to about 10 to 15 per cent. Their results are sometimes extremely good. However, the objections to the helium method remains in some quarters as strong as before.

Let us see how far these different methods give us concordant results. Nier and Wells have examined a Samarskite from Connecticut, U.S.A. (Mineral 7 of fig. 6), analysed in the table by various methods as tabulated below.

Age in millions of years	Chemical		Pb^{203}/Pb^{207}	U+Th —He
	U+Th —Pb	U— Pb^{206} Th— Pb^{208}		
	350	253 266	280 ± 60	180

The results obtained by the helium method is given in the last column for comparison.

The example cited above is rather exceptional. Most minerals and their combination, the rocks, since their original formation from magma, undergo various changes (metamorphism) due to weathering action of water and air and due to their being brought under different conditions of pressure and temperature on account of folding and faulting of strata as well as due to the burying of the rocks under subsequent younger deposits. These changes may not only wear away the rocks or minerals, but change their composition and constitution as well. Certain uranium compounds are very soluble in water whereas the lead

produced from its disintegration is not so easily acted on by water. Such a rock may show greater proportion of lead content to the uranium and may be mistakenly attributed to a greater age. The lead 206/207 method will, to a certain extent, correct such errors. As we mentioned before helium escapes very easily from a rock and the helium estimate may be considerably lower than the actual value. Other types of changes can leach out the lead and cause underestimates or natural helium in rocks can give excessive estimations of age. Field evidences of the formation from which the rock or mineral is collected are thus of paramount importance in age determinations and the co-operation of geologists in interpreting the evidence is essential.

While we have mainly dealt with the major methods of measuring geologic time, it may be worthwhile to mention briefly some of the minor methods of interest and occasional usefulness. We have mentioned the first of these: the computation of heat loss due to the heat conductivity of the Earth's material. The modern and more precise variant of this method is that of geotherms and actual determination of heat generation and loss. This method is still in an embryonic stage and, though capable of giving valuable information, has not yet proved to be of much use in actual computations of age. The radio-activity of Potassium and Rubidium yields two independent methods. The accumulation of Strontium in Rubidium bearing mica has been studied and estimated by Hahn and Strassman in 1937. In one experiment 1 kgm. of old mica from Norway, belonging to early pre-Cambrian times, was examined. The mica contained 2 to 3% Rubidium, and 250 milligrams of Strontium Carbonate was extracted from the mineral. 99% of the Strontium was found to be the Strontium isotope 87 by mass-spectroscopic examination. If the Strontium isotope 87 is supposed to be formed by the beta radio-activity of Rubidium 87, then

$$\frac{\text{Number of Rubidium (87) atoms transformed to Sr (87)}}{\text{Number of Rubidium (87) atoms present}} = \frac{\Delta N}{N} = \lambda t = \frac{.69t}{T}$$

calculating from above percentages of Rubidium and Strontium present in the mica one gets

$$\frac{\text{Sr (87)}}{\text{Rb (87)}} = \frac{1}{45} = \frac{.69t}{T}$$

The age of the mineral calculated on the basis of the half-value period of Rubidium as $\sim 10^{11}$ years exceeds that of 2×10^9 years the accepted age of the Earth. Hahn assumed that a certain amount of Rubidium had been lost causing the present discrepancy. It is interesting to note, however, that such methods in special cases may give an idea of age of the mineral. Geologists have studied the deposition of sediment and varves to estimate ages and duration of

epochs. Another method recently suggested by Ellsworth and amplified by Lane is the process of auto-oxidation of uranium from naturally occurring uranium dioxide to the trioxide. Each disintegrating uranium atom sets free two atoms of oxygen $\text{UO}_2 \rightarrow \text{Pb} + 8\text{He} + 2\text{O}$. These two atoms of oxygen can oxidise the neighbouring uranium dioxide in the mineral to the trioxide $2\text{UO}_2 + \text{O}_2 = 2\text{UO}_3$. Thus, according to Lane, one can estimate the number of uranium atoms that have disintegrated from the amount of trioxide of uranium present in the mineral. The age equation is T (in million years) $= 1.44 \times 10^4 \log \text{UO}/\text{Ut}$, where UO is the amount of U in dioxide form and Ut is the uranium in the trioxide form. The method has not yet been tried extensively nor has it been yet shown to give concordant results.

Another method which enjoyed a vogue about a decade or more ago is the observation of the intensity of discoloration of pleochroic haloes. These haloes are formed in mica due to very small inclusions of uranium or thorium. The ionisation of the emitted α -rays gradually discolours the mica and the amount of discoloration gives an estimate of age if the amount of intruding uranium or thorium can be estimated. As the inclusion may be normally as small as 10^{-19} gms. of uranium it is very difficult to get a reliable estimate of the quantity of radioactivity. This is the strongest criticism against this method.

All these minor methods may be of corroborative value but have not yet stood trial against extensive criticism that may be levelled against them. Mention may be made of the work recently started in this laboratory on these lines with measurements on radio-active contents of several minerals.

Further samples and information regarding them will be needed to work out comprehensive methods to deal with such problems. Co-operation of geologists and chemists to determine mode of occurrence, nature of alteration, geological epoch, etc., will be very necessary to such work. Further work on the determination of isotope ratios is also in contemplation.

It may be pointed out that such complicated analysis is not only desirable but extremely necessary to take various factors into account in estimating geological time. An extensive work of this type needs the co-operation of geologists, chemists and physicists working in a team to ensure taking into account various factors, like conditions of occurrence and associated minerals, chemical analysis, microanalysis, radio-active measurements and mass-spectrographic analysis of samples. Such a scheme of extensive work has been in operation for the last 12 years under the National Research Council of the U.S.A. in a Committee on the Measurement of Geologic Time under the Chairmanship of Prof. A. C. Lane with the collaboration of physicists like Nier and Evans, chemists like Baxter of Harvard and Sage and geologists like Keevil and Berman. Such an organisation with funds at its disposal would seem

to the author to be eminently desirable in this country for furthering such a work in an efficient and collaborative way. It is a matter of sincere congratulation that the Council of Scientific and Industrial Research of the Government of India has seen fit to make a grant for the development of the physical methods to the determination of the geological age. A great deal of work has to be done in this connection and co-ordination of efforts between the geologists and physicists has to be achieved. Some of the fundamental apparatus for routine determination, e.g. mass-spectrograph for isotope ratios, are still unavailable in this country.

It is hoped that with future co-operative efforts greater strides in the path of progress will be made in this field of fundamental work.

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82. ON THE PROPAGATION OF ELECTRO-MAGNETIC WAVES THROUGH THE UPPER ATMOSPHERE

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ABSTRACT

This paper reports a comprehensive working of the problems of an ionised atmosphere, traversed by a magnetic field, as in the case of the Earth's atmosphere. Expressions are deduced for electrical polarisation and complex conductivity for such an atmosphere when traversed by radio waves, in a tensor-form, as first suggested by Darwin. The equations of propagation of radio frequency waves through such a medium are obtained by the use of cardinal axes, and then the equations of vertical propagation are deduced. Expressions are obtained for refractive indices of ordinary and extraordinary waves, which agree with the expressions given by Appleton. Expressions are obtained for polarisation, absorption etc. of the radio waves travelling in the ionosphere. Curves are given for the polarisation ratio and refractive indices of the two waves as functions of the magnetic latitude of the place of observation.

INTRODUCTION

Ever since the classical works of Appleton (1932) and Hartree (1932), the problem of the propagation of e.m. waves in the ionosphere has received attention from numerous workers. Summaries of these works are available in various reports. Recently B. K. Banerjea (1947) made a critical and comparative study of the fundamental methods of Appleton (1932), Hartree (1932), Saha, Rai and Mathur (1937) and Saha and Banerjea (1945) and showed that these various methods can be deduced as special cases of

a general method developed according to Darwin's (1925) suggestion of treating the e.m. properties of the medium as tensor quantities. The present paper continues the treatment further and aims at giving a true wave formulation of the general problem. For the convenience of the reader some results of the previous works carried out by the senior author and his early collaborators are included so that no further references to these papers are needed. Part

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