DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Radiometric Dating, Geologic Time, And The Age Of The Earth: A Reply To "Scientific" Creationism

by

G. Brent Dalrymple[1]
U. S. Geological Survey

Open-File Report 86-110

[1]Menlo Park, CA

CONTENTS

RADIOMETRIC DATING, GEOLOGIC TIME, AND THE AGE OF THE EARTH: A REPLY TO "SCIENTIFIC" CREATIONISM

by
G. Brent Dalrymple, Ph.D.
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

INTRODUCTION

"Scientific" creationism, as represented by Morris (1974, 1977), Kofahl and Segraves (1975), and others is a model for the creation and history of the universe based on a literal interpretation of parts of the book of Genesis. These authors claim that "scientific" creationism is a legitimate scientific theory that explains extant scientific observations about the history of the universe, the Earth, and living things as well as, if not better than, the current theories and concepts of chemistry, physics, biology, geology, and astronomy. Although clearly religious apologetics and not a scientific theory, many of the major tenets of "scientific" creationism can be tested as if they were rational scientific hypotheses. Two of the principal geologic propositions of the creation model are that the Earth is only about 6,000 to 10,000 years old (Morris, 1974; Kofahl and Segraves, 1975; Slusher, 1980) and that nearly all of the sedimentary rocks on the Earth were deposited in about one year during a worldwide flood that occurred about 7,000 to 9,000 years ago[1] (Morris and Whitcomb, 1961; Morris, 1974; Kofahl and Seagraves, 1975). These two "hypotheses" are contrary to a vast and consistent body of scientific data and are demonstrably false.

----

[1] Cook (1968) dates the flood at roughly 4500 years ago.

Era	Period		Epoch	Estimated Millions of Years Ago
Cenozoic	Neogene	Quaternary	(Recent)	.01
			Pleistocene	2
		Tertiary	Pliocene	5
			Miocene	24
	Paleogene		Oligocene	38
			Eocene	55
			Paleocene	63
Mesozoic	Cretaceous			138
	Jurassic			205
	Triassic			240
Paleozoic	Permian			290
	Carboniferous†	Pennsylvanian		330
		Mississippian		360
	Devonian			410
	Silurian			435
	Ordovician			500
	Cambrian			570
Precambrian				4550

No worldwide divisions of the Precambrian have been devised, although various local classifications exist. By definition, the Precambrian embraces the time between the origin of the earth and the beginning of the Cambrian Period.

Figure 1. Simplified geological time scale. The relative order of the eras, periods, and epochs was determined on the basis of stratigraphy and paleontology. The time scale was independently confirmed and quantified by radiometric dating. After Harbaugh (1974). Ages are based on the new IUGS decay constants.

The ages of the various rock formations, the Earth, the Moon, and meteorites have been measured using radiometric (also called isotopic) dating techniques--- atomic clocks within the rocks themselves that, if properly used, reveal the elapsed time since the rocks formed. There is overwhelming scientific evidence that the oldest rocks on the Earth are 3.6 to 3.8 billon years old, that the oldest rocks on the Moon are 4.4 to 4.6 billion years old, that the oldest meteorites are 4.5 to 4.6 billion years old, and that the Earth, the Moon, and meteorites all formed about 4.5 to 4.6 billion years ago. In addition, these same dating techniques have conclusively verified and quantified the relative geologic time scale (Fig. 1), which was independently deduced by stratigraphers and paleontologists on the basis of nearly two centuries of careful scientific observations of the sequence of sedimentary rock units and fossils.

In defense of "scientific" creationism, Slusher (1973), Morris (1974), and Kofahl and Segraves (1975) have argued that radiometric dating techniques are unreliable and that the scientific data support their belief in a very young Earth. The purpose of this paper is to explain the basic principles of the major radiometric dating methods, to illustrate how they are used to determine the ages of rocks, to show that they provide reliable and consistent age data when properly applied, and to review briefly the evidence for the age of the Earth and the solar system. I will also show that the arguments used by the proponents of "scientific" creationism to discredit radiometric dating are without scientific merit.

The topics covered herein are the subjects of volumes, and this paper is not a comprehensive treatment. It is an explanation, written for the intelligent layman, rather than a thorough review. I have, however, included sufficient references to current texts and to the scientific literature to enable readers to pursue any topic on which they desire additional information. If there is any point about which readers are doubtful, I strongly urge that they plunge in and learn for themselves. The evidence is all in libraries open to the public.

I have intentionally avoided the use of mathematics and formulae in favor of descriptive text except where absolutely necessary to illustrate some of the fundamentals of radioactivity and radiometric dating. Readers should be aware, however, that the quantitative aspects of the various radiometric dating techniques are expressed by formulae that can be rigorously derived. The various mathematical expressions, their derivations, and their rationale can be found in the references cited. I have also not included any discussion about the way in which the various measurements are made. These also are covered in other literature and are apt not to be of sufficient interest to the average reader to warrant the space required to describe them.

The advocates of "scientific" creationism frequently point to apparent inconsistencies in radiometric dating results as evidence invalidating the techniques (for example, Woodmorappe, 1979). This is akin to concluding that all wristwatches do not work because the one on your arm does not keep accurate time. In fact, the small number of "wrong" ages are nearly all due to unrecognized geologic factors, to unintentional misapplication of the techniques, or to technical difficulties. Also, some of the examples cited by the proponents of "scientific" creationism are not anomalous but instead are misrepresentations by the creation "scientists" of radiometric dating techniques and the way in which they are used. Like any complex procedure, radiometric dating does not work <u>all</u> the time under <u>all</u> circumstances. Each technique works only under a particular set of geologic conditions. In addition, scientists are continually learning, improving techniques, and sharpening methods of interpretation, and some of the "errors" are not errors at all but are simply results obtained in the continuing effort to improve the methods and their application. There are, to be sure, inconsistencies, errors, and results that are not understood, but these are very few compared to the vast body of consistent and sensible results that clearly indicate that the methods do work and that the results, properly applied and carefully evaluated, can be trusted.

A favorite claim of creation "scientists" is that geologists have somehow devised the geologic time-scale and an ancient age for the Earth in order to provide adequate time for the biologists' theory of evolution (for example, Morris, 1974; Slusher, 1980). The idea that the theory of evolution and the age of the Earth are the result of a conspiracy is absurd. I have no reason whatsoever to want the age of the Earth to be any more or less than it happens to be. I would take great delight in proving that the Earth is only 10,000 years old if it were possible to do so. As for the biologists, they are entirely on their own--they will have to make do with whatever we geologists are able to discover about the age and history of the Earth. If there is a conspiracy of "evolutionists", neither I nor my colleagues were invited to join.

ACKNOWLEDGMENTS

This paper was substantially improved because of the comments, suggestions, and advice of my friends and colleagues Frank Awbrey, Charles Berkstresser, Duane Champion, Preston Cloud, Max Crittenden, James Cunliffe, Garniss Curtis, Fred Edwords, Niles Eldredge, Craig Hatfield, Norman Horowitz, Junji Kumamoto, Marvin Lanphere, Claire Patterson, Carl Sagan, John Stacey, John Sutter, Christopher Weber, and Edward Wiley. William Mayer first suggested that I write the paper, and Richard Dickerson provided additional prodding. To these people and to all of the others who offered encouragement in various forms, I extend my sincere thanks.

FUNDAMENTALS OF RADIOMETRIC DATING

Radiometric dating techniques are based on the decay of natural, long-lived radioactive isotopes[2] (the parent) of certain elements, incorporated into a rock or mineral at the time of formation, into other stable isotopes (the daughter). To understand how these techniques work, it is necessary to understand a bit about the process of radioactive decay.

Radioactive decay is a statistical process in which the number of atoms that decay per unit of time is proportional to the number of atoms present. While at first this statement may seem to defy logic, it really does not. The probability that any given atom will decay within any given period of time is exactly the same for all atoms. Each atom decays independently of all others, so the more there are, the more decays occur. Radioactive decay is not the only natural process that works in this way. There are many circumstances in nature where the rate of

----

[2] The atoms of elements are composed of protons, neutrons, and electrons. Protons are positively charged particles that reside in the atomic nucleus. Electrons are negatively charged particles that orbit the nucleus. The mass of an electron is only about 1/1840 that of a proton. Neutrons are electrically neutral particles of about the same mass as a proton and also reside in the nucleus. The chemical characteristics of an element and the number of electrons in a neutral atom are determined by the number of protons in the nucleus. If a proton is added or subtracted, then the atom changes to that of another element. For example, if a proton is added to the nucleus of a helium atom, then the atom becomes a lithium atom. Nearly all elements may contain a variable number of neutrons. The addition or subtraction of a neutron to or from the nucleus of an atom does not change the element, but does change the atomic mass and may make the nucleus unstable, causing it to become radioactive. By convention, the number of neutrons plus protons are indicated by a left-hand superscript to the elemental symbol. Thus hydrogen of mass two (one proton and one neutron) is written ^{2}H. Atoms of an element with differing numbers of neutrons in the nucleus are called isotopes of the element. Thus ^{12}C, ^{13}C, and ^{14}C are isotopes of carbon. All contain six protons but ^{12}C contains six neutrons, ^{13}C seven neutrons, and ^{14}C eight neutrons. ^{14}C is unstable and radioactive. A nuclide is any atom with differing numbers of neutrons and protons. Thus ^{12}C, ^{14}C, ^{18}O, and ^{238}U are all nuclides. If an isotope or nuclide occurs in nature, it is called a natural isotope. Isotopes created in the laboratory are called artificial, although there is nothing artificial about them at all.

----

growth[3] is directly related to the size of the growing quantity. The growth of the world's population is one example---the more people there are, the faster the population grows provided that the birth rate is constant. In radioactive decay, as the number of decaying atoms decreases, the fewer parent atoms there are to decay so the rate decreases proportionately. This type of growth is sometimes called "organic growth" because so many organic processes exhibit it.

If the rate of decay is proportional to the number of decaying atoms present, then there should be some simple formula that can be used to predict the number of radioactive parent atoms left after any given amount of time has elasped, and indeed there is. This basic radioactive decay equation, which is also the basis for radiometric dating techniques, is

$$P_t = P_o e^{-\lambda t} \qquad (1)$$

where P_o is the number of parent atoms at some starting time, P_t is the number of parent atoms left after a time t has elasped, and λ is the decay constant, which is the probability that any given atom will decay in some choosen period of time (i.e., year, minute, or second). The letter "e" signifies the fundamental mathematical constant[4] equal to 2.71828+. The type of equation represented by equation (1) is called an exponential equation because it contains the constant e raised to some power. All types of organic growth, whether truly organic or physical, can be described by exponential equations. Readers interested in the derivation

----

[3] Or decrease, which is simply negative growth.

[4] e is one of the most important and interesting of mathematical constants, having many fundamental and unique properties. For additional information on this mathematical marvel, the reader is referred to an article by Gardner (1961).

----

of this formula, which is straightforward but requires a modest knowledge of the calculus, are referred to Dalrymple and Lanphere (1969), Faure (1977), or nearly any text that deals with radioactivity or radiometric dating.

Because radioactive decay is a statistical process, it is not possible to tell exactly when any particular atom will decay. Also, if the number of parent atoms is small, it is not possible to predict exactly how many will decay in any given period of time. For large numbers of atoms, however, the statistical uncertainty becomes vanishingly small and we can predict with great accuracy, using equation (1), exactly how many will decay in a particular period of time. Fortunately, the numbers of atoms in even small amounts of natural substances are large[5] so the statistical uncertainties of radioactive decay are of no practical concern.

A term familiar to most people is the <u>half-life</u>, $t_{1/2}$. This is the length of time required for exactly one-half of the parent atoms to decay. Once the decay constant is known (more on this later) the half-life can be found from equation (1) by setting $P_t=(1/2)P_o$ and solving for t. (Readers who are allergic to math may skip equations 2 through 5, glance at 6, and read on).

$$(1/2)\,P_o = P_o e^{-\lambda t_{1/2}} \qquad (2)$$

$$1/2 = e^{-\lambda t_{1/2}} \qquad (3)$$

$$\log_e (1/2) = -\lambda t_{1/2} \qquad (4)$$

$$\log_e 2 = \lambda t_{1/2} \qquad (5)$$

$$t_{1/2} = \frac{\log_e 2}{\lambda} = \frac{0.693}{\lambda} \qquad (6)$$

----

5 As little as 0.000001 gram of carbon, for example, still contains 5×10^{16} atoms.

This calculation also shows the simple and direct relation between the decay constant and the half-life. Note also that the half-life is a constant and is not related to the number of atoms present.

As it stands, equation (1) is not very useful for radiometric dating because we cannot determine the original number of parent atoms, P_o. There is, however, an easy solution to this problem. In any closed system, the sum of the number of parent atoms left, P_t, and the number of daughter atoms formed, D_t, must equal the original number of parent atoms, P_o.

$$P_o=P_t+D_t \tag{7}$$

If we now substitute P_t+D_t for P_o into equation (1), then

$$P_t=(P_t+D_t)e^{-\lambda t} \tag{8}$$

and

$$D_t = P_t\ (e^{\lambda t}-1). \tag{9}$$

This equation can be solved for t

$$t= \frac{1}{\lambda} \log_e \left(\frac{D_t}{P_t} + 1\right), \tag{10}$$

which is the basic age equation and contains only quantities that can be measured today in the laboratory.[6]

If the rock to be dated contained none of the daughter isotope at the time of formation and the rock remained closed to gain or loss of parent and daughter, then at any later time the age of the rock could be found from equation (10) after measuring D_t and P_t in the laboratory. If the rock incorporated some of the daughter isotope at the time of formation, then we would have to subtract the amount of this initial daughter, D_o,

----

[6] $\log_e$ means logarithm to the base e. Values of $\log_e$ can be found in math tables or computed with many of the modern pocket calculators.

----

before we could calculate the correct age

$$t = \frac{1}{\lambda} \log_e \left(\frac{D_t - D_o}{P_t} + 1\right), \qquad (11)$$

where D_t is now the total number of atoms of the daughter present. Although at first glance it may seem that the requirement of knowing D_o is a formidable limitation to the accuracy of radiometric dating, for the principal methods, the quantity D_o is either zero or negligible or is not required in the age calculation.

Each radiometric dating method has its own special set of requirements, but all have three requirements in common. These are:

1. Radioactive decay must be constant and predictable.
2. The rate of decay must be known.
3. The analyses must be of sufficient quality to give geologically meaningful results.

The last requirement can be disposed of easily. Modern analytical methods and instruments are routinely capable of yielding measurements of parent and daughter isotopes of much higher precision than is necessary for most geologic problems. With regard to the sensitivity of ^{14}C instrumentation, Slusher (1973, p.35) has stated:

> "Now, the radioactivity of carbon-14 is very weak and even with all its dubious assumptions the method is not applicable to samples that supposedly go back 10,000 to 15,000 years. In those intervals of time the radioactivity from the carbon-14 would become so weak that it could not be measured with the best of instruments. Claims have been made that dating can be done back to from 40 to 70 thousand years, but it seems highly improbable that instruments could measure activity of the small amounts of C^{14} that would be present in a sample more than 15,000 years old."

This statement was as untrue in 1973 as it is today. Modern counting instruments, available for more than two decades, are capable of counting the activity of the ^{14}C in a sample as old as 35,000 years in an ordinary laboratory and as old as 50,000 years in laboratories constructed with special shielding against cosmic radiation. New techniques using accelerators and highly sensitive mass spectrometers, now in the experimental stage, have pushed these limits back to 70,000 or 80,000 years and may extend them beyond 100,000 years in the near future.

CONSTANCY OF RADIOACTIVE DECAY

Most radioactive decay involves the ejection of one or more sub-atomic particles from the nucleus. Alpha (α) decay occurs when an alpha particle (a helium nucleus), consisting of two protons and two neutrons, is ejected from the nucleus of the parent isotope. Beta (β^-) decay involves the ejection of a β^- particle (an electron) from the nucleus. Gamma (γ) rays (very small bundles of energy) are the device by which an atom rids itself of excess energy. Because these types of radioactive decay occur spontaneously in the nucleus of an atom, the decay rates are, in essence, unaffected by physical or chemical conditions. The reasons for this are that the distances over which nuclear forces act are much smaller than the distances between nuclei, and that the amounts of energy involved in nuclear transformations are much greater than the amounts of energy involved in normal chemical reactions or normal physical conditions. Put another way, the "glue" holding the nucleus together is very effective and the nucleus is very well insulated from the external world by the electron cloud surrounding every atom. This combination of insulation of the nucleus and the strength of nuclear binding is the reason why scientists must use powerful accelerators or atomic reactors to penetrate and induce changes in the nuclei of atoms.

A great many experiments have been done in attempts to change radioactive decay rates, but these have invariably failed to produce significant changes. It has been found, for example, that decay constants are the same at a temperature of 2000°C or at a temperature of -186°C, and are the same in a vacuum or under a pressure of several thousand atmospheres. Changes in α, β^-, and γ decay rates are theoretically possible, but theory also predicts that such changes would be very small (Emery, 1972) and would not affect dating methods.

There is a fourth type of decay that can be affected by physical and chemical conditions, but only very slightly. This type of decay is electron capture (ec), in which an orbital electron falls into the nucleus and a proton is converted into a neutron. Because this type of decay involves a particle outside of the nucleus, the decay rate may be affected by variations in the electron density near the nucleus of the atom. For example, the decay constant of ^{7}Be in the metal and in several beryllium chemical compounds varies by as much as 0.07 percent (Emery, 1972). The only isotope of geologic interest that undergoes decay by electron capture is ^{40}K, which is the parent isotope in the K-Ar method. Measurements of the decay rate of ^{40}K in different substances under a variety of conditions indicate that varying the chemical and physical environment has no detectable effect on its electron-capture decay constant.

Another type of decay for which small changes in rate have been observed is internal conversion (IC). Internal conversion, however, is a process whereby an atom goes from one energy state to a lower energy state.

It does not involve any elemental transmutation and is, therefore, of little interest with regard to geologic dating methods. Slusher (1976, p.283) states that, "there is excellent laboratory evidence that external influences can change the decay rates", but the examples he cites are either IC decays or ec decays in which the changes in rates are exceedingly small. Slusher (1973) claims that the decay rate of ^{57}Fe has been changed by as much as 3% by electric fields, but this decay is an IC decay and ^{57}Fe remains ^{57}Fe. Note, however, that even a 3% change in the decay constants of our radiometric clocks would still leave us with the inescapable conclusion that the Earth is more than 4 billion years old.

Morris (1974) has claimed that free neutrons might change decay rates, but it is clear from his arguments that he does not understand either neutron reactions or radioactive decay. Neutron reactions do not change decay rates but instead transmute one nuclide to another. The result of the reaction depends on the properties of the target isotope and the energy of the penetrating neutron. There are no neutron reactions that produce the same result as either beta or alpha decay. A n,p reaction (neutron in, proton out) produces the same change in the nucleus of an atom as electron capture decay, but there are simply not enough free neutrons in nature to affect any of the isotopes used in radiometric dating. If enough free neutrons did exist, they would produce other measureable nuclear transformations in common elements that would clearly indicate the existence of such a process.

Morris (1974) also suggests that neutrinos might change decay rates, citing a column by Jueneman (1972) in Industrial Research. The subtitle of Jueneman's columns, which appear regularly, is, appropriately, "scientific speculation". He speculates that neutrinos released in a supernova explosion might have "reset" all of the radiometric clocks. Jueneman describes a highly speculative hypothesis that accounts for radioactive decay by interaction with neutrinos rather than by spontaneous decay, and he notes that an event that temporarily increased the neutrino flux might "reset" the clocks.

It is important to note that Jueneman did not propose that decay rates would be changed, that he did not state how the clocks would be reset, and that there is no evidence to support his speculation. Neutrinos are particles with no charge and very small or possibly no rest mass and are emitted during beta decay. Their existence was proposed by Pauli in 1931 to explain why beta particles are given off with a wide range of energies from any one isotope, rather than with a constant energy. The "missing" energy is carried off by the neutrino. Because they have no charge and little or no mass, neutrinos do not react much with matter -- most pass unimpeded right through the Earth -- and can be detected experimentally only with great difficulty. It is highly unlikely that neutrinos could have any effect on decay rates or produce nuclear transmutations in sufficient quantity to have any significant effect on our radiometric clocks.

Slusher (1976, p.283) states, "evolutionist geologists have long ignored the evidence of variability in the radii of pleochroic haloes, which shows that the decay rates are not constant and would, thus, deny that some radioactive elements such as uranium could be clocks." In a review of the subject, however, Gentry (1973) concludes that the data from pleochroic halo[7] studies are inconclusive on this point--the uncertainties

----
[7] Pleochroic haloes are rings of discolored areas around radioactive inclusions in some minerals. The discoloration is caused by radiation damage in the crystals by α particles. The radii of the rings are proportional to the energies of the α particles.
----

in the measurements and other factors are too great.

Thus, there are both theoretical and experimental reasons to conclude that radioactive decay rates are constant within the range of physical and chemical conditions affecting rocks available to scientists. There is also no evidence of any mysterious perturbing factors, such as those invoked by Morris (1974). Confirmation of the constancy of decay also comes from the large body of concordant radiometric age measurements on the rocks themselves. Some examples of these data will be discussed later.

DECAY CONSTANTS

The decay constants of the parent isotopes used in the principal radiometric dating methods, including ^{235}U, ^{238}U, ^{232}Th, ^{87}Rb, ^{40}K, and ^{14}C, are all known to an accuracy of a few percent or better from direct laboratory experiments. These experiments usually involve counting the number of particles emitted per unit time from a known quantity of the parent isotope. In the early days of radiometric dating, when techniques were first being developed and laboratory instruments lacked the precision and reliability of those now available, some of the constants were not well known and had to be estimated by comparing results from two or more dating methods. But all of the constants have been known to within 5-6 percent or better for nearly three decades (see Aldrich and Wetherill, 1958; Wetherill 1966).

Because of its very long half-life (49 billion years), the ^{87}Rb decay constant is difficult to measure in the laboratory, but recent experiments by Davis and others (1977) seem to have solved that problem. The ^{87}Rb decay constant is still the least well known of the common decay constants, but the uncertainty amounts to no more than two percent, probably less. The decay constants for ^{40}K that were in use from about 1958 to 1976 were known from physical laboratory experiments done in the 1950's (Aldrich and Wetherill, 1958).

In 1976, the Subcommission on Geochronology of the International Union of Geological Sciences (IUGS) evaluated the decay and abundance constants of uranium, thorium, rubidium, strontium, and potassium and adopted a uniform set of values based on the best experimental data (Steiger and Jäger, 1977). These values are now in use in most laboratories throughout the world.

Some authors have criticized the reliability of radiometric dating by claiming that some of the decay constants, particularly those for ^{87}Rb and ^{40}K, are not well known (Cook, 1966, 1968; Slusher, 1973; Morris, 1974), but they fail to cite the relevant literature on the subject. The fact is that neither the decay nor abundance constants are a significant source of error in any of the principal radiometric dating methods. Readers can easily satisfy themselves on this point by reading the paper by Steiger and Jäger (1977) and the references cited therein.

A final word about decay constants. By mutual agreement, most laboratories use the same values so that ages produced by different laboratories may be easily compared. Several times over the past three decades there have been changes in these accepted values because of better measurements. These changes have been made only when enough new data became available to ensure that the change was worth the trouble. In some instances, several values are in current use. For example, the journal Radiocarbon, which catalogs nearly all ^{14}C ages, still uses the pre-1962 half-life of 5568 $\pm$ 30 years instead of the more accurate value of 5730 $\pm$ 40 years so that all ages in the catalog are comparable. This is simply a convention of which scientists are aware, and ages are converted from one half-life to another when necessary. Most papers published after about 1977 use the IUGS decay constants recommended in Steiger and Jäger (1977) for ^{238}U, ^{235}U, ^{232}Th, ^{87}Rb and ^{40}K; those published before may use slightly different values. The examples used in this paper were not all calculated with the same decay constants. I have not bothered to recalculate all of the various examples because it is time-consuming and unnecessary for the purposes of this paper. The resulting changes would amount to only a few percent or less, depending on the particular examples involved.

RADIOMETRIC DATING METHODS

There are a number of long-lived radioactive isotopes used in radiometric dating, and a variety of ways in which they are used to determine the ages of rocks, minerals, and organic materials. Some of the isotopic parents, end-product daughters, and half-lives involved are given in Table 1. Sometimes these decay schemes are used individually to determine an age (e.g., Rb-Sr) and sometimes in combinations (U-Th-Pb). Each of the various decay schemes and dating methods has unique characteristics that make it applicable to particular geologic situations. For example, a method based on a parent isotope with a very long half-life, such as ^{147}Sm, is not very useful for measuring the age of a rock only a few million years old because insufficient amounts of the daughter isotope accumulates in this short time. Likewise, the ^{14}C method can only be used to determine the age of certain types of young organic material and is useless on old granites. Some methods work only on closed systems, whereas others work on open systems.[8] The point is that not all methods are applicable to all rocks of all ages. One of the primary functions of the

Table 1. Principal parent and daughter isotopes used in radiometric dating.

Parent isotope	End-product (daughter) isotope	Half-life (years)
potassium-40 (^{40}K)	argon-40 (^{40}Ar)	1.25×10^{9}
rubidium-87 (^{87}Rb)	strontium-87 (^{87}Sr)	4.88×10^{10}
carbon-14 (^{14}C)	nitrogen-14 (^{14}N)	5.73×10^{3}
uranium-235 (^{235}U)	lead-207 (^{207}Pb)	7.04×10^{8}
uranium-238 (^{238}U)	lead-206 (^{206}Pb)	4.47×10^{9}
thorium-232 (^{232}Th)	lead-208 (^{208}Pb)	1.40×10^{10}
lutetium-176 (^{176}Lu)	hafnium-176 (^{176}Hf)	3.5×10^{10}
rhenium-187 (^{187}Re)	osmium-187 (^{187}Os)	4.3×10^{10}
samarium-147 (^{147}Sm)	neodymium-143 (^{143}Nd)	1.06×10^{11}

dating specialist (sometimes called a geochronologist) is to select the applicable method for the particular problem to be solved, and to design the experiment in such a way that there will be checks on the reliability of the results. As we shall see, some of the methods have internal checks, so that the data themselves provide good evidence of reliability or lack thereof. Sometimes the relative sequence of rock units, as determined independently by the geologist in the field, can be used to check the dating results. Frequently the dating is done on several samples of different type from the same unit, or by more than one method. Most scientists are very hesitant to trust a single age on a single sample as being definitive.

This paper is too short to review and discuss all of the dating methods in use. Instead, I will describe briefly only the four principal methods. These are the K-Ar method (including the newer $^{40}Ar/^{39}Ar$ technique), the Rb-Sr isochron method, the U-Pb concordia-discordia method, and the ^{14}C method. These four methods are the ones most commonly used by scientists to determine the ages of rocks, Earth history, and ancient cultural artifacts because they have the broadest range of applicability and are very reliable when properly used. For additional information on these methods or on methods not covered here, readers are referred to the books listed below, which are probably the best available sources on the subjects listed. In particular, the book by Faure (1977) is current, comprehensive, and covers in considerable detail nearly all of the methods in use as well as the fundamentals. For lighter and easier

----

[8] A closed system is one in which neither matter nor energy enters or leaves. A system that is not closed is an open system. A "system" may be of any size, including very small (like a mineral grain), or very large (like the entire universe). For radiometric dating the system, usually a rock or some specific mineral grains, need only be closed to the parent and daughter isotopes.

----

reading, the book by Faul (1966) might be the best starting point.

Subject	Reference
all methods	Faure (1977), Faul (1966), York and Farquhar (1972)
K-Ar and $^{40}Ar/^{39}Ar$	Dalrymple and Lanphere (1969), Jäger and Hunziker (1979)
Rb-Sr	Faure and Powell (1972)
U-Th-Pb methods	Doe (1970), Jäger and Hunziker (1979)
Fission track dating	Fleischer and others (1975), Jäger and Hunziker (1979)

THE K-Ar METHOD

The K-Ar method is the most widely used radiometric dating technique available to geologists. It is based on the radioactivity of ^{40}K, which undergoes dual decay by electron capture to ^{40}Ar and by beta emission to ^{40}Ca. The ratio of ^{40}K atoms that decay to ^{40}Ar to those that decay to ^{40}Ca is 0.117, which is called the branching ratio. Because ^{40}Ca is practically ubiquitous in rocks and minerals and occurs in relatively large amounts, it is usually not possible to correct for the ^{40}Ca initially present (the initial daughter problem) and the $^{40}K/^{40}Ca$ method is rarely used for dating. ^{40}Ar, however, is an inert gas that escapes easily from rocks when they are heated, but is trapped within the crystal structures of many minerals after a rock cools. Thus in principle, while a rock is molten the ^{40}Ar formed by the decay of ^{40}K escapes from the liquid. After the rock has solidified and cooled, the radiogenic ^{40}Ar is trapped within the solid crystals like a bird in a cage and accumulates with the passage of time. If the rock is heated or melted at some later time, then some or all of the ^{40}Ar may be released and the clock partially or totally reset.

In the process of analysis, a correction must be made for the atmospheric argon[9] present in most minerals and in the vacuum apparatus used for the analyses. This correction is easily made by measuring the amount of ^{36}Ar present and, using the known isotopic composition of atmospheric argon ($^{40}Ar/^{36}Ar = 295.5$), subtracting the appropriate amount of ^{40}Ar that is due to atmospheric contamination. What is left is the radiogenic ^{40}Ar. This correction can be made very accurately and has no appreciable effect on the calculated age unless the atmospheric argon is a very large proportion of the total argon in the analysis. The geochronologist takes this factor into account when assigning experimental errors to the calculated ages.

The K-Ar method has two requirements in addition to the general requirements discussed earlier. First, there must be no argon other than that of atmospheric composition trapped in the rock or mineral when it forms. Second, the rock or mineral must not lose or gain either potassium or argon from the time of its formation to the time of analysis. By many experiments over the last three decades, geologists have learned which types of rocks and minerals meet these requirements and which do not. The K-Ar clock works primarily on igneous rocks, i.e., those that form from a rock liquid such as lava and granite and have simple post-formation histories. It does not work well on sedimentary rocks because these rocks are composed of debris from older rocks. It does not work well on most metamorphic rocks because this type of rock usually has a complex history, often involving one or more heatings after initial formation. The method does work on certain minerals that retain argon well, such as muscovite, biotite, and volcanic feldspar, but it does not work on other minerals, such as feldspar from granitic rocks, because they leak their argon even at

----

[9] Approximately one percent of the earth's atmosphere is argon, of which 99.6 percent is ^{40}Ar.

----

low temperatures. The method works very well on subaerial lava flows, but does not work on most submarine pillow basalts because they frequently trap excess ^{40}Ar when they solidify. One of the principal tasks of the geochronologist is to select the type of material used for a dating analysis. A great deal of effort goes into the sample selection, and the choices are made before the analysis, not on the basis of the results. Mistakes are sometimes made but are usually caught by the various checks employed in the well-designed experiment.

The efficacy of the K-Ar method is best demonstrated by two examples from the scientific literature.

Dating North American Land Mammal Ages

Paleontologists and stratigraphers divide geologic time into various relative time scales based on distinctive groups of fossils, called faunas or faunazones. There is one such scale for North American land mammals, one for Pacific Coast foraminifers (small, one-celled animals that float in the sea), etc. Each period of relative time is given a name, usually derived from some locality where the fossils occur. On the basis of decades of careful investigations, vertebrate paleontologists have divided the Cenozoic (see Fig. 1) into some 15-20 "North American Land Mammal Ages". The relative sequence of these ages was known both from stratigraphy and from the relative stage of evolution of the various fossils, but the exact age in years and amount of time represented by each Mammal Age could only be estimated (though pretty well as it turns out).

In the early 1960's, two geochronologists and two vertebrate paleontologists at the University of California at Berkeley did an experiment to determine whether the relative sequence of North American Land Mammal Ages was correct and to quantify the scale. The results are

Table 2. Summary of the K-Ar dates of the North American Land Mammal Ages for the Cenozoic. Data from Evernden and others (1964). Data include ages on only those units whose relative order was known before the dating experiment was done. The ages were calculated with the old ^{40}K constants.

Land Mammal Age (top youngest, bottom oldest)	Range of K-Ar ages (million years)	Number of samples dated
Irvingtonian	1.36	1
Blancan	1.5 - 3.5	7
Hemphillian	4.1 - 10.0	8
Claredonian	8.9 - 11.7	16
Barstovian	12.3 - 15.6	9
Hemingfordian	17.1	1
Arikareean	21.3 - 25.6	4
Orellan	---	0
Chadronian	31.6 - 37.5	9
Duchesnean	37.5	3
Uintan	42.7 - 45.0	2
Bridgerian	45.4 - 49.0	2
Wasatchian	49.2	1
Puercan	64.8	1

summarized in Table 2, and their significance nicely expressed by the authors in their classic paper (Evernden and others, 1964, p.166).

> "Of all the samples dated that met the mineralogic and geologic standards outlined above, not one has given a date that is in serious conflict with the associated vertebrate paleontologic data. On the contrary, in almost very case, they have given support to the proposed time-stratigraphic position of faunal aggregates and mammal ages."

and (p.145)

> "The K/A ages and the Mammal Age designations are in essentially perfect agreement, thus substantiating the usefulness of the K/A technique throughout the Tertiary and suporting the conclusion that the defined Mammal Ages have true evolutionary significance."

and (p.166)

> "Vertebrate paleontologists have relied upon 'stage-of-evolution' as the criterion for determining the chronologic relationships of faunas. Before the establishment of physical dates, evolutionary progression was the best method for dating fossiliferous strata. The physical dates presented in this paper (table 6) demonstrate that temporal position of genera and species of fossil mammals in their accepted phylogenies is accurate at Mammal Age degree of refinement."

Morris (1974) has cited the first sentence of the last quote out of context as evidence that the relation between paleontologic dating and evolution involves circular reasoning, but he clearly does not understand either the purpose of the experiment or the significance of the results. The point is that the results summarized in Table 2 could not have been obtained unless both the Mammal Ages, which were indeed ordered partly on the basis of evolutionary principles, and the K-Ar dating method were right! Readers should note also that the more general Geologic Time Scale shown in Fig. 1 was confirmed and quantified by radiometric dating long after the stratigraphers and paleontologists had concluded what the relative order had to be. This is powerful proof of the correctness of the geologic column, the phylogeny deduced from the fossil record, the vast amounts of

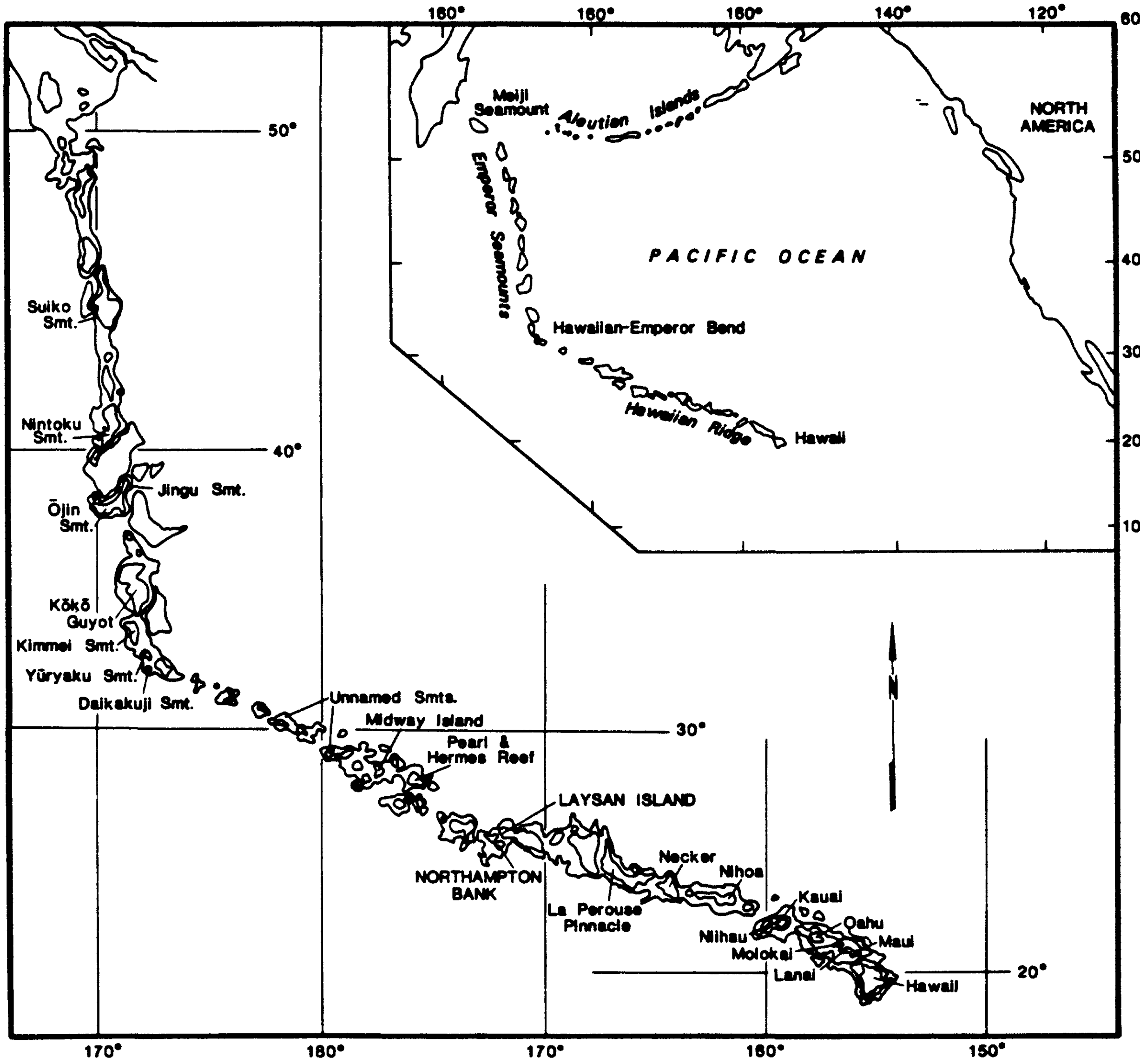

Figure 2. Location of the Hawaiian-Emperor volcanic chain in the Pacific. After Dalrymple and others (1981).

time involved in Earth history, and radiometric dating methods.

Dating of the Hawaiian-Emperor Chain

The Hawaiian Islands lie at the southeast end of a long chain of more than 100 volcanoes that stretches nearly 6000 kilometers across the floor of the Pacific (Fig. 2) (Dalrymple and others, 1973). In 1963, J. T. Wilson (1963) proposed that the Hawaiian Islands chain was formed as the floor of the Pacific moved over a stationary source of lava in the Earth's mantle. According to Wilson, each volcano becomes extinct as it is carried away from its lava source, leaving a trail of volcanoes on the sea floor. Morgan (1972) extended this hypothesis to include the Emperor Seamounts, and proposed that the bend in the chain of volcanoes was caused by a change in direction of motion of the Pacific lithospheric plate. A corollary of this "hot-spot" hypothesis, as it is now known, is that the age of the volcanoes should increase as a function of distance from the active volcanoes of Kilauea and Manua Loa on the Island of Hawaii. In an experiment to test the hot-spot hypothesis, nearly 30 of the volcanoes in the chain have now been dated by the K-Ar method and the newer $^{40}Ar/^{39}Ar$ method (which is explained later). The results, summarized in recent papers by Jackson and others (1980) and Dalrymple and others (1980, 1981b), are shown in Figure 3. As can be readily seen, the volcanoes do indeed increase in age as a function of distance from Hawaii. Like the previous example, the only reasonable conclusion that can be reached from these data are that both the hot-spot hypothesis and the dating methods must be correct. The data clearly show that the Hawaiian- Emperor chain of volcanoes has formed by processes related to plate tectonics over a period of more than 65 million years.

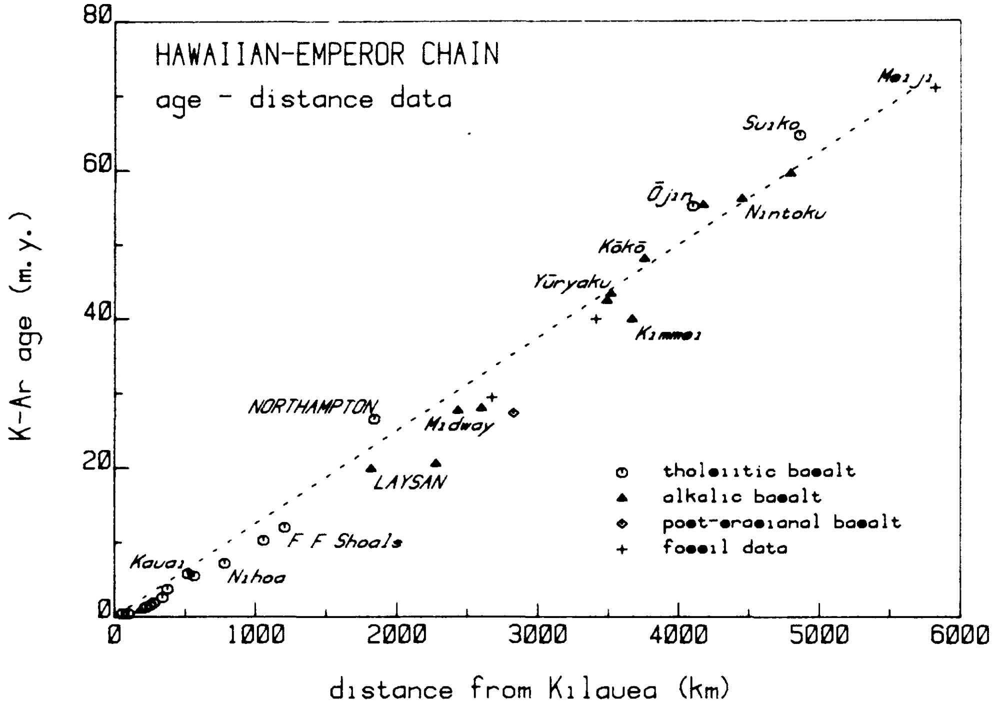

Figure 3. K-Ar and $^{40}Ar/^{39}Ar$ ages of volcanoes in the Hawaiian-Emperor chain as a function of distance from the active volcanoes Kilauea and Mauna Loa on the Island of Hawaii. Data from Dalrymple and others (1980, 1981). Ages are based on the new IUGS constants.

Discussion of Some Criticisms of K-Ar Dating

Slusher (1973), Morris (1974), and Kofahl and Segraves (1975) have criticized the validity of the K-Ar dating method, citing some examples of "anomalous" ages from the literature. It is worth discussing a few of their examples to illustrate how little validity their criticisms have.

1. The 1801 Flow from Hualalei Volcano

> "Volcanic rocks produced by lava flows which occurred in Hawaii in the years 1800-1801 were dated by the potassium-argon method. Excess argon produced apparent ages ranging from 160 million to 2.96 billion years."
> (Kofahl and Segraves, 1975, p.200)

> "Similar modern rocks formed in 1801 near Hualalei, Hawaii, were found to give potassium-argon ages ranging from 160 million years to 3 billion years."
> (Morris, 1974, p.147)

These authors cite a study by Funkhouser and Naughton (1968) on xenolithic inclusions in the 1801 flow from Hualalei Volcano on the Island of Hawaii.

The 1801 flow is an unusual flow because it carries very abundant inclusions of rocks foreign to the lava. These inclusions, called xenoliths (meaning foreign rocks), consist primarily of olivine, a pale-green, iron-magnesium silicate mineral. They come from deep within the mantle and were carried upward to the surface by the lava. In the field, they look like large raisins in a pudding, and even occur in beds piled one on top of the other, glued together by the lava. The study by Funkhouser and Naughton (1968) was on the xenoliths, not on the lava. The xenoliths, which vary in composition and range in size from single mineral grains to rocks the size of basketballs, do indeed carry excess argon in large amounts. Funkhouser and Naughton were quite careful to point out that the apparent "ages" they measured were not geologically meaningful. Quite simply, xenoliths are one of the types of rocks that cannot be dated by K-Ar techniques. Funkhouser and Naughton were able to determine that the excess gas resides primarily in fluid bubbles in the minerals of the xenoliths, where it cannot escape upon reaching the surface. Studies such as the one by Funkhouser and Naughton (1968) are done to determine which materials are suitable for dating and which are not, and to determine the cause of sometimes strange results. They are part of the continuing effort to learn.

There have been two extensive K-Ar studies on historic lava flows (Dalrymple, 1969; Krummenacher, 1970) that showed that excess argon is not a serious problem for dating lava flows. An exception is the lava from the 1801 Hualalei flow, which is so badly contaminated by the xenoliths that it is not possible to obtain a completely inclusion-free sample.

2. The Hawaiian basalts

> "Still another study on Hawaiian basalts obtained seven "ages" of these basalts ranging all the way from zero years to 3.34 million years. The authors, by an obviously unorthodox application of statistical reasoning, felt justified in recording the "age" of these basalts as 250,000 years."
> (Morris, 1974, p.147)

The data to which Morris refers were published by Evernden and others (1964), but include samples from different islands of different age! The age of 3.34 million years is from the Napali Formation on the Island of Kauai and is consistent with other ages on this formation (McDougall, 1964,1979). The approximate age of 250,000 years was the mean of the results from the four samples from the Island of Hawaii. Contrary to Morris' concerns, nothing is amiss with these data and the statistical reasoning used by Evernden and his colleagues is perfectly rational and orthodox.

3. The Kilauea Submarine Pillow Basalts

> "Many of the rocks seem to have inherited Ar^{40} from the magma from which the rocks were derived. Volcanic rocks erupted into the ocean definitely

> inherit Ar^{40} and helium and thus when these are dated by the K^{40}-Ar^{40} clock, old ages are obtained for very recent flows. For example, lavas taken from the ocean bottom off the island(sic) of Hawaii on a submarine extension of the east rift zone of Kilauea volcano gave an age of 22 million years, but the actual flow happened less than 200 years ago."
>
> (Slusher, 1973, p.31, and similar statements by Morris, 1974)

Two studies independently discovered that the glassy margins of submarine pillow basalts, so named because lava extruded under water forms globular shapes resembling pillows, trap ^{40}Ar dissolved in the melt before it can escape (Dalrymple and Moore, 1968; Noble and Naughton, 1968). The effect is most serious in the rims of the pillows and increases in severity with water depth. The excess ^{40}Ar approaches zero toward pillow interiors, which cool more slowly and allow the ^{40}Ar to escape, and in water depths of less than about 1000 meters because of the lessening of hydrostatic pressure. The purpose of these two studies was to determine, in a controlled experiment with samples of known age, the suitability of submarine pillow basalts for dating, because it was suspected that such samples might not be reliable. This sort of study is not unusual, as each different type of mineral and rock has to be carefully tested before it can be used for any of the radiometric dating techniques. In the case of the submarine pillow basalts, the findings clearly indicated that these rocks were not suitable for dating, and as a result they are not often used for this purpose except in special circumstances and unless there is some independent way of verifying the results.

4. "Excess" Argon in Lunar Rocks

> "On the other hand, many lunar rocks contain such large quantities of what is considered to be excess argon that dating by K/Ar is not even reported"
>
> (Kofahl and Segraves, 1975, p.200)

The citation for this statement is to a paper by Turner (1970). Turner made no such comment about excess argon in lunar rocks, and there are no data in his paper on which such a conclusion can be based. The statement by Kofahl and Segraves (1975) is unjustified.

THE $^{40}Ar/^{39}Ar$ METHOD

The $^{40}Ar/^{39}Ar$ method is a form of K-Ar dating wherein the sample is irradiated in an atomic reactor in order to convert a known fraction of the ^{39}K, which is the most abundant isotope of potassium, to ^{39}Ar. Instead of measuring the amount of potassium and argon in separate experiments by different techniques, as in the conventional K-Ar method, it is then possible to determine the exact ratio of daughter to parent by measuring the ratio of ^{40}Ar to ^{39}Ar in one experiment. Corrections must be made for atmospheric argon and for certain interfering argon isotopes produced by unwanted neutron reactions with calcium and potassium, but these corrections can be made quite precisely (for example, Brereton, 1970; Dalrymple and Lanphere, 1971; Dalrymple and others, 1981a). When all of the argon in a sample is analyzed in one experiment, this method generally gives ages comparable to those determined with the conventional K-Ar method.

If the irradiated sample is heated in increments to progressively higher temperatures and the gas released at each heating is analyzed separately, however, the results have some remarkable properties. Such data are usually plotted in either an age-spectrum diagram (apparent age as a function of the percent of ^{39}Ar released; Fig. 4) or an isochron diagram ($^{40}Ar/^{36}Ar$ vs $^{39}Ar/^{36}Ar$; Fig. 5A), or both. An age-spectrum for an undisturbed (closed system) sample is a flat line that gives the age of the

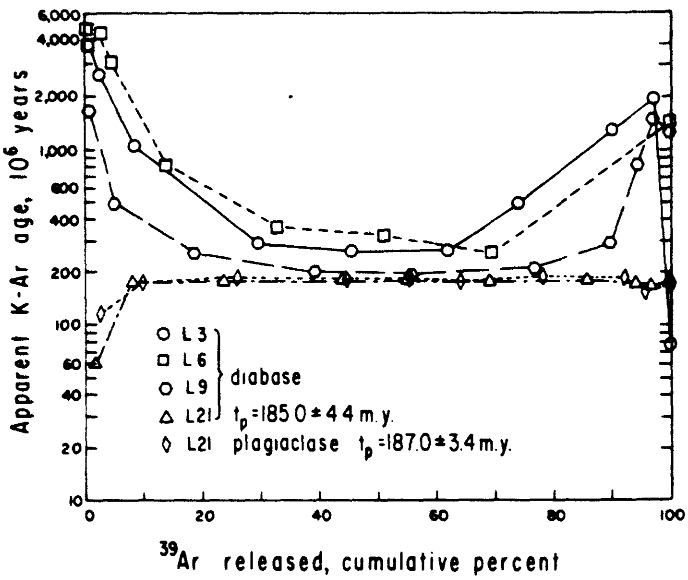

Figure 4. $^{40}Ar/^{39}Ar$ age-spectra of samples from diabase dikes in Liberia. Samples from sites L3, L6, and L9 contain excess ^{40}Ar, whereas the samples from site L-21 do not. The age-spectra reveal that the ages of the samples from site L21 are reliable but the others are not. From Dalrymple and others (1975).

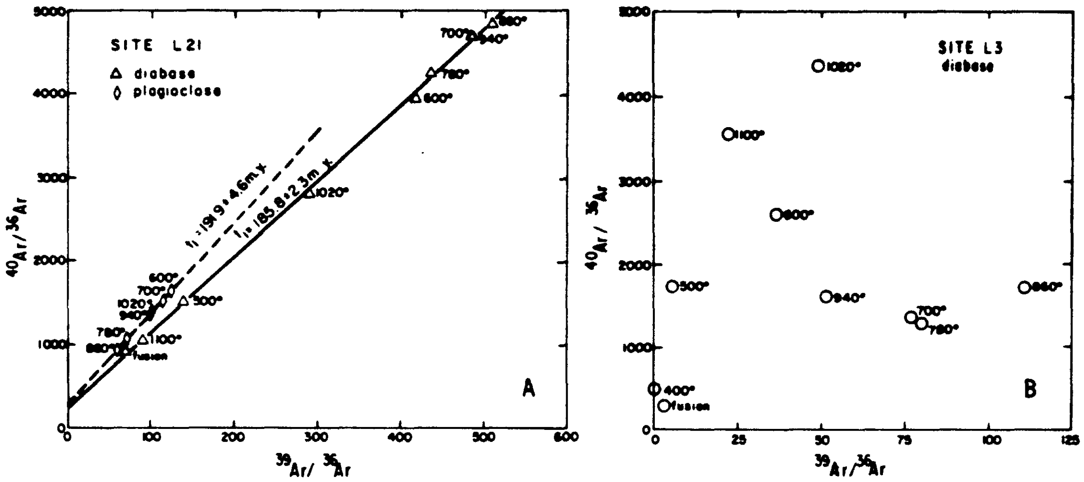

Figure 5. $^{40}Ar/^{39}Ar$ isochron diagrams for some of the samples shown in Figure 4. From Dalrymple and others (1975).

rock. The ratios $^{40}Ar/^{36}Ar$ and $^{39}Ar/^{36}Ar$ for such a sample will also plot on a straight line, or isochron, whose slope gives the ratio $^{40}Ar/^{39}Ar$ and hence the age, and whose intercept on the ordinate will be the atmospheric ratio of 295.5. Note that this latter treatment requires no assumptions about the composition of the non-radiogenic (or atmospheric) argon. The intercept independently gives that answer. Examples of such data are shown in Fig. 4 (samples from site L21) and Fig. 5A.

Samples that have lost some of their argon and would give a meaningless conventional K-Ar age, often still give a plateau and isochron that record the true age of the rock with the higher temperature gas increments. Many lunar rocks have been reliably dated in this way (see, for example, Turner, 1970). Samples that have been very open systems or contain excess argon nearly always give age spectra that are not flat lines and do not plot on an isochron. Examples of data from samples with known excess ^{40}Ar are shown in Fig. 4 (sites L3, L6, and L9) and Fig. 5B. Note that both the age-spectrum and the isochron diagram for these samples clearly show that something is wrong with the samples and that their "ages" are not to be believed.

The $^{40}Ar/^{39}Ar$ technique is relatively new, and many of the age-spectra from rocks with complex histories cannot yet be interpreted. But the technique has the desirable feature of internal checks on sample and technique reliability. Not only can the method give reliable ages for some rocks that have not been entirely closed systems, the data themselves reveal whether the sample has been badly disturbed or contains excess ^{40}Ar. This method has been used to date lunar rocks, meteorites, altered samples of lava from seamounts, and some metamorphic rocks with complex post-formation histories. As scientists continue to learn more about the interpretation of complex age spectra, this technique becomes increasingly useful.

Rb-Sr ISOCHRON METHOD

The Rb-Sr method is based on the radioactivity of ^{87}Rb, which undergoes simple beta decay to ^{87}Sr with a half-life of 48.8 billion years. There are very few minerals in which rubidium is a major constituent, but the chemistry of rubidium is similar to that of potassium and sodium, both of which do form many common minerals, and rubidium occurs as a trace element in most rocks. Because of the very long half-life of ^{87}Rb, Rb-Sr dating is used mostly on rocks older than about 50 to 100 million years. This method is very useful on rocks with complex histories because the daughter product, strontium, does not escape from minerals nearly as easily as does argon. As a result, a sample can obey the closed-system requirements for Rb-Sr dating over a wider range of geologic conditions than can a sample for K-Ar dating.

Unlike argon, which escapes easily and entirely from most molten rocks, strontium is present as a trace element in most minerals when they form. Slusher (1973) and Morris (1974) have used this fact to claim that the Rb-Sr method is, therefore, unreliable.

> "Extraneous Strontium 87 can easily be incorporated into Rubidium 87 minerals from the surrounding rocks." (Morris, 1974, p.148)

> "It seems utterly impossible to determine the initial concentration of Sr^{87} atoms" and "There is no really valid way of determining what the initial amounts of Sr^{87} in rocks were." (Slusher, 1973, p.32)

These criticisms are partly irrelevant and partly wrong. Simple Rb-Sr ages can be calculated with equation (10) above for those minerals that are high in Rb and contain a negligible amount of initial strontium. In such minerals, the age is insensitive to the initial strontium amount and composition. For most rocks, however, initial strontium is present in significant amounts, and dating is done with the isochron method, which completely eliminates the problem of initial strontium.

In the Rb-Sr isochron method, several (3 or more) minerals from the same rock or several cogenetic rocks with different rubidium and strontium contents are analyzed and the data plotted on an isochron diagram (Fig. 6). The ^{87}Rb and ^{87}Sr contents are normalized to the quantity of ^{86}Sr, which is not a radiogenic daughter product. When a rock is first formed, say from a magma, the $^{87}Sr/^{86}Sr$ ratios in all of the minerals will be the same regardless of the rubidium or strontium contents of the minerals, so all of the samples will plot on a horizontal line (a-b-c in Fig. 6). The intercept of this line with the ordinate represents the isotopic composition of the initial strontium. From then on, as each atom of ^{87}Rb decays to ^{87}Sr, the points will follow the paths[10] shown by the arrows. At any time after formation, the points will lie along some line a'-b'-c'(Fig. 6), whose slope will be a function of the age of the rock. The intercept of the line on the ordinate will give the isotopic composition of the initial strontium present when the rock formed. Note that the intercepts of line a-b-c and that of a'-b'-c' are identical, so that the initial strontium composition can be determined from this intercept regardless of the age of the rock.

Note that the Rb-Sr isochron method requires no knowledge or assumptions about either the isotopic composition or the amount of the

----

[10] These paths will be at an angle of 45° if the scales on the abscissa and ordinate are the same.

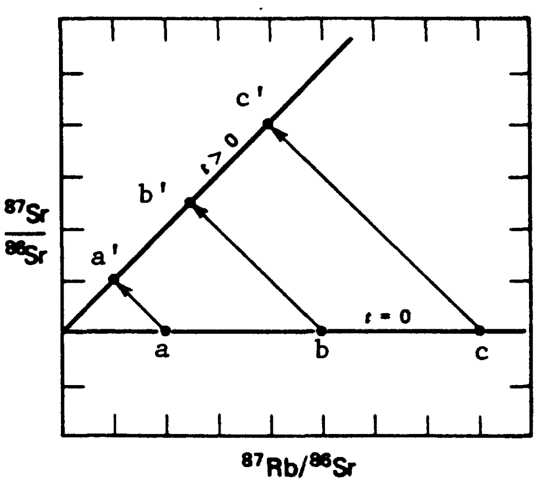

Figure 6. Rb-Sr isochron diagram showing the time-dependent evolution of Rb and Sr isotopes in a closed system. See text for explanation. After Faure (1977).

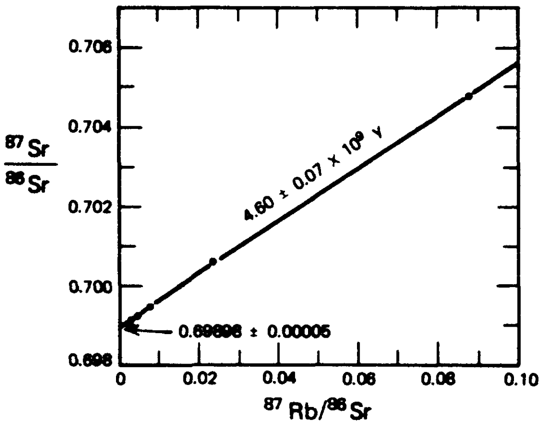

Figure 7. Rb-Sr isochron for the meteorite Juvinas. The points represent analyses on glass, tridymite and quartz, pyroxene, the total rock, and plagioclase. After Faure (1977). Data from Allegre and others (1975).

initial daughter---in fact, that is something learned from the method. The rocks or minerals must have remained closed systems to rubidium and strontium since formation, but if this condition is not true, then the data will not plot on an isochron. Also, if either the initial isotopic composition of strontium is not uniform or the samples analyzed are not cogenetic, then the points will not fall on a straight line. As the reader can easily see, the Rb-Sr isochron method is elegantly self-checking. If the requirements of the method have been violated, the data clearly show it.

An example of a Rb-Sr isochron is shown in Figure 7, which includes analyses of five separate phases from the meteorite Juvinas (Allegre and others, 1975). The data form an isochron indicating an age for Juvinas of 4.60 ± 0.07 billion years. This meteorite has also been dated by the Sm-Nd isochron method, which works like the Rb-Sr isochron method, at 4.56 ± 0.08 billion years (Lugmair, 1974).

In summary, the Rb-Sr isochron dating method is very useful and contains internal self-checking features that independently show whether or not the results are reliable. It is widely used by scientists to determine the ages of rocks from the Moon and the Earth, and of meteorites. The statement by Moore (1976, p.40) that "The method involving decay of rubidium 87 into strontium 87 is considered so unreliable that it has been discarded", is simply untrue.

THE U-Pb CONCORDIA-DISCORDIA METHOD

The various U-Th-Pb methods rely on the decays of ^{235}U, ^{238}U, and ^{232}Th. These parent isotopes all undergo series decay involving several intermediate radioactive daughter products before the stable lead daughter (Table 1) is reached. Less than ten years after the discovery of radioactivity, Boltwood (1907) attempted to determine the ages of several rocks by the decay of uranium to lead. Boltwood's ages, which were chemical ages rather than isotopic ages, were not very accurate, however, because his attempt was made before isotopes were discovered, before the disintegration rate of uranium was known accurately, and before it was known that lead was also the final decay product of thorium. Various dating methods using the decays of uranium and thorium to lead have been tried over the years. Some work well and some do not work at all.

Three simple, independent "age" calculations can be made from the U-Th-Pb decays: ^{238}U to ^{206}Pb, ^{235}U to ^{207}Pb, and ^{232}Th to ^{208}Pb. In addition, an "age" based on the ratio of $^{207}Pb/^{206}Pb$ can be calculated, since this ratio changes with time. If necessary, a correction can be made for the initial lead in these systems using ^{204}Pb as an index. If these four age calculations agree, then the age represents the age of the rock. Lead, however, is a volatile element and lead loss is frequently a problem. As a result, the simple U-Th-Pb ages are often discordant. Because of lead loss, it often happens that for a given mineral or rock the ^{232}Th age $<$ ^{238}U age $<$ ^{235}U age $<$ $^{207}Pb/^{206}Pb$ age. In these instances, the $^{207}Pb/^{206}Pb$ age is usually closest to the age of the rock, because it is the least sensitive to lead loss.

The U-Pb concordia-discordia method circumvents the problem of lead loss in discordant systems and provides internal checks on reliability. This method involves the ^{238}U and ^{235}U decays and is used in minerals like zircon, a common accessory mineral in igneous rocks, that contains uranium but no or negligible initial lead. This latter requirement can be checked, if necessary, by checking for the presence of ^{204}Pb, which would indicate the presence and amount of initial lead. In a closed, lead-free system, a

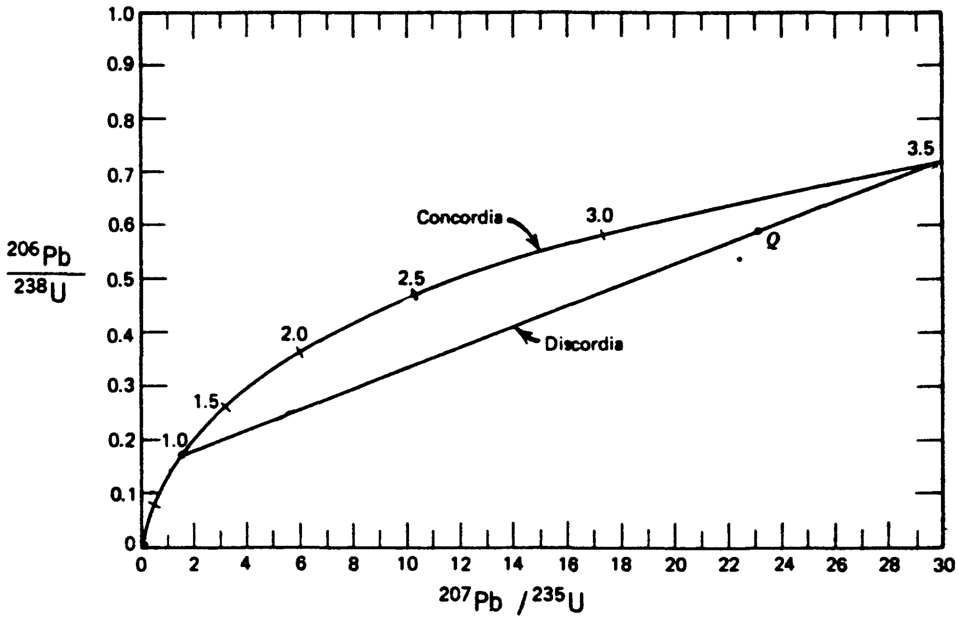

Figure 8. U-Pb concordia-discordia diagram showing the evolution of a system that is 3.5 b.y. old and experienced episodic lead loss 1.0 b.y. ago. See text for explanation. After Faure (1977).

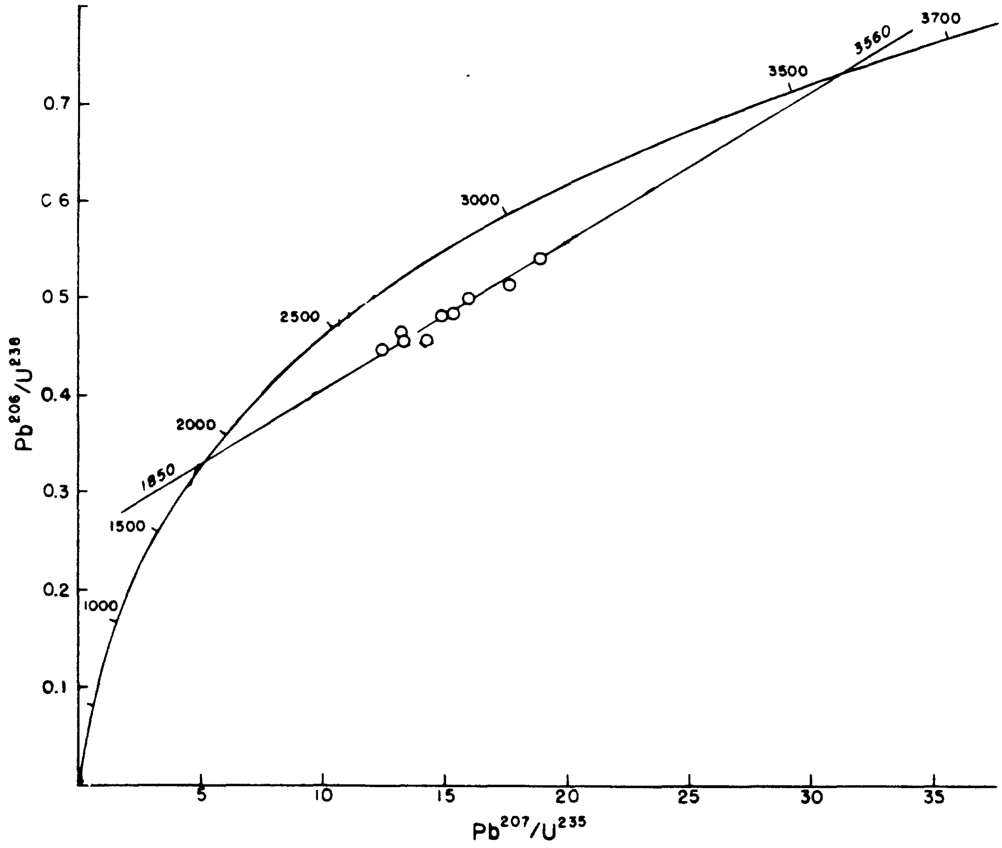

Figure 9. U-Pb concordia-discordia diagram for nine samples of the 3.56-b.y.-old Morton Gneiss, Minnesota. After Goldich and others (1970).

point representing the ratios $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ will plot on a curved line known as concordia (Fig. 8). The location of the point on concordia depends only on the age of the sample. If at some later date (say 2.5 billion years after formation) the sample loses lead in an episodic event, the point will move off of concordia along a straight line toward the origin. At any time after the episodic lead loss, say 1.0 billion years, the point (Q in Figure 8) will lie on a chord to concordia connecting the original age of the sample and the age of the lead loss episode. This chord is called discordia. If we now consider what would happen to several different samples, say different zircons, from the same rock, each of which lost differing amounts of lead during the episode, we find that at any time after the lead loss, say today, all of the points for these samples will lie on discordia. The upper intercept of discordia with concordia gives the original age of the rock, or 3.5 billion years in the example shown in Figure 8. There are several models for the interpretation of the lower intercept, but usually it indicates the age of the event that caused the lead loss, or 1 billion years in Figure 8. Note that this method is not only self-checking, but it also works on open systems. What about uranium loss? Uranium is so refractory that uranium loss does not seem to be a problem. If uranium was lost, however, the concordia-discordia plot would indicate that also.

The U-Pb concordia-discordia method is one of the most powerful and reliable dating methods available. It is especially resistant to heating and metamorphic events and thus is extremely valuable in rocks with complex histories. Quite often this method will be used in conjunction with the K-Ar and the Rb-Sr isochron method to unravel the history of metamorphic rocks, since each of these methods responds differently to metamorphism and heating. For example, the U-Pb discordia age might give the age of initial formation of the rock, whereas the K-Ar method, being especially sensitive to argon loss by heating, might give the age of the latest heating event.

An example of a U-Pb discordia age is shown in Fig. 9. This example shows an age of 3.56 billion years for the oldest rocks yet found in North America, and an age of 1.85 billion years for the latest heating event experienced by these rocks. The K-Ar ages on rocks and minerals from this area in southwestern Minnesota also record the 1.85-billion-year heating event, and the Rb-Sr isochron ages reflect a high-grade metamorphism that occurred 2.65 billion years ago (Goldich and others, 1970).

DISCUSSION OF SOME CRITICISMS OF U-Th-Pb METHODS

Two examples will suffice to show that the criticisms of U-Th-Pb methods by Slusher (1973), Morris (1974), and Kofahl and Segraves (1975) are meaningless.

1. The Katanga Uranium Deposits:

Slusher (1973) and Morris (1974) both cite a book by Cook (1966) in which Cook claims to have developed circumstantial evidence for the conversion, in nature, of one lead isotope to another by free neutrons. Cook's argument is that analyses of uranium ores from Katanga showed the existence of ^{208}Pb but no ^{232}Th parent or ^{204}Pb common lead. Since the ^{208}Pb could not have come from <u>in situ</u> decay (no ^{232}Th present) or be common lead (no corresponding ^{204}Pb present), it must have come from some other source. In spite of sound evidence that there are many orders of magnitude too few free neutrons in rocks, even in these uranium ores, Cook reasoned that the ^{208}Pb must have been generated by n,γ reactions with ^{207}Pb. Cook then asks how any type of U-Th-Pb isotopic dating can be trusted if free neutron reactions can transmute one lead isotope to another? Cook cites a compilation by Faul (1954) for the Katanga data, and Faul credits the analyses to Nier (1939).

The answer to this "mystery" is contained in Nier's paper. ^{204}Pb is not absent from the Katanga samples, as Cook and those who enthusiastically endorse Cook's hypothesis claim, Nier simply did not measure it. In his paper, Nier (1939, p.156) says:

> "Actually, in 20 of the 21 samples investigated the amount of common lead is so small that one need not take account of the variations in its composition. In a number of samples where the abundance of ^{204}Pb was very low no attempt was made to measure the amount of it as the determination would be of no particular value."

Cook (1966) has misinterpreted Faul's compilation of data and Cook's rigorous calculations are meaningless as they are based on data that do not exist.

2. The Reunion "Discordance"

> "A series of volcanic rocks from Reunion Island in the Indian Ocean gives K/Ar ages ranging from 100,000 to 2 million years, whereas the $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages are from 2.2 to 4.4 billion years. The factor of discordance between 'ages' is as high as 14,000 in some samples."
> (Kofahl and Segraves, 1975, p.201)

There are two things wrong with this argument. First, the lead data they cite, which comes from a paper by Oversby (1972), are common lead measurements done primarily to obtain information on the genesis of the Reunion lavas and secondarily to obtain an estimate of the time that the parent magma from which the lava was derived was separated from primitive mantle material. These data cannot be used to calculate the age of the lava flows and no knowledgable scientist would do so. Second, the U-Pb and Pb-Pb lava "ages" cited by Kofahl and Segraves (1975) do not appear in

Oversby's paper. The K-Ar ages are the correct ages of the Reunion lava flows, whereas the U-Pb and Pb-Pb "ages" do not exist. We can only speculate on where Kofahl and Segraves (1975) obtained their numbers.

RADIOCARBON METHOD

Radiocarbon (or ^{14}C) dating is somewhat different from the other radiometric dating techniques discussed so far because it is based on the disappearance of the parent isotope by decay rather than the accumulation of the daughter. The ^{14}C method is used on organic material, primarily plant matter. ^{14}C has a half-life of 5730 ± 40 years, and the method is useful for dating material back to about 30,000 to 50,000 years, depending on how the particular laboratory is constructed and equipped. Because of the limited range, the ^{14}C method can provide no information about most of geologic history, but it is extremely valuable for determining ages of very young geologic events and of historic and prehistoric cultural artifacts.

^{14}C is continuously produced in the upper atmosphere by a variety of nuclear reactions, the most important by far being the reaction between slow cosmic ray neutrons and ^{14}N, the most common isotope of nitrogen.

$$\text{neutron} + {}^{14}N = {}^{14}C + \text{proton}$$

^{14}C is radioactive and decays by beta decay back to ^{14}N. The ^{14}C produced in the atmosphere combines chemically with oxygen to form CO and CO_2, which is incorporated into plants by photosynthesis and into animals by ingestion. As long as the organism lives and continues to incorporate carbon compounds, the ^{14}C content in the tissue remains at a constant level because the incorporation of ^{14}C is balanced by ^{14}C decay. When tissue growth stops, ^{14}C absorption stops and the amount of ^{14}C begins to decrease because of continuing decay. In order to measure the ^{14}C age of a sample, the scientist determines the amount of ^{14}C left in the sample compared to the amount of ^{14}C in a standard modern sample of known age. The ^{14}C age is the age of cessation of tissue growth, which frequently coincides with the death of the organism. In the case of tree rings, a ring stops growing as a new outer ring is formed.

There are several special requirements for the measurement of accurate ^{14}C ages:

1. The sample must have remained a closed system to ^{14}C after death.
2. The ^{14}C activity in living plant and animal tissues must be a known constant that is independent of time and geographic location. This depends on a constant and uniform ^{14}C inventory in the atmosphere and on uniform absorption by the organisms.

The first requirement is simply a matter of intelligent sample selection, but the second is a more complex matter.

It is known that the amount of ^{14}C in plant and animal tissue does not vary with the type of organism and that ^{14}C is uniformly distributed around the world by rapid atmospheric mixing. It is also known, however, that the production of ^{14}C in the upper atmosphere has not been constant with time. This is primarily because of changes in the solar and cosmic ray proton flux due to changing solar activity and to magnetic field variations, both of which affect the production of neutrons and hence the production of ^{14}C. The effects of this temporal variation of ^{14}C production have been determined by dating tree rings from the Giant Sequoias and the Bristlecone Pines, for which there exists a well-determined dendrochronology back to about 5400 B.C.[11]. The results of these studies (Fig. 10) show that ^{14}C ages prior to about 400 B.C. are too young by as much as 700 years at 4500 B.C., or about 10 percent. These data now can be used to make reasonably accurate corrections to ^{14}C ages back to about 5400 B.C. when necessary. The accuracy of the corrections have been confirmed by studies on Egyptian artifacts of known age and on the annual layers (varves) found in some lakes (Ralph and Michaels, 1974). What about ^{14}C ages prior to 5400 B.C.? The uncertainties in this age range are not yet well known, but the existing data suggest that the atmospheric ^{14}C content has varied by about 10 percent or a bit more above and below the nineteenth century value. Thus the accuracy of ^{14}C ages older than 5400 B.C. may have uncertainties of $\pm$ 10 percent, but probably not much more. An important thing to remember is that the relative ages between samples are not affected by this uncertainty, and this relative-age information is often more important to scientists than is the absolute age.

^{14}C dating has been used to determine ages and rates of late Quaternary geologic events, such as the uplift and faulting along the western coast of the United States and the most recent glaciations in North America. It has also been used extensively to determine the

---

[11] Supporters of "scientific" creationism frequently criticize dendrochronology, arguing that two or more growth rings may occur in any given year and that this precludes an accurate annual count (for example, Morris, 1974). Their objections are fallacious. Not all trees growing in all climates are suitable for tree ring dating. Certain species of juniper, for example, are notorious for producing multiple rings. Likewise, many woody trees in tropical climates can produce several growth rings in one year. For these reasons, dendrochronologists use only about three dozen genera of trees and only in particular geographic areas. In addition, the annual counts are meticulously verified by crossdating using ring matching in multiple radii, trees, and tree stands. Tree ring dating is complicated but very reliable when properly done (Fritts, 1972, 1976).

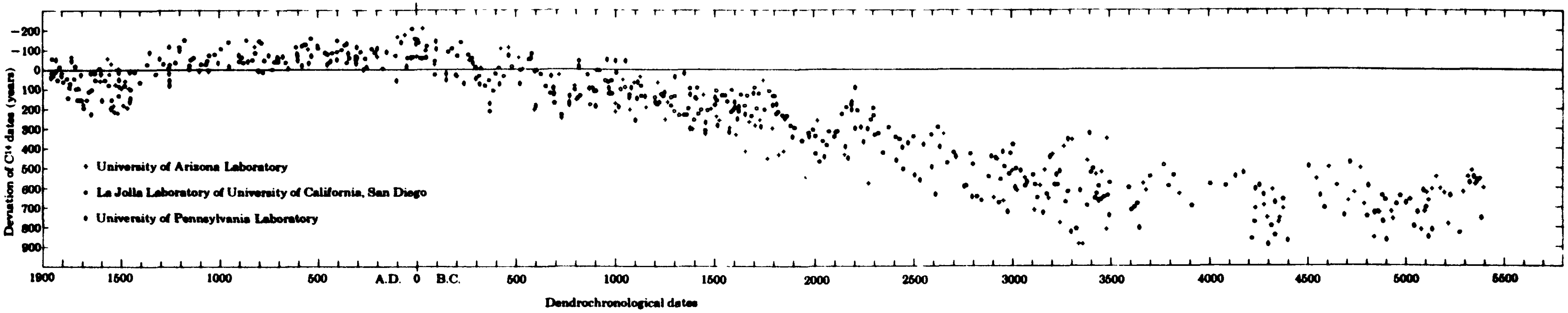

Figure 10. Deviations of ^{14}C ages from dendrochronologic ages. From Ralph and Michaels (1974).

chronology of development and the migration patterns of early man. For example, ^{14}C dating and other methods have shown that Homo sapiens (anatomically modern man) existed in Africa during the Middle Stone Age more than 50,000 and probably some 80,000 to 90,000 years ago (Vogel and Beaumont, 1972; Protsch, 1975). From Africa, Homo sapiens migrated to other continents, arriving in Europe, Asia, and Australia about 32,000 to 34,000 years ago. ^{14}C dates on sites in southern California and in Central and South America show that Homo sapiens arrived on the American continent about 28,000 to 30,000 years ago from Asia via the Bering Strait, where a land bridge was formed when sea level was lowered during a period of glaciation (Protsch, 1979). Thus, ^{14}C dating, in concert with other techniques, has not only provided archeologists and anthropologists with a chronology for the emergence of modern man, but has also proved invaluable in efforts to trace the first migration of our ancestors to the continents of the world.

THE AGE OF THE EARTH

Three basic approaches are used to determine the age of the Earth. The first is to search for and date the oldest rocks exposed on the surface of the Earth. Because these oldest rocks are metamorphic rocks with earlier but now erased histories, the ages obtained in this way are minimum ages for the Earth. Since the Earth formed as part of the solar system, a second approach is to date extraterrestrial objects, i.e., meteorites and samples from the Moon. Many of these samples have not had as intense histories as the oldest Earth rocks, and they frequently record events nearer and equal to the time of formation of the planets. The third approach, and the one that scientists think gives the most accurate age for the Earth, planets, and solar system, is to determine model lead ages for the Earth, Moon, and meteorites. This method is thought to represent the time that lead isotopes were last homogeneously distributed and thus the time that the planetary bodies were segregated into discrete chemical systems.

The results from these methods indicate that the Earth, meteorites, Moon, and, by inference, the entire solar system are 4.5 to 4.6 billion years old. Each of these methods and some of the evidence obtained by their use will be reviewed briefly.

But first a word about the formation of the Earth, the solar system, and the universe with respect to the Earth's age. The formation of the Earth was but one in a series of events in the formation and evolution of the universe. There is now good evidence that the present universe began with the explosion of a primordial ball of subatomic matter some 10 to 20 billion years ago (Schramm, 1974a,b; Gott and others, 1976). This "Big Bang" resulted in the formation of the lighter elements and threw matter outward in all directions at high velocity. The universe is still expanding from this initial event and the velocity of expansion can be observed and measured by the red shift of light coming to Earth from distant galaxies. It was from the matter expelled during this initial cataclysmic event that the first galaxies, stars, and planets formed.

As stars go, the sun is rather ordinary and is neither old nor young. Some stars were formed, ran their course, and died before the sun came into being. Others are forming now, and doubtless still others will form in the future. Present scientific evidence indicates that the Galaxy, in which the Sun is but one of billions of stars, began to condense about 12 $\pm$ 2 billion years ago. The dust and gas of the solar nebula separated from the galactic interstellar medium about 4.7 billion years ago (Wetherill, 1975). Condensation and accretion of this nebular material over a period of about 150 million years led to the formation of the Sun and its planets, including the Earth.

A thorough discussion of the history of the universe is beyond the scope of this paper. Readers who are interested in pursuing this facinating subject further should see the recent summaries by Gott and others (1976); Wetherill (1975); Schramm (1974a, b), or any of the numerous popular texts available. The important point for the purposes of this paper is that the formation of the solar system and the Earth was not an instantaneous event but occurred over a finite period of time as the result of processes set in motion when the universe formed. Thus it is more correct to talk about formation intervals rather than discrete ages for the solar system and Earth. Present evidence indicates, however, that these intervals were rather short (100-200 million years) compared to the length of time that has elapsed since the formation began some 4 to 5 billion years ago. Thus, the ages of the Earth, the Moon, and meteorites measured by different methods represent slightly different events, although the differences in the ages are usually very small, and for the purpose of this paper they will be treated as a single event. With this in mind, we shall proceed to review the evidence for the age of the Earth.

THE EARTH'S OLDEST ROCKS

All of the major continents contain a core of very old rocks fringed by younger rocks. These cores, called Precambrian shields, are all that remain of the Earth's oldest crust. The rocks in these shields are mostly metamorphic rocks, meaning that they have been changed from other rocks into their present form by great heat and pressure beneath the surface. Most have been through more than one such metamorphism and have had very complex histories. Not all metamorphisms completely erase the radiometric record of a rock's age, but on the other hand, many do. Thus the radiometric ages obtained from these oldest rocks are not necessarily the age of the first event in the history of the rock. In addition, many of the oldest dated rocks intrude still older but undatable rocks. In all cases, the ages provide only a minimum age for the Earth.

So far, rocks older than 3.0 billion years have been found in North America, India, Russia, Greenland, Australia, and Africa. The oldest rocks in North America, found in Minnesota, give a U-Pb discordia age of 3.56 billion years (Fig. 9). The oldest rocks yet found on the Earth are in Greenland, South Africa and India. The Greenland samples have been especially well studied. The Amitsoq gneisses in western Greenland, for example, give a Rb-Sr isochron age of 3.70 $\pm$ 0.14 billion years, a $^{207}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ isochron age of 3.80 $\pm$ 0.12 billion years (Moorbath and others, 1975), a U-Pb discordia age on zircons of 3.65 $\pm$ 0.05 billion years, a Th-Pb discordia age on zircons of 3.65 $\pm$ 0.08 billion years (Baadsgaard, 1973), and a Lu-Hf isochron age of 3.55 $\pm$ 0.22 billion years (Pettingill and others, 1981; Pettingill and Patchett, 1981).

Whole-rock samples from the Sand River Gneisses in Limpopo Valley, South Africa, have been dated by the Rb-Sr isochron method at 3.79 ± 0.06 billion years (Barton and others, 1978). These samples are from rocks that contain xenoliths of still older but as yet undatable rocks. Recently, Basu and others (1981) have reported a nine-sample Sm-Nd isochron age of 3.78 ± 0.11 billion years for rocks in eastern India.

Studies of the oldest rocks from the Precambrian shields show that the Earth is older than 3.8 billion years. The geology of these oldest rocks shows that there was a substantial period of time in the history of the Earth before 3.8 billion years ago for which there now exists no datable geologic record. There are several possible reasons for the apparent absence of this earliest record. One is that during that period of Earth's history not only was the first continental crust forming, it was also being vigorously recycled and regenerated. A second is that the Moon, and by inference the Earth, was subjected to intense bombardment of large meteorites from the time of its initial formation to about 3.8 billion years ago. This bombardment occurred because the planets were still sweeping up material in their orbital paths. A third explanation may be that the record of Earth's early history exists but simply has not yet been found. The correct reason for the lack of data may well be some combination of the above. Whatever the reasons, if we are to learn more about Earth's history prior to 3.8 billion years ago, we must examine the evidence obtained from other, older sources, particularly the meteorites and the Moon.

THE AGES OF METEORITES

There are two basic types of meteorites, stones and irons; other types are intermediate in composition between the two. Stone meteorites are composed primarily of the silicate minerals olivine and pyroxene, while iron meteorites consist primarily of nickel-iron alloy. Stones frequently contain small amounts of nickel-iron, and irons often include small amounts of silicate minerals. Once thought to be the remains of a shattered planet, meteorites probably originated from some 20 to 70 different parent bodies the size of large asteroids. Some of the meteorites are samples of parent bodies that were apparently large enough to undergo partial melting and differentiation that produced different rock types. Others, primarily the stones called chondrites, seem to represent rocks essentially unchanged since condensation from the solar nebula. The orbits of meteorites show that they are part of the solar system, probably samples of the asteroids, and thus their age is relevant to the age of the earth.

Like most things in nature, meteorites are not simple objects. This is especially true of those that have undergone differentiation, heating, and collisions with other bodies in space. In order to determine the age of the solar system and the Earth, we must search for the oldest, least-disturbed meteorites.

A histogram of K-Ar ages of some stone meteorites is shown in Figure 11. There are now many more data than shown in the figure, but the general distribution of ages has not changed appreciably. The ages range from about 400 million years to nearly 5 billion years, with a large concentration at 4.4 to 4.6 billion years. The younger ages reflect heating and collision events, to which the K-Ar method is particularly susceptible, while the older ages record events near and equal to the time of meteorite formation. Many meteorites have now been dated by the $^{40}Ar/^{39}Ar$ age-spectrum method. This method confirms the general distribution of ages shown in the figure and also shows that many of the

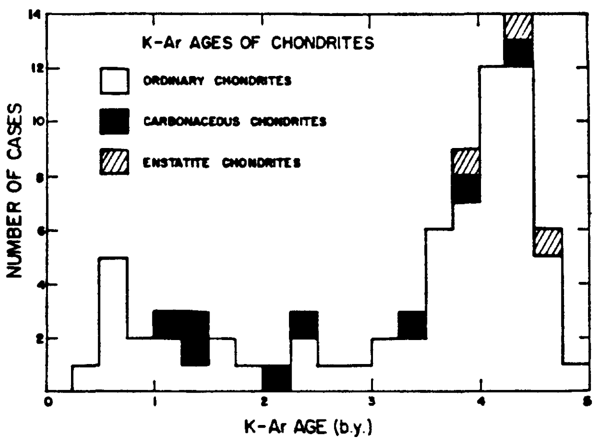

Figure 11. K-Ar ages of some stone meteorites. The oldest meteorites have ages near the age of the solar system. After Anders (1963) and York and Farquhar (1972).

meteorites were heated subsequent to their formation. The metal phases in iron meteorites cannot be reliably dated with the K-Ar method because of the nearly negligible potassium content and cosmic ray effects. However, silicate inclusions in several iron meteorites have been dated by K-Ar at 4.5 ± 0.2 billion years (Bogard and others, 1968).

Some of the most precise ages for meteorites have been obtained by the Rb-Sr isochron method. Some of the ages, from a summary by Faure (1977) are given in Table 3. The isochron for the meteorite Juvinas is shown in Figure 7. Some iron meteorites with small silicate inclusions have also been dated by the Rb-Sr isochron method, and the results show that the least-disturbed irons are the same age (4.6 billion years) as the least-disturbed stones.

Meteorites have also been dated by the Sm-Nd isochron method. Jacobsen and Wasserburg (1980), for example, have shown that 10 chondrites and the achondrite Juvinas all fall on an isochron with an age of 4.60 billion years.

The results of radiometric dating on meteorites clearly show that these objects formed about 4.6 billion years ago. Since astrophysical considerations require that the formation of the planets and meteorites by condensation from the solar nebula was essentially simultaneous, we can infer with considerable certainty that the age of the most primitive meteorites also is the age of formation of the Earth. Even if we wished to deny this inference, we would still be forced to conclude that meteorites, which must at least post-date the formation of the solar system and the universe, are 4.6 billion years old.

Table 3. Summary of some Rb-Sr isochron ages of meteorites. From a compilation by Faure (1977).

Material	Method	Age (billion years)
Juvinas (achondrite)	Mineral isochron	4.60 ± 0.07
Allende (carbonaceous chondrite)	Mixed isochron	4.5-4.7
Colomera (silicate inclusion, iron meteorite)	Mineral isochron	4.61 ± 0.04
Enstatite chondrites	Whole-rock isochron	4.54 ± 0.13
Enstatite chondrites	Mineral isochron	4.56 ± 0.15
Carbonaceous chondrites	Whole-rock isochron	4.69 ± 0.14
Amphoterite chondrites	Whole-rock isochron	4.56 ± 0.15
Bronzite chondrites	Whole-rock isochron	4.69 ± 0.14
Hypersthene chondrites	Whole-rock isochron	4.48 ± 0.14
Krähenberg (amphoterite)	Mineral isochron	4.70 ± 0.01
Norton County (achondrite)	Mineral isochron	4.7 ± 0.1

Note: All ages are based on a value of $1.39 \times 10^{-11} y^{-1}$ for the decay constant of ^{87}Rb. The current value of 1.42×10^{-11} yr^{-1} has the effect of lowering the ages slightly.

MODEL LEAD AGE OF METEORITES AND THE EARTH

The generally accepted age of the Earth is based on a simple but elegant model for the evolution of lead isotopes. This model was developed independently by Houtermans (1946) and Holmes (1946) and first applied to meteorites and the Earth by Clair Patterson, now of the California Institute of Technology, in 1953. In a classic paper, Patterson (1956) reasoned that if the isotopic composition of lead was uniform in the planetary bodies and meteorites at the time of formation, and if these bodies contained differing amounts of uranium, then the lead isotopic composition of these bodies should lie on a straight line isochron when the ratio $^{207}Pb/^{204}Pb$ is plotted against $^{206}Pb/^{204}Pb$ (Fig. 12). The lower end of the isochron in the figure represents the lead composition in a phase of iron meteorites (troilite, or iron sulfide) that contains no uranium. This point represents the initial lead composition of the solar system.

The lead compositions of iron meteorites and the lead compositions of stone meteorites form an isochron with an age of 4.55 billion years (Fig. 12). Note that this method, like the other isochron methods, is self-checking. Modern Earth leads, as represented by the lead composition in some very young, non-uranium-bearing minerals, also fall close to the meteoritic isochron[12], which is what we would expect if the Earth and meteorites formed at the same time. The leads in lunar rocks have much higher values than those in terrestrial rocks and meteorites. They fall out of the field of Figure 12, but they do lie very close to the extension of the meteoritic isochron, and therefore have a similar age.

----

[12] While modern Earth leads lie near the meteoritic isochron, many do not lie exactly on it. This evidently is because many have had complex, or multi-stage histories (for example, Stacey and Kramers, 1975).

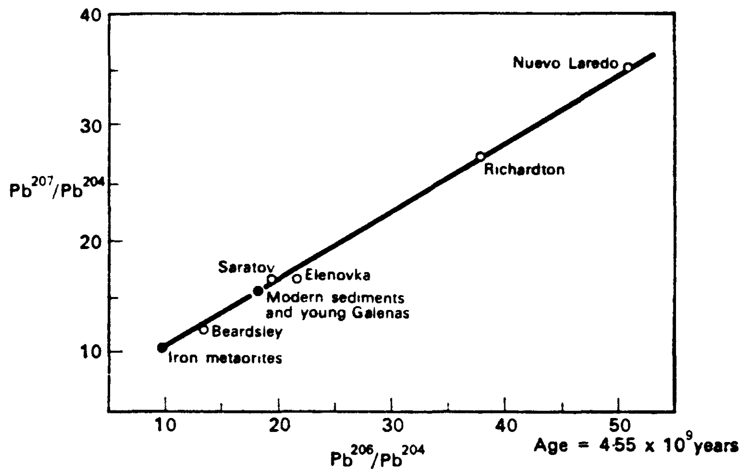

Figure 12. Meteoritic lead isotope isochron showing that the age of meteorites and the Earth is about 4.55 b.y. After Murthy and Patterson (1962) and York and Farquhar (1972).

If the Earth, Moon, and meteorites were not genetically related and the same age, there would be no reason for their lead compositions to lie along the same isochron. This is convincing evidence that the planetary bodies, including the Earth, all formed about 4.55 billion years ago. It is interesting to note that Patterson's original estimate of the age of the Earth has changed very little over the past three decades. In a recent reevaluation Tera (1980) concluded that the age of the Earth was about 4.54 billion years. Tera also summarized several other lead models for the Earth's age; they all fall within the range 4.43 to 4.59 billion years. Thus, while there is still some debate about the exact age of the Earth and solar system, scientists are quibbling only about the first one or two tenths of a billion years. The age of the Earth is known to within about one part in 45, or about two percent.

AGES OF LUNAR ROCKS

The Apollo missions for the first time gave scientists the exciting opportunity to study samples from another planet. While all samples give important information about the history of the Moon, for data on the age of formation of the Moon we must again look at the oldest rocks.

The surface of the Moon can be divided into the lunar highlands and the lunar maria. The highlands are mountainous upland areas that still preserve some aspects of the original impact morphology of the earliest Moon. The maria, or "seas", are younger, lowland areas that were flooded by lava after impact by asteroid-size bodies. The Apollo missions returned samples from both highlands and maria.

Because of the severe impact history of the early Moon and the consequent heating and metamorphism of lunar samples, the conventional K-Ar method is not very useful in the study of lunar rock formation as it tends to record the latest heating and impact events rather than original rock ages. The ages of lunar rocks are known primarily from $^{40}Ar/^{39}Ar$ age-spectrum and Rb-Sr isochron dating. Some of these ages are shown in Table 4. As can be seen from the table, the rocks from each landing site give similar ages by both methods, which cannot be a coincidence but must reflect the true ages of the rocks within the analytical uncertainties. This table, however, presents only data prior to 1974, and since that time older rocks have been analyzed.

Figure 13 is a histogram of 138 $^{40}Ar/^{39}Ar$ age-spectrum ages of highland rocks. There is a strong mode at about 4.0 billion years and the ages range nearly to 4.5 billion years. The oldest ages, however, have been measured by the Rb/Sr isochron method on samples from the Apollo 17 site. These include mineral isochron ages of 4.55 $\pm$ 0.1 billion years, 4.60 $\pm$ 0.1 billion years, 4.49 billion years, and 4.43 $\pm$ 0.05 billion years for four different rock types. In addition, $^{40}Ar/^{39}Ar$ age spectrum analyses from the Apollo 16 site have now shown two rocks with ages of 4.47 and 4.42 billion years (see summary by Kirsten, 1979), and Sm-Nd isochron ages of 4.23 $\pm$ 0.05 billion years and 4.34 $\pm$ 0.05 billion years have been found for two Apollo 17 samples (Carlson and Lugmair, 1981).

Radiometric ages on lunar rocks and model lead ages on meteorites, Earth, and Moon, show that the initial formation of the Moon took place 4.5 to 4.6 billion years ago. There are, to be sure, some uncertainties about the exact chronology and events that led to the Moon we now see, but there is little doubt about when the Moon formed or about the age of the major volcanic events that produced the igneous rocks at the various Apollo sites. Kofahl and Segraves (1975) have claimed that the age of the Moon is

TABLE 4: Summary of some radiometric ages of lunar basalts. From compilation by Head (1976)

Location	Age billion years	Rock Type	Sample Number	Method
Apollo 14 - highlands	3.96	Al basalt	14053	Rb-Sr
	3.95	Al basalt	14053	^{40}Ar-^{39}Ar
	3.95	Al basalt	14321	Rb-Sr
Apollo 17 - highlands	3.83	High-Ti basalt	75055	Rb-Sr
	3.82	High-Ti basalt	70035	Rb-Sr
	3.76	High-Ti basalt	75055	^{40}Ar-^{39}Ar
	3.74	High-Ti basalt	75083	^{40}Ar-^{39}Ar
Apollo 11- mare	3.82	Low-K basalt	10062	^{40}Ar-^{39}Ar
	3.71	Low-K basalt	10044	Rb-Sr
	3.63	Low-K basalt	10058	Rb-Sr
	3.68	High-K basalt	10071	Rb-Sr
	3.63	High-K basalt	10057	Rb-Sr
	3.61	High-K basalt	10024	Rb-Sr
	3.59	High-K basalt	10017	Rb-Sr
	3.56	High-K basalt	10022	^{40}Ar-^{39}Ar
Luna 16 - highlands	3.45	Al basalt	B-1	^{40}Ar-^{39}Ar
	3.42	Al basalt	B-1	Rb-Sr
Apollo 15 - highlands	3.44	Quartz basalt	15682	Rb-Sr
	3.40	Quartz basalt	15085	Rb-Sr
	3.35	Quartz basalt	15117	Rb-Sr
	3.33	Quartz basalt	15076	Rb-Sr
	3.32	Olivine basalt	15555	Rb-Sr
	3.31	Olivine basalt	15555	^{40}Ar-^{39}Ar
	3.26	Quartz basalt	15065	Rb-Sr
Apollo 12 - mare	3.36	Olivine basalt	12002	Rb-Sr
	3.30	Olivine basalt	12063	Rb-Sr
	3.30	Olivine basalt	12040	Rb-Sr
	3.27	Quartz basalt	12051	^{40}Ar-^{39}Ar
	3.26	Quartz basalt	12051	Rb-Sr
	3.24	Olivine basalt	12002	^{40}Ar-^{39}Ar
	3.24	Quartz basalt	12065	^{40}Ar-^{39}Ar
	3.18	Quartz basalt	12064	Rb-Sr
	3.16	Quartz basalt	12065	Rb-Sr

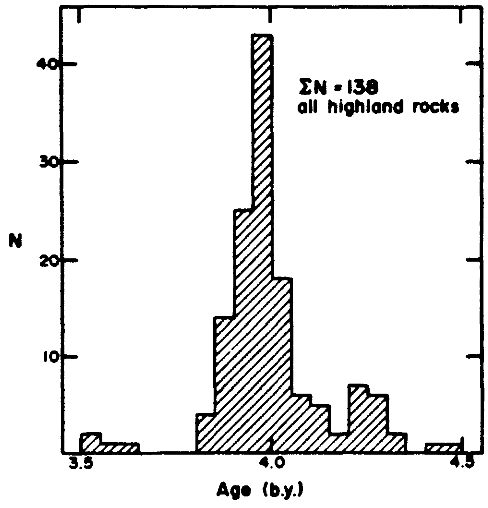

Figure 13. Histogram of $^{40}Ar/^{39}Ar$ ages on rocks from the lunar highlands. From Kirsten (1979).

not known.

> "As one reads the research reports and the lunar conference reports concerning moon rocks, the impression is gained that the collection of a great mass of facts has resulted in the raising of more questions than have been answered. It would seem that one unanswered question is the age of the moon."
>
> (Kofahl and Segraves, 1975, p.203)

Although some of the details of early lunar chronology are still uncertain, the uncertainty in the age of the Moon is at most about two percent and the doubts expressed by Kofahl and Segraves need not be taken seriously.

Finally, a brief word about the Moon rocks and the origin of the Moon. Morris (1974, p.31) makes the following statement:

> "Finally, the moon landings have permitted man actually to study the composition and structure of the materials from at least one extra-terrestrial body. Enough has been found now to permit the firm conclusion that the earth and its moon are of vastly different structure and therefore could not have the same celestial evolutionary 'ancestor'. 'To the surprise of scientists, the chemical makeup of the moon rocks is distinctly different from that of rocks on earth. This difference implies that the moon formed under different conditions,...and means that any theory on the origin of the planets now will have to create the earth and the moon in different ways.'[1]
> This is an extremely important scientific discovery and by all means should be emphasized in the classroom. The moon and the earth have different structures and therefore different origins!"

The footnote reference is to an article by Bishop (1972).

In the first place, the similarities between Moon rocks and Earth rocks are much greater than the differences. Most igneous Moon rocks are basalt, which is a volcanic rock that is also the most common rock in the Earth's crust. Basalt makes up the sea floors and the Hawaiian Islands, for example. The other types of Moon rocks also have terrestrial counterparts. There are some interesting chemical differences between

Earth rocks and Moon rocks, but these differences are simply in some of the detailed proportions of the major and minor elements.

In the second place, scientists did not expect the Earth and the Moon to be exactly alike. They are different planets, of different size, and condensed from the solar nebula as individual bodies. The conclusion by Morris that because there are differences the two could not have originated from the same celestial ancestor is illogical and wrong. Condensation of the various bodies from the solar nebula would be expected to produce considerable differences between the Sun and the planets, as indeed there are.

I was in the Lunar Receiving Laboratory when the first box of rocks returned by the Apollo 11 mission was opened and the rocks examined. My colleagues and I were amazed, not because the rocks were greatly different than we expected them to be, but because there before us were the first samples collected from another planet. I do not recall anyone being surprised that the lunar rocks were basalts. On the contrary, we were all delighted, for basalts were what we had predicted them to be.

DISCUSSION OF SOME NON-CLOCKS

Decay of the Earth's Magnetic Field

Barnes (1973) has claimed to have proved that the Earth can be no more than 10,000 years old.

> "Applying the reasonable premise that this planet never had a magnetic field as great as that of a magnetic star, one can note from Table 2 that the origin of the earth's magnetic field had to be more recent than 8000 B.C. That is to say, the origin of the earth's magnetic field was less than 10,000 years ago. Just how much more recent than 10,000 years cannot be determined from present scientific knowledge. If one assumes that the initial value

of the earth's magnetic field were about an order-of-magnitude less than that of a magnetic star the origin would have been about six or seven thousand years ago"

(Barnes, 1973, p.25)

Similar statements are made by Morris (1974), Slusher (1973), and Kofahl and Segraves (1975), who cite Barnes as their source.

Barnes' argument goes like this. The strength of the Earth's dipole moment has been decreasing linearly since magnetic field measurements were begun in the early 1800s. The decrease amounts to about 7 percent between 1835 and 1965. Following a hypothesis he erroneously attributes to Sir Horace Lamb, Barnes claims that the magnetic field has been decaying exponentially since the creation of the Earth and calculates that the half-life of the decay is 1400 years. He then extrapolates the decay of the field backward in time until he arrives at the value of a magnetic star, and uses that time (8000 B.C.) to arrive at an upper limit for the age of the Earth. Barnes' elegant calculations and his conclusions are flawed by false initial assumptions and an overly simplified view of magnetic field behavior.

To a first approximation, the Earth's field is that of a dipole[13] with the lines of flux emerging at the poles. On the average, over periods of 100,000 to 1,000,000 years, the magnetic poles coincide with the Earth's rotational poles. The magnetic poles slowly move, however, and at any given time the magnetic poles usually differ from the rotational poles by several degrees. Today, for example, the north magnetic pole is located not at the north geographic pole, but at latitude 77.3° N., longitude 101.8° W. In 1831, when Commander James C. Ross found and claimed the north magnetic pole for Great Britain, the pole was located at 70.1° N.,

----

[13] A dipole is simply a magnet with one north and one south pole. A simple bar magnet is one type of dipole.

96.8° W. Thus the north magnetic pole has moved about 800 kilometers in the past 150 years.

The shape of the dipole field is not ideal, but is highly distorted by irregularities superimposed on the dipole field. These irregularities, collectively called the non-dipole field, are thought to be caused by eddy currents in the liquid core at the Earth's core/mantle boundary. Like the dipole field, the non-dipole field is slowly and constantly changing. The combination of dipole and non-dipole field motion is called secular variation and is the reason that a compass does not point exactly north. The Earth's field we actually observe at any spot on the Earth is the sum of the dipole and the non-dipole fields.

As if this strange behavior were not complicated enough, the earth's dipole field does other remarkable things. For example, it occassionally reverses polarity so that the north pole becomes the south pole and vice versa (Cox and others, 1967). Paleomagnetic measurements on lava flows have shown that these polarity reversals have occurred at irregular but frequent intervals (Fig. 14). The field also changes intensity or strength, but not in the way Barnes claims.

A careful analysis of the Earth's field by McDonald and Gunst (1968) showed that the decrease in the dipole moment over the past 50 years has been balanced by a corresponding increase in the non-dipole component of the field, so that the total energy of the field external to Earth's core has been constant. Over the past 120 years, the non-dipole energy increase has not been quite sufficient to balance the dipole decrease, so the total energy appears to have been decreasing at an average annual rate of about 0.01 percent (Verosub and Cox, 1971), which is much less than the figure used by Barnes. Is this short-term decrease permanent as Barnes claims?

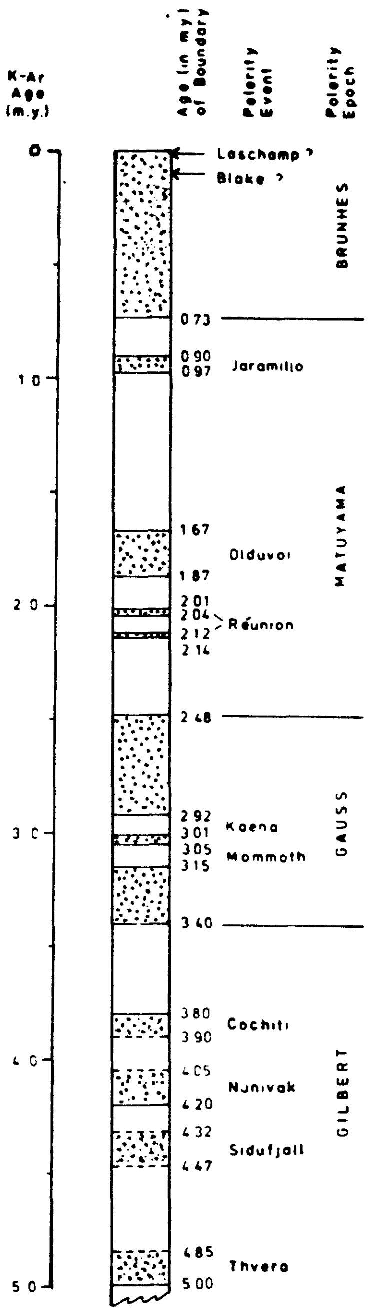

Figure 14. Geomagnetic reversal time scale for the late Cenozoic. Shaded areas indicate normal polarity, unshaded reversed polarity. The scale was determined by K-Ar dating of subaerial lava flows and confirmed by studies on deep-sea cores and sea floor magnetic anomalies. After Mankinen and Dalrymple (1979). The ages are based on the new IUGS constants.

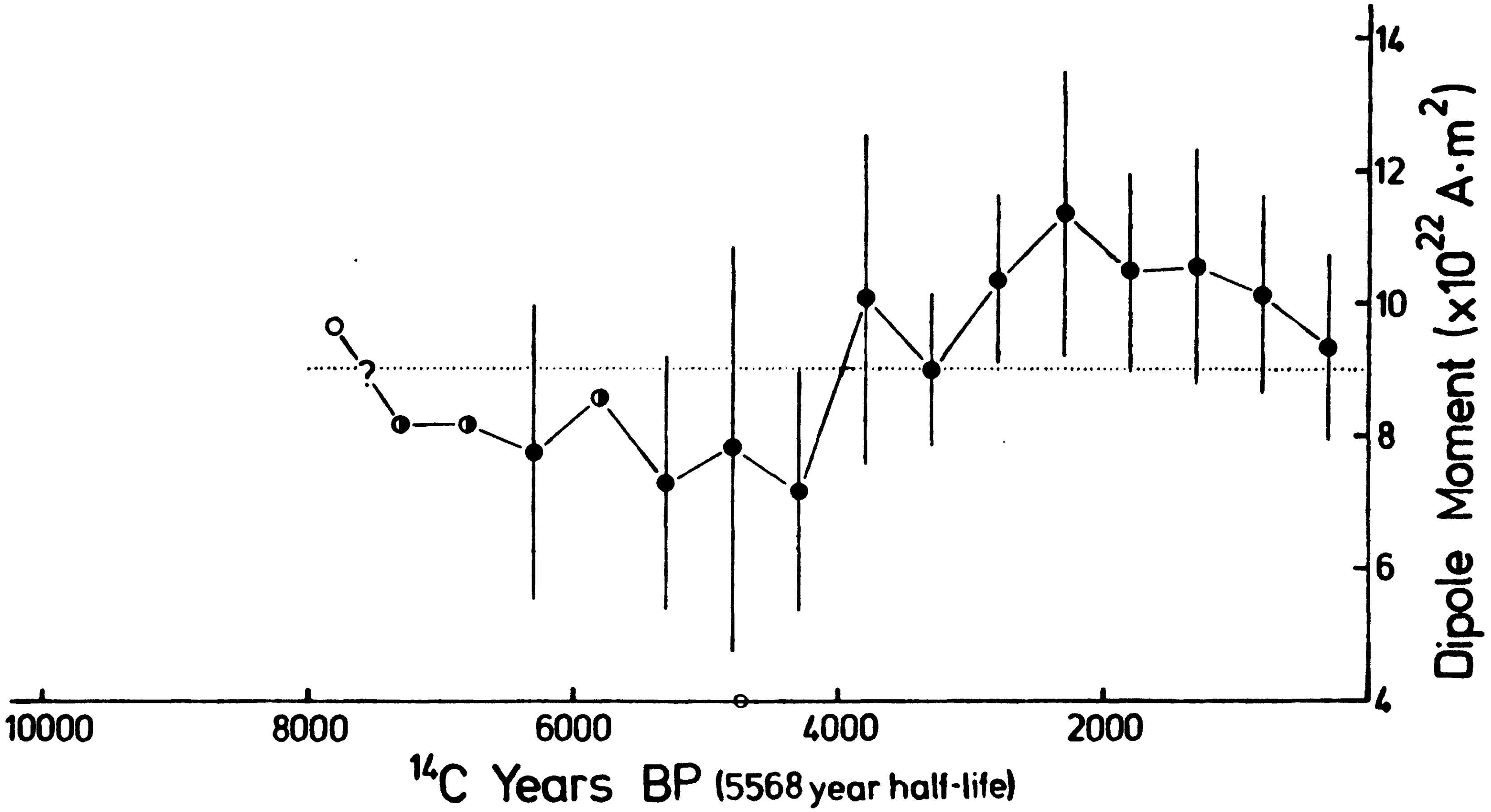

Figure 15. Geomagnetic dipole moment estimated from 500-year global averages. Vertical lines indicate an interval of ± 1 standard deviation. Filled circles indicate three or more regions of the earth included in the average. Half-filled circles indicate two regions included in the average, and open circles indicate data from a single region. Dotted line is the average of all data. From Champion (1980).

No. There is conclusive evidence, for example, that the Earth's field temporarily decays during polarity reversals, which have been frequent during geologic history. Paleomagnetic measurements of the magnetic record in rocks have shown that the Earth's dipole moment over the past 8000 years or so has not been continually decaying, but instead has been fluctuating (Fig. 15). How much of this fluctuation is balanced by the non-dipole field and how much is a fluctuation in the total magnetic field energy is not known, but it is clear that the field does not behave as Barnes claims.

The magnetic record in rocks also shows that the Earth's field during Precambrian time was within about 50 percent or so of its present strength (McElhinny, 1973). These observations are consistent with theoretical considerations, showing that the Earth's field is probably generated by a self-exciting, fluid dynamo in the Earth's liquid-metal core, with the necessary energy coming from either radioactive heat within the Earth, from gravitational energy, or both. Some time in the far-distant future, the magnetic field of the Earth may begin to decrease permanently as the Earth's available energy is used up, but the Earth is not quite ready to give up her field just yet.

The Earth cannot be dated by its magnetic field, and Barnes' calculations are meaningless, as is his maximum age for the Earth.

Cooling of the Earth

Barnes (1974) summarizes and supports the arguments developed first in 1862 by Sir William Thomson (Lord Kelvin), who calculated that the Earth could be no less than 20 million and no more than 400 million years old (Thomson, 1862b). Kelvin's calculations were based on the presumption that the Earth was cooling from an initial white-hot molten state, and his calculations determined how long it would take for the observed geothermal gradient to reach its present configuration. Kelvin also calculated that the Sun was probably no more than 100 million years old, and almost certainly no more than 500 million years old (Thomson, 1862a). These upper limits for the age of the Sun were based on his estimate of the available supply of gravitational energy, which, he concluded, would not last many millions of years longer. Nuclear reactions, which we now know are responsible for the Sun's fires, were unknown in Kelvin's time.

Kelvin and several noted geologists feuded over the age of the Earth for more than 35 years, because the geologists, basing their estimates on the rates of observable processes, felt strongly that Kelvin's estimates were much too low. The feud came to a culmination in 1899 when Science published an address by Lord Kelvin to the Victoria Institute titled "The Age of the Earth as an Abode Fitted for Life" (Kelvin, 1899). In this address, Kelvin renewed his attack on the geologists' concept of the length of geologic time, and cited an upper limit of 24 million years, calculated by the geologist Clarence King[14] (1893). The same year, the American geologist T. C. Chamberlin replied to Kelvin's address, and criticized Kelvin thus:

> "The facinating impressiveness of rigorous mathematical analysis, with its atmosphere of precision of elegance, should not blind us to the defects of the premises that condition the whole process. There is, perhaps, no beguilement more insidious and dangerous than an elaborate and elegant mathematical process built upon unfortified premises"
>
> (Chamberlin, 1899, p.890)

----

[14] Barnes (1974) errs when he attributes the 24 million year figure to Kelvin. Kelvin agreed with the number, but King first published this particular calculation. King was the first Director of the United States Geological Survey.

Chamberlin atttacked Kelvin's assumption of a white-hot liquid Earth, which Kelvin had described as a "very sure assumption", by adding:

> "I beg leave to challenge the certitude of this assumption of a white-hot liquid earth, current as it is among geologists alike with astronomers and physicists. Though but an understudent of physics, I venture to challenge it on the basis of physical laws and physical antecedents"

Chamberlin then showed that Kelvin's assumptions were not necessarily so certain, and noted that Kelvin's model took no account of the "latent and occluded energies of an atomic or ultra-atomic nature". This last statement was especially prophetic, for although the phenomenon of radioactivity had been discovered by Henri Becquerel three years earlier, the nature of radioactivity, the isolation of radium, the measurements of the amount of energy released in radioactive transmutations, the discovery of isotopes, and a realistic atomic theory were all in the future.

The dispute between Kelvin and the geologists was resolved in 1903 when Rutherford and Soddy (1903) first determined the amount of heat generated by radioactive decay. Rutherford and Soddy readily appreciated the significance of their discovery for cosmological hypotheses.

> "It [the energy from radioactive decay] must be taken into account in cosmical physics. The maintenance of solar energy, for example, no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, i.e., if processes of sub-atomic change are going on."
>
> (Rutherford and Soddy, 1903, p.591)

Subsequent measurements of the amount of radioactive uranium, thorium, and potassium in the Earth and in meteorites have shown that all of the heat flowing from the interior of the Earth outward can easily be accounted for by radioactive decay.

Barnes (1974, p.3), in championing Kelvin's calculations[15], states:

> "Some scientists claim that radioactivity in the earth would alter this limit upward, but none has given any clear analysis of how much it would alter Kelvin's value. Kelvin was well aware of radioactivity, as is demonstrated by the fact that he wrote several papers on it. That did not appear to him to alter the problem at all. He was working from an actual measured thermal flux gradient and a knowledge of thermal conductivity of the crustal rocks and was still confident that he had shown that the earth's age does not exceed 24 million years."

The first statement is simply untrue. There is a considerable literature on the subject of the thermal state and history of the Earth. Most beginning geology textbooks treat the subject. The remainder of Barnes' paragraph also is wrong. Kelvin's last published remarks on the age of the Earth from his cooling calculations were in 1899, four years before Rutherford and Soddy published their findings of the energy available from radioactive decay. While it is true that Kelvin published several papers on radioactivity, these papers were unrelated to his age of the Earth calculations. Barnes implies that Kelvin considered the matter and concluded that it was unimportant. In fact, Kelvin privately admitted that his hypothesis regarding the age of the Earth had been disproved by the discovery of the enormous amount of energy available from within the atom (Burchfield, 1975), although he never recanted. Kelvin apparently realized that he had lost the argument and simply gave up, turning his energies to other matters until his death in 1907.

----

[15] It is curious that Barnes endorses Kelvin's calculations and conclusions so enthusiastically. Kelvin thought that the Earth was millions of years old.

The pre-twentieth century history of the various attempts by scientists and philosphers to estimate the age of the Earth is a facinating subject that readers may wish to explore in more detail (Faul, 1978; Albritton, 1981). Probably no estimate caused more controversy than Kelvin's, and his role in this debate, which lasted for nearly half a century, is the subject of a recent monograph (Burchfield, 1975).

Kelvin's calculations are interesting from a historical point of view, but for nearly all of this century they have been known to be wrong.

Other Non-Methods

Morris (1974, 1977), Barnes (1974), Kofahl and Segraves (1975), and Nevins (1973) discuss a variety of "age of the Earth" calculations that give greatly inconsistent results. Morris (1977) presents a list of 70 such "ages". The methods range from the time to accumulate the sediments now in the ocean basins of the world (30 million years), through the influx of meteoritic dust from space (too small to measure) and the influx of magma from the mantle to form crust (500 million years), to the influx of aluminum into the oceans (100 years). From these various values, Morris concludes:

> "The most obvious characteristic of the values listed in the table is their extreme variability--all the way from 100 years to 500,000,000 years. This variability, of course, simply reflects the errors in the fundamental uniformitarian assumptions. Nevertheless, all things considered, it seems that those ages on the low end of the spectrum are likely to be more accurate than those on the high end. This conclusion follows from the obvious fact that: (1) they are less likely to have been affected by initial concentrations or positions other than "zero"; (2) the assumption that the system was a "closed system" is more likely to be valid for a short time than for a long time; (3) the assumption that the process rate was

constant is also more likely to be valid for a short time than for a long time. Thus, it is concluded that the weight of all the scientific evidence favors the view that the earth is quite young, far too young for life and man to have arisen by an evolutionary process. The origin of all things by special creation--already necessitated by many other scientific considerations-- is therefore also indicated by chronometric data"

(Morris, 1977, p.53-54)

The problem with these 70 "ages" of the Earth is that they are all based on either false initial assumptions or have too many unknown variables for a reliable solution, or both. Nearly all of these methods have been aired in the scientific literature and found so worthless that scientists do not use them for determining the age of the Earth.

An inspection of the reference list provided by Morris (1977) shows that most of the calculations were done and published by Morris and his colleagues. Those that are attributed to scientific journals most often do not appear there. For example, Morris lists, as number 33, an "indicated age of Earth" of 100,000 years from "formation of carbon-14 on meteorites". He references a paper by Boeckl (1972). Boeckl's paper, however, was about tektites[16], not meteorites, and he was attempting to establish a cosmic ray exposure age for these objects. To do so, he assumed a terrestrial age for the tektites of 10,000 years in order to do his calculations. Boeckl did not calculate an age for the Earth, nor did he produce any data that can be used to do so. Morris (1977) even has the number wrong.

As another example, consider Morris' (1977) number 43, "accumulation of calcareous ooze on sea floor". He lists an "indicated age of earth" of

----

16 Tektites are small globules of glass whose origin has been the subject of much debate, but is now thought to be due to meteoritic impact on the Earth.

----

5 million years, and references a paper by Ewing and others (1964)[17]. The paper by Ewing and his colleagues describes a study of the sediment distribution on the mid-Atlantic Ridge. They found that the sediment there was quite thin and concluded that at the present rate of sedimentation, the sediment could have accumulated in about 2 to 5 million years. This short time was puzzling to them because the ocean basins were then thought to be very old -- their paper was published before the theory of plate tectonics and sea-floor spreading was formulated, tested, and confirmed. We now know that the mid-ocean ridges are very young and still active. In fact, their age is zero at the ridge crests. The 2 to 5 million years calculated by Ewing and his co-workers is about right for the part of the ridge surveyed by them. Note that Ewing and his colleagues did not calculate an age for the Earth nor did they produce or describe any data with which such a calculation can be made.

These "age of the Earth" calculations summarized and discussed by Morris (1974, 1977), Kofahl and Segraves (1975), Barnes (1974), and Nevins (1973) are red herrings. None of the 70 methods listed by Morris (1974) can be used to calculate an age for the Earth and the values are worthless. Neither can these values be used to discredit the legitimate age of the Earth found by radiometric methods.

CONCLUSIONS

Radiometric dating methods provide a reliable means of determining the ages of critical points in geologic and planetary history, including the

----

[17] Morris cites the Bulletin of the Geophysical Society of America, but there is no such organization. It is The Geological Society of America.)

----

age of the Earth, the Moon, the meteorites, and the solar system. That the age of the Earth is about 4.5 to 4.6 billion years is virtually beyond question, as it is supported by a variety of independently determined scientific evidence. Scientists are continually refining this age, but it is highly unlikely that it will change in the future by more than a percent or two. In the past, the age of the Earth has been the subject of much dispute, but the past few decades has seen the development of new techniques not previously available. There is virtually no dispute among knowledgeable scientists about the antiquity of the Earth and her sister planets.

Radiometric dating has independently confirmed and quantified the various geologic and paleontologic time scales (Fig. 1, Table 2, for example). These time scales originally were constructed on the basis of stratigraphic and faunal succession before the development of modern isotopic dating techniques. Radiometric dating has allowed scientists to assign ages and to establish the lengths of the various eras, periods, epochs, and fossil ages, but the relative order of these geologic time units, as determined over the past two centuries by stratigraphers and paleontologists without the benefit of isotopic dating, has remained unchanged. This is powerful proof that both the dating techniques and the paleontologic and stratigraphic principles on which the time scales were originally based are sound.

The geologic corollaries of "scientific" creationism---namely, that the Earth is no more than 10,000 years old and that the sedimentary rocks of the geologic column were deposited within about a year during a worldwide flood 7000 years ago---are demonstrably wrong. There is no scientific evidence to support these tenets and no scientific grounds for seriously considering "scientific" creationism, as described by Morris

(1974, 1977), and by Kofahl and Segraves (1975), as a valid scientific theory. There is conclusive scientific evidence that the Earth was formed 4.5 to 4.6 billion years ago along with the rest of the planets of the solar system. There is also no doubt that the rocks now exposed on the surface of the Earth or accessible to scientists by drilling were deposited and emplaced over the geologic epochs starting in the earliest Precambrian more than 3.8 billion years ago. To accept, or even take seriously the tenets of "scientific" creationism requires the total abandonment of the results of two centuries of scientific investigations and of the principles of objectivity and rationality that are fundamental to science.

REFERENCES

Albritton, C. C. Jr., 1980, The Abyss of Time: San Francisco, Freeman, Cooper & Co., 251 pp.

Aldrich, L. T., and Wetherill, G. W., 1958, Geochronology by radioactive decay: Ann. Rev. Nuclear Sci., v. 8, p. 257-298.

Allegre, C. J., Birek, J. L., Fourcade, S., and Semet, M. P., 1975, Rubidium-87/Strontium-87 age of Juvinas basaltic achondrite and early igneous activity in the solar system: Science, v. 187, p. 436-438.

Anders, E., 1963, The Moon, Meteorites and Comets: The Solar System, Vol. 4, Chicago, Univ. of Chicago Press.

Baadsgard, H., 1973, U-Th-Pb dates on zircons from the early Precambrian Amitsoq gneisses, Godthaab District, West Greenland: Earth Planet. Sci. Lett., v. 19, p. 22-28.

Barnes, T. G., 1973, Origin and Destiny of the earth's magnetic field: Inst. Creation Res. Tech. Monograph No. 4, 64 pp.

Barnes, T. G., 1974, Physics: A challenge to "geologic time": ICR Impact Series, No. 16, 4 p.

Barton, J. M., Jr., Ryan, B., and Fripp, R. E. P., 1978, The relationship between Rb-Sr and U-Th-Pb whole-rock and zircon systems in the >3790 m.y. old Sand River Gneisses, Limpopo mobile belt, Southern Africa, in Zartman, R. E., ed., Short Papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology: U.S. Geol. Survey Open-file Report 78-701, 476 pp.

Basu, A. R., Ray, S. L., Saha, A. K., and Sarkar, S. N., 1981, 3.8 b.y.-old tonalites from eastern India: evidence for early differentiation (abs): EOS, v. 62, p. 420.

Bishop, J. E., 1972, New theories of Creation: Science Digest, v. 42, p. 42.

Boeckl, R. S., 1972, Search for carbon 14 in tektites: Jour. Geophys. Res., v. 77, p. 367-377.

Bogard, D., Burnett, D., Eberhardt, P., and Wasserburg, G. J., 1968, ^{40}Ar-^{40}K ages of silicate inclusions in iron meteorites: Earth Planet. Sci. Lett., v. 3, p. 275-283.

Boltwood, B. B., 1907, On the ultimate disintegration products of the radio-active elements, Part II. The disintegration products of uranium: Am. Jour. Sci., ser. 4, v. 23, p. 77-88.

Brereton, N. R., 1970, Corrections for interfering isotopes in the $^{40}Ar/^{39}Ar$ dating method: Earth Planet. Sci. Lett., v. 8, p. 427-433.

Burchfield, J. D., 1975, Lord Kelvin and the Age of the Earth: New York, Science History Publications, 260 pp.

Carlson, R. W., and Lugmair, G. W., 1981, Time and duration of lunar highlands crust formation: Earth Planet. Sci. Lett. v. 52, p. 227-238.

Chamberlin, T. C., 1899, Lord Kelvin's address on the age of the earth as an abode fitted for life: Part I: Science, new ser., v. 9, p. 889-901; Part II: Science, new ser., v. 10, p. 11-18.

Champion, D. E., 1980, Holocene geomagnetic secular variation in the western United States: Implications for the global geomagnetic field: Ph.D. thesis, California Inst. Tech., 314 p.

Cook, M. A., 1966, Prehistory and Earth Models: London, Max Parrish and Co. Ltd., 353 pp.

Cook, M. A., 1968, Do radiological "clocks" need repair?: Creat. Res. Soc. Quart., v. 5, p. 69-77.

Cox, A., Dalrymple, G. B., and Doell, R. R., 1967, Reversals of the earth's magnetic field: Sci. Amer., v. 216, no. 2, p. 44-54.

Dalrymple, G. B., 1969, $^{40}Ar/^{36}Ar$ analyses of historic lava flows: Earth Planet. Sci. Lett. v. 6, p. 47-55.

Dalrymple, G. B., Alexander, E. C., Jr., Lanphere, M. A., and Kraker, G. P., 1981a, Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA reactor: U.S. Geol. Survey Prof. Paper 1176, 55 p..

Dalrymple, G. B., Clague, D. A., Garcia, M. O., and Bright, S. W., 1981b, Petrology and K-Ar ages of dredged samples from Laysan Island and Northampton Bank volcanoes, Hawaiian Ridge, and evolution of the Hawaiian-Emperor chain: Geol. Soc. America Bull., in press.

Dalrymple, G. B., Gromme, C. S., and White, R. W., 1975, Potassium-argon age and paleomagnetism of diabase dikes in Liberia: initiation of central Atlantic rifting: Geol. Soc. America Bull. v. 86, p. 399-411.

Dalrymple, G. B., and Lanphere, M. A., 1969, Potassium-Argon Dating: Principles, Techniques, and Applications to Geochronology: San Francisco, W. H. Freeman and Co., 258 pp.

Dalrymple, G. B., and Lanphere, M. A., 1971, $^{40}Ar/^{39}Ar$ technique of K-Ar dating: A comparison with the conventional technique: Earth Planet. Sci. Lett., v. 12, p. 300-308.

Dalrymple, G. B., Lanphere, M. A., and Clague, D. A., 1980, Conventional and $^{40}Ar/^{39}Ar$ K-Ar ages of volcanic rocks from Ojin (Site 430), Nintoku (Site 432), and Suiko (Site 433) seamounts and the chronology of volcanic propagation along the Hawaiian-Emperor chain: Initial Reports of the Deep Sea Drilling Project, v. 55, p. 659-676.

Dalrymple, G. B., and Moore, J. G., 1968, Argon-40: Excess in submarine pillow basalts from Kilauea Volcano, Hawaii: Science, v. 161, p. 1132-1135.

Dalrymple, G. B., Silver, E. A., and Jackson, E. D., 1973, Origin of the Hawaiian Islands: Amer. Sci., v. 61, p. 294-308.

Davis, D. W., Gray, J., Cumming, G. L., and Baadsgaard, H., 1977, Determination of the ^{87}Rb decay constant: Geochim. Cosmochim. Acta, v. 41, p. 1745-1749.

Doe, B. R., 1970, Lead Isotopes: Berlin, Heidelberg and New York, Springer-Verlag, 137 pp.

Emery, G. T., 1972, Perturbation of nuclear decay rates: Ann. Rev. Nuclear Sci., v. 22, p. 165-202.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: Amer. Jour. Sci., v. 262, p. 145-198.

Ewing, M., Ewing, J. I., and Talwani, M., 1964, Sediment distribution in the oceans: The mid-Atlantic Ridge: Geol. Soc. Amer. Bull., v. 75, p. 17-36.

Faul, H., 1954, Nuclear Geology: New York, John Wiley and Sons, Inc., 414 pp.

Faul, H., 1966, Ages of Rocks, Planets, and Stars: New York, McGraw-Hill Book Co., 109 p.

Faul, H., 1978, A history of geologic time: Amer. Sci., v. 66, p. 159-165.

Faure, G., 1977, Principles of Isotope Geology: New York, John Wiley and Sons, 464 pp.

Faure, G., and Powell, J. L., 1972, Strontium Isotope Geology: Berlin, Heidelberg, and New York, Springer-Verlag, 188 pp.

Fleischer, R. L., Price, P. B., and Walker, R. M., 1975, Nuclear Tracks in Solids: Berkeley, University of California Press, 605 pp.

Fritts, H. C., 1972, Tree rings and climate: Sci. Amer. v. 226, no. 5, p. 93-100.

Fritts, H. C., 1976, Tree rings and climate: London, New York, San Francisco, Academic Press, 567 p.

Funkhouser, J. G., and Naughton, J. J., 1968, Radiogenic helium and argon in ultramafic inclusions from Hawaii: Jour. Geophys. Res., v. 73, p. 4601-4607.

Gardner, M., 1961, Diversions that involve the mathematical constant "e": Sci. Amer., v. 205, no. 4, p. 160-168.

Gentry, R. V., 1973, Radioactive halos: Amer. Rev. Nuclear Sci., v. 23, p. 347-362.

Goldich, S. S., Hedge, C. E., and Stern, T. W., 1970, Age of the Morton and Montevideo Gneisses and related rocks, southwestern Minnesota: Geol. Soc. Amer. Bull., v. 81, p. 3671-3696.

Gott, J. R., III, Gunn, J. E., Schramm, D. N., and Tinsley, B. M., 1976, Will the Universe expand forever?: Sci. Amer., v. 234, no. 3, p. 62-79.

Harbaugh, J. W., 1974, Stratigraphy and the Geologic Time Scale: Dubuque, Iowa, Wm. C. Brown Co., 136 p.

Head, J. W., III, 1976, Lunar volcanism in space and time: Rev. Geophys. Space Phys., v. 14, p. 265-299.

Holmes, A., 1946, An estimate of the age of the earth: Nature, v. 157, p. 680-684.

Houtermanns, F. G., 1946, Die Isotopenhäufigkeiten in natürlichen Ble: und das Alter des Urans: Naturwissenshaften, v. 33, p. 185-186.

Jackson, E. D., Koizumi, I., Dalrymple, G. B., Clague, D.A., Kirkpatrick, R. J., and Greene, H. G., 1980, Introduction and summary of results from DSDP Leg 55, the Hawaiian-Emperor hot-spot experiment: Initial Reports of the Deep Sea Drilling Project, v. 55, p. 5-31.

Jacobsen, S. B., and Wasserburg, G. J., 1980, Sm-Nd isotopic evolution of chondrites: Earth Planet. Sci. Lett., v. 50, p. 139-155.

Jäger, E., and Hunziker, J. C., eds., 1979, Lectures in Isotope Geology: Berlin, Heidelberg, and New York, Springer-Verlag, 329 pp.

Jueneman, F. B., 1972, Will the real monster please stand up: Indust. Res., Sept. 1972, p. 15.

Lord Kelvin (William Thomson), 1899, The age of the earth as an abode fitted for life: Science, new ser., v. 9, p. 665-674, 704-711.

King, C., 1893, The age of the earth: Amer. Jour. Sci., Third Ser., v. 45, p. 1-20.

Kirsten, T., 1979, Lunar highland chronology, in L. H. Ahrens, editor, Origin and Distribution of the Elements: Oxford and New York, Pergamon Press, p. 91-98.

Kofahl, R. E., and Segraves, K. L., 1975, The Creation Explanation: Wheaton, Ill., Harold Shaw Publishers, 255 p.

Krummenacher, D., 1970, Isotopic composition of argon in modern volcanic rocks: Earth Planet. Sci. Lett., v. 8, p. 109-117.

Lugmair, G. W., 1974, Sm-Nd ages: a new dating method (abs): Meteoritics v. 9, p. 369.

Mankinen, E. A., and Dalrymple, G. B., 1979, Revised geomagnetic polarity time scale for the interval 0-5 m.y. B.P.: Jour. Geophys. Res., v. 84, p. 615-626.

McDonald, K. L., and Gunst, R. H., 1968, Recent trends in the earth's magnetic field: Jour. Geophys. Res., v. 73, p. 2057-2067.

McDougall, I., 1964, Potassium-argon ages from lavas of the Hawaiian Islands: Geol. Soc. America Bull., v. 75, p. 107-128.

McDougall, I., 1979, Age of shield-building volcanism of Kauai and linear migration of volcanism in the Hawaiian Island chain: Earth Planet. Sci. Lett., v. 46, p. 31-42.

McElhinny, M. W., 1973, Paleomagnetism and Plate Tectonics: Cambridge, Cambridge University Press, 358 pp.

Moorbath, S., O'Nions, R. K., and Pankhurst, R. J., 1975, The evolution of early Precambrian crustal rocks at Isua, West Greenland - geochemical and isotopic evidence: Earth Planet. Sci. Lett., v. 7, p. 229-239.

Moore, J. N., 1976, Questions and Answers on Creation/Evolution: Grand Rapids, Mich., Baker Book House,128 p.

Morgan, W. J., 1972, Plate motions and deep mantle convection, in Shagam, R., ed., Studies in Earth and Space Sciences (Hess Volume): Geol. Soc. Amer. Mem. 32, p. 265-282.

Morris, H. M., 1974, Scientific Creationism (Public School Edition): San Diego, Creation-Life Publishers, 217 pp.

Morris, H. M., 1977, The Scientific Case for Creation: San Diego, CLR Publishers, 87 p.

Morris, H. M., and Whitcomb, J. C., 1961, The Genesis Flood: Philadelphia, Presbyterian and Reformed Co., 518 pp.

Murthy, V. R., and Patterson, C. C., 1962, Primary isochron of zero age for meteorites and the earth: Jour. Geophys. Res., v. 67, p. 1161.

Nevins, S. E., 1973, Evolution: The ocean says no!: ICR Impact series, No. 8, p. i-iv.

Nier, A. O., 1939, The isotopic constitution of radiogenic leads and the measurement of geological time. II: Phys. Rev., v. 55, p. 153-163.

Noble, C. S., and Naughton, J. J., 1968, Deep-ocean basalts: Inert gas contents and uncertainties in age dating: Science, v. 162, p. 265-267.

Oversby, V. M., 1972, Genetic relations among the volcanic rocks of Reunion: chemical and lead isotopic evidence: Geochim. Cosmochim. Acta, v. 36, p. 1167-1179.

Patterson, C. C., 1956, Age of meteorites and the earth: Geochim. Cosmochim. Acta: v. 10, p. 230-237.

Pettingill, H. S., Patchett, P. J., Tatsumoto, M., and Moorbath, S., 1981, Lu-HF isotope systematiacs of the Amitsoq gneisses, West Greenland: EOS, v. 62, p. 419.

Pettingill, H. S., Patchett, P. J., 1981, Lu-Hf total-rock age for the Amitsoq gneisses, west Greenland: Earth Planet. Sci. Lett., v. 55, p. 150-156.

Protsch, R., 1975, The absolute dating of Upper Pleistocene SubSaharan fossil hominids and their place in human evolution: Jour. Human Evol., v. 4, p. 297-322.

Protsch, R., 1979, New absolute dates on upper Pleistocene fossil hominids from America, p. 69-75 in Berger, R., and Suess, H. E., eds, Radiocarbon Dating: Berkeley, University of California Press, 787 pp.

Ralph, E. K., and Michaels, H. N., 1974, Twenty-five years of Radiocarbon dating: Amer. Sci., v. 62, p. 553-560.

Rutherford, E., and Soddy, F., 1903, Radioactive change: Philos. Mag., ser. 6, v. 5, p. 576-591.

Schramm, D. N., 1974a, The age of the elements: Sci. Amer., v. 230, no. 1, p. 69-77.

Schramm, D. N., 1974b, Nucleo-cosmochronology: Ann. Rev. Astron. Astrophys., v. 12, p. 383-406.

Slusher, H. S., 1973, Critique of radiometric dating: Inst. Creation Res. Tech. Monograph No. 2, 46 p.

Slusher, H. S., 1976, Some recent developments having to do with time, p. 278-285 in Morris, H. M., and Gish, D. T., eds., the Battle for Creation: San Diego, Creation-Life Publishers, 321 pp.

Slusher, H. S., 1980, Age of the Cosmos: Inst. Creation Res. Tech. Mon., no. 9, 76 pp.

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth Planet. Sci. Lett., v. 26, p. 207-221.

Steiger, R. H., and Jäger, E., 1977, Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth Planet. Sci. Lett., v. 36, p. 359-362.

Tera, F., 1980, Reassessment of the "age of the earth": Ann. Rept. Director, Dept. Terr. Mag., Carnegie Inst., 1979-1980, p. 524-531.

Thomson, W., 1862a, On the age of the sun's heat: Macmillan's Mag., March, p. 388-393 (Reprinted in Thomson and Tait, 1890, Treatise on natural philosophy, Part II: Cambridge University Press, p. 485-494).

Thomson, W., 1862b, On the secular cooling of the earth: Roy. Soc. Edinburgh Trans., v. 23, p. 157-159 (Reprinted in Thomson and Tait, 1890, Treatise on natural philosophy. Part II: Cambridge Univ. Press, p. 468-485.

Turner, G., 1970, Argon-40/Argon-39 dating of lunar rock samples: Science, v. 167, p. 466-468.

Verosub, K. L., and Cox, A., 1971, Changes in the total magnetic energy external to the earth's core: Jour. Geomag. Geoelec., v. 23, p. 235-242.

Vogel, J. C., and Beaumont, P. B., 1972, Revised radiocarbon chronology for the stone age in South Africa: Nature, v. 237, p. 50-51.

Wetherill, G. W., 1966, Radioactive decay constants and energies, in: Handbook of Physical Constants, S. Clark, ed., Geol. Soc. Amer. Mem. 97, p. 513-519.

Wetherill, G. W., 1975, Radiometric chronology of the early solar system: Ann. Rev. Nuclear Sci., v. 25, p. 283-328.

Wilson, J. T., 1963, A possible origin of the Hawaiian Islands: Canadian Jour. Phys., v. 41, p. 863-870.

York, D., and Farrquhar, R. M., 1972, The Earth's Age and Geochronology: Oxford, Pergamon Press, 178 pp.