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PLENARY LECTURE

Geochronometry—A geophysical necessity

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"The surface of this planet has been the theatre of reiterated change, and is still the subject of slow but never-ending fluctuations."

CHARLES LYELL—*Principles of Geology*, 1830.

"The wisest thing is Time, for it brings everything to light."

THALES—*Diagnosis Laertius, Thales, Bk. i, sec.* 35.

Geochronological studies aim at determination of time sequence of events in the past which would allow one to construct a consistent geological time scale of important events characterizing the evolution of the earth. Careful and detailed examinations of terrestrial samples such as sediments, rocks and their matrix allow one to (i) delineate the geological events and to (ii) find the time when the particular event occurred. The two are distinct tasks and are usually performed by different breeds of scientists, but are not unrelated. Actually it is not possible to determine a meaningful chronology unless one understands clearly the nature of events and physical processes which occurred prior to and subsequent to the event.

Thus, one can not dissociate the task of measuring time from the task of studying the past history of the earth. The phenomenon of radioactivity was discovered in 1896 by Henri Bacquerel and the first radiometric dates were obtained in 1907. Advances in nuclear physics and in the techniques of measurement of trace amounts of radioactive and stable nuclides have led to development of new dating methods and at the present moment, a large number of very sophisticated dating methods exist. But it must be stressed that the rather precise detailed information which exists today about the history of the earth, as a result of investigations in the last decade, is a result of simultaneous developments in chronometric methods and a better understanding of geophysical processes. Exciting developments in the methods of studying the "record" have taken place. An example is the study of solid state changes in the rock matrix due to the fission of uranium. The record of earth's magnetism, flora and fauna has been explored in much greater detail. We also have acquired a greater understanding of the principal geological and geochemical processes. The present day ideas of plate tectonics which can be traced back to the ideas propounded by Wegener in 1912 and Du Toit and Holmes in the 1920s provide a consistent framework for understanding the evolution of the surface of earth. On the other hand, an insight into processes which led to the formation of the earth and about the earth's interior has largely resulted from the recent lunar and planetary explorations.

In this article I will attempt to briefly dwell on some of the geophysical concepts which brought about a revolution in geological sciences and will outline the basic principles behind the nuclear, physical, chemical and biological methods of measuring geological time. The principal geochronological and some of the new methods of dating marine sediments in particular will be outlined. I will also briefly touch upon some of the planetary studies which are useful for understanding the evolution of the earth.

NATURE OF GEOLOGICAL CHANGES AND GEOPHYSICAL PROCESSES

It is now well recognized that the outlook of our learned world was profoundly altered by two major scientific revolutions. First of these is the Copernican-Keplerian-Galilean revolution and the second is the Huttonian-Lyellian-Darwinian revolution. These major intellectual revolutions brought about the demise of a purely philosophical outlook of the earth and the supporting theological dogmas. These revolutions ended the erroneous concepts of a geocentric solar system and a young geologically static earth whose plant and animal inhabitants were the result of divine intervention. And began the concepts of evolution, evolution of a typical star and its planetary system and evolution of biological species on a planet on a very long time scale—termed the geologic time scale where one of the units of time is million years.

Any discussion of geologic time is, by virtue of the fact that it must include everything that happens on the earth, a formidable task. Any gap or hiatus can be serious. It is therefore very essential that a variety of independent methods are used to study time and processes. Fortunately the nuclear clocks which provide absolute time scales have been extensively developed and the chance of our constructing a chronology with major gaps in information about geophysical/biological episodes is minimised. However, the radiometric dates are based on plausible models and one has to be very cautious about possible inadequacies of assumed models. Key to understanding the past does not lie in merely having a few nuclear clocks at hand ; one has to understand the character of geophysical and geological processes.

Before going into nuclear and other methods of geochronometry, I will briefly dwell on some of the important developments in geophysical sciences which have led to the present state of the art.

(i) *Development of ordering principles in earth history*—Not long ago, the earth was viewed in a strictly temporal framework and the concept of time was reserved for man alone (Eicher, 1968).

"Hendrik Van Loon once measured the scope of time in the following tale :

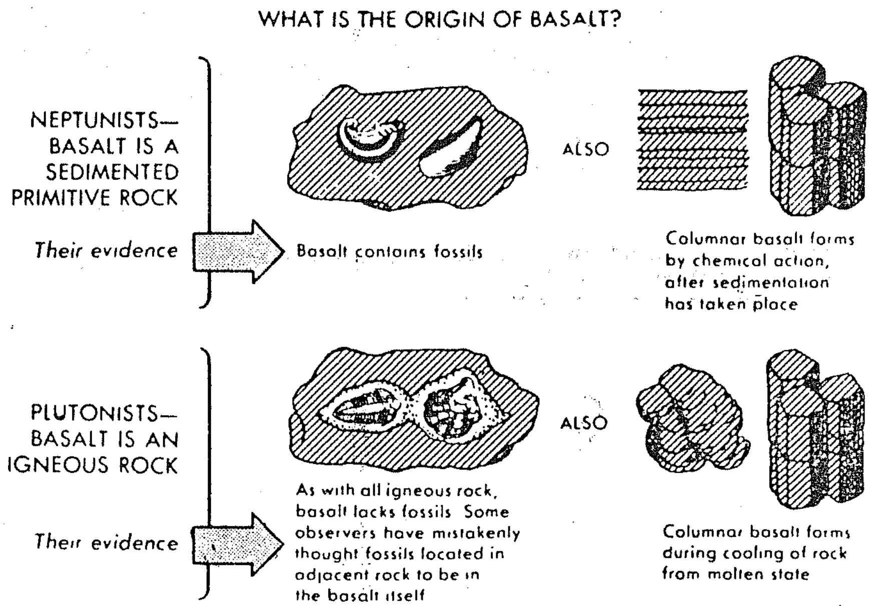
> High up in the North in the land called Svithjod, there stands a rock. It is a hundred miles high and a hundred miles wide. Once every thousand years a little bird comes to this rock to sharpen its beak.
>
> When the rock has thus been worn away, then a single day of eternity will have gone by."

It is of course well recognized today that the earth we live on is in a continuous state of change. But this view took long time to be accepted. It was James Hutton (1726—1797) who propounded the fundamental doctrine that the earth has not always worn the same look which it wears now. The lands we see now have emerged from wrecks of an older land. Continents and the gravel, sand and mud forming them have undergone cycles of change due to action of running water and volcanic activity. Hutton also perceived that not only had the consolidated materials been fragmented and elevated but that masses of molten rocks had been thrust above them leading to large bodies of granite and other rocks which are a prominent feature on the earth's surface.

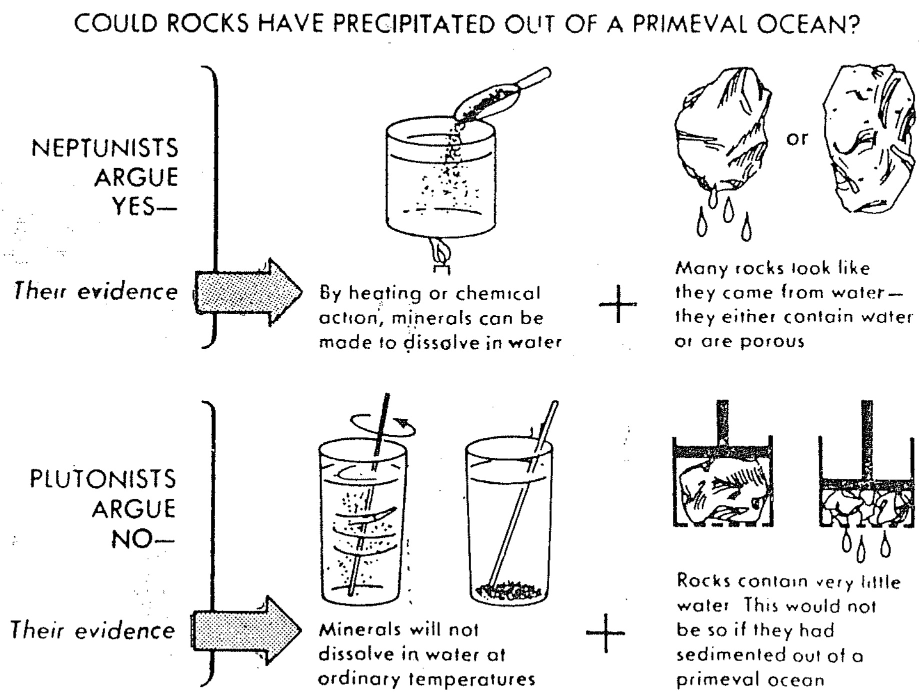
Hutton's Principle of Uniformity may be stated as follows (Hubbert, 1967) :

1. The present is the key to the past.
2. Former changes of the earth's surface may be explained by reference to causes now in operation.
3. The history of the earth may be deciphered in terms of present observations, on the assumption that physical and chemical laws are invariant with time.
4. Not only are physical laws uniform, that is, invariant with time, but the events of the geologic past have proceeded at an approximately uniform rate, and have involved the same processes as those which occur at present.

Hutton's theory which was fully founded by Charles Lyell, 1797—1875, was simple in outline, so bold, so refreshing and so suggestive that it should have immediately attracted the attention of scientists. It, however, attracted notice only very slowly because one then failed to comprehend that Hutton's doctrine was consistent with a continued existence of land and water in a certain proportion, and the comparatively recent appearance of man on the earth. All this of course seems so obvious now. It may therefore be appropriate to bring out some of the earlier thoughts that dimmed the minds of the most active scientists of that time. For example, one of the great controversies which arose between 1775—1820 regarding the mechanisms leading to formation of rocks (Blinn, 1968 ; Eicher, 1968). A group of people known as Neptunists believed that rocks formed by the action of water. Plutonists, on the other hand, believed that heat and pressure were the principal agents. The cause of Neptunists was championed by Abraham Werner (1750—1817) while that of Plutonists by James Hutton. We will not go into the details of the dispute and how the two groups championed equally strongly their cause, but Text-figs. 1 and 2 taken from



Text-fig. 1. Alternate view points advanced by Neptunists/Plutonists on the origin of basalts. The leader of the Naptunists was Abraham Werner (1750-1817), the cause of the Plutonists was championed by Hutton (1726-1797). Figure taken from Blinn (1968).



Text-fig. 2. Alternate view points on the process leading to formation of rocks, advanced by Neptunists and Plutonists. Figure taken from Blinn (1968).

Blinn (1968) will illustrate some of the key points of discussion.

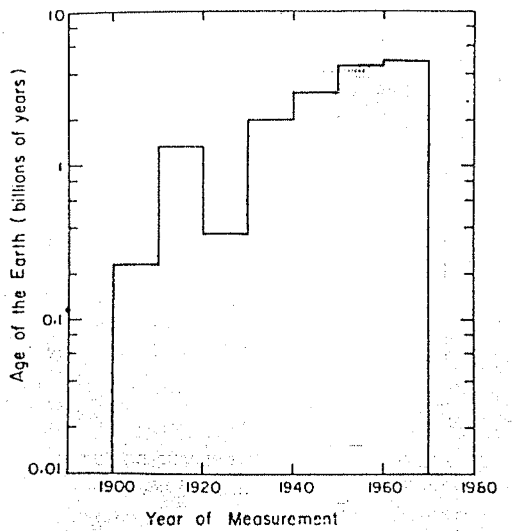
(ii) *Early controversies about the age of the earth*—As noted earlier, prior to the Copernican revolution, every heavenly body revolved around the earth, an abode created especially for man. In the seventeenth century, the scholarship was grounded in religion and the Bible was referred to for information about the earth. It has often been commented that James Ussher, an Archbishop of Armagh, decreed in 1654 that the world was created on October 24, 4004 B.C.—a date obtained by adding up the ages of the people listed in lineages of the scriptures. The Huttonian revolution brought proper perspective on geological processes and scientific enquiry began about the age of the earth and subsequently about the age of the solar system/the Universe. Today, of course there exists no major controversy on the age of the earth/solar system, since we have available a number of independent radiometric age determinations. It is interesting to note that once the scientific enquiry began, significant alternate approaches were made in the mid-nineteenth century and the age of the earth was already pushed into the (10-500) $\times 10^6$ yr. time bracket. Charles Lyell, with certain bold assumptions about the rates of evolution of life, placed the beginning of the Ordovician period at 240 million years ; he guessed that 20 million years were necessary for a complete change of molluscan species and there were 12 such intervals since the beginning of the Ordovician period (Eicher, 1968).

As early as 1715, in the pre-Hutton era, the English astronomer Edmund Halley made a simple budget type calculation for the saltiness of the oceans. He suggested that a redetermination of the salt content of the oceans after a decade would allow one to estimate their age ; he did not have any idea of the time scales of geologic processes. In 1899, Joly estimated the age of the oceans to be about 90 m.y. This estimate is low because he underestimated the amount of exchange of sodium between the sea water and rocks ; part of the sodium liberated in weathering is recycled via sedimentary rocks.

Between 1860 and 1909, the estimates of the age of the earth based on rates of deposition of sediments varied between 10-1000 m.y. (Eicher, 1968). Towards the end of 18th century, a very interesting situation was reached in that a totally incorrect estimate was made for the age of the earth based on a very scientific reasoning. A physicist, William Thomson (1824-1907) better known today as Lord Kelvin, was at the height of his fame and powers at the age of forty-four. Equally at home with abstract theories and practical applications of science, mathematics, engineering, he theorised in several branches of physics including physical astronomy and physical geology. He made estimates of the age of the Sun and rates of heat loss from the earth. He concluded that the Sun has at most illuminated the earth for only a few tens of millions of years. Based on rate of heat loss the estimates of the age of the earth vary between 20 and a few hundred million years. Kelvin preferred the lesser figure and in 1897 he concluded that the earth had probably been habitable for periods ranging between 20 and 40 m.y. Kelvin charged that uniformitarianism, the then dominant geological theory in Britain, had ignored the established laws of physics and had thus made grossly incorrect claims in realms of geology. Some geologists then shortened concepts of geologic events into the time frame work acceptable to Kelvin but palaeontologists and evolutionary biologists ignored Kelvin's estimates.

For an account of the earth's age controversy, reference is made to lucid accounts by Eicher (1968), Fitch *et al.* (1974) and Burchfield (1975). Fortunately, this major difference of opinion between the physicists and the geologists could soon be resolved with the discovery of radioactivity by Becquerel in 1896. The work by the Curies in 1903 and by Strutt (1906) showed that radioactive decay was a source of heat that was not taken into account by Kelvin in his calculations. Kelvin had therefore underestimated the age of the earth ; the heat loss from earth's surface had been about the same for a long time. Soon thereafter, in 1907 Boltwood published the results of uranium—lead age determinations ; these ages are surprisingly close to the presently accepted values.

In the foregoing we have just seen how the various estimates for the age of the earth changed with time ; Text-fig. 3 from Jackson (1973) shows a histogram of the post-1900 estimates which are spread over a factor of over two thousand. There need not be attached any special relevance to the fact that the age estimates continually increased with improvements in the dating methods. It however highlights the dangers inherent in inaccurate models. It seems fairly certain today that future scientists will not find it necessary to revise the age estimates any more except by a few hundred million years or so. In any case the general increasing trend in Text-fig. 3 has met its limit and the age estimates are not expected to change unless our present day basic concepts change radically.



Text-fig. 3. The histograms show various post-1900 estimates of the Earth's age. Present estimates of the age of the earth have asymptotically levelled off at a value between 4.5 and 4.7 billion years. After Jackson (1973).

(iii) *Disputes of 1920-1940 regarding continental movement*—Today a host of geophysical phenomena can be satisfactorily understood in the framework of our present concepts of sea-floor spreading, continental drift and plate tectonics. The drifting continent concept has been with us for more than a century but it was not accepted until recently. The acceptance is a result of overwhelming geophysical evidence which accumulated in the last few decades. Geochronology played a very important role in settling the controversial issues (Text-fig. 4). The history of the developments in this field represents a fascinating example of how developments in various disciplines contributed to reconstruction of the history of the earth in great details. In fact, accounts of our present day inferences about the physical changes which have occurred on the surface of the earth during the last few hundred million years are as detailed as those had geographers/geophysicists been present on the earth in these bygone periods.

Edward Bullard has recently written a very fascinating account of the emergence of plate tectonics (Bullard, 1975). He has discussed the nature of disputes during 1920-1930. I quote here a few paragraphs from his paper to illustrate some of the reasons underlying the slow acceptance of the continental drift ideas.

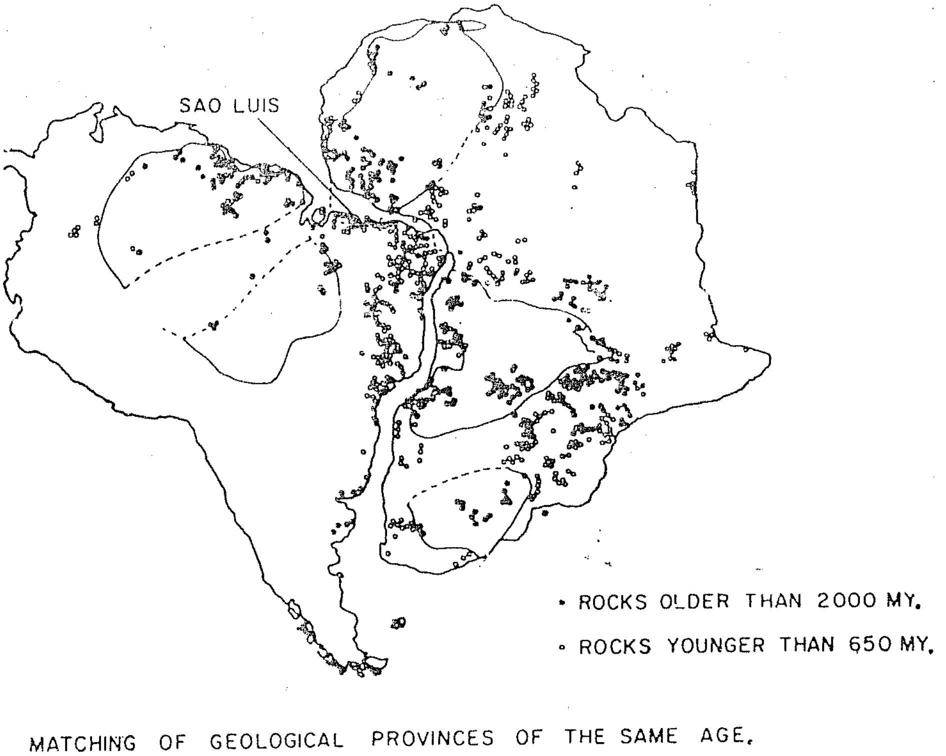
> "It is easy to see why there was such strong opposition to Wegener in the 1920s and 1930s. If weak or fallacious arguments are mixed with strong ones, it is natural for opponents to refute the former and to believe that the whole position has been refuted. There is always a strong inclination for a body of professionals to oppose an unorthodox view. Such a group has a considerable investment in orthodoxy ; they have learned to interpret a large body of data in terms of the old view, and they have prepared lectures and perhaps written books with the old background. More sanguine defenders of orthodoxy may be driven by similar motives to quite violent and logically indefensible attacks on the innovators. Examples of this class of argument are Chamberlain's (1928) approving quotation from an unnamed colleague : If we are to believe Wegener's hypothesis we must forget everything which has been learned in the last 70 years and start all over again."

One of the reasons why Wegener's theory was unacceptable was the absence of plausible mechanism driving the movements. In the words of Bullard (1975) :

> "The absence of a mechanism may have been unfortunate, but it was not strictly an argument against drift"...

The arguments about the mechanism were rendered somewhat inconclusive by the almost complete ignorance of mechanics of several of the contestants. Baily Willis (1944) for example, wrote :

> "I confess that my reason refuses to consider continental drift possible ... when conclusive negative evidence regarding any hypothesis is available, that hypothesis should, in my judgement, be placed in the discard, since further discussion of it merely incumbers the literature and befogs the minds of fellow students ... Now, it is a well



Text-fig. 4. Chronological mapping of the geological provinces of same age in South America and Africa prove that these continents were in contact before 200 million years from present. Figure taken form Hurley and Rand (1968).

established principle of mechanics that any floating object moving through air, water, or a viscous medium creates behind it a suction of the same order as the pressure developed in front of it. This law applies equally to aiiplanes, ships, rafts, and drifting continents (if there are any). The pressure which could raise the Andes must, therefore, have been approximately equalled by the suction and tension in the rear. Sections of the continent must have been sucked off."

I would also like to mention here of one of the important contributions made by Prof B. Sahni in the field of geology. Prof Sahni was originally an agnostic to Wegener's theory of continental drift. But in the light of his data, he soon realized its validity. I quote Sahni (1937) :

"The main facts of the Gondwana glaciation have always strongly urged me in favour of Wegener. But speaking, as I should, only as a palaeobotanist. I confess that my position until recently was that of an agnostic. Latterly, I have felt myself drifting gradually towards Wegener's ideas of continental displacements. But whereas Wegener applied his evidence chiefly to the disruption of a Pangaea by the drifting apart of its fragments (a view which may later find more palaeobotanical support than it seems to have at present), I have tried to elaborate what may be regarded as a complementary counterpart to his theory : a drifting together of continents once separated by a wide ocean."

Prof Sahni had thus presumably anticipated what has now come to be called as the great unifying concept of plate tectonics. The theories of crustal movement lay dormant for a decade between 1930-1940. In the years 1945-50 the continental movement theory re-emerged primarily due to studies of palaeomagnetism and the ocean floor. These studies led to well founded ideas in the 1960s about seafloor spreading and plate tectonics.

The present example of developments of ideas about the history of the earth's surface again clearly underscores the importance of geochronometry in geology/geophysics. Determination of the time of geological events requires an explicit understanding of their nature and it is of course the determination of the element of time which flows as an independent variable, that allows reconstruction of the earth's history.

PRINCIPLES AND METHODS OF GEOCHRONOLOGY

We are concerned with the measurement of time in relation to geological/geophysical processes. For doing this one needs to discover a natural record of some kind. Whereas in the case of a *historical* record one directly documents both the events and their time of occurrence, in the case of a *geological* record one has to first recognize it and subsequently determine the time of its occurrence.

Observations of materials on the surface of the earth reveal the presence of a host of substances of varied time history. The *atmosphere* and *hydrosphere* have continuously evolved ; their size and composition have changed with time. Likewise, the *lithosphere* has undergone continuous changes. Most substances undergo continuous alterations in their physical state and form. Such materials are non-recording, i.e. they can not reveal any information about the time of evolution—one can only examine their latest state at any given time. A corollary to this is that if one wants to study the evolution of "non-recording" types of materials, one has to have ways and means of obtaining their samples at different times in the past ; nature has to isolate the specimens and preserve them for our enquiry.

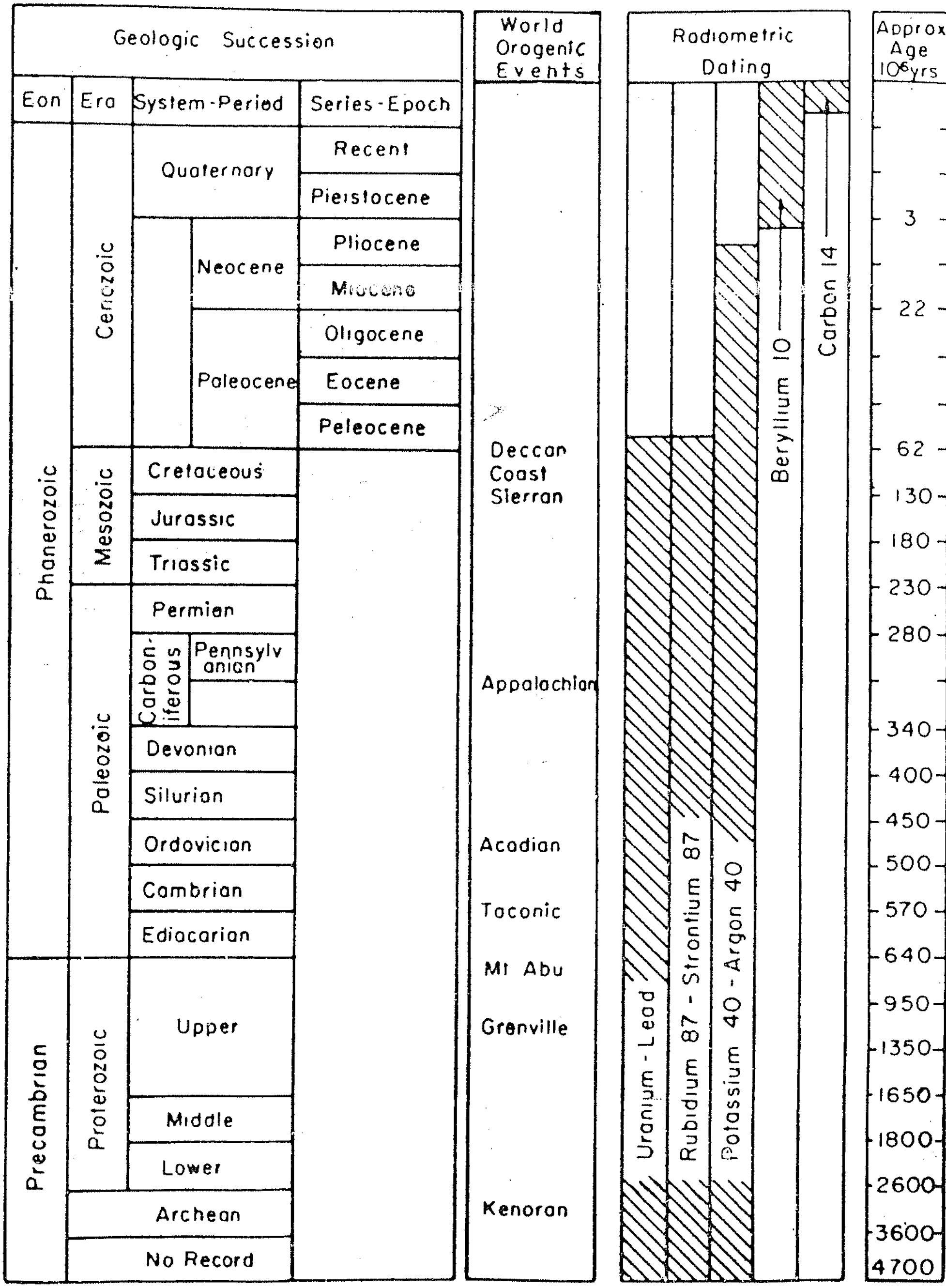
A prime requisite in prehistoric exploration is an explicit understanding of natural processes ; one has to learn about the conditions under which information about the physical/chemical state of substances can be frozen/fossilized to provide the vestigial record. The "frozen" record has to be well-preserved for if it altered with time and if it continued to interact with the environment, the time when the information was isolated would not be well-defined. One would then only learn about some time averaged, poorly defined state of the earth in the past—and in geophysics such information is useless. The problem then boils down to finding materials which preserve the record. Simplest example of a record would be a volcanic rock. An igneous rock solidifies/crystallises after eruption of the lava. In cooling through the Curie point, it acquires magnetisation in the ambient field. This rock, if it does not undergo subsequent heating to high temperatures, can be dated for its age, the time of its solidification, because a variety of nuclear transmutations will lead to a host of *in situ* effects which can be measured quantitatively. Studies of physical properties, and chemical composition of the rock will reveal the conditions under which the rock was formed, and about the intensity of earth's magnetic field at that time. In practice, the situation is complicated due to occurrence of slow but significant physical/chemical changes even when a given rock may not undergo intensive heating. Any physical/chemical alterations in the "recorder" due to extraneous causes will lead to errors possibly both in estimation of the time when it solidified and about the environmental conditions.

Geological studies provide a relative chronology of geological processes. Based on the evidence of rock inter-relationships and evolutionary sequence of fossil faunas, four main fundamental concepts have evolved (i) rock stratigraphic units, (ii) biostratigraphic units, (iii) time stratigraphic, and (iv) geologic time units (c.f. Pitch, 1974).

TABLE 1

Fundamental concepts of stratigraphic nomenclature

(i) *Rock stratigraphic units*	(ii) *Biostratigraphic units*
Supergroup	Biostratigraphic zones
Formation	
Member	
Bed	
(iii) *Time stratigraphic units* (*stratomeric units*)	(iv) *Corresponding geological time units* (*chronomeric units*)
System	Eon
Series	Era
Stage	Period
Chronozone	Epoch
	Age
	Chron



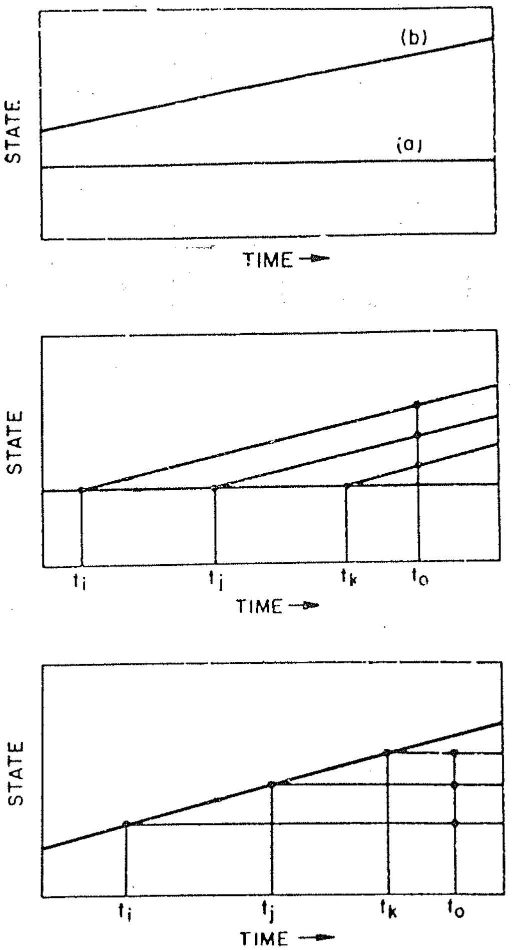
Text-fig. 5. Geological time scales based on absolute time calibration of the basic time—stratigraphic units of historical geology using various radioactive dating methods. Figure taken from Jackson (1973).

In Text-fig. 5, we show the geological time units alongside world orogenic events (Jackson, 1973). The relative geologic time scales have been correlated with absolute time scales using various radioactive dating methods. We discuss below the principles underlying geochronometry and list some of the principal nuclear and non-nuclear dating methods.

Several geochronometric methods rely on the measurement of accumulated effects of a process which has operated at a known and irreversible rate, such as the gradual accumulation of a stable daughter product from the radioactive decay of a parent radionuclide. The samples to be dated may be independent systems, each with their clocks starting at different times t_i, t_j and t_k before present, t_0 (Text-fig. 6). Geochronometric dating becomes feasible if a given sample, after its isolation from the matrix at some time undergoes change in a certain specified manner and at a certain rate, irrespective of whether the matrix itself evolved or not, before the isolation event. In other cases, where a sample ceases to change in its state after isolation from the matrix, which itself underwent changes earlier in a specified manner, it is also possible to deduce the time when the sample was isolated. Two of the simple situations which permit determination of interval of time elapsed since the isolation of a sample from the matrix, are schematically illustrated in Text-fig. 6, centre and lower graphs.

In the case of radiocarbon dating, the radio-activity of atmospheric carbondioxide which is assimilated by plants, remains essentially constant because of an equilibrium between productionby cosmic rays and decay ; changes in the radioactivity occur only after a sample has been isolated from the terrestrial carbon reservoir ; this situation is illustrated in the central graph of Text-fig. 6. Igneous rocks derive from a melt, which continuously evolves with time with respect to the isotopic composition of uranium and lead isotopes. The evolution of uranium and lead isotopes is therefore more complex than the two cases shown in Text-fig. 6.

The mathematical basis of nuclear geochronometry is simple. If a substance P undergoes radioactive decay to another substance D, the number of atoms of P_t at time t is given by the following fundamental relation :



Text-fig. 6. Chronometric methods of determining intervals of time are based on change of "state" —physical or chemical, within a system. If the "state" is a single valued function of time, time becomes the independent. unique, labelling parameter. The intervals of time elapsed between isolation of a sample from a system in equilibrium, static or dynamic [curve (*a*)] can be determined provided the system undergose a known rate of change subsequent to isolation (illustrated in middle graph); the radiocarbon dating method is an example of this case. The case of isolation from an evolving system (where "state" changes with time ; curve (*b*), with no change after isolation, is shown in the lower graph.

$$\frac{dP_t}{dt} = -\lambda P_t \qquad (1)$$

where λ is the disintegration constant of the radionuclide P. The solution of equation (1), for the case of P_0 atoms at $t=0$ is :

$$P_t = P_0 e^{-\lambda t} \qquad (2)$$

Equation (2) is used in a number of situations to determine the time intervalsin in geology and in solar system chronology (Wetherill & Tilton, 1967; Wetherill, 1975). In the case of principal radiometric methods for determination of solidification ages (Table 2), the equation used is :

$$t = \frac{1}{\lambda} \ln \left[1 + \frac{D_t - D_o}{P_t} \right] \quad (3)$$

Equation (3) is derived directly from equation (2) ; P_o and D_o are the amounts of parent and daughter nuclides in the substance at $t=0$. D_t is the total amount of D at time t in the system.

In the case of radiocarbon, equation (2) itself is used since radioactive decay of ^{14}C begins once a carbon containing sample has been isolated from the dynamic carbon reservoir. In practice, it is convenient to study the specific activity A_t of the sample, the ratio of radiocarbon to stable carbon atoms in the sample. The age of the sample is given by :

$$t = \frac{1}{\lambda} \ln (A_o/A_t) \quad (4)$$

where A_o is the specific activity of radiocarbon in the sample at $t=0$, the equilibrium value in the dynamic carbon reservoir.

The nuclear methods applicable in geophysics are either those belonging to the primordial radionuclides (Text-fig. 7; Table 2, 3) or the cosmic rays produced radionuclides (Libby, 1955, Lal & Peters, 1967). The nuclides belonging to the uranium and thorium series (Table 3 ; Text-fig. 7) and some of the cosmic rays produced isotopes find diverse applications in the study of marine and lacustrine sediments. A number of excellent reviews exist on the various radiometric methods which are currently used to date rocks and sediment samples (c.f. Wetherill & Tilton, 1967 ; Fitch *et al*; 1974 ; Goldberg & Bruland, 1974 ; Ku, 1976).

Recently it has become possible to "date" terrestrial rocks based on the decay of ^{147}Sm (half-life$=1.06\times10^{11}$ yrs.) into ^{143}Nd. The Sm-Nd System has been successfully employed for dating lunar rocks and basaltic achondrites (Lugmair & Scheinin, 1976). The small decay constant of ^{147}Sm makes it necessary to measure $^{147}Sm/^{144}Nd$ and $^{143}Sm/^{144}Nd$ ratios with very high precision. The application of Sm-Nd dating method in terrestrial systems requires great care but the special efforts needed are worthwhile since both the parent and daughter nuclides belong to the rare-earth elements, the 'time' deduced relates to time of differentiation of the 'source' material. This method is therefore useful for obtaining information on magma sources as well the structure of mantle. A number of Sm-Nd dates available to date bear testimony to this special promise of the method (DePaolo & Wasserburg 1976 ; Richard *et al*; 1976 ; O'Nions *et al*; 1978 ; Carlson *et al*; 1978).

In Table 3 are also listed some of the other methods ; the fossil track, the thermoluminiscence, the hydration and the racemisation dating methods. In each case we have indicated the type of materials which be dated and the range of time over which a given method is applicable.

As a result of improvements of the various absolute dating methods, relative chronologies have been successfully erected. We cite as examples the magnetic and the microfossil stratigraphy given in Text-figs. 8 and 9 respectively.

THE CHRONOLOGY OF PRINCIPAL GEOLOGICAL EVENTS

The main aim of geochronometry is to provide absolute dates for the principal relative stratigraphic units (Table 1). From time to time, several attempts have been made to do this (c.f. Kulp, 1961). For a recent excellent review on the subject, reference is made to Fitch *et al.* (1974). As in the case of age of the earth, the quantification of the geological time scale is now fairly complete. Besides the chronology of the principal terrestrial events, our understanding of the solar system events has also increased rapidly mainly due to the recent manned expeditions to the moon and unmanned expeditions to planets of the solar system. The reader is in particular referred to a recent review article (Wetherill, 1975) which contains a discussion of major events in the early history of the solar system. In fact the solar system studies have clearly pointed out the necessity to consider this information in detail to understand the history of the earth. It should be realized here that palaeontological record of the earth is largely restricted to the Phanerozoic portion of the time scale (600 m.y. B. P.). The oceanic record takes one back to about 100×10^6 yrs, 200×10^6 yrs, at best. Thus, the Pre-Cambrian record which is largely based on the observed

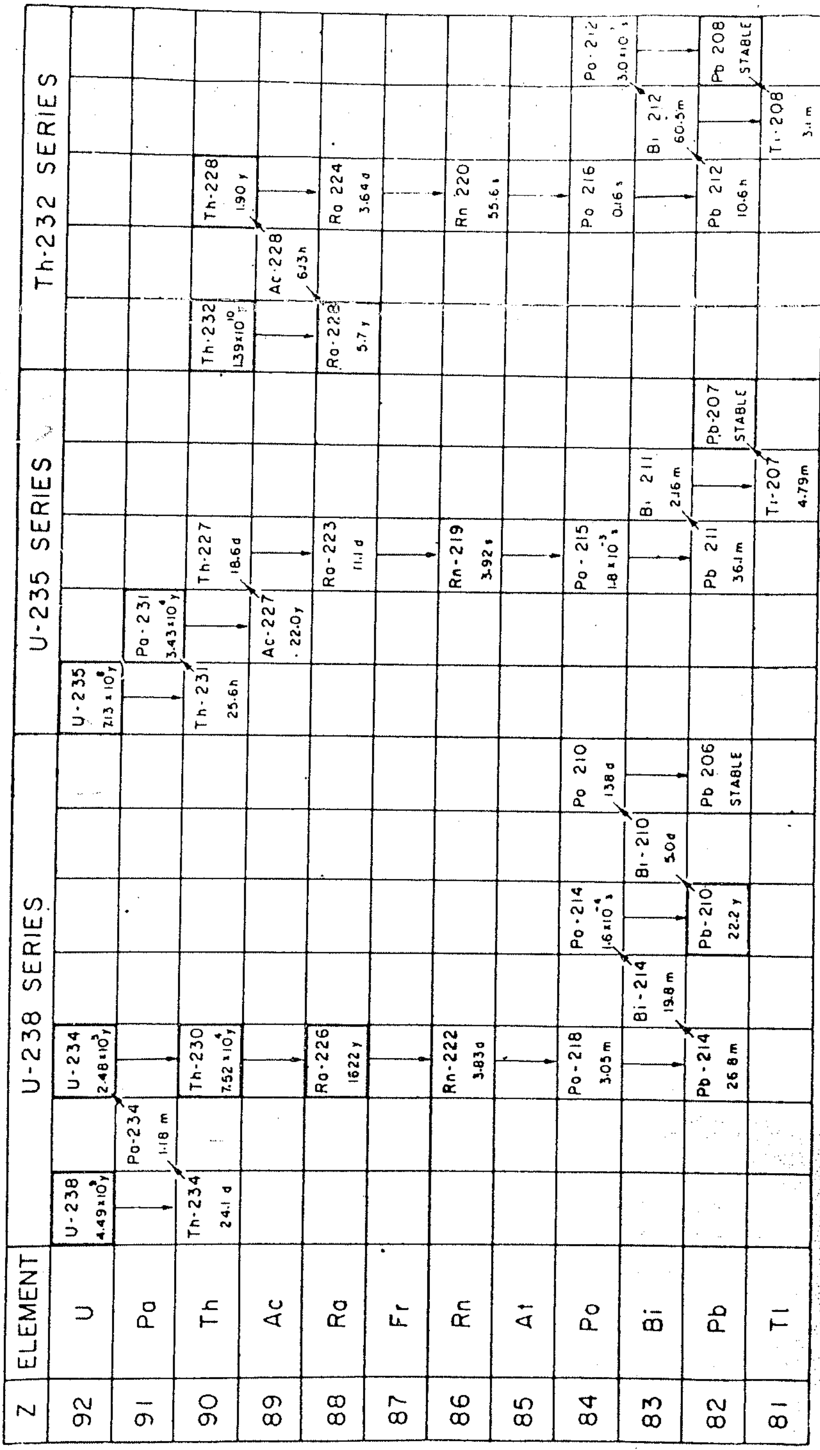
TABLE 2

NUCLIDE PAIR		Half-life of Parent (years)	Materials which can be dated
Parent	Daughter		
^{238}U ..	^{206}Pb ..	4.51×10^9	Uranium bearing minerals and some whole rocks.
^{235}U ..	^{207}Pb ..	0.71×10^9	
^{232}Th ..	^{208}Pb ..	13.9×10^9	
^{40}K ..	^{40}Ar ..	1.31×10^9	Potassium bearing minerals and some rocks.
^{87}Rb ..	^{87}Sr ..	47.0×10^9	Rubidium-rich minerals and rocks.
^{187}Rs ..	$^{187}O_s$ ..	$(43 \pm 5) \times 10^9$	Molybdenite and rare earth minerals.

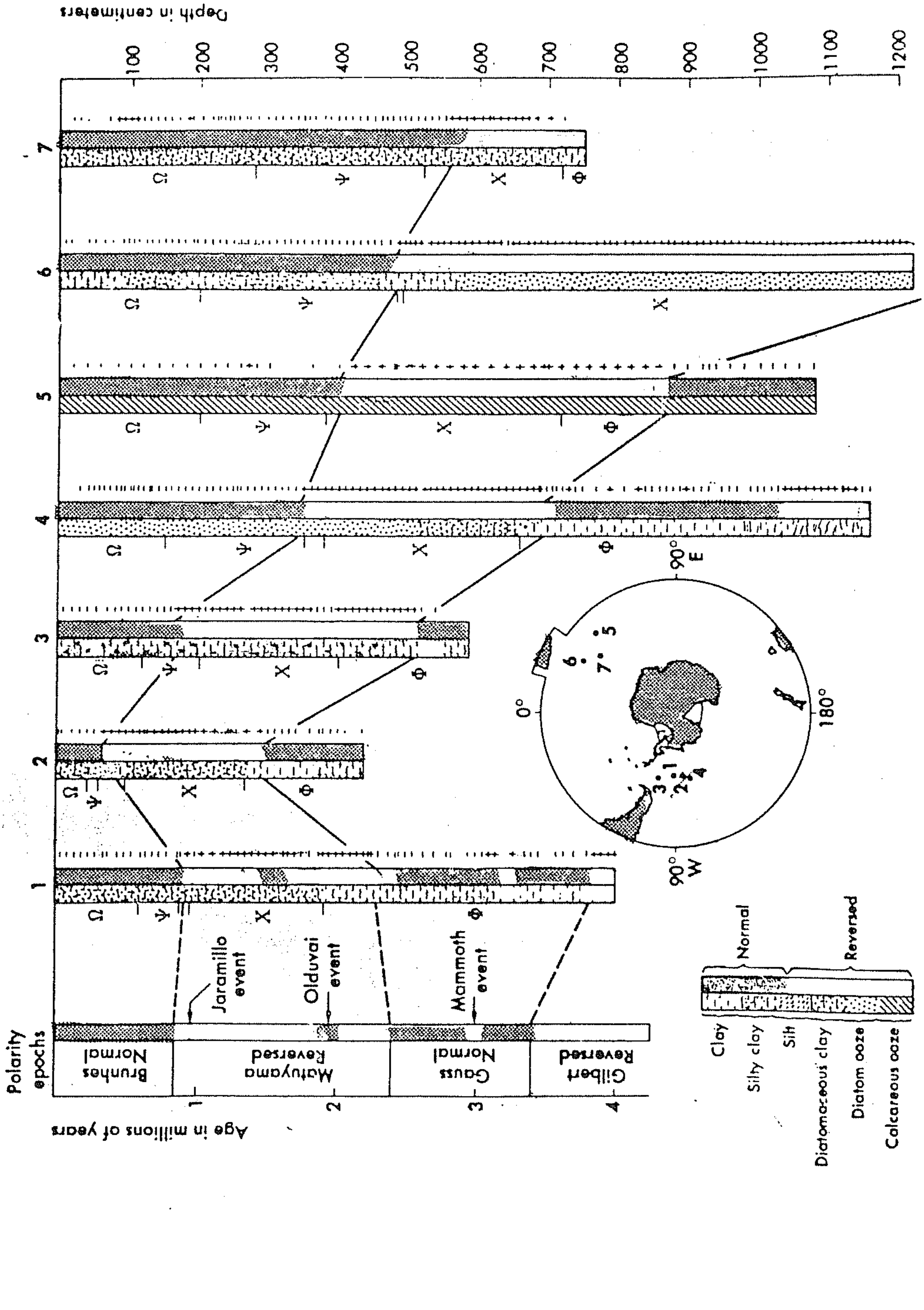
TABLE 3

Method	General Remarks	References
(i) *Fossil tracks in crystalline mineral grains :*		
^{244}Pu	Applicable to meteorite and lunar samples. Study of time intervals in early history. Range 0-500 m. y.	1, 2
^{238}U ..	Also applicable to terrestrial minerals. Determination of solidification ages. No limit on range.	3, 4, 5
Cosmic ray heavy nuclei	Early and late history of extraterrestrial samples. No limit on range..	6, 7
(ii) *Cosmic Ray produced isotopes :*		
^{10}Be ..	Half-life = 1.5 m.y. Dating marine sediments and manganese nodules Range $\simeq$ 5 m.y. B. P.	8, 9
^{14}C ..	Half-life = 5,730 yrs. Dating charcoal, peat, shells, groundwater, marine sediments. Range $\simeq$ 60,000 yrs.	10
(iii) *Uranium—Thorium series :*		
^{230}Th ..	Half-life = 75,200 yrs. Dating marine sediments and manganese nodules. Range $\simeq 4 \times 10^5$ yrs. B. P.	11, 12
^{231}Pa ..	Half-life = 34,300 yrs. Dating marine sediments and manganese nodules. Range $\simeq 10^5$ yrs. B. P.	11, 12
^{210}Pb ..	Half-life = 22 yrs. Dating glaciers, lakes and near shore sediments. Range $\simeq$ 100 yrs. B. P.	13, 14
(iv) *Physical method*		
Thermoluminiscence.	Quartz, Feldspar, bones, pottery	15
(v) *Chemical methods*		
Racemisation of amino-acids.	Dating marine sediments, bone and organic materials, range of temperature dependent : .. 10^6 yrs. at 10°C	16, 17
Hydration ..	Volcanic glasses ; Range $\simeq 10^4$ yrs.	18, 19

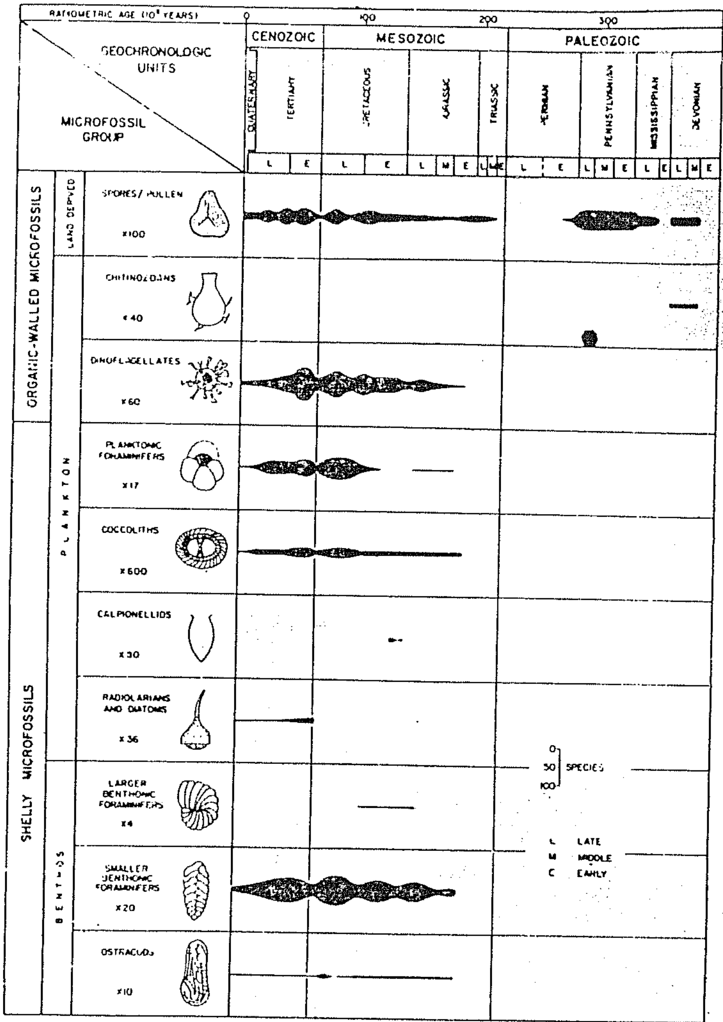
1. Shirck *et al.* (1969).
2. Bhandari *et al.* (1971).
3. Fleischer *et al.* (1967a).
4. Fleischer & Hart (1972).
5. Fischer (1975).
6. Fleischer *et al.* (1967b).
7. Lal (1972).
8. Lal & Peters (1967).
9. Amin *et al.* (1975).
10. Libby (1955).
11. Broecker (1965)
12. Ku (1976).
13. Krishnaswamy *et al.* (1971)
14. Koide *et al.* (1973).
15. Aitken *et al.* (1968)
16. Bada *et al.* (1970)
17. Bada & Schroeder (1972)
18. Friedman *et al.* (1963)
19. Friedman *et al.* (1966)



Text-fig. 7. Uranium and Thorium decay series. Radionuclides boxed with heavy lines are commonly used for dating marine sediments.



Text-fig. 8. Magnetic stratigraphy observed in deep sea cores from the Antarctic area. Figure taken from Opdyke *et al*, 1966.



MICROFOSSIL SPECIES DIVERSITY IN PALEOZOIC, MESOZOIC AND CENOZOIC SEDIMENTS SCOTIAN SHELF, GULF ST LAWRENCE AND GRAND BANKS

Text-fig. 9. Microfossil stratigraphy observed in sediments from Scotian Shelf, Gulf St. Lawrence and Grand Banks. Figure taken from Gradstein (1974).

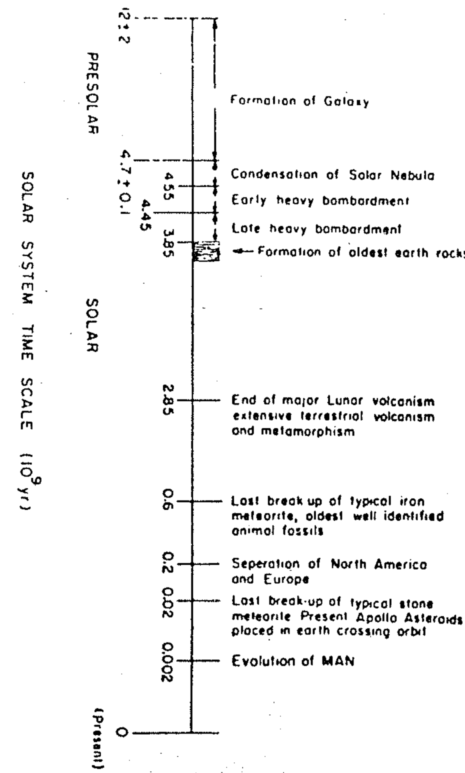
cyclic nature of geological history, has yet to be understood properly.

In Text-fig. 10, we show schematically some of the events in the formational era of the Solar System. This figure is based on the tentative Solar System time scale given by Wetherill (1975).

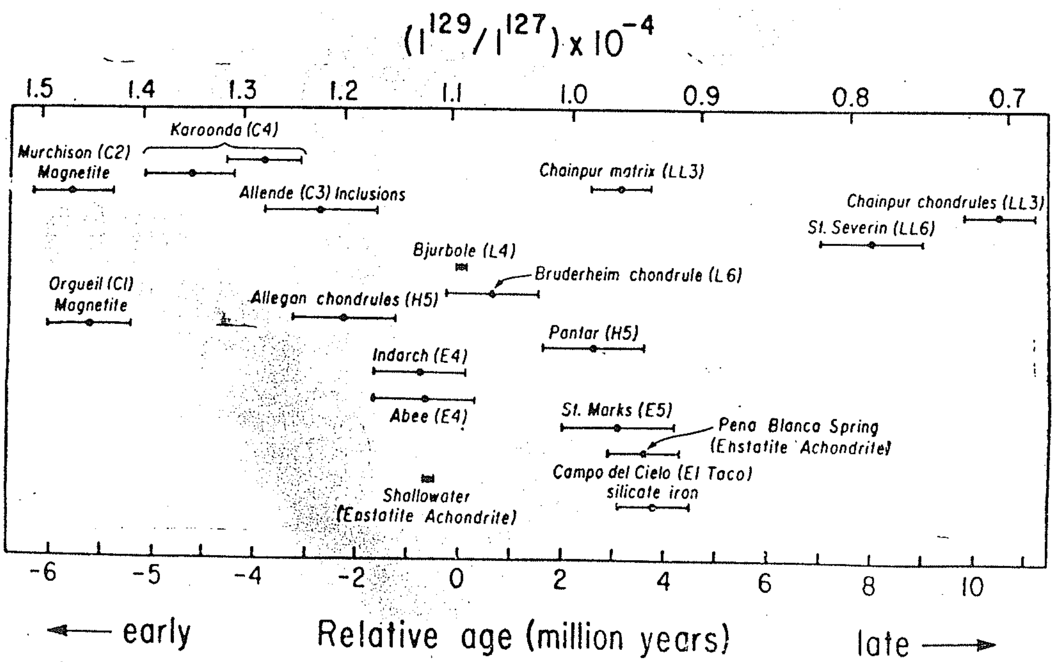
Quite apart from the fact that these studies have provided time scales for the nebular period of the solar system, the formation and metamorphism ages of different meteorites have been obtained. The accretion of moon, earth, various planets and the meteorite parent bodies seems to have ended within a short period of 50-200 m.y., 4.55 billion years ago (Text-fig. 10). Text-fig. 11 which shows the relative formation intervals of meteorites, exhibits the "sharp isochronism".

Lunar data have provided valuable information on the history of early and late bombardment (due to impact of high velocity planetary subjects) which occurred between 4.55—3.85 b.y. ago. The same bombardment must have also occurred on the earth. Since for this period of time, our geological record is poor, the information has to be largely based on lunar and planetary data.

We thus see that the science of geochronology has revealed the time sequence of a large



Text-fig. 10. Chronology of some Solar System events. Based on Wetherill (1975).



Text-fig. 11. Relative formation intervals of meteorites exhibiting a sharp isochronism. The relative chronology is based on estimated values of the ratio of $^{129}I/^{127}I$ in different meteorites. Figure taken from Wetherill (1975).

number of milestones in the history of the earth/solar system. The task is not that of just building a calendar of events. It is one of the express ways of learning about the laws of nature, about geophysical processes and how planetary systems evolve. As an example, I would like to end by citing one of the recent development in the field of climatology.

Careful investigations of the climatic changes in the past 450,000 yrs, based on studies of microorganisms preserved in deep sea sediments, have revealed periodic changes which match the changes expected due to periodic changes in the earth's orbital geometry (Hays *et al.*, 1976). The data clearly display a dominant 100,000 yrs climatic component ; other cycles of 23,000 and 42,000 yrs are also found as expected due to orbital changes. This dramatic result, if true, could never have been obtained unless a precise chronological measurement had been made of the ancient sedimentary record indicative of temperature changes.

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