ARTICLES

GEO AND COSMIC CHRONOLOGY

R.H. Brown
Geoscience Research Institute

WHAT THIS ARTICLE IS ABOUT

This article represents an added feature to Origins. *The material on geo and cosmic chronology is presented in brief outline form and is supplemented by an extensive bibliography. In the narrative portion, the author discusses the various evidences for a 4.5 billion-year-old universe and lists the different methods used to develop this date. Twenty-four different methods for dating and their conclusions are briefly listed. It is hoped that the readers of* Origins *will find this format useful as a reference tool for their own research. The Editors invite your suggestions to assist us in determining other areas that should be considered.*

Scientific creationism that is neutral with respect to religious issues has no need to defend a particular viewpoint regarding time. Proceeding only on the basis of inductive logic, it is free to pursue any interpretation that may seem to be suggested by available data. The data related to chemical evolution probabilities, thermodynamic considerations, spontaneous origin of life, genetics, and paleontology lead naturally to the conclusion that life and the life support system are products of intelligent design and creative ability. But at present there are no data that independently suggest inductively either a 6-day creation week or placement of such an event within the last 8000 years.

In contrast with neutral scientific creationism, apologetic scientific creationism utilizes deductive logic in an effort to relate satisfactorily available scientific data to viewpoints derived from religious sources. Some individuals would insist that only neutral scientific creationism is truly "scientific." However, apologetic scientific creationism can be defended as truly "scientific" to the extent that it does not go beyond sound principles of logic, data collection, and data evaluation. Efforts to explain data concerning the natural world within the constraints of the first eleven chapters of Genesis, if carried out in a sound scientific manner, would be classified as apologetic scientific creationism.

In certain areas apologetic scientific creationism may have an advantage over neutral scientific creationism and non-theistic science in that it operates from a larger data base and may develop scientifically sound interpretive models that would not have been accessible by pure inductive logic. This advantage is illustrated by a comparison between a reconstruction of an event based on both the testimony of a reliable eyewitness and analysis of the consequences, and a reconstruction based on only analysis of the consequences. These two reconstructions may be

evaluated on the basis of which one provides a better account of the available after-the-event data.

On the basis of the principle that truth is consistent, irrespective of the means by which it is apprehended, one can say that when rightly understood, natural science and authentic historical or religious source material agree, each complementing and supplementing the other. Accordingly, apologetic scientific creationism can be an instrument for arriving at a more correct understanding of specifications obtained from a religious source, as well as of data obtained from investigation in the natural sciences.

It may be appropriate to digress at this point and state my conviction that in a pluralistic society such as the United States only neutral scientific creationism is appropriate for inclusion in public school science curricula. A limited amount of apologetic scientific creationism would be appropriate in a public school sociology course that aims to acquaint the student with the various streams of thought in modern culture.

Geo and cosmic chronology are major concerns of creationist literature, usually from an apologetic viewpoint. The major purpose of this essay is to provide the reader with convenient access to the principal areas of evidence that must be taken into account by any scientific treatment of geo and cosmic chronology. For each of these areas I have endeavored to provide an introduction to the pertinent literature. Limitations of time and interest have prevented me from providing an adequate bibliography for some of the areas that are included in this outline.

RADIATION COOLING OF THE EARTH (1)

Serious attempts to determine the scale of geochronology on a scientific basis began in 1862 when William Thomson, who later became Lord Kelvin, estimated that planet Earth could have cooled from a molten state to its present temperature configuration within between 400 and 20 million years (m.y.). This constraint was an irritation to Charles Darwin who sensed that it did not provide sufficient time for his model of biologic evolution. By 1897 Lord Kelvin had narrowed the range of uncertainty in his estimate to between 40 and 20 m.y. By including the contribution of heat presumed to be available from radioactive material, the geophysicist, Arthur Holmes was able in 1947 to extend this estimate of cooling time to between 2 and 4 billion years (b.y.).

MINERAL CONTENT OF SEAWATER (2)

The astronomer Edmund Halley suggested in 1715 that planet Earth might be “much older than many have hitherto imagined,” and proposed that the salinity of the ocean might provide a basis for an estimate of its minimum age. By 1898 sufficient information on the rates at which the major rivers carry salt into the ocean became available to permit John Joly to estimate that the present salinity of the ocean could be attained within

80 to 90 m.y. In the early 1940s this estimate was reexamined and extended to between 150 and 250 m.y. on the basis of processes by which salt is now known to be recycled from the sea back to the land. By postulating slower input from rivers in the ancient past, Arthur Holmes was finally able to suggest an age of the Earth between 1 and 7 b.y. on the basis of ocean salinity.

EARTH-MOON SEPARATION (3)

As the principles of celestial mechanics were developed it became evident that tidal friction causes both Earth and Moon to slow down in their rotations until they each maintain the same face toward the other (no further tidal energy dissipation). During this process the separation between them gradually increases as required to conserve angular momentum. On the basis of his study of tides throughout the world Lord Kelvin came to the conclusion that the Earth-Moon system had been in existence less than a billion years. G. H. Darwin estimated that the present Earth-Moon separation has been achieved in 57 m.y. More recent calculations indicate that, beginning with close proximity to Earth, the Moon would reach its present separation distance in between 1 and 4 b.y.

DENUDATION OF IGNEOUS ROCKS (4)

The previously mentioned early efforts to obtain an age estimate for planet Earth are significant only for their historical interest. They depend on highly uncertain initial assumptions concerning a molten state of the planet, a fresh-water ocean, and a tightly bound Earth-Moon system. Another interesting attempt to obtain an age for the Earth is based on the assumption that all sedimentary rocks have been produced by erosion of igneous rocks, at present rates. The uncertainties in these rates and in the volume of sediments involved lead to estimates in the range between approximately 400 million and 3 billion years.

COMET FREQUENCY (5)

The existence of comets has been taken to indicate that the Solar System has not been in existence longer than a few million years. This conclusion comes from recognition that because of evaporation, radiation pressure, and solar wind effects very few comets survive as many as ten trips around the Sun. Since there is only speculation concerning the manner in which the Solar System has acquired cometary material, and there is absolutely no data with respect to the inventory of this material at any time, one should not expect the frequency with which comets appear to give a reliable indication of the scale for Solar System chronology.

COSMIC DUST DENSITY (6)

There is sufficient cosmic dust in interplanetary space to produce the phenomenon known as Zodiacal Light. In the order of 10-100 thousand

tons of this dust are captured by Earth each year. Since this dust is constantly swept up by the planets, driven out of the Solar System by radiation pressure, and pulled into the Sun as a result of the Poynting-Robertson effect, its present existence has been taken as evidence that the Solar System has been in existence no longer than approximately 2 b.y. It can be shown that all particles smaller than one centimeter in diameter would be removed from the space between Earth and the Sun within 10 m.y. The credibility of maximum Solar System age estimates based on the density of cosmic dust suffers from our ignorance concerning the distribution of this material in the past, and particularly from our ignorance concerning the amount of such material that may be swept up as the Solar System moves through its galaxy.

SYNCHRONOUS ORBITS OF SATELLITES (7)

The Moon is in a synchronous orbit, i.e., it makes precisely one rotation on its axis for each revolution about the Earth, with the result that it always shows the same face toward Earth. Any elastic object orbiting in a force field that causes deformation will approach a synchronous orbit due to conversion of rotational energy into heat by internal friction. The synchronous orbit of the Moon may be taken as evidence that the Earth-Moon system has been in existence for many hundreds of millions of years, presuming the Moon was once rotating more rapidly than at present. All planetary satellites that have been adequately observed (telescopic observation of Jupiter and Saturn, space probe observation of Mars, direct observation of the Moon) are in a synchronous orbit. Most of these satellites are marked by craters from meteoroid impacts that would have changed the rotation rate of these satellites. Calculations have been made of the amount of time that would be required for the Martian satellites to reach a synchronous orbit after the last significant perturbation by meteoroid impact. The greater the orbit radius the weaker the tidal forces will be, and the longer the time required to achieve a synchronous orbit. For the outermost satellite of Mars, Deimos, the estimated minimum synchronization time is 3 m.y. if the structure is compacted sand, and 100 m.y. if it is solid basalt.

SYNCHRONOUS ORBITS OF PLANETS (8)

The planets experience tidal forces that reduce their motions to synchronous orbits with respect to the Sun. The motion of Venus is within -8% of perfect synchronism (retrograde spin with -243/225 spin/orbit periods in Earth days). Mercury has a commensurate orbit with a spin/orbit period ratio of 2/3 (58.6/88 in Earth days). A spin/orbit period coupling of 2/3 is a resonant state that is stable and is a special case of synchronous orbits. A mass distribution of Mercury and/or the Sun that does not have perfect spherical symmetry (dipole and higher terms in the gravitational

field) could prevent a transition of the spin/orbit ratio from the 2/3 state to the 1/1 state.

More amazing is the discovery that Venus is in a synchronous relationship with respect to Earth. Venus turns the same face to Earth at each inferior conjunction. The most reasonable explanation of this relationship requires gravitational coupling between Earth and Venus over a time period in the magnitude of billions of years. The lack of a synchronous relationship of Earth with respect to Venus is explainable as the consequence of the diurnal cycle necessary for the maintenance of organic life and established at the beginning of the creation week described in the first chapter of Genesis. In summary, one can say that the observed characteristics of the inner planet orbits indicate that the Solar System has been in existence for a billion years, or more.

EXTRATERRESTRIAL EROSION (9)

Rocks on the surface of the Moon are found to be highly eroded. They are pitted, have rounded edges, and are often surrounded by a sloping bank of fine material that can be described as soil, while the buried portion may have relatively smooth surfaces bounded by sharp angular edges. The factors that produce this erosion are expansion and contraction associated with rapid extreme changes in temperature, the "sandblasting" effect of micrometeoroid bombardments, and sputtering produced by the solar wind.

Fresh-looking craters with sharp edges are found superimposed on highly eroded, "old," rounded-off craters, some of which are so eroded as to be scarcely discernible. In the highland areas of the Moon craters are found in a saturation distribution (further meteoroid bombardment would not produce a major change in the crater density, obliterating previous craters as rapidly as new ones are formed). But in the mare areas the crater density is only $^{1}/_{10}$ to $^{1}/_{50}$ as great. The evident interpretation is that since the mare areas were filled in by lava flow they have been exposed to meteoroid impact for a much shorter time than have the highland areas. The impact crater density on the Moon cannot be accounted for within a 5 b.y. time span unless the meteoroid impact rate is assumed to have been much greater during the early history of the Solar System than it has been during recorded Earth history.

The totality of this evidence leads to the conclusion that the Moon has been in existence as a solid object for a time in the order of at least one billion years.

Similar features of crater distribution and erosion have been revealed in the televised pictures sent from Mercury and Mars by space probes. The erosion features seen on Mercury are probably due to the same processes that have been operating on the Moon. Mars is experiencing strong aeolean erosion at the present time. It appears to have had an

episode of severe fluid erosion under climatic conditions vastly different from those that can be accounted for under present circumstances.

LIGHT-YEAR SCALE (10)

Astronomers have good reasons for believing that they are now observing galaxies and quasars that are tens of billions of light years distant from Earth. If the current estimation of distance for these objects is correct, the universe must have been in existence for at least tens of billions of years.

GALAXY CLUSTERS (11)

Galaxies are known to be grouped in clusters. At the present state of our knowledge concerning the mass of matter contained within galaxies, the gravitational forces that can be expected to act between members of a cluster are not sufficient to hold the cluster together. With the individual galactic motions that have been observed, the known galactic clusters can be expected to dissolve within less than 100 b.y. On the basis of this argument some galactic clusters have been considered to be no more than 2-4 b.y. old.

SPIRAL GALAXY STRUCTURE (12)

The Milky Way and its neighbor, Andromeda, belong to the Spiral Galaxy classification. It is thought that the spiral arm features of these galaxies would be obliterated after between one and three full rotations of the galaxy about its center of mass, since the angular velocity of revolution increases the closer a star is to the galactic center. On the basis of the rotation rates that have been observed, the lifetime of spiral galaxies has been estimated to be in the order of 300 m.y. Accordingly, our own galaxy would not be more than 300 m.y. old. It has been suggested that spiral arm galactic structure is not due to an initial star distribution, but rather is the result of gravity waves that cause the stars to bunch together in a cyclic manner as they revolve about the galactic center of gravity.

STAR CLUSTERS (13)

Many of the stars within galaxies are themselves grouped into clusters. It is expected that perturbing gravitational influences from nearby stars and star clusters will gradually pull these clusters apart. Detailed consideration leads to the estimate that star clusters are no more than 3-6 b.y. old.

BINARY STARS (14)

Within our own Milky Way galaxy it is possible to observe that many of the stars are gravitationally coupled in pairs that revolve about a common center of mass. It can be expected that a high proportion of binary stars is to be found only in a relatively young galaxy, for the perturbing influences of nearby stars should slowly pull the binary stars apart. On the basis of the expected mean lifetime of a binary star system our galaxy has been estimated to be less than 10 b.y. old.

STELLAR DYNAMICS (15)

With the knowledge of thermonuclear reactions man has acquired since World War II, and with the aid of electronic computers, it is possible to predict the detailed history of a large mass of hydrogen gas that will experience nuclear fusion under gravitational confinement — i.e., calculate the history of a star. Astronomers can observe numerous stars that have the characteristics associated with each state but one in the theoretical life history of a star. The stage for which no definite example has yet been found is the extremely rapid transition (lifetime measured in months) to the White Dwarf stage.

If the correspondence between real stars and the theoretically determined life history of a star is not merely fortuitous, one can confidently state that an average star such as our Sun has a life of approximately 10 b.y., provided it is maintained as an isolated system without replenishment of fuel (hydrogen). According to this model, the observed distribution of star types places the age of our galaxy, as well as the age of the universe, at not less than 10 b.y.

RESIDUAL RADIOACTIVITY (16)

The accidental discovery of radioactivity by Henri Bequerel in 1896 initiated a series of developments that have provided man with his most precise and most reliable tools for investigating geo and cosmic chronology. The most crucial steps in this development were the discovery of spontaneous atomic transmutation by Madame Curie in 1898, and the discovery of isotopes by Sir J. J. Thomson in 1913. Instrumentation and laboratory techniques developed since World War II have made possible spectacular advances in geo and cosmic chronology.

An infinitely old object would not be radioactive, for any radioactive isotopes it may have contained originally would have transformed to stable daughter isotopes. The presence of uranium in minerals from Earth, the Moon, and meteorites indicates that these components of the Solar System have been in existence less than 20 b.y. The present ratio of uranium-235 to uranium-238 further indicates that Earth and the Solar System have not been in existence longer than about 5 b.y.

EXTINCT RADIOACTIVITY (17)

Uranium-235, which is the basis of the contemporary nuclear energy technology, is present as only 0.72 atom percent of relatively rare uranium. The half-life of uranium-235, 704 m.y., is the lowest among unsupported radioactive nuclides that are known to exist in significant quantity throughout the Solar System. The next lower half-life among the nuclide possibilities is 170 m.y. (within a factor of two) niobium-92. There is 90 percent confidence that niobium-92 has been observed at $(1.2 \pm 0.7) \times 10^{-10}$ percent isotopic abundance in association with stable niobium-93.

No evidence for natural occurrence of 100 m.y. samarium-146 has yet been found. Diligent search with the most sophisticated techniques has detected 83 m.y. plutonium-244 at approximately 10^{-16} weight percent in a sample of the rare earth bastnaesite. Since plutonium is chemically similar to cerium, it is most likely to be found in a high-cerium-content mineral such as bastnaesite. Search for other unsupported radioactive nuclides with half-life less than 80 m.y. has been diligent but unfruitful.

All nuclides that are stable or have half-lives greater than 80 m.y. have been found in Earth, Moon and meteorite material. In Solar System material there is both fission-track and daughter-product isotope evidence for the prior existence of extinct 100 m.y. samarium-146, 83 m.y. plutonium-244, 15.9 m.y. iodine-129, 15.4 m.y. curium-247, 6.5 m.y. palladium-107 and 740,000 year aluminum-26. The conclusion from this evidence is that at least some components of Earth and other members of the Solar System have been in existence as solid objects for no less than 300 m.y. — the time for a 90 m.y. half-life nuclide to reach 1/10 of its initial concentration. Since there is good reason for expecting that in a creation of elementary matter plutonium-244 appears in the ratio of 0.013/1 with respect to uranium-238, the data on the present availability of natural plutonium-244 indicates that the matter from which the bulk of the Solar System is constructed has been in existence in the order of 5 b.y. Similar consideration regarding niobium-92 yields the same conclusion.

COSMOGENIC RADIOACTIVITY (18)

Atomic nuclei that have been ejected from stars and acquired immense amounts of kinetic energy are known as cosmic rays. (The relatively low energy atomic particles emitted by a star are known as “solar wind”). These cosmic particles have the capability to shatter atoms which they may strike. Some of the atom fragments thus produced are unstable atoms of a simpler construction than the target atom that was shattered. (Spallation is the scientific name for this process). Unstable atoms produced in this matter are described as having cosmogenic radioactivity.

The half-lives of the principle cosmogenic radioactive products range from 5.7 day Mn^{52} to 740 thousand year Al^{25}, 1.6 m.y. Be^{10}, and 3.7 m.y. Mn^{53}. Some 1.28 b.y. K^{40} is also produced in this manner. After exposure to a constant cosmic ray flux for a time equal to about four half-lives, a cosmogenic radioactive nuclide reaches an equilibrium concentration at which the number of new atoms formed within a given period of time is equal to the number that experience radioactive decay during the same time.

The land and water surface of Earth is protected by the atmosphere from primary cosmic radiation. In meteorites and in material that has been secured from the Moon we have access to objects that contain cosmogenic radioactivity. The cosmogenic nuclides from 5.7 day Mn^{52} to 740 thousand

year Al^{26} and 3.7 m.y. Mn^{53} found in these objects are in almost all cases in equilibrium with the present cosmic ray flux. This implies that the meteoroids and the surface of the Moon have been exposed to cosmic rays for at least 15 m.y., that the intensity of cosmic rays at present is very close to the average intensity over the past 15 m.y., and that the intensity of cosmic rays probably has not varied by more than a factor of two during this time. A short burst of radiation at some time in the recent past could adjust *two* cosmogenic nuclides to be in equilibrium with the present cosmic ray intensity, but it is inconceivable that as many as eleven could be simultaneously adjusted in this way.

COSMIC RAY EXPOSURE (19)

The shattering of atoms by impact from cosmic rays produces both stable and unstable nuclides. The stable spallation products accumulate continuously as long as there is exposure to cosmic radiation. In many cases stable cosmogenic nuclides can be clearly distinguished from primordial matter. In such cases the concentration of a cosmogenic nuclide indicates the amount of exposure to cosmic radiation. The time of exposure, or cosmic ray exposure age, is readily obtained by dividing the amount of exposure by the exposure rate — the cosmic ray intensity. Within the experimental uncertainties, independent cosmic ray exposure age determinations with nuclides such as He^3, Ne^{21}, Ne^{22}, and Ar^{38} are usually in agreement.

As a primary cosmic ray particle passes through a solid it disrupts the crystalline arrangement along its track. In certain minerals it is possible with appropriate etching techniques to make these tracks visible in a microscope. The density of these cosmic ray tracks provides an independent measure of the total exposure to cosmic radiation, and the cosmic ray exposure age. If the mineral has not experienced heating or shock that erases damage patterns by realignment of crystal structure, the cosmic ray exposure age determined by track analysis may be expected to be in agreement with that determined by stable cosmogenic nuclide analysis.

Cosmic ray exposure ages for meteorite and lunar material that has been studied are scattered over a range from one million to one billion years, with strong grouping at several points over this range. The range over which these exposure ages fall has been taken to indicate that at various times portions of the lunar surface have experienced turnover due to volcanic activity and meteoroid impact; and that meteorites have been formed by the breakup of larger objects at various times in the history of the Solar System.

RADIOACTIVE DECAY SEQUENCES (20)

The possibility of using radioactive elements for determining chronology was recognized by Lord Rutherford in 1904. Substantial radiometric

dating was not achieved until many years later, after techniques had been developed for quantitative analysis of isotopes. At the present time as many as ten independent techniques may be available for determining radioisotope age of a mineral specimen.

Among the various radioisotope age determination techniques there is potential capability for indicating the time at which the matter of which a specimen is composed, experienced events such as nucleogenesis, solidification, heating, remelting, shock, mixing with other material, exposure to water, and exposure to high energy radiation. Because a given sample may have experienced two or more such events all the various radiometric age determinations that may be performed on it should not be expected to be in agreement. Disagreement between independent radiometric age determinations (discordance is the technical term) may be taken as an indication that the sample has a complex history, and may provide useful insight into the chronology of events that the sample has experienced.

The many cases in which chemically and physically independent radiometric age determinations are in agreement (concordant) within limits of precision and accuracy indicate that radiometric dating procedures may yield physically significant results, regardless of whether there may not be a one-to-one correspondence between a specific radioisotope age and real time. Discordant ages generally have a rational explanation in terms of metamorphic events that the sample may have experienced.

It is well known that a radiometric age is equivalent to the corresponding real time age if the initial conditions are specified with sufficient accuracy and precision, the associated radioactive decay constant(s) has (have) not changed essentially during the time involved, and the sample has been chemically isolated during this time. The large number of cases in which essential agreement exists between diverse radiometric age determinations can hardly be fortuitous, and indicate that samples can be obtained which meet the requirements for conversion of radiometric age into real time. All the radiometric age data that have accumulated for minerals from meteorites, the Moon and planet Earth lead to the conclusion that these portions of the Solar System have been in existence and contained solid material for 4.56 b.y. The available radiometric evidence indicates that the present crust of Earth does not contain rocks older than 3.9 b.y.

INHERITED RADIOMETRIC AGE (21)

If a radiometric age can be satisfactorily converted into real time there often still remains a problem in determining the nature of the event that initiated the time period. Radiometric dating techniques were developed in a climate that fostered a presumption concerning vast ages for the evolutionary development of living organisms, and that stimulated search for evidence supporting such ages. This situation gave rise to a naive, oversimplified, and unjustified assumption that radiometric “clocks” are

set at zero in transport of mineral by igneous processes, and also in many sedimentary processes. According to this assumption a radiometric age of mineral that has replaced organic material, that has been injected into a fossiliferous stratum, or that overlies fossils gives a minimum real-time age for the association with the fossils involved. It would be both unfair and unkind to most of the individuals who have supported this assumption to describe it as "the graveyard hoax"; yet such description emphasizes an important consideration that is generally overlooked. Radiometric ages for the mineral components of the soil in a cemetery plot are not expected to date the burials made there.

There is ample evidence that radiometric chronometer systems are often set to zero time in natural processes that transport or metamorphose minerals, as popularly assumed. It is not so well recognized that the inheritance of previously established radiometric age characteristics through metamorphic and transfer processes is also well established in the scientific literature. Situations are known in which even fission track and potassium-argon age characteristics have survived through a subaerial volcanic event. The survival may be anywhere between total and zero. A potassium-argon age of 465,000 years has been reported for volcanic material overlying trees that were buried by the eruption and have a carbon-14 age of only 225 years (McDougall et al. 1969). It has become recognized that the radioisotope characteristics of intrusive and volcanic material may be related more to the crustal material through which the magma was ejected and to the characteristics of successive zones in the magma chamber than to the time at which the transfer took place. There also is evidence that the radioisotope age characteristics of sediments may be related more to the source from which the material was derived than to the time at which sedimentation occurred. Extensive references to the literature on inherited radiometric age are appended to this paper.

RADIATION DAMAGE (22, 23)

Radioactive decay produces structural and electronic damage tracks in the host mineral. These damage tracks can be quantitatively analyzed to determine the total radiation exposure. A quantitative analysis of the amount of radioactive material available for producing the observed damage tracks readily leads to a computation of the irradiation time. The result is a radiometric age based on the evidence left by the radiogenic products, rather than on an assay of the products themselves. The evidence may be trapped excited electron states produced by alpha, beta or gamma radiation; or it may be crystal lattice dislocation produced by alpha particles, recoil of alpha-emitting parent nuclei, or fission products.

The excited electrons are detected by observing the optical radiation produced when the mineral is heated sufficiently to free the trapped electrons and allow them to return to their ground (lowest energy) state. The

technique involved is known as thermoluminescence or electroluminescence dating. Since the excited electrons slowly return to the ground state at normal temperatures, this technique has a relatively short time range. Although a 300,000 year range has been claimed (Göksu et al. 1974) other authorities limit its usefulness to about 4000 years (Michels 1973). This method of dating further suffers in lack of precision.

The crystal lattice dislocation tracks produced by radioactive decay can be seen with a microscope after suitable etching. Where high concentrations of radioactive material have existed regions that contain alpha-particle damage tracks can be seen without resort to etching techniques, as in pleochroic halos (more correctly termed radiohalos). The density of these halos can be related to the concentration of radioactive material at their center to obtain a crude estimate of the minimum exposure time involved in producing the halo. Microprobe analysis permits relatively precise evaluation of radiogenic daughter to radioactive mother ratios in the halo nucleus. These ratios can readily be expressed in terms of a radioisotope age.

Radiometric ages obtained from tracks produced by parent nucleus recoil, alpha-particles, or fission fragments often are in agreement, or at least consistent, with ages obtained from daughter/parent ratios. Discordant but consistent situations arise when there has been total or partial annealing of radiation tracks by elevation of temperature, or migration of either parent or daughter atoms as a result of heating or contact with water.

The existence of isolated polonium radiohalos in uraniferous fossil wood (Gentry et al. 1976) indicates that radiohalos may be formed as a result of prolonged deposition of radioactive material at a halo center site, and are not always dependent on an initial concentration of radioactive material.

CHONDRITE STRUCTURE FEATURES (24)

Radiation damage track investigations have turned up some remarkable evidence concerning the history and formation of meteoroids. Meteorites that have been classified as chondrites are made up of units called chondrules that are cemented together in a matrix to form the meteorite body. Some of these chondrules from inside the meteorite body have been found to be marked on their surfaces by micro-meteoroid impact pits, and to contain in a thin layer of their surface solar wind atom implants and damage tracks from the low energy cosmic radiation produced by the Sun. Identical phenomena are found on the surface of rocks obtained from the Moon. (Ablation during passage through Earth's atmosphere removes such features from the surface of meteorites). Some chondrules have sharp fracture edges. This evidence strongly indicates that chondrites have been formed from an accretion of smaller meteoroid bodies which had been in

existence long enough to acquire substantial exposure to solar radiation and cosmic dust.

SUMMARY

The picture that emerges from all the data that relate to cosmic chronology appears to be one of dynamic physical processes operating over extended periods of time, during the last 4.5 billion years of which discrete entities of the Solar System have been in existence.

THEOLOGICAL ISSUES

It would not be appropriate to conclude this presentation without some consideration of related theological issues.

Any interpretation that is made of the available inspired testimony must satisfactorily accommodate the various lines of evidence concerning geo and cosmic chronology in accord with the basic hermeneutic principle that the books of nature and the Scriptures should be consistent with each other.

It is possible to interpret the book of Genesis to require that all matter in the Solar System came into existence *ex nihilo* by fiat creation less than 10,000 years ago. This interpretation requires that all the features of mineral, meteoroid, planetary body, and planetary satellite age were the immediate expression of deliberate design on the part of the Creator, and have no relationship to actual age. We should recognize that God has the prerogative to produce a creation in this manner, and that doing so would be less extraordinary than producing the total complex of organic life on this planet within four 24 hour days.

It also is possible to interpret the inspired testimony concerning creation as an eyewitness-style account using language of appearance to describe creative activity that within six consecutive 24-hour days equipped this planet with the total complex of its organic life and established the physical circumstances on which this life depends. According to this interpretation our planet may now contain matter that was in existence as a consequence of creative activity prior to the Genesis Creation Week, matter that was brought into existence during Creation Week, and a relatively minute amount of matter that came into existence in connection with Christ's miracles (specifically His feeding of the multitudes).

Let everyone be persuaded in his own mind as to which interpretation he should favor, giving appropriate respect to the considerations that may lead others to choose differently.

REFERENCES

(1) Radiation Cooling of Earth

· Jeffreys H. 1952. The earth. 3rd ed., Ch IX. Cambridge: Cambridge University Press.

· ter Har D. 1953. The age of the universe. Scientific Monthly 77:173-181.

(2) Mineral Content of Seawater

- Goldberg ED. 1965. Minor elements in sea water. In: Riley JP, Skirrow G, editors. Chemical Oceanography, Vol. 1, Chapter 5. London and NY: Academic Press.
- Jeffreys H, *loc. cit.*
- Livington D. 1963. The sodium cycle and the age of the ocean. Geochimica et Cosmochimica Acta 27:1055-1069.
- ter Har D, *loc. cit.*

(3) Earth-Moon Separation

- Hughes DW. 1981. Why is the moon slowing down? Nature 290:190.
- Jeffreys H, *op. cit.*, Ch VIII.
- Kahn PCK, Pompea SM. 1978. Nautiloid growth rhythms and dynamical evolution of the Earth-Moon system. Nature 275:606-611.
- Kaula WM, Harris AW. 1975. Dynamics of lunar origin and orbital evolution. Reviews of Geophysics and Space Physics 13:363-371.
- Rosenberg CD, Runcorn SK, editors. 1975. Growth rhythms and history of the earth's rotation. NY: John Wiley & Sons.
- ter Har D, *loc. cit.*

(4) Denudation of Igneous Rocks

- Jeffreys, Harold, *op. cit.*, Chapter IX.
- ter Har, D., *loc. cit.*

(5) Comet Frequency

- Alfvén H, Mendis A. 1973. Nature and origin of comets. Nature 246:410-411.
- Bailey ME. 1976. Can 'invisible' bodies be observed in the solar system? Nature 259:290-291.
- Gribbin J. 1975. Halley lecturer produces new theory of comet origins. Nature 255:196.
- Hanson JN. 1974. Comets: the Lord's weapon and sign. Bible-Science Newsletter, January 1974.
- Lindsay JF, Srnka LJ. 1975. Galactic dust lanes and lunar soil. Nature 257:776-777.
- Slusher HS. 1971. Some astronomical evidences for a youthful solar system. Creation Research Society Quarterly 8:55-57.
- Wetherill GW. 1976. Where do the meteorites come from? A reevaluation of the Earth-crossing Apollo objects as sources of chondritic meteorites. Geochimica et Cosmochimica Acta 40:1297-1317.
- Whipple FL. 1976. Background of modern comet theory. Nature 263:15-19.

(6) Cosmic Dust Density

- Briggs RE. 1962. Steady-state distribution of meteoric particles under the operation of the Poynting-Robertson effect. Astronomical Journal 67:711ff.
- Brownlee DE. 1979. Interplanetary dust. Reviews of Geophysics and Space Physics 17:1735-1743.
- Herbig GH. 1974. Interstellar smog. American Scientist 62:200-217.

· Kerker M. 1974. Movement of small particles by light. American Scientist 62:92-98.
· Levy EH, Jokipii JR. 1976. Penetration of interstellar dust into the Solar System. Nature 264:423-424.
· Lindsay JF, Srnka LJ. 1975. Galactic dust lanes and lunar soil. Nature 257:776-777.
· Misconi NY. 1976. On the rotational bursting of interplanetary particles. Geophysical Research Letters 3(10):585-588.
· Paddack SJ, Rhee JW. 1976. Rotational bursting of interplanetary dust particles. Geophysical Research Letters 2(9):365-367.
· Pettersson H. 1960. Cosmic spherules and meteoric dust. Scientific American 202:123-133.
· Reyss JL, Yokoyama Y, Tanaka S. 1976. Aluminum-26 in deep-sea sediment. Science 193:1119-1121. Footnote 15.
· Sakamoto K. 1974. Possible cosmic dust origin of terrestrial plutonium-244. Nature 248:130-132.
· Slusher HS. 1971. Some astronomical evidences for a youthful solar system. Creation Research Society Quarterly 8:55-57.
· Slusher HS, Duursma SJ. 1978. The age of the solar system: a study of the Poynting-Robertson Effect and extinction of interplanetary dust. Institute for Creation Research Technical Monograph No. 6.
· Wetherill GW. 1976. Where do the meteorites come from? A reevaluation of the Earth-crossing Apollo objects as sources of chondritic meteorites. Geochimica et Cosmochimica Acta 40:1297-1317.

(7) Synchronous Orbits of Satellites

· Pollack JB, Veverka J, Noland M, Sagan C, Duxbury TC, Acton, Jr. CH, Born GH, Hartman WK, Smith BA. 1973. Mariner 9 television observations of Phobos and Deimos, 2. Journal of Geophysical Research 78:4313-4326.
· Jeffreys H, *op. cit.*, Chapter VIII.

(8) Synchronous Orbits of Planets

· Anderson JD. 1974. Geodetic and dynamical properties of planets. EOS, Transactions of the American Geophysical Union 55:515-523.
· Gold T, Soter S. 1979. Theory of the Earth-synchronous rotation of Venus. Nature 277:280-281.
· Goldreich P, Peale SJ. 1966. Spin orbit coupling in the solar system. Astronomical Journal 71:425-438.

(9) Extraterrestrial Erosion

· Bloch MR, Fechtig H, Gentner W, Neukum C, Schneider E. 1971. Meteorite impact craters, crater simulations, and the meteoroid flux in the early solar system. Proceedings of the Second Lunar Science Conference, Vol. 3, p 2639-2652. Cambridge, MA: The M.I.T. Press.
· Hartman WK. 1962. Martian cratering, 4, Mariner 9 initial analysis of cratering chronology. Journal of Geophysical Research 78:4096-4116.

· Hiners NW. 1971. The new moon: a view. Reviews of Geophysics and Space Physics 9:447-522, specifically p 490-503.
· Hörz F, Hartung JB. 1971. The lunar-surface orientation of some Apollo 12 rocks. Proceedings of the Second Lunar Science Conference, Vol. 3, p 2629-2638. Cambridge, MA: The M.I.T. Press.

(10) Light-Year Scale

· Weinberg S. 1972. Gravitation and cosmology: principles and applications of the general theory of relativity, Ch 14. NY: John Wiley & Sons.

(11) Galaxy Clusters

· Bouw GD. 1977. Galaxy clusters and the mass anomaly. Creation Research Society Quarterly 14:108-112.
· Editorial. 1949. American astronomers report. Sky and Telescope 8:123-126.
· Geller MJ. 1978. Large-scale structure in the universe. American Scientist 66:176-184.

(12) Spiral Galaxy Structure

· Icke V, Pringle J. 1975. Structure and dynamics of spiral galaxies. Nature 253:312-313.
· Lindsay JF, Srnka LJ. 1975. Galactic dust lanes and lunar soil. Nature 257:776-777.
· Mulfinger G. 1970. Critique on stellar evolution. Creation Research Society Quarterly 7:7-24.

(13) Star Clusters

· Chandrasekhar S. 1942. Principles of stellar dynamics, Ch V. Chicago: University of Chicago Press.

(14) Binary Stars

· ter Har D. 1953. The age of the universe. Scientific Monthly 77:173-181.

(15) Stellar Dynamics

· Appenzeller I, Lequeux JL, Silk J. 1980. Star formation. Sauverny, Switzerland: Geneva Observatory.
· Clayton DD. 1968. Principles of stellar evolution and nucleosynthesis. NY: McGraw-Hill Book Co.
· Jastrow R, Thompson MH. 1972. Astronomy, fundamentals and frontiers, Ch 7. NY: John Wiley & Sons.

(16) Residual Radioactivity

· Cowan GA. 1976. A natural fission reactor. Scientific American 235(1):36-47.
· Jeffreys H, *op. cit.*, Ch IX.
· Rankma K. 1954. Isotope geology, p 415-418. NY: McGraw-Hill Book Co.
· Ruffenach JC, Menes J, Devillers C, Lucas M, Hagemann R. 1976. Etudes chimiques et isotopiques de l'urianium, du plomb et de plusiers produits de fission clans un enchatillon de mineral du reactor naturel d'Oklo. Earth and Planetary Science Letters 30:94-108.
· ter Har D, *loc. cit.*

(17) Extinct Radioactivity

- Apt KE, Knight JD, Camp DC, Perkins RW. 1974. On the observation of ^{92}Nb and ^{94}Nb in nature. Geochimica et Cosmochimica Acta 38:1485-1488.
- Arden JW. 1977. Isotopic composition of uranium in chondritic meteorites. Nature 269:788-789.
- Bernatowicz TJ, Hohenberg CM, Kennedy BM, Podosek FA. 1978. Excess fission xenon in Apollo 16. Proceedings of the Ninth Lunar and Planetary Science Conference, p 1571-1597. NY: Pergamon Press.
- Bradley JG, Hupeke JC, Wasserburg GJ. 1978. Ion microprobe evidence for the presence of excess ^{26}Mg in an Allende anorthite crystal. Journal of Geophysical Research 83:244-254.
- Brown RH. 1969. Radioactive time clocks. Ch 25 *in* Coffin HG, editor. Creation: Accident or Design? Washington DC: Review & Herald Publishing Association. More recent half-life determinations differ by as much as a factor of two from some of the data given in Table VII — 100 m.y. for Samarium-146, e.g.
- Carver EA, Anders E. 1976. Nuclear tracks in the Angra dos Reis and Moore County meteorites. Geochimica et Cosmochimica Acta 40:935-944.
- Gray CM, Compton W. 1974. Excess ^{26}Mg in the Allende meteorite. Nature 251:495-497.
- Hennecke EW, Manuel OK. 1975. Noble gases in an Hawaiian xenolith. Nature 257:778-780.
- Herzog GF. 1977. ^{26}Al in stony meteorites with gas losses. Geochimica et Cosmochimica Acta 41:1526-1529.
- Hoffman DC, Lawrence FO, Mewherter JL, Rourke FM. 1971. Detection of plutonium-244 in nature. Nature 234:132-134.
- Hohenberg CM, Munk MN, Reynolds JH. 1967. Spallation and fissiogenic xenon and krypton from stepwise heating of the Pasamonter achondrite; the case for extinct Plutonium-244 in meteorites; relative ages of chondrites and achondrites. Journal of Geophysical Research 72:3139-3177.
- Hutcheon ID, Steele IM, Smith JV, Clayton RN. 1978. Ion microbe, electron microprobe and cathodoluminescence data for Allende inclusions with emphasis on plagioclase chemistry. Proceedings of the Ninth Lunar and Planetary Science Conference, p 1345-1368. NY: Pergamon Press.
- Kaiser T, Kelly WR, Wasserburg GJ. 1980. Isotopically anomalous silver in the Santa Clara and Pinon iron meteorites. Geophysical Research Letters 7:271-274.
- Kelley WR, Wasserburg GJ. 1978. Evidence for the existence of ^{107}Pd in the early Solar System. Geophysical Research Letters 5:1079-1082.
- Lee T. 1979. New isotopic clues to solar system formation. Reviews of Geophysics and Space Physics 17:1591-1611.
- Lee T, Papanastassiou DA. 1974. ^{26}Mg isotopic anomalies in the Allende meteorite and correlation with O and Sr effects. Geophysical Research Letters 1:225.
- Lee T, Papanastassiou DA, Wasserburg GJ. 1976. ^{26}Mg excess in Allende and evidence for ^{26}Al. Geophysical Research Letters 3:109.
- Lee T, Papanastassiou DA, Wasserburg GJ. 1977. Astrophysics Journal Letters 211:1107. (Primordial ^{26}Al).
- Lewis RS. 1975. Rare gases in separated whitlockite from the St. Severin chondrite: xenon and krypton from fission of extinct ^{244}Pu. Geochimica et Cosmochimica Acta 39:417-432.

· Lugmair GW, Marti K. 1977. Sm-Nd-Pu timepieces in the Angra dos Reis meteorite. Earth and Planetary Science Letters 35:273-284.
· Podosek FA. 1970. The abundance of ^{244}Pu in the early Solar System. Earth and Planetary Science Letters 8:183-187.
· Podosek FA. 1970. Dating of meteorites by the high-temperature release of Iodine-correlated Xe^{129}. Geochimica et Cosmochimica Acta 34:341-365.
· Podosek FA. 1972. Gas retention chronology of Petersburg and other meteorites. Geochimica et Cosmochimica Acta 36:755-772.
· Podosek FA. 1979. Solar system. Geotimes (June), p 18, 19.
· Reynolds JH, Alexander, Jr. EC, Davis PK, Srinivasan B. 1974. Studies of K-Ar dating and xenon from extinct radioisotopes in breccia 14318; implications for early lunar history. Geochimica et Cosmochimica Acta 38:401-417.
· Sahamoto K. 1974. Possible cosmic dust origin of terrestrial plutonium-244. Nature 248:130-132.
· Scheinin NB, Lugmair GW, Marti K. 1977. Sm-Nd systematics and evidence for extinct ^{146}Sm in an Allende inclusion (abstract). Meteoritics 11:357-368.
· Srinivasan B, Alexander, Jr. EC, Manuel OK. 1971. Iodine-129 in terrestrial ores. Science 173:327-328.
· Stegmann W, Begemann F. 1981. Al-correlated ^{26}Mg excess in a large Ca-Al-rich inclusion of the Leoville meteorite. Earth and Planetary Science Letters 55:266-272.
· Storzer D, Pellas P. 1977. Angra dos Reis plutonium distribution and cooling history. Earth and Planetary Science Letters 35:285-293.

(18) Cosmogenic Radioactivity

· Bogard DD, Cressy, Jr. PJ. 1973. Spallation production of ^{3}He, ^{21}Ne, and ^{38}Ar from target elements in the Bruderheim chondrite. Geochimica et Cosmochimica Acta 37:527-546.
· Cressy, Jr. PJ. 1971. Cosmogenic nuclides in the Lost City and Ucera meteorites. Journal of Geophysical Research 76:4072-4075.
· Shedlovsky JP, Cressy, Jr. PJ, Kohman TP. 1967. Cosmogenic radioactivities in the Peace River and Harleton chondrites. Journal of Geophysical Research 72:5051-5058.
· Trivedi BMP, Goel DS. 1973. Nuclide production rates in stone meteorites and lunar samples by galactic cosmic radiation. Journal of Geophysical Research 78:4885-4900.

(19) Cosmic Ray Exposure

· Bhai NB, Gopalan K, Goswami JN, Rao MN, Venkatesan TR. 1978. Solar cosmic ray produced neon and xenon isotopes and particle tracks in feldspars from lunar fines 14148 and 24087. Proceedings of the Ninth Lunar and Planetary Science Conference, p 1629-1645. NY: Pergamon Press.
· Bhandari N, Padia JT. 1974. Secular variations in the abundances of heavy nuclei in cosmic rays. Science 185:1043-1045.
· Bogard DD, Cressy, Jr. PJ. 1973. Spallation production of ^{3}He, ^{21}Ne, and ^{38}Ar from target elements in the Bruderheim chondrite. Geochimica et Cosmochimica Acta 37:527-546.

· Brown RH. 1971. The age of meteorites. Spectrum 3 (Winter):19-27.
· Eberhardt D, Geiss J, Graf H, Grögler N, Krähenbühl U, Schwaller H, Stettler A. 1974. Noble gas investigation of lunar rocks 10017 and 10071. Geochimica et Cosmochimica Acta 38:97-120.
· Eugster O, Grögler N, Medina MD, Eberhardt P, Geiss J. 1973. Trapped solar wind noble gases and exposure age of Luna 16 lunar fines. Geochimica et Cosmochimica Acta 37:1991-2003.
· Fleischer RL, Price PB, Walker RM, Maurette M; Morgan G. 1967. Tracks of heavy cosmic rays in meteorites. Journal of Geophysical Research 72:355-366.
· Fleischer RL, Hart, Jr. HR. 1974. Particle track record of Apollo 16 rocks from Plumb Crater. Journal of Geophysical Research 79:766-768.
· Hampel W, Schaeffer OA. 1979. ^{26}Al in iron meteorites and the constancy of cosmic ray intensity in the past. Earth and Planetary Science Letters 42:348-358.
· Heimann M, Parekh PP, Herr W. 1974. A comparative study of ^{26}Al and ^{53}Mn in eighteen chondrites. Geochimica et Cosmochimica Acta 38:217-234.
· Herzog GF. 1973. Variability of the He^{3} and Ne^{21} production rates in ordinary chondrites. Geochimica et Cosmochimica Acta 37:2125-2133.
· Hohenberg CM, Marti K, Podosek FA, Reedy RC, Shirck IR. 1978. Comparisons between observed and predicted cosmogenic noble gases in lunar samples. Proceedings of the Ninth Lunar and Planetary Science Conference, p 2311-2344. NY: Pergamon Press.
· Kohl CP, Murrell MT, Russ III GP, Arnold JR. 1978. Evidence for the constancy of the solar cosmic ray flux over the past ten million years: ^{53}Mn and ^{26}Al measurements. Proceedings of the Ninth Lunar and Planetary Science Conference, p 2299-2310. NY: Pergamon Press.
· Rajan RS. 1974. On the irradiation history and origin of gas-rich meteorites. Geochimica et Cosmochimica Acta 38:777-788.
· Smith S, Fireman EL. 1973. Ages of eight recently fallen meteorites. Journal of Geophysical Research 78:3249-3259.
· Trivedi BMP, Goel DS. 1973. Nuclide production rates in stone meteorites and lunar samples by galactic cosmic radiation. Journal of Geophysical Research 78:4885-4900.
· Voshage H, Feldmann H. 1979. Investigations on cosmic-ray-produced nuclides in iron meteorites, 3. Exposure ages, meteoroid sizes and sample depths determined by mass spectrometric analyses of potassium and rare gases. Earth and Planetary Science Letters 45:293-308.
· Wilkening LL, Herman GF, Anders E. 1973. Aluminum-26 in meteorites — VII. Urelites, their unique radiation history. Geochimica et Cosmochimica Acta 37:1803-1810.

(20) Radioactive Decay Sequences

· Brown RH. 1969. Radioactive time clocks. Ch 25 *in* Coffin HG, editor. Creation: Accident or Design? Washington DC: Review & Herald Publishing Association.
· Chen JH, Wasserburg GJ. 1981. The isotope composition of uranium in Allende inclusions and meteoric phosphates. Earth and Planetary Science Letters 52:1-15.
· Emery GT. 1972. Perturbation of nuclear decay rates. Annual Review of Nuclear Science 22:165-202.

· Hamilton EI, Farquhar RM, editors. 1968. Radiometric dating for geologists. NY: John Wiley & Sons.
· Hiners NW. 1971. The new moon: a view. Reviews of Geophysics and Space Physics 9:447-522, specifically, p 477-490.
· Hart SR, Davis GL, Steiger RH, Tilton GR. 1968. A comparison of the isotope mineral age variations and petrologic changes induced by contact metamorphism. In: Hamilton & Farquhar, *op. cit.*, p 73-110.
· Shlyakhter AI. 1976. Direct test of the constancy of fundamental nuclear constants. Nature 264:340.
· Spector RM. 1972. Pleochroic halos and the constancy of nature. Physical Review A 5(3):1323-1326.
· Wolfe AM, Brown RL, Roberts MS. 1976. Limits on the variation of fundamental atomic quantities over cosmic time scales. Physical Review Letters 37(4):179-181. See also discussion in Physics Today, September 1976, p 17, 18.
· York D, Farquhar M. 1972. The earth's age and geochronology. NY: Pergamon Press.

(21) Inherited Radiometric Age

· Aleinikoff JN, Dusel-Bacon C, Foster HL, Futa K. 1981. Proterozoic zircon from augen gneiss, Yukon-Tanana Upland, east-central Alaska. Geology 9:469-473.
· Anderson RE, Longwell CR, Armstrong RL, Marvin RF. 1972. Significance of K-Ar ages of Tertiary rocks from the Lake Mead region Nevada-Arizona. Geological Society of America Bulletin 83:273-288.
· Armstrong RL. 1975. The geochronometry of Idaho (Part 1 and 2). Isochron/West, Nos. 15 and 16.
· Armstrong RL, Leeman WP, Malde HE. 1975. K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River plain, Idaho. American Journal of Science 275:225-251.
· Bailey SW, Hurley PM, Fairbairn HW, Pinson, Jr. WH. 1962. K-Ar dating of sedimentary illite polytypes. Geological Society of America Bulletin 73:1167-1170.
· Banks NG, Cornwall HR, Silverman ML, Creasy SC, Marvin RF. 1972. Geochronology of intrusion and ore deposition of Ray, Arizona, Part I, K-Ar ages. Economic Geology 67:864-878.
· Bickford ME, Van Schmus WR. 1979. Geochronology and radiogenic isotope research. Reviews of Geophysics and Space Physics 17:824-839.
· Brewer MS. 1969. Excess radiogenic argon in the metamorphic micas from the Eastern Alps, Austria. Earth and Planetary Science Letters 6:321-331.
· Brooks C, James DE, Hart SR. 1976. Ancient lithosphere: its role in young continental volcanism. Science 193:1086-1094.
· Cherdyntsev VV, Kislitsina GI, Zverev VL. 1967. Isotopic composition of uranium and thorium in rocks and products of active volcanism. Doklady Akademii Nauk USSR 172:456-458. (English translation in Geochemistry.).
· Clarke Jr. RS, Wosinski JF, Marvin RF, Friedman I. 1966. Potassium-argon ages of artificial tektite. glass. Transactions, American Geophysical Union 47:144.

· Condomines M, Bernat M, Allegre CJ. Evidence for contamination of Recent Hawaiian lavas from ^{230}Th-^{238}U data. Earth and Planetary Science Letters 33:122-125.
· Dallmeyer RD. 1975. The Palisades sill; a Jurassic intrusion? Geology 3:243-245.
· Dalrymple GB. 1969. ^{40}Ar/^{36}Ar analyses of historic lava flows. Earth and Planetary Science Letters 6:47-55.
· Dalrymple GB, Lanphere MA. 1969. Potassium-argon dating, Ch 8. San Francisco: W. H. Freeman & Co.
· Dalrymple GB, Moore JG. 1968. Argon-40 excess in submarine pillow basalts from Kilauea volcano, Hawaii. Science 161:1132-1135.
· Damon PE. 1968. Potassium-argon dating of igneous and metamorphic rocks with applications to the Basin ranges of Arizona and Sonora. In: Hamilton EI, Farquhar RM, editors. Radiometric Dating for Geologists, p 1-71, particularly Section E, p 12-18. NY: John Wiley & Sons.
· Damon PE, Laughlin AW, Percious JK. 1967. Problems of excess argon-40 in volcanic rocks. In: Radioactive Dating and Methods of Low-Level Counting, p 463-481. Vienna: International Atomic Energy Agency.
· Dickinson DR, Gibson IL. 1972. Feldspar fractionation and anomalous Sr^{87}/Sr^{86} ratios in a suit of peralkaline silicic rocks. Geological Society of America Bulletin 83:231-240.
· Doe BR. 1970. Lead isotopes, p 55. NY: Springer-Verlag.
· Duncan RA, Compston W. 1976. Sr-isotope evidence for an old mantle source region for French Polynesian volcanism. Geology 4:728-732.
· Dymond J. 1970. Excess argon in submarine basalt pillows. Geological Society of America Bulletin 81:1229-1232.
· Faure G. 1977. Principles of isotope geology, p 103, 172. NY: John Wiley & Sons.
· Faure G, Powell JL. 1972. Strontium isotope geology, p 35, 41, 48-50, 63. NY: Springer-Verlag.
· Fisher DE. 1969. Fission track ages of deep sea glasses. Nature 221:549-550.
· Fisher DE. 1971. Excess rare gases in a subaerial basalt from Nigeria. Nature Physical Science 232:60-61.
· Fisher DE. 1972. U/He ages as indicators of excess argon in deep-sea basalts. Earth and Planetary Science Letters 14:255-258.
· Funkhouser JG, Barnes IL, Naughton JJ. 1968. The determination of a series of ages of Hawaiian volcanoes by the potassium-argon method. Pacific Science 22:369-372.
· Funkhouser JG, Fisher DE, Bonatti E. 1968. Excess argon in deep sea rocks. Earth and Planetary Science Letters 5:95-100.
· Funkhouser JG, Naughton JJ. 1968. Radiogenic helium and argon in ultramafic inclusions from Hawaii. Journal of Geophysical Research 73:4601-4607.
· Gentry RV, Christie WH, Smith DH, Emery JF, Reynolds SA,Walker R, Cristy SS, Gentry PA. 1976. Radiohalos in coalified wood: new evidence relating to the time of uranium introduction and coalification. Science 194:315-318.
· Giletti BJ. 1971. Discordant isotopic ages and excess argon in biotites. Earth and Planetary Science Letters 10:157-164.
· Ghosh PK. 1972. Use of bentonites and glauconites in potassium-40/argon-40 dating in Gulf Coast stratigraphy. Doctoral dissertation, Rice University. Ann

Arbor, MI: University Microfilms 72-26, 413.

· Hanson GN. 1975. $^{40}Ar/^{39}Ar$ spectrum ages on Logan intrusions, a Late Keweenawan flow, and mafic dikes in northeastern Minnesota-northwestern Ontario. Canadian Journal of Earth Sciences 12:821-835.

· Harrison TM, McDougall I. 1981. Excess ^{40}Ar in metamorphic rocks from Broken Hill, New South Wales: implications for $^{40}Ar/^{39}Ar$ age spectra and the thermal history of the region. Earth and Planetary Science Letters 55:123-149.

· Hart R. 1978. Excess ^{40}Ar in Precambrian cherts. EOS, Transactions of the American Geophysical Union 59:1215-1216.

· Hart SR, Dodd, Jr. RT. 1962. Excess radiogenic argon in pyroxenes. Journal of Geophysical Research 67:2998-2999.

· Hayatsu A. 1972. On the basic assumptions in K-Ar dating method. Comments on Earth Sciences: Geophysics 3:69-76.

· Hawkesworth CJ, Norry MJ, Roddick JC, Vollmer R. 1979. $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios from the Azores and their significance in LIL-element enriched mantle. Nature 280:28-31.

· Hebeda EH, Boelrijik NAIM, Priem HNA, Verdurmen EAT, Versuchure RH. 1973. Excess radiogenic argon in the Precambrian Avanavero dolerite in Western Suriname (South America). Earth and Planetary Science Letters 20:189-200.

· Hebeda EH, Boerlrijik NAIM, Priem HNA, Verdurman EAT, Versuchure RH. 1980. Excess radiogenic Ar and undisturbed Rb-Sr systems in basic intrusives subjected to Alpine metamorphism in southeastern Spain. Earth and Planetary Science Letters 47:87-90.

· Hedge CE, Noble DC. 1971. Upper Cenozoic basalts with high Sr^{87}/Sr^{86} and Sr/Rb ratios, Southern Great Basin, Western United States. Geological Society of America Bulletin 82:3503-3510.

· Hennecke EW, Manuel OK. 1975. Noble gases in lava rock from Mount Capulin, New Mexico. Nature 256:284-287.

· Hoffmann AW, Mahoney, Jr. JW, Giletti BJ. 1974. K-Ar and Rb-Sr data on detrital and postdepositional history of Pennsylvanian clay from Ohio and Pennsylvania. Geological Society of America Bulletin 85:639-644.

· Hower J, Hurley PM, Pinson WH, Fairbairn HW. 1963. The dependence of K-Ar on the mineralogy of various particle size ranges in shale. Geochimica et Cosmochimica Acta 27:405-410.

· Kaneoka I. 1974. Investigation of excess argon in ultramafic rocks from the Kola Peninsula by the $^{40}Ar/^{39}Ar$ method. Earth and Planetary Science Letters 22:145-156.

· Kaneoka I, Aoki K-I. 1978. $^{40}Ar/^{39}Ar$ analysis of phlogopite nodules and phlogopite-bearing peridotites in South African kimberlites. Earth and Planetary Science Letters 40:119-129.

· Kirsten T, Muller O. 1967. Argon and potassium in mineral fractions of three ultramafic rocks from the Baltic Shield. In: Radioactive Dating and Methods of Low-Level Counting, p 483-498. Vienna: International Atomic Energy Agency.

· Krogh TE, Davis GL. 1973. The effect of regional metamorphism on U-Pb systematics in zircon and a comparison with Rb-Sr systems in the same whole rock and its constituent minerals. Carnegie Institution Yearbook 72:601-610.

· Krummenacher D. 1970. Isotopic composition of argon in modern surface volcanic rocks. Earth and Planetary Science Letters 8:109-117.
· Lanphere MA, Dalrymple GB. 1971. A test of the $^{40}Ar/^{39}Ar$ age spectrum technique on some terrestrial materials. Earth and Planetary Science Letters 12:359-372; specifically, section 3.3.
· Laughlin AW. 1969. Excess radiogenic argon in pegmatite minerals. Ph.D. thesis, University of Arizona.
· Leventhal JS. 1975. An evaluation of the U-Th-He method for dating young basalts. Journal of Geophysical Research 80:1911-1914.
· Ludwig KR. 1978. Uranium-daughter migration and U/Pb isotope apparent ages of uranium ores, Shirley Basin, Wyoming. Economic Geology 73:29-49.
· Macdougall JD. 1976. Fission track annealing and correction procedures for oceanic basalt glasses. Earth and Planetary Science Letters 30:19-26.
· McCulloch MT, Gregory RT, Wasserburg GJ, Taylor, Jr. HP. 1980. A neodymium, strontium, and oxygen isotope study of Cretaceous Samil ophialite and implications for petrogenesis and sea water-hydrothermal alteration of oceanic crust. Earth and Planetary Science Letters 46:201-211.
· McDougall L, Green DH. 1964. Excess radiogenic argon in pyroxenes and isotopic ages on minerals from Norwegian eclogites. Norsk Geologisk Tidsskrift 44:183-196.
· McDougall I, Polach HA, Stipp JJ. 1969. Excess radiogenic argon in young subaerial basalts from Auckland volcanic field, New Zealand. Geochimica. et Cosmochimica Acta 33:1485-1520.
· Maluski H. 1978. Behaviour of biotites, amphibolites, plagioclases and K-feldspars in response to tectonic events with the ^{40}Ar-^{39}Ar radiometric method. Example of Corsican granite. Geochimica et Cosmochimica Acta 42:1619-1633.
· Mellor DW, Mussett AE. 1975. Evidence for initial ^{36}Ar in volcanic rocks, and some implications. Earth and Planetary Science Letters 26:312-318.
· Mikheyenko VI, Nenasher NI. 1961. Absolute age of formation and relative age of intrusion of the kimberlites of Yakutia. Akademiya Nauk USSR, Moskva Leningrad, p 146-164. Translated from the Russian by H. Faul. 1962. International Geological Review 4:916-924.
· Moorbath S. 1975. Geological interpretation of whole-rock isochron dates from high grade gneiss terrains. Nature 255:391.
· Naeser CW. 1971. Geochronology of the Navajo-Hopi diatremes, Four Corners area. Journal of Geophysical Research 76:4978-4985.
· Nevins SE. 1974. Post-Flood strata of the John Day Country, northeastern Oregon. Creation Research Society Quarterly 10:191-204.
· Nkomo IT, Rosholt JN. 1973. Evidence of uranium migration in Precambrian granitic rocks from south-central Wyoming. Geological Society of America Abstracts 5:752-753.
· Noble CS, Naughton JJ. 1968. Deep ocean basalts: inert gas content and uncertainties in age dating. Science 162:265-267.
· Noble DC, Hedge CE. 1969. Sr^{87}/Sr^{86} variations within individual ash-flow sheets. U.S. Geological Survey Professional Paper 650-C:133-l39.

· Odin GS. 1978. Results of dating Cretaceous, Paleogene sediments, Europe. Contributions to the Geologic Time Scale, p 129 of p 127-141. American Association of Petroleum Geologists Studies in Geology No. 6.
· Oversby VM, Gast PW. 1968. Lead isotope compositions and uranium decay series equilibrium in recent volcanic rocks. Earth and Planetary Science Letters 5:199-206.
· Pankhurst RJ, Pidgeon RT. 1976. Inherited isotope systems and the source region pre-history of early Caledonian granites in the Dalradian series of Scotland. Earth and Planetary Science Letters 31:55-68.
· Perry Jr. EA. 1974. Diagenesis and the K-Ar dating of shales and clay minerals. Geological Society of American Bulletin 85:827-830.
· Polach H, Chappell J, Lovering JF. 1969. ANU radiocarbon date list III. Radiocarbon 11:253-254.
· Roddick JC, Farrar E. 1971. High initial argon ratios in hornblends. Earth and Planetary Science Letters 12:208-214.
· Roddick JD, Cliff RA, Rex DC. 1980. The evolution of excess argon in alpine biotites; A ^{40}Ar-^{39}Ar analysis. Earth and Planetary Science Letters 48:185-208.
· Rosholt JN, Zartman RE, Nkomo IT. 1973. Lead isotope systematics and uranium depletion in the Granite Mountains, Wyoming. Geological Society of America Bulletin 84:989-1002.
· Saxon J. 1978. Fossil radioactive bones. Catastrophist Geology 3:9-11.
· Seidemann D. 1978. ^{40}Ar/^{39}Ar studies of deep-sea igneous rocks. Geochimica et Cosmochimica Acta 42:1721-1734.
· Shaffer NR, Faure G. 1976. Regional variation of ^{87}Sr/^{86}Sr ratios and mineral compositions of sediment from the Ross Sea, Antarctica. Geological Society of America Bulletin 87:1491-1500.
· Shafiqullah M, Damon PE. 1974. Evaluation of K-Ar isochron methods. Geochimica et Cosmochimica. Acta 38:1341-1358.
· Smith RL, Bailey RA. 1966. The Bandelier tuff: a study of ash-flow eruption cycles from zoned magma chambers. Bulletin of Volcanology 29:83-103.
· Stapor FW, Tanner WF. 1973. Errors in pre-Holocene carbon-14 scale. American Association of Petroleum Geologists Bulletin 57:1838.
· Stieff LR, Stern TW, Milkey RG. 1953. A preliminary determination of the age of some uranium ores of the Colorado Plateaus by the lead-uranium method. U.S. Geological Survey Circular 271.
· Takaoka N, Nagao K. 1978. Mantle ^{40}Ar/^{36}Ar trapped in Cretaceous deep-sea basalts. Nature 276:491-492.
· Taylor KS, Faure G. 1981. Rb-Sr dating of detrital feldspar: a new method to study till. Journal of Geology 89:97-107.
· Van Schmus WR. 1978. Rb-Sr geochronologic analysis of metagabbro at the bottom of the Michigan Basin deep drill hole. Journal of Geophysical Research 83B(12):5832.
· Wanless RK, Stevens RD, Loveridge WD. 1970. Anomalous parent-daughter isotopic relationships in rocks adjacent to the Grenville Front near Chibongamau, Quebec. Ecologae Geologicae Helvetiae 63:345-364.

· Wensink H, Hebeda EH, Boelrijk NAIM, Priem HNA, Verdurmen EAT, Verschure RH. 1976. Radiometric age dating and paleomagnetism of the Deccan Traps, India. EOA, Transactions of the American Geophysical Union 57:654.
· Wilson MR. 1972. Excess radiogenic argon in metamorphic amphiboles and biotites from the Sulitjelma region, central Norwegian Caledenides. Earth and Planetary Science Letters 14:403-412.
· Woodmorappe J. 1979. Radiometric geochronology reappraisal. Creation Research Society Quarterly 16:102-129, 147, 148.
· Worden JM, Compston W. 1973. A Rb-Sr isotopic study of weathering in the Mertondale granite, Western Australia. Geochimica et Cosmochimica Acta 37:2567-2576.
· York D, Farquhar RM. 1972. The earth's age and geochronology, p 101-102. NY: Pergamon Press.
· York D, MacIntyre RM, Guttins J. 1969. Excess radiogenic ^{40}Ar in cancrinite and sodalite. Earth and Planetary Science Letters 7:25-28.
· Zhirov KK, Fedotov ZA, Kravchen MP, Surovtse LN. 1974. Manifestation of primarily entrapped excess argon in main dike intrusions of Northern Pechenga on Kola Peninsula. Geokhimiya 12:1856.

(22) Thermoluminescent Dating

· Garlick GFJ, Lamb WE, Steigmann GA, Geake JE. 1971. Thermoluminescence of lunar samples and terrestrial plagioclases. Proceedings of the Second Lunar Science Conference, Vol. 3, p 2277-2283. Cambridge, MA: The M.I.T. Press.
· Göksu HY, Fremlin JH, Irwin HT, Fryxell R. 1974. Age determination of burned flint by a thermoluminescent method. Science 183:651-654.
· Hedges R. 1979. Physics in archeology. Nature 278:691-692.
· Hoyt Jr. HP, Miyajima M, Walker RM, Zimmerman DW, Zimmerman J, Britton D, Kardos JL. 1971. Radiation dose rates and thermal gradients in the lunar regolith: thermoluminescence and DTA of Apollo 12 samples. Proceedings of the Second Lunar Science Conference, Vol. 3, p 2245-2263. Cambridge, MA: The M.I.T. Press.
· McDougall DJ, editor. 1968. Thermoluminescence of geological materials. NY: Academic Press.
· May RJ. 1979. Thermoluminescence dating of Hawaiian basalt. U.S. Geological Survey Professional Paper 1095.
· Michels JW. 1973. Dating methods in archaeology, Ch 12. NY: Seminar Press.

(23) Nuclear Radiation Track Dating

· Burnett D, Monnin M, Seitz M, Walker R, Yuhas D. 1971, Lunar astrology — U-Th distributions and fission-track dating of lunar samples. Proceedings of the Second Lunar Science Conference, Vol. 2, p 1503-1519. Cambridge, MA: The M.I.T. Press.
· Calk LC, Naeser CW. 1973. The thermal effect of a basalt intrusion on fission tracks in quartz monzonite. Journal of Geology 81:189-198.
· Crittenden MD, Stuckless JS, Kistler RW, Stern TW. 1973. Radiometric dating of intrusive rocks in the Cottonwood area, Utah. Journal of Research of the U.S.G.S. 1:173-178.

· Gentry RV. 1973. Radioactive halos. Annual Review of Nuclear Science 23:347-362.
· Gentry RV. 1974. Radiohalos in radiochronological and cosmological perspective. Science 184:62-66.
· Gentry RV, Hulett LD, Cristy SS, McLaughlin JF, McHugh JA, Bayard M. 1974. 'Spectacle' array of ^{210}Po halo radiocenters in biotite: a nuclear geophysical enigma. Nature 252:564-566.
· Gentry RV, Christie WH, Smith DH, Emery JF, Reynolds SA, Walker R, Cristy SS, Gentry PA. 1976. Radiohalos in coalified wood: new evidence relating to the time of uranium introduction and coalification. Science 194:315-318.
· MacDougall D. 1973. Fission track dating of ocean basalts. Transactions, American Geophysical Union 54:987-988.
· Naeser CW. 1969. Etching fission tracks in zircons. Science 165:388.
· Naeser CW. 1971. Geochronology of the Navajo-Hopi diatremes, Four Corners area. Journal of Geophysical Research 76:4978-4985.

(24) Chondrite Structure Features

· Brownlee DE, Rajan RS. 1973. Micrometeorite craters discovered on chondrule-like objects from Kapaeta meteorite. Science 182:1341-1344.
· Chen JH, Tilton GR. 1976. Isotopic lead investigations on the Allende carbonaceous chondrite. Geochimica et Cosmochimica Acta 40:635-643.
· Dominik B, Jessberger EK, Staudacher T, Nagel K, ElGoresy A. 1978. A new type of white inclusion in Allende: petrography, mineral chemistry, ^{40}Ar-^{39}Ar ages, and genetic implications. Proceedings of the Ninth Lunar and Planetary Science Conference, p 1249-1266. NY: Pergamon Press.
· Hughes DW. 1974a. Editorial. Even small meteoroids are fluffy. Nature 248:99.
· Hughes DW. 1974b. Editorial. Where do meteorites come from? Nature 248:278-279.
· Hutcheon ID, Goswami JN. 1975. Microcraters and solar flare records in C2 chondrites. EOS, Transactions of the American Geophysical Union 56:1016.
· Lange DE, Larimer JW. 1973. Chondrules: an origin by impacts between dust grains. Science 182:920-922.
· Lindsay JF, Srnka LJ. 1975. Galactic dust lanes and lunar soil. Nature 257:776-777.
· Macdougall JD. 1976. Extraterrestrial materials. Geotimes 21(5):25-27.
· Macdougall JD, Kothari BK. 1976. Formation chronology for C2 meteorites. Earth and Planetary Science Letters 33:36-44.
· MacPherson GJ, Grossman L. 1981. A once-molten, coarse-grained, Ca-rich inclusion in Allende. Earth and Planetary Science Letters 52:16-24.
· Rajan RS. 1974. On the irradiation history and origin of gas-rich meteorites. Geochimica et Cosmochimica Acta 38:777-788.
· Sabu DC. 1973. Solar wind xenon in some carbonaceous chondrites. Journal of Geophysical Research 78:3245-3248.
· Tatsumoto M, Unruh DM, Desborough GA. 1976. U-Th-Pb and Rb-Sr systematics of Allende and U-Th-Pb systematics of Orgueil. Geochimica et Cosmochimica Acta 40:617-634.